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Assessment of Upper Cretaceous Strata for Offshore CO_2 Storage, Southeastern United States

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Abstract: This is the first assessment ofUpper Cretaceous strata for offshore CO_2 storage resources in the southeastern United States outer continental shelf. This study focuses on Upper Cretaceous geological units using legacy industry 2-D seismic reflection and well data. Itprovides an integrated description, and reliable subsurface evaluation of Upper Cretaceous potential storage reservoirs.Structure and thickness (isochore) maps were generated for the main potential reservoirs and seals. Results indicate that Upper Cretaceous geologic units consist of moderately to highly compartmentalized stratigraphic systems. Five reservoirs and seals were recognized as potential storage units. Two reservoirs are particularlyconsidered as the main CO_2 storage units with quality and integrity capableto meet the CO_2 storage requirements by the U.S. Department of Energy. They consist of limestone deposits with significant interbedded sandstones, shales and dolomites, and are sealed by thick shales interbedded with limestone. The porosity ranges from 20 to 30% and the permeability ranges from 1 to 447 mD. Regional CO_2 storage capacity is estimated to be approximately 32 GT in Upper Cretaceous units. The local storage capacity for the two significant reservoirs in the Southeast Georgia Embayment contribute ~ 9 GT of that amount.

Key words: Atlantic offshore, Southeast Georgia Embayment, CO_2 Sequestration, Geologic Storage, Upper Cretaceous

1. Introduction and Objectives

With more than 80% of the world's energy derived from fossil fuel, and considering that the U.S. Environmental Protection Agency estimates that about 40 percent of the anthropogenic CO_2 emissions in the U.S. are generated in the southeast, the lack of an offshore CO_2 assessment constitutes a major gap in understanding the prospective regional storage resource. The contribution is about 1444 million metric tons of CO_2 [1]. Offshore geological repositories have received relatively little attention as potential CO_2 storage sites, despite having a number of important advantages over onshore sites [2]. Subsurface geologic storage of carbon dioxide (CO_2) can play a major role in offsetting greenhouse gas emissions in a manner that is safe, economical, and acceptable to the public. Due to legal advantages and apparently vast resource capacity, offshore storage offers an attractive alternative to onshore storage. Although the storage capacity of offshore reservoirs is expected to be vast, no comprehensive assessment of the offshore storage resource in the southeastern United States has been performed.

In an analysis of a 10,000 mi^2area of offshore Alabama and the western Florida Panhandle, Hills and Pashin (2010) suggested that about 170 GT of CO_2 could be stored in the Miocene Sandstone and that at least 30 GT could be stored in deeper Cretaceous formations [3]. To date, only limited studies have been conducted. Smyth et al. (2008) considered storage options in the Carolinas and recognized that significant storage potential exists along the length of the Atlantic

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continental shelf (ACS), although the potential storage resource was not quantified. Two potential CO_2 sinks are present in geologic strata below the Atlantic seafloor, in Upper and Lower Cretaceous (Fig. 1) and the estimated capacities are about 16 Gt and up to 175 Gt, respectively [4, 5]. However, this research is part of the Southeast Offshore Storage Resource Assessment (SOSRA) research project funded by Department of Energy (DOE), U.S., for assessment of offshore CO_2storage resources. The project study areas are the offshores of North Carolina, South Carolina, Georgia and Florida (Fig. 2). Since the project is divided based on the age of the geological units, this paper focuses only on development of offshore prospective storage resource assessment of subsurface saline formations, especially Upper Cretaceous section of the Mid and South Atlantic offshore regions.

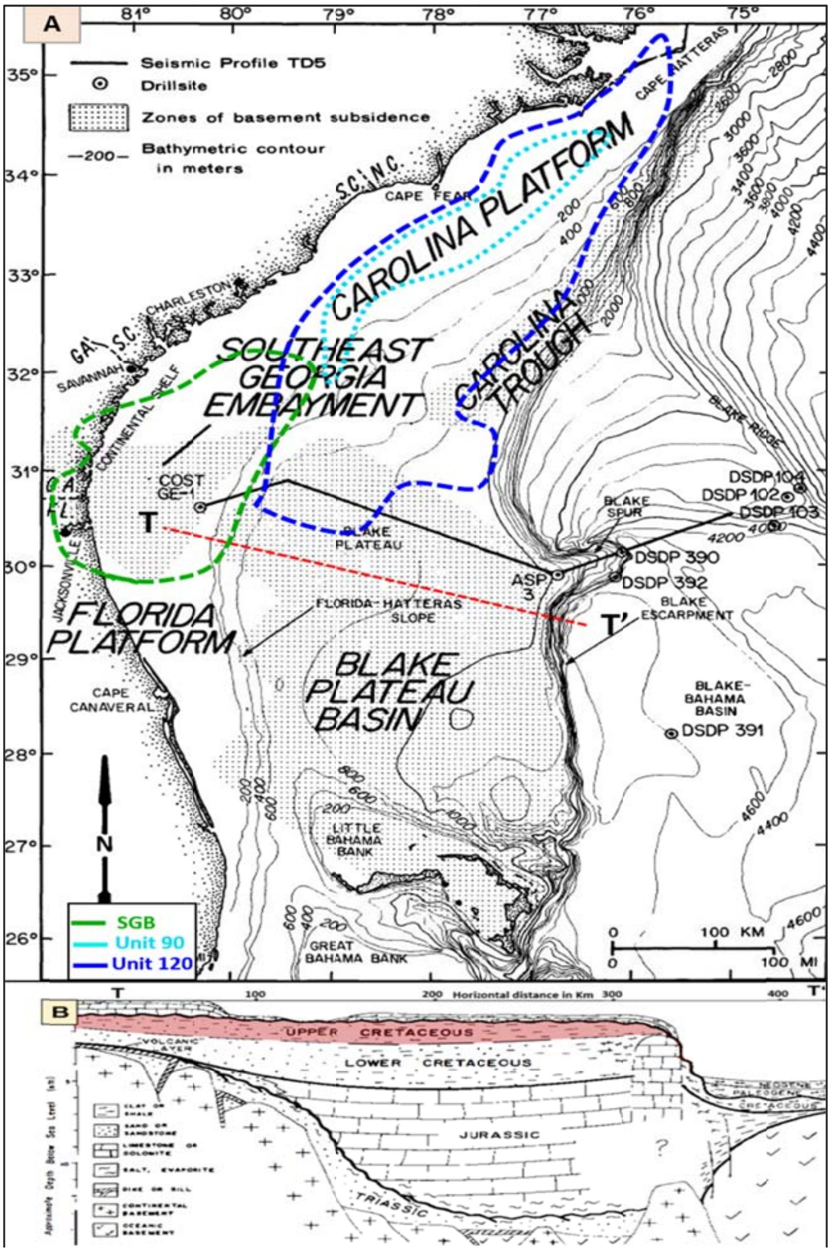

Fig.1 (A) Location map showing the main regional geologic provinces withinthe offshore areas considered for potential storage of CO_2, (modified after [4]), (B) Schematic geologic cross section *T-T'* of the Southeast Georgia Embaymentand Blake Plateau, modified after [19] and [20].

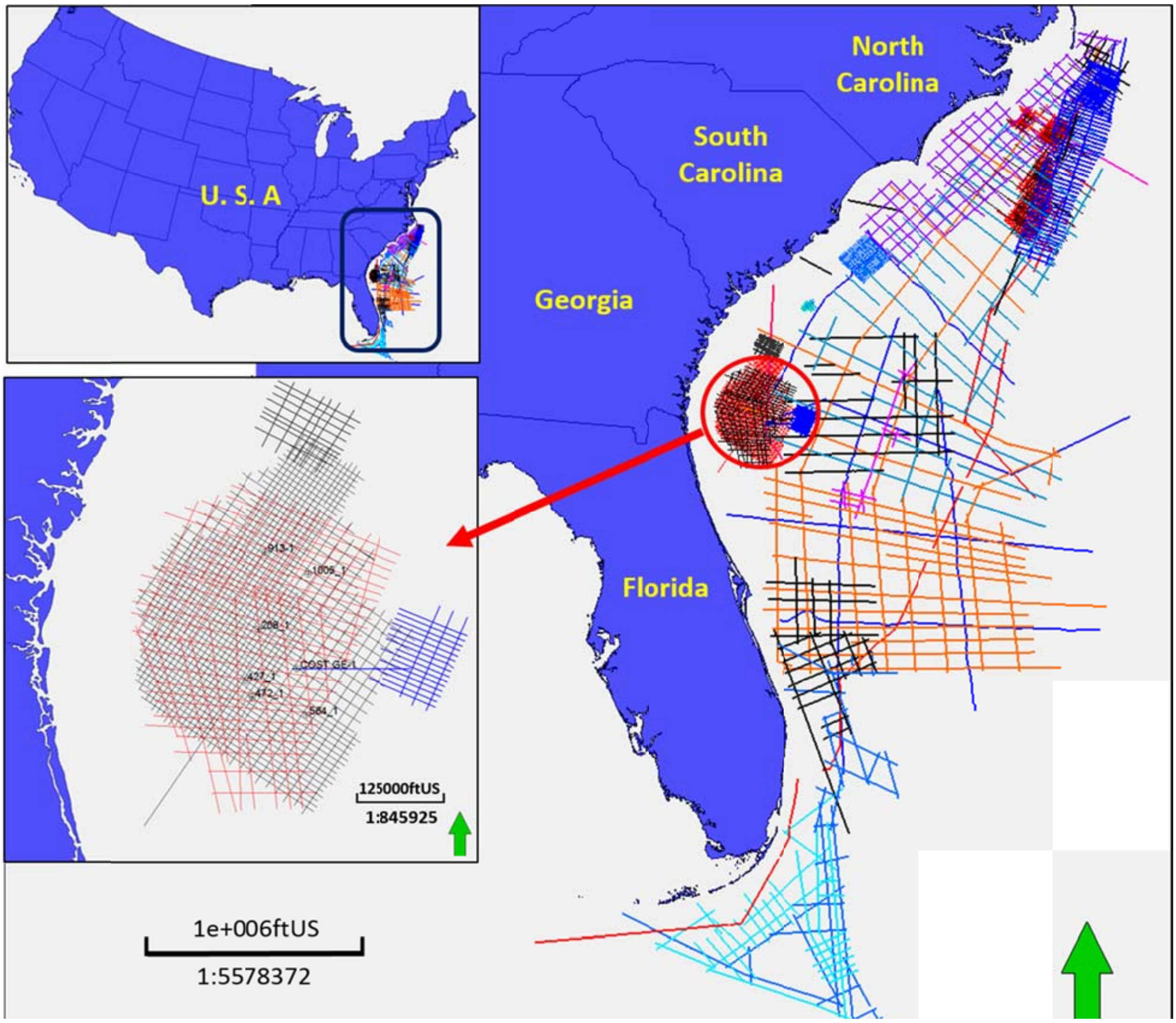

Fig. 2 Location map of legacy Atlantic Margin industry seismic reflection data, with a total length of more than 100,000 miles. Red circle indicates location of high-density seismic survey within Southeast Georgia Basin.

The objectives of this research are to: (1) provide a consistent, integrated description, and a reliable subsurface evaluation of Upper Cretaceous section to predict potential for CO_2 geologic storage, (2) identify seismic reflectors and create maps to characterize the structure for Upper Cretaceous section, (3) understand the regional porosity and permeability regime, the quality of potential reservoirs and seals and the storage capacity of Upper Cretaceous section, (4) identify stratigraphic units containing reservoirs or sinks that might be suitable for effective, large-volume geologic storage of CO_2 in Upper Cretaceous age, and (5) evaluate the quality and lateral extent of the sealing rock and its ability to safely ensure the retention of the trapped CO_2 within the confined porous formation for hundreds of years.

To achieve the research objectives, several hypotheses were proposed. These are (1) Upper Cretaceous formations have potential for at least 16 GT of CO_2 storage capacity, (2) Upper Cretaceous potential sink is overlain by a low-permeability seal layer, (3) distinct porosity and permeability regimes, which are influenced by depositional environments and lithologic composition are present and widely distributed in Upper Cretaceous, and (4) Upper Cretaceous units consist of moderately to highly compartmentalized stratigraphic systems which help increase the storage capacity.

After assessing the study area for CO_2 sequestration, this paper will attempt to answer additional research questions that are connected with the research objectives. These questions are: (1) Do Upper Cretaceous geologic units have potential for significant CO_2 storage capacity? (2) What are the quality and spatial extent of the prospective reservoirs and seals? (3) How do reservoir and seal structures affect long-term CO_2 sequestration? (4) To what extentdoesthe Upper Cretaceous sedimentary section extend offshore beneath the continental shelf? (5) Does it have distinct porosity and permeability regimes? And how dothese regimes impact CO_2 storage quality and capacity?

For CO_2 sequestration and storage, supercritical conditions are required. At depths of 2625 ft (800 m) or greater, CO_2 can be sequesteredunderground as a supercritical fluid. Supercritical CO_2 means that the CO_2 is at its thermodynamic critical point, which includes a temperature exceeding 88.3°F (31.1°C) and a pressure exceeding of 72.9 atmospheres. At such high values, the CO_2 has hybridpropertiesofbotha gas and liquid [6]. Since the liquid, or supercritical CO_2, at reservoir conditions (with good porosity and permeability) occupies a much smaller volume than the gaseous state at atmospheric conditions, this provides the possibility of more effective exploitation of underground storage space and improves storage security [7, 8]. At sufficient depths, CO_2 is more like a liquid than a gas and the CO_2 density ranges from 50 to 80% of the density of water, and is close to the density of some crude oils. In this case, since the CO_2 is less dense than saline water, the buoyant forces will drive CO_2 upwards within the geologic formations and accumulates withina porous reservoir when a cap seal is reached, i.e., an impermeable layer and enclosed trap [9].

In the study area, the CO_2 geological storage options are deep saline formations which are found within the Upper and Lower Cretaceous sections. Geological criteria are needed to qualify the Upper Cretaceous section for CO_2 storage. The criteria include: (1) high porosity (more than 20% is preferable, andnot less than 10%), (2) good permeability, such as ~200 millidarcy (mD), (3) a trapping mechanism, an overlying caprock, or seal, is very important to prevent vertical migration into overlying freshwater aquifers, however, stratigraphic trapping through lateral facies changes may be of greater interest in this study area than in other basins along the Atlantic offshore margin [10], (4) cap-rock efficacy includes lateral continuity, no faults, and capillary entry pressure, (5) the Cap-rock thickness (100 m is perfect but not less than 20 m), (6) reservoir properties which include reservoir, seal, areal extent, depth, net reservoir thickness greater than 50 m, and (7) pressure, temperature, salinity, uniform stratigraphy, and seal integrity [11, 12].

2. Geological Setting of the Southeast Atlantic Offshore

The geology of the offshore area of the Southeastern United States is complex, therefore, a brief description of the Atlantic Continental Shelf is included here. Following the latest collisional event of Laurentia and Gondwana at the end of the Paleozoic (Alleghenian), continental rifting began in the Early Mesozoic as part of the breakup of the supercontinent Pangea. Locally, this involved tectonic subsidence in restricted extensional basins, followed by thermal subsidence along the Eastern North American margin that still continues today. Generally speaking, stratigraphic sequences on this passive margin are characterized by extensive lateral continuity and relatively minor structural disruption. The oldest post-rift sediments, above a regional unconformity known as the “post rift unconformity”, are of Jurassic age and are the product of rapid clastic sedimentation from erosion followed by a period of evaporite deposition and subsequent initiation of widespread, shallow water carbonate deposition with some terrigenous input [13]. Geophysical and stratigraphic studies suggest that the

Jurassic section is at least 4.6 miles thick in the basins, and thickens seawards [14]. The Cretaceous section is characterized by more clastic sedimentation in the north and more carbonate deposition in the south, forming a large carbonate platform over the Blake Plateau and offshore Florida. In Upper Cretaceous, the Suwanee Strait provided clastic sedimentationto the Blake Plateau creating a distinct facies change to the neighboring offshore Florida and Bahamas carbonate platforms[15]. Strong paleo-currents controlled the sedimentationin large portions of the offshore region from the Upper Cretaceous to the Cenozoic. The Suwannee Strait eventually evolved into today's Gulf Stream providing strong erosive power that eroded most of the Paleogene sediments on the Blake Plateau and prevented deposition off the Florida-Hatteras slope where it continues to the north along the shelf edge [15]. The major sedimentary deposits from north to south include the Carolina Trough, the Southeast Georgia Embayment, and the Blake Plateau Basin, which range in sediment column thicknesses from 10,000 to 23,000 ft [16].

2.1 Carolina Trough

The Carolina Trough is a long, narrow sedimentary basin located at the edge ofthe Atlantic Continental Shelf directly east off the coast of the Carolinas (Fig. 1). The trough is roughly linear and positioned in a SW-NE trend parallel to the Eastern North American coastline. The CarolinaTrough formed from initiation of rifting during the Triassic-Jurassic periods. During this time, evaporateswere deposited in the trough, followed by a clastic deposition at the end of the Jurassic through the Cretaceous. This gave rise to salt diapirism as the salt beds mobilized and deformed the overlying sediments. The salt dome deformations are visible on the ocean floor, and are placed at a depth of 9800 ft under water[17]. The deformations are characterized by major faults centered on the dome structures. Throughout the Cenozoic, the Gulf Stream eroded many of the sediments from the area; however, around a total of 7.5 miles of sediments is believed to have been accumulated in the Carolina Trough [17].

2.2 Southeast Georgia Embayment

The Southeast Georgia Embayment is a broad depression plunging eastward from the Atlantic Coastal Plain (Fig. 1). It is a major structural feature of the Florida-Hatteras Shelf, but is considered a minor sedimentary geologic unitcompared to the other sedimentary basins in the region. Based oncores recovered from the COST GE-1 well, Paleozoic rocks sit at a depth of 10560 ft and are overlain by probable Jurassic non-marine clasts, dolomites, coal, and anhydrite. This sedimentary sequence continued throughout the Mesozoic, until carbonate sedimentation took over in the Cretaceous. Sedimentation in the Southeast Georgia Embayment is still likely ongoing today [17, 18].

2.3 Florida-Hatteras Slope

The Florida-Hatteras Slope is a prominent geological feature, but is not a "true" continental slope (Fig. 1). This feature separates the North American Continental Shelf from the Blake Plateau and was formed by mainly erosive processes of the Suwanee Strait. This prevented deposition on the eastern margin of the shelf while coastal margin sedimentation was unaffected, resulting in a slope-like feature [17].

2.4 Blake Plateau Basin

The Blake Plateau Basin (Fig. 1) is a major sedimentary basin formed at the same time and bythe same processes that resulted in formation of the CarolinaTrough. The basin lies at depth ranging approximately from 2000 to 3300 ft, and its subsidence depth is much greater than the Carolina Trough. Blake Plateau has a complexgeology and tectonic history [19]. The Blake Plateau basin is separated into two parts, northern and southern, and is separated by an east to west trending fracture system terminating at the Blake Spur on the western margin of the plateau [14]. The southern portion of the plateau is characterized by increased subsidence relative to the northern portion, and is the product of new oceanic crust created during rifting. The seaward margin of the southern portion consists of reef development from the Cretaceous time. In contrast, the northern seaward margin was developed from erosional sedimentation [17].

3. Geophysical Data

Two-dimensional (2D) industry seismic reflection data were collected on the Atlantic Margin in the 1970's and 1980's as part of a phase of offshore petroleum exploration.The acquisition parameters, navigation references, and processing methodologies vary among the various seismic surveys. These seismic data are available through the Bureau of Ocean Energy Management (BOEM) and United States Geological Survey (USGS) databases. There are seven exploratory wells with a variety of geophysical logs in the south Atlantic area (Fig. 2). Three wells have the digital logs necessary to conduct integration with seismic data; the others have reports (Table 1). In addition, there is a report of the Atlantic Margin Coring (AMCOR) for shallow wells (maximum depth is 1,010 ft) drilled in 1976. All depth references in this paper are based on depth below the Kelly Bushing (KB).

Table 1 Wells used for seismic-well tie and formation evaluation.

Well name	Long. X	Lat. Y	Water Depth (ft)	KB (ft)	TD (ft)	TVD (ft)
COST GE-1	-80.2997	30.619	136	99	13254	13254
Exxon 564_1	-80.25583	30.43972	145	81	12863	12863
Transco 1005_1	-80.2439	30.9928	134	101	11635	11635

4. Methodology and Data Analysis

Seismic reflection data provide the basic structural control of the subsurface geology constrained by available exploration wells. For quality control, a series of data analysis techniques were applied in this study. A flowchart of the seismic data calibration with well control and further interpretation is provided in Fig. 3. Seismic mis-tie analysis was performed and applied among the seismic lines used in this research. Well logswere used to derive a detailed assessment of the geologic formations penetrated by the boreholes and tie the interpreted geologic strata to key seismic horizons. This helped with the calibration and consistency of the seismic data interpretation. Wells with sonic and density logs were selected to calculate reflection coefficients. Wavelets were extracted from the seismic lines that intersected in the proximity of the wells and were used to generate synthetic seismograms. Check-shot surveys were used to verify the resulting seismic-well ties. Geophysical well logs were used to identify rock types and determine fundamental storage parameters, including porosity and permeability.For seismic interpretation and geophysical log analysis, *Schlumberger's Petrel Software (2015)* was employed for stratigraphic and structural interpretation and for defining the storage geological windows of interest and the respective sealswithin the Upper Cretaceous unit. The seismic interpretation workflow includes picking significant horizons constrained bywell control, creating main surfacesstratigraphy, and generating structural maps in time, and converting time to depth unit. Stratigraphic and structural cross sections as well as isochore, isolith, and structural contour maps provided the basis for geological characterization, and identification of prospective CO_2 sinks and reservoir seals (Fig. 3). This characterization helps to define the areal extent and thickness of prospective storage formations.

4.1 Data Calibration and Normalization

To accomplish the research objectives, the data needed to be pre-processed to common specifications. The seismic datasets have different acquisition and processing parametersand were acquired over many years. The data sets have seismic mis-ties and variations in amplitude scaling. Therefore, two main steps were undertaken prior to interpretation includingdata calibration and amplitude normalization. These steps were necessary to account for the vintage and datum differences within the data. Fig. 3 gives an overview of the data calibration and interpretation workflow.

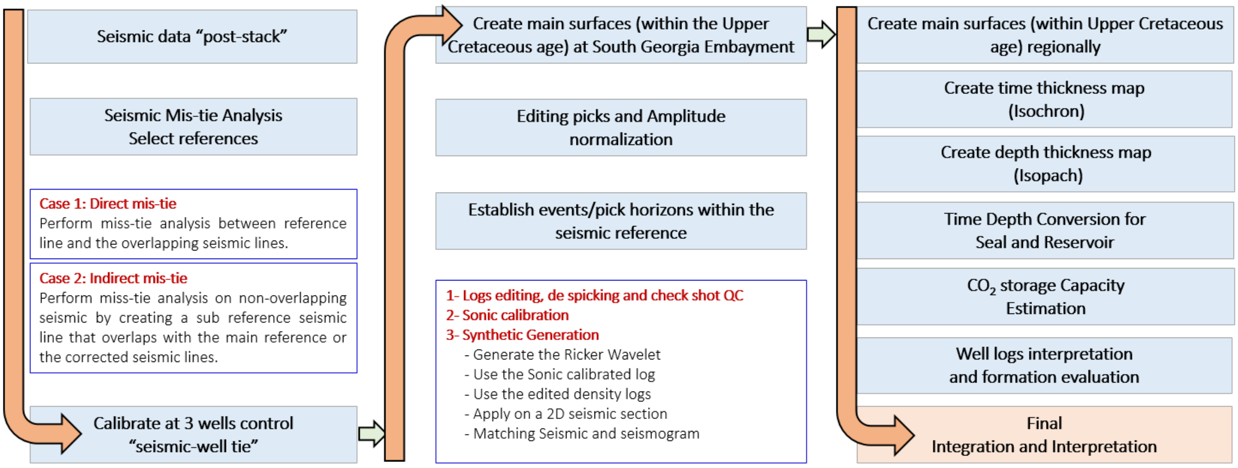

Fig. 3 Flowchart outlining seismic data calibration and interpretation workflow.

4.2 Mis-Tie Analysis

Given different vintages and varying acquisition parameters, most seismic data sets have seismic mis-ties. The various data sets were acquired with different geographic coordinate projections, different datums, and different processing flows. Analysis and removal of mis-ties from the seismic data is very important when an interpreted reflection does not close, or tie, when interpreting intersecting lines. Some solutions to the mis-tie issues include (1) application of amplitude normalization or scaling to unify the amplitude scale in the data sets, and (2) application of vertical mis-tie (absolute value) and phase mis-tie (absolute value) with constant correction.

4.3 Seismic-Well Tie

Seismic-well tie analysis has been conducted to compare well logs (measured in depth units), with seismic data (measured in time units). It is important to relate horizon tops identified in the wells with specific reflectors on the seismic sections in order to create the reservoir and seal structure maps to assess CO_2 potential storage. For quality control and verification of the check shot data, editingwas applied to the sonic and the density logs to remove unwanted spicks before sonic calibration. For synthetic seismogram generation, several different wavelets were generated and assessed, especially the deterministic extended and the Ricker wavelets. Ricker wavelets were generated for several different central frequencies, the center frequency of 22.5 Hz (USA phase) provides the best fit. The same sampling rate of 4 msec was used for all seismic data sets. Seismic-well tie analysis was applied using data from the COST GE-1, Exxon 564-1 and Transco 1005-1 wells. The COST GE-1 well data is shared to conduct multi seismic-well tie analysis using the neighboring seismic lines. Reflection coefficients (RC) were calculated using the calibrated sonic and density logs which were convolved with the selected wavelet to get the synthetic seismogram. Finally, the synthetic seismograms matched the seismic data achievingagood fit. The methods applied included (1) using key well tops to match peak — peak or trough — trough, (2) using bulk shift to tie synthetic to seismic, or variable time shift to move and stretch two or more horizons, and (3) using the alignments points to make small adjustments between the synthetic and seismic data (Fig. 4) [22].

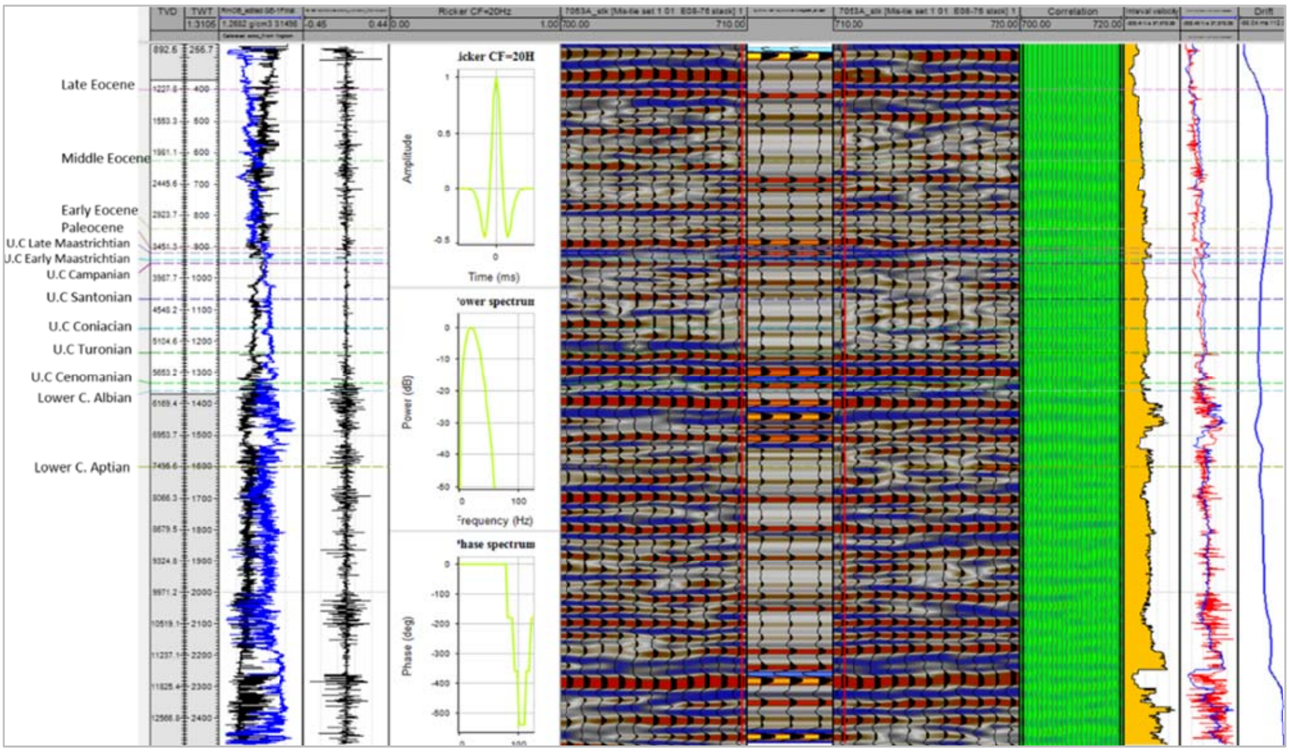

Fig. 4 Seismic-well tie for COST GE-1well.

5. Structural Interpretation

5.1 Picking Horizons and Creating Surfaces

To achieve the research objectives, some factors were considered for selecting horizons in the Upper Cretaceous section. Porosity and permeability distribution versus depth are critical factors. Also, the lithology descriptions according to the cores and cuts, and well log interpretation were considered. The available control wells are clusteredinthe Southeast Georgia Embayment and not widely distributed along the Atlantic offshore. Although it was difficult to pick all horizons due to the reflectors pinch out caused by lateral facies changes [10], the significant markers and the top and baseof the Upper Cretaceous were picked within the Southeast Georgia Embayment, and then extrapolated at a larger regional scale. However, the tops wereselected basedon the paleontological data, depths versus geologic series or stage, from the COST GE-1well [23]. The corresponding geological formations to these horizons are illustrated in Table 2 [21]. The main units picked are (1) Maastrichtian top, which represents the top of Upper Cretaceous, (2) Turonian top and (3) Albian top, which represents the baseof Upper Cretaceous. More detailed picking of horizons was conducted using the close loop approach which is based on selecting at least three adjacent seismic intersections as guides in order to close the picking loop and to make sure that the same reflectors are selectedat the seismic intersections. Manual interpretation was used for picking horizons in some cases. In a few cases where the reflectors were clearly continuous, the seeded 2D auto tracking feature in Petrel was used. Structure maps were generated and smoothed gently to remove any random noise or spikes. The maps' statistics and visual display werechecked for quality control. However, the horizons picked in the Southeast Georgia Embayment have a high degree of confidence due to the high densityof track lines, were diligently interpolated and extrapolated regionally along the offshore areas of Carolina Trough and Blake Plateau Basin.

Table 2 Stratigraphic nomenclature of rock formations identified onshore along the U.S. southeastern coast [21].

Epoch	Stage / Age	South Carolina	Southeast Georgia	Florida
Upper Cretaceous	Maastrichtian	Peedee	Unnamed Marine Beds	Lawson Limestone / Pine Key
	Campanian	Black Creek Group		
	Santonian	Middendorf	Middendorf	
	Coniacian	Cape Fear		
	Turonian	Clubhouse	Atkinson	Atkinson
	Cenomanian	Beech Hill		

5.2 Time Depth Conversion

Two methods were used to convert the interpreted structural maps from time to depth. Both methods give similar depths, when compared with the well data. The two methods are shown below; however, there is uncertainty with depth due to insufficient data.

(1) A simple polynomial equation was used for plotting the relationship between the measured depth (ft) and TWT (ms)for the COST GE-1 well, where (x) and (R) represent the surface structure map (in msec) and the correlation coefficient for the linear regression, respectively [24]. This polynomial equation gives an accurate depth for the interpreted surfaces at wells COST GE-1, Exxon 564-1 and Transco 1005-1 after converting the domains from time (ms) to depth (ft). Below is an example of apolynomial equation that wasused, where the correlation coefficient is high ($R^2 = 0.9995$).

$$y = 0.00063x^2 + 3.9496x - 470.74$$

(2) To get a more accurate depth to the top of the reservoir, major velocity boundaries of the overburden layers are taken into consideration in order to build linear velocity models in a layer cake model from the surface down to the top of the reservoir. Schlumberger *Petrel 2015* offers an option to create an advanced velocity model. This velocity model is defined using input parameters such as tops, surfaces, time-depth relationship, and includes using two types of linear velocity functions.

Those velocity functions are ($V=V_0+ K*Z$) and ($V=V_0+K*(Z-Z_0)$), where V_0 derives at different locations [25]. The parameter K represents the linear velocity slope and describes the velocity increment with depth, which reflects the layer compaction. For each layer, the K value of the velocity law is the average of the K value derived at each well for the layer under consideration. A minimum error estimation of the compaction factor K is obtained and used derive a V_0 surface and any correction built into the velocity model is reflected in the V_0 surface. Due to the compaction being considered as a regional event, K remained constant. To create the velocity model, the time-depth relationship of the COST GE-1, Exxon 564-1 and Transco 1005-1 wells are used. The procedures included: (1) using cross plots of picked two-way travel times and the interval velocities from the check shot data for quality control in order to check the time-depth relationships, (2) calculating the interval velocity based on the well top depths, checking shot data and the interpreted surface times at the well top positions, and (3) using well tops to define the correction. However, the interpolated interval velocities range from 7600 to 7800 ft/sec along the top of Upper Cretaceous, and from 8500 to 14000 ft/sec along the Turonian surface (Fig. 6).

5.3 Structure Maps

The regional extents of Upper Cretaceous formations have similarity. They are shallow towards the shoreline and dip gradually seaward beneath the offshore of Southeast Georgia Basin and continental shelf, and become deeper towards the continental slope. The top of Upper Cretaceous section varies from 1000 ft to 6000 ft depth, and it is encountered at a depth of 945 ft below MSL in well 6004B [26]. Such a depth is not suitable for CO_2 sequestration because the CO_2 would not reach supercritical conditions [6]. However, the Turonian structure, which appears to be compartmentalized in several reservoirs, has a depth range from 2500 ft (near the Carolinas), to approximately 9000 ft (in the Carolina Trough). For the base of Upper Cretaceous surface, the depth ranges from 2700 ft to 12000 ft (Fig. 7).

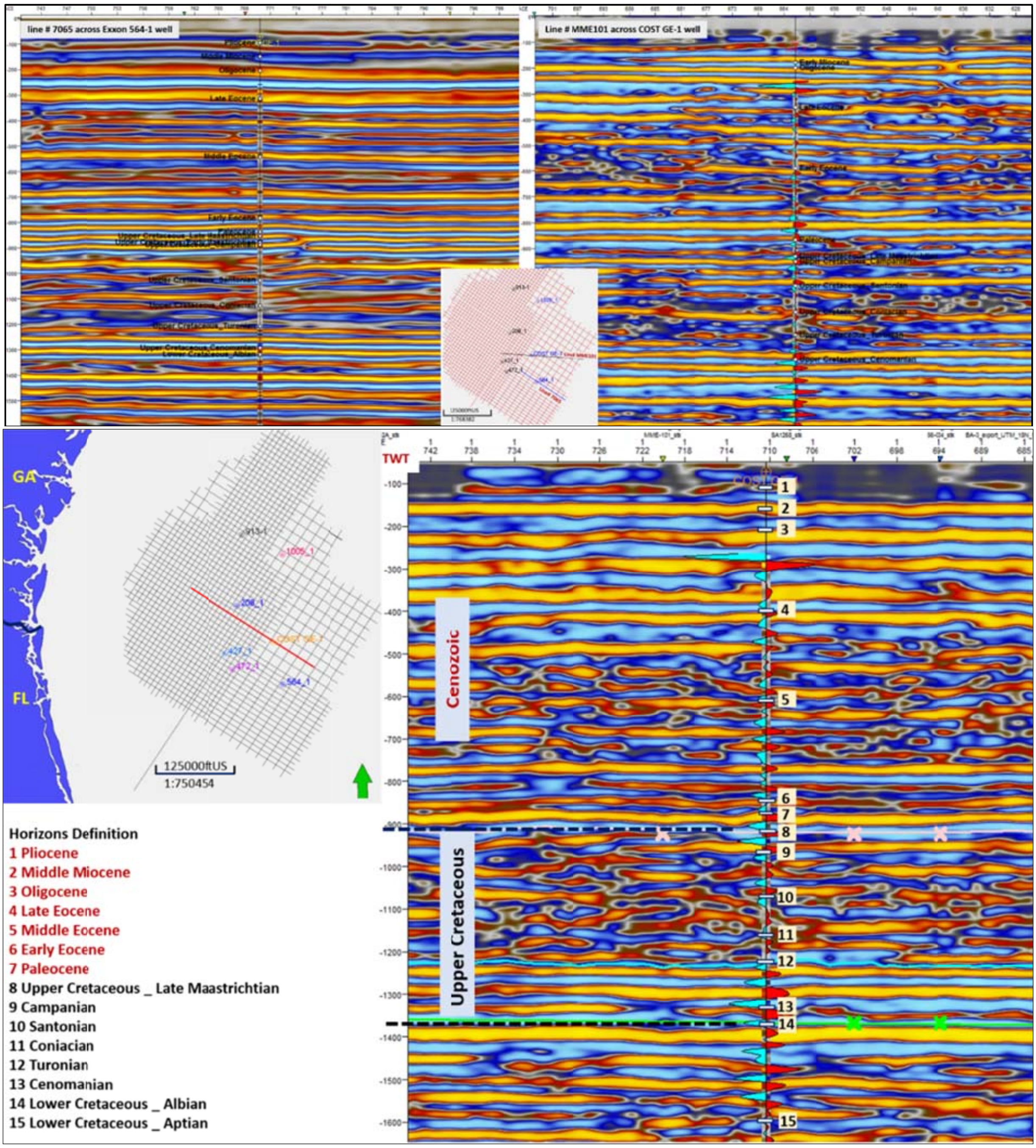

Fig. 5 Analysis of seismic sections: (Top) Two seismic sections that were tied with different wells; (Bottom) Paleontological tops and picking the top and baseof Upper Cretaceous at the COST GE-1 well.

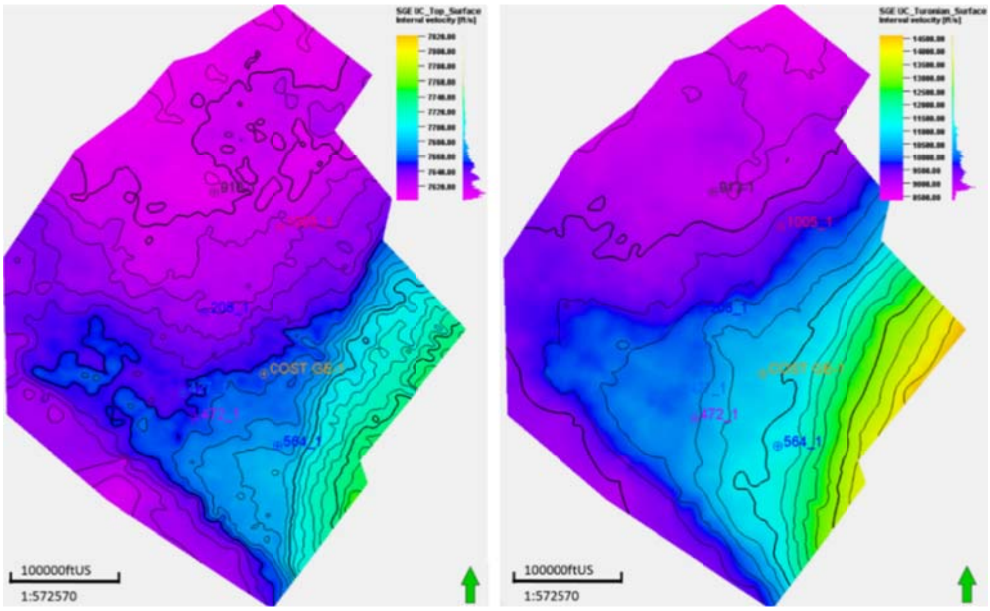

Fig. 6 Examples of the interval velocity interpolation within the Southeast Georgia Embayment using the advanced Velocity Model; (Left):between the top of Upper Cretaceous and Turonian surface; (Right): between the Turonian surface and the base of Upper Cretaceous.

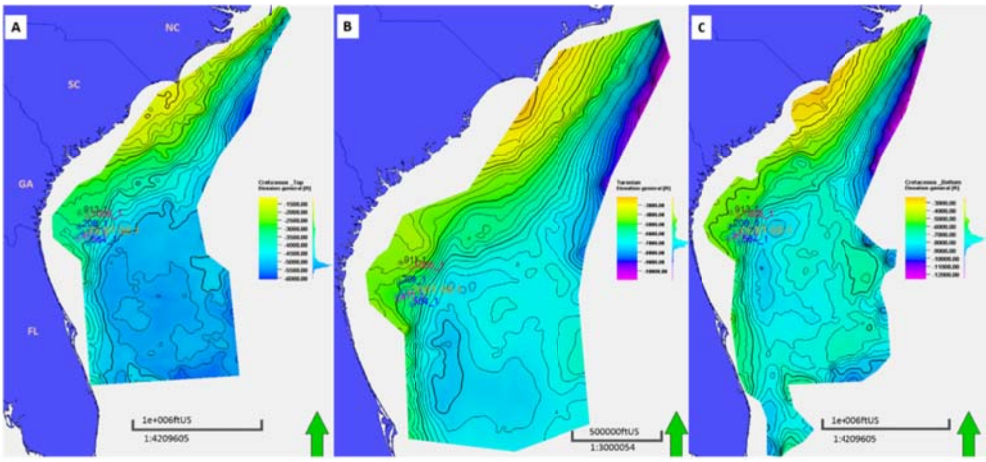

Fig. 7 Regional 2D structure maps (in feet) for: (A) top of Upper Cretaceous (Maastrichtian), (B) Turonian and (C) base of Upper Cretaceous [Albian].

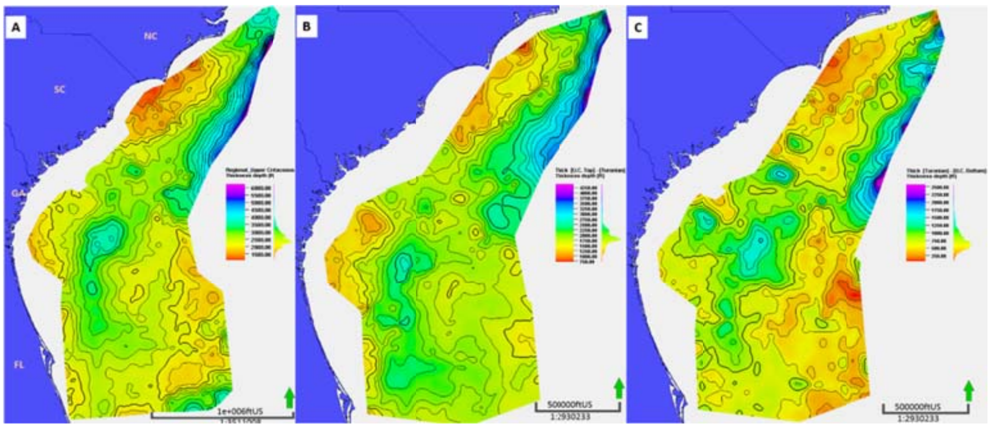

Fig. 8 Regional thickness maps [isochore, in feet]: for (A) entireUpper Cretaceous section, (B) Maastrichtian to Turonian, and (C) Turonian to baseof Upper Cretaceous.

Nevertheless, the regional thickness map of the entire Upper Cretaceous section indicates the presence of thick accumulated sediments in the Atlantic offshore, especially the Carolina Trough. The thickness range is approximately from 1200 ft to more than 6000 ft. This would represent a significant opportunity for CO_2 sequestration with large storage capacities since it has sequences of limestone and calcareous shales in the upper part, limestone and dolomites interbedded with sandstones in the middle, and shales with reasonable porosity and permeability values according to the cores and side-wall cuts in the lower part [10]. Sediments between the top of Upper Cretaceous and the Turonian surface,which are mostly calcareous shales with some limestone, arrange in thickness from 750 ft to more than 4000 ft. It has potential to be the best regional seal. It has shale intervalssequences with low permeability less than 3 mD [10]. Similarly, sediments between the Turonian surface and the base of Upper Cretaceous, have thicknesses from 250 ft to more than 2500 ft (Fig. 8). It has potential for two compartmented reservoirs (Fig. 12).

At the local scale in the Southeast Georgia Embayment, which has been extensively covered with seismic surveys and wells, the depth of the top of Upper Cretaceous section varies approximately from 3000 ft to 4500 ft; similarly, the Turonian surface, which would serve as a reservoir, has a depth range from 4000 to 7000 ft. Such depths and thicknesses are suitable for CO_2 sequestration. The sediment column between the top of Upper Cretaceous and Turonian surface, mostly shales with low permeability, would serve as a thick (800 to 2600 ft) seal. Similarly, the difference in depth between the Turonian surface and the base of Upper Cretaceous has a thickness between 250 to 1200 ft (Fig. 9). It represents the prospective reservoirs where high porosity and permeability exist (Fig. 12). All structure and thickness maps were created within specific boundaries (polygons), in which horizons were picked with high spatial density in order to get good lateral interpolation.

5.4 Well Log Interpretation

Well logs provide critical information on the geologic formations in the subsurface. The gamma-ray (GR) log tool measures the natural radioactivity in different rocks. Spontaneous Potential (SP) measures the potential difference versus depth between the voltage in the wellbore and an electrode on the surface [27]. Both GR and SP can be used to determine lithology and correlate stratigraphy and they have the same response to porous layers. For pure sandstones and carbonates, the gamma-ray values are generally less than 90 API due to very low radioactive material. Spontaneous Potential also has low values. However, shale has high radioactive elements which elevate the gamma-ray values as well as the Spontaneous Potential that also shows high voltage [27]. Density logsprovide a continuous record of the formation's bulk density which is a function of formation porosity, fluid content in the pore spaces, and matrix density [27]. It is commonly used to calculate porosity. However, neutron log provides fluid-filled porosity and measures hydrogen concentration in a formation. The crossover between neutron and density logs is the most reliable indicator to a formation reservoir (Fig. 10). With the lower density and the higher neutron values, the two curves will crossover or touch each other. Therefore, greater crossover between the density and neutron logs indicates a better quality reservoir [28]. This occurs at small intervals since most of the lithology is limestone and dolomite. In the lower part of upper Cretaceous, some intervals have crossover which in reality represent sandstone. Also, at small intervals, since the neutron porosity curve is to the right of the density porosity curve, it indicates a wet sand and/or porous medium. However, at most depth intervals, the neutron porosity curve is to the left of the density porosity curve; this is a good indicator of shale. Fig. 10 also shows stratigraphy correlation between wells after flattening the structure to the top of Upper Cretaceous (Early Maastrichtian surface). Although porosity values ($\emptyset$) are available from core and side-wall cuts at specific intervals in the well COST GE-1, in this study, porosity was also calculated from the sonic logs using the Wyllie time average formula [29] at COST GE-1, Exxon 564-1 and Transco 1005-1 wells:

$$\emptyset = [\frac{\Delta t_{log} - \Delta t_{matrix}}{\Delta t_{f} - \Delta t_{matrix}}],$$

where:

Δt_{log} = acoustic transit time, in µsec/ft.

Δt_{matrix}= acoustic transit time of the formation matrix, in µsec/ft, and

Δt_{f}= acoustic transit time of interstitial fluids, in µsec/ft.

Acoustic transit timesof 47.5 µsec/ft and 89 µsec/ft wereobtained from the sonic log andused forthe limestone matrix and the interstitial fluid (brine), respectively [30]. Log interpretations indicate a sequence of shale interbedded withlimestone. In COST GE-1 well, the lithologic description indicates that the Coniacian couldserve as a seal at a depth between 4870 and 5150 ft since it has poor to fair porosity, and consists of silt and calcareous. The intervals of depths from 5500 to 5575 ft and from 5700 to 5950 ft, which include Turonian and Cenomanian ages, have high porosity and permeability. These could serve as compartmentalized reservoirs (Figs. 10 and 12).

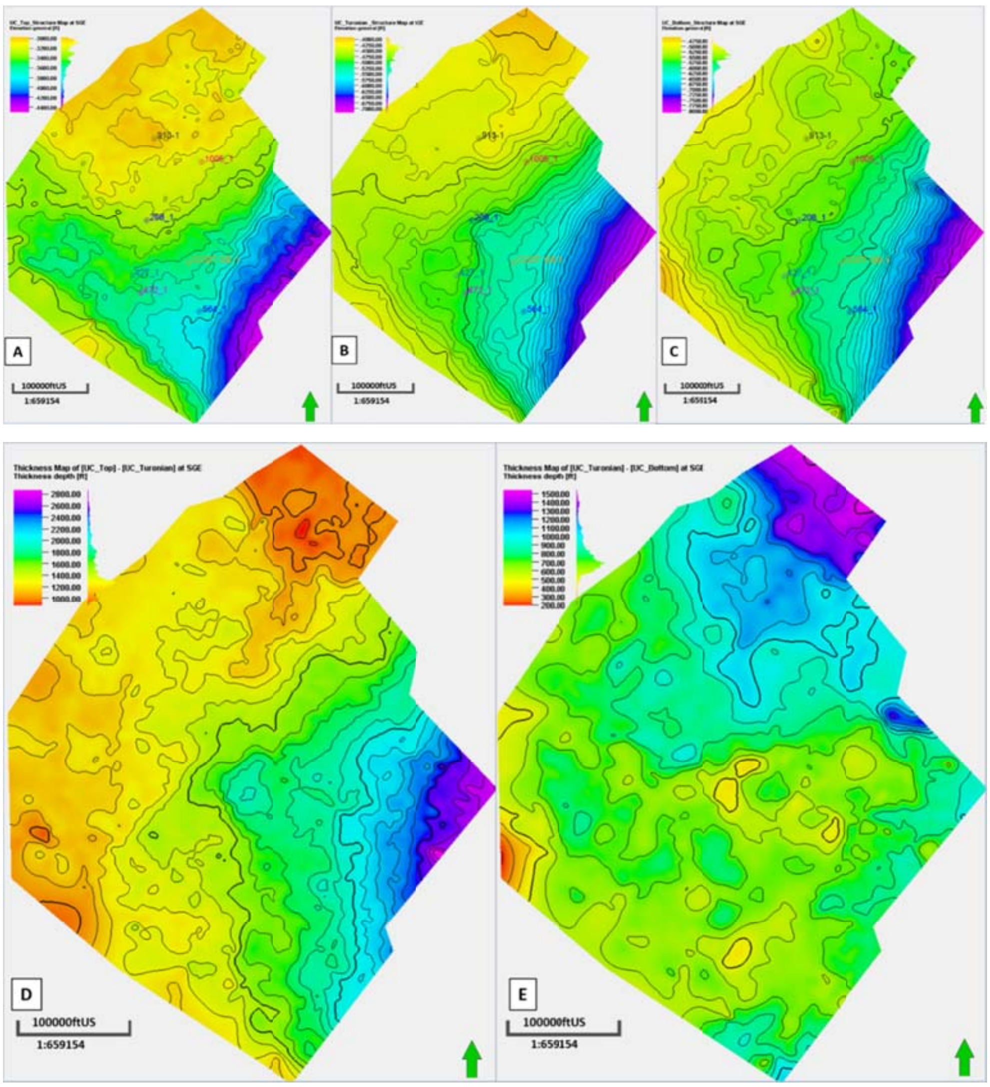

Fig. 9 Structure maps, in feet, for (A) top of Upper Cretaceous (Late Maastrichtian), (B) Turonian, and (C) base of Upper Cretaceous (Albian). Thickness maps (isochore) in feetfor (D) prospective seal and (E)potential reservoir within the offshore of Southeast Georgia Basin.

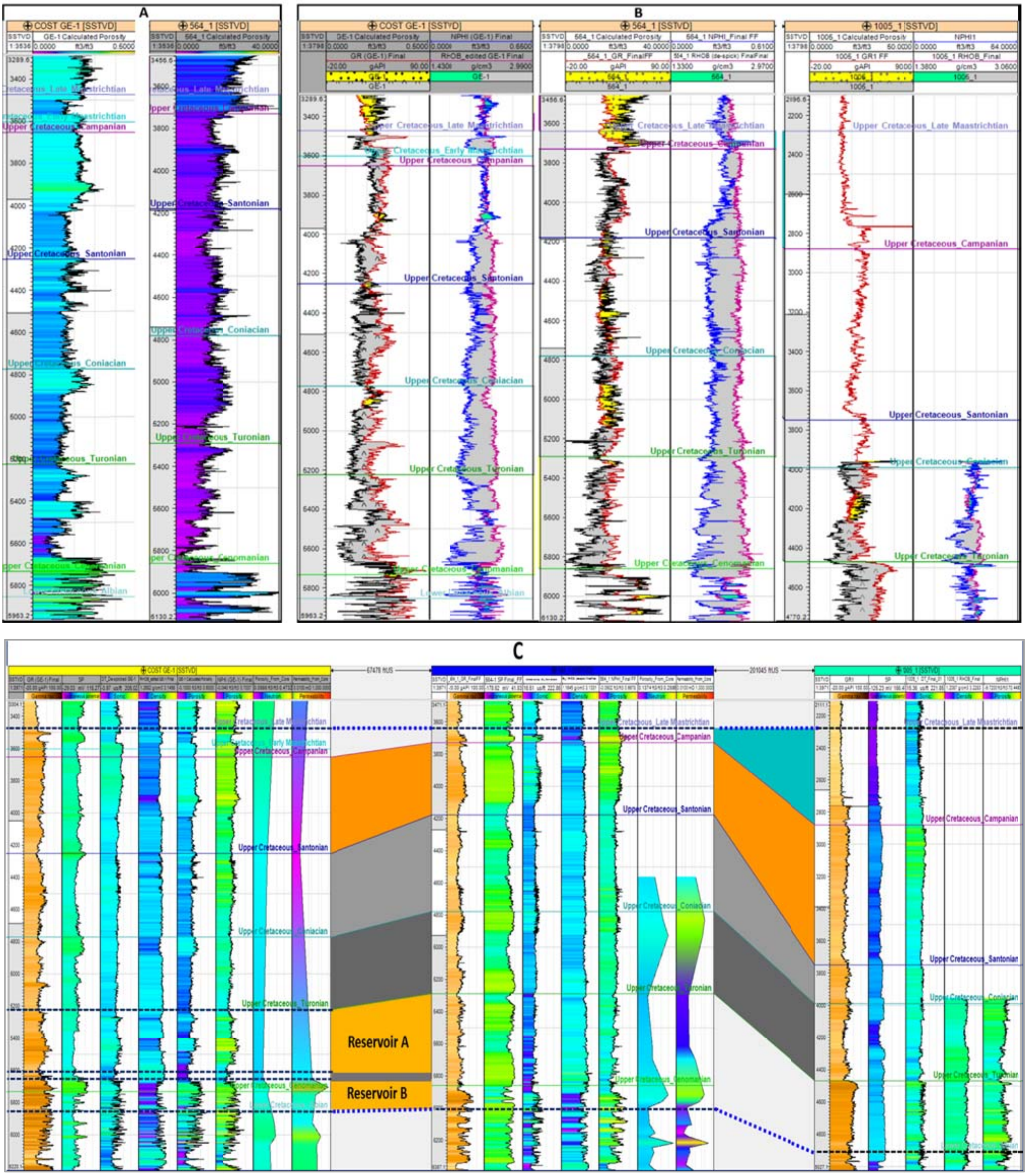

Fig. 10 Logs for different wells: (A)calculated porosity logs at COST GE-1 and Exxon 564-1 wells, (B) gamma ray versus calculated porosity in one track to emphasize the sand and shale cut-offs, similarly in the next track, shows density versus neutron log to emphasize the crossover which is indication to fluid-filled porosity which is a reflection to porous lithology; (C) lithology logs (gamma and SP) and the porosity logs (sonic, density, neutron) and porosity and permeability that calculated from core, for the COST GE-1, Exxon 564-1 and Transco 1005-1 wells respectively.

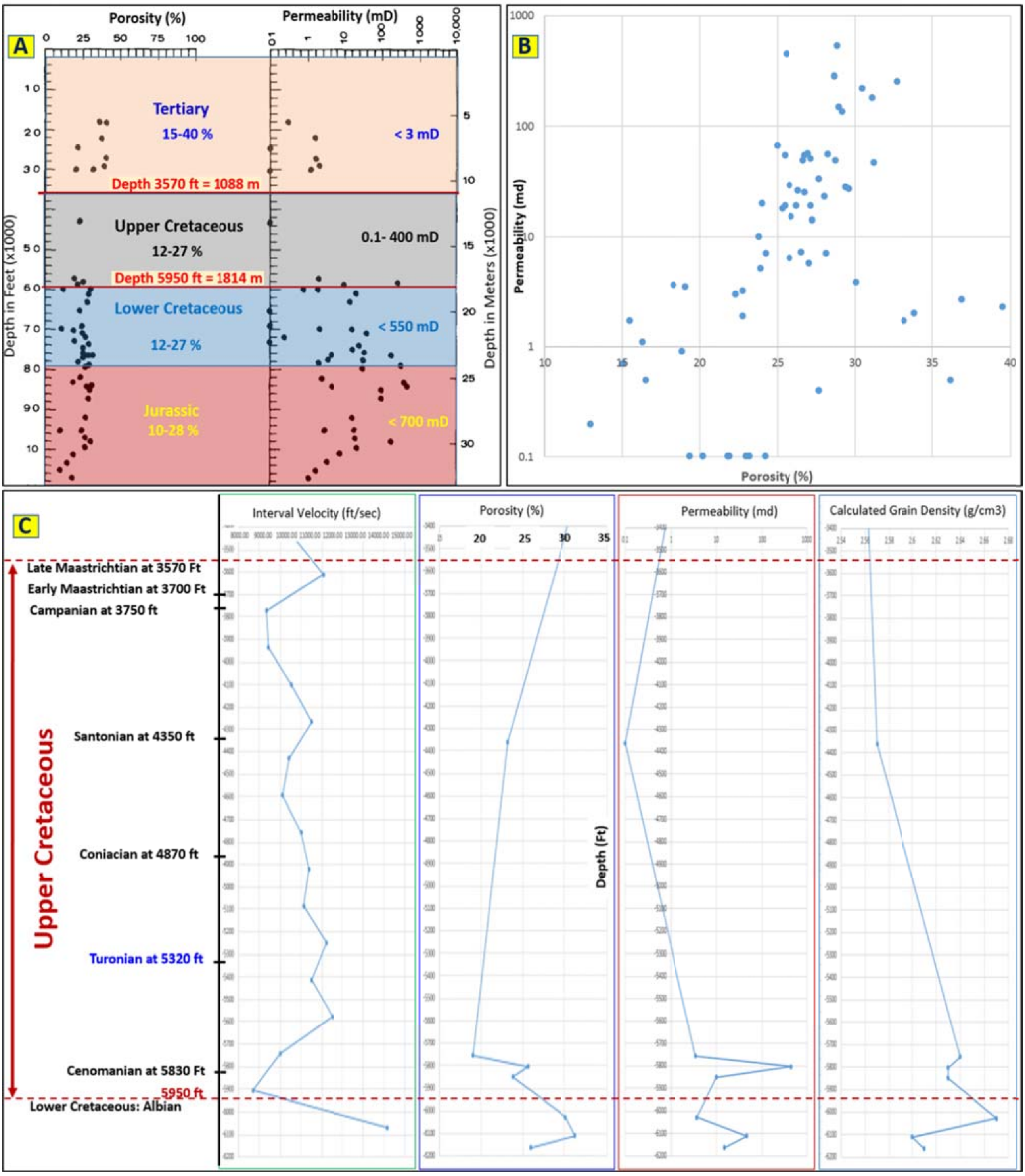

Fig. 11 Relationship between porosities and permeabilities versus depth for the COST GE-1 well: (A) values measured on conventional and sidewall cores [23]; [B] core porosities plotted against core permeabilities for the entire well [10]; (C)plotting interval velocity, porosity, permeability, and densities that calculated from the cores, for Upper Cretaceous section [23].

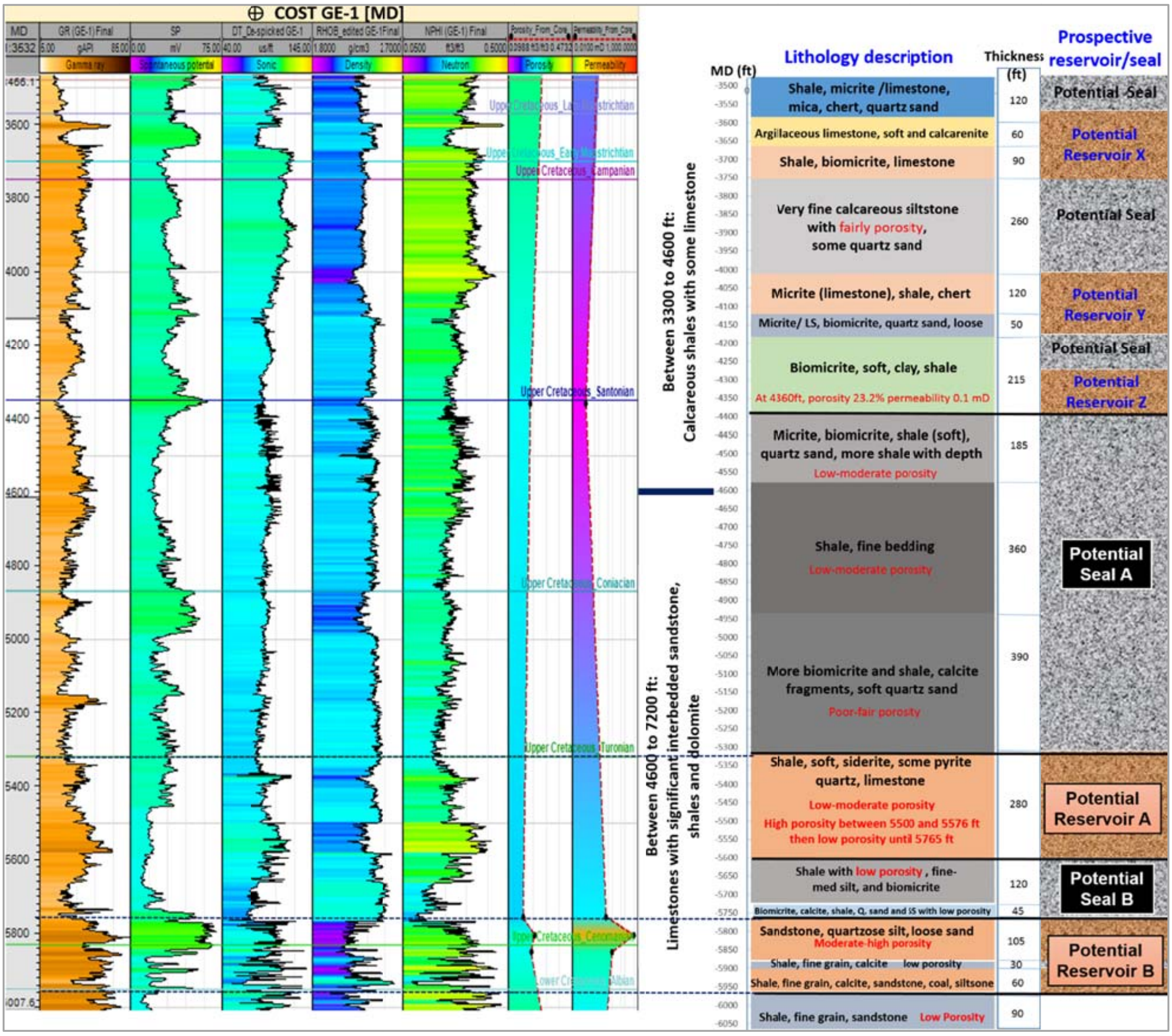

Fig. 12 Logs of gamma ray, self-Potential, sonic, density, neutron as well as porosities and the permeabilities that calculated from the core data. Also, lithology description with a geological model for the main two potentials reservoirs and seals at the Upper Cretaceous Section.

6. Results and Discussion

The lithological section of the COST GE-1 well has two main intervals [10]: (1) the depth interval from 3300 to 4600 ft, includes Upper Cretaceous, Paleocene, and lower Eocene, consists of limestone and calcareous shales, and (2) the depth interval from 4600 to 7200 ft, consists of limestone and dolomites interbedded with sandstones. Fig.12 shows the lithologic description versus depth and thickness from the COST GE-1 well based on core cuts and geophysical logs. In addition, it provides a geological model of the potential CO_2 storage reservoirs and seals.

Loss of fluid circulation in the chalk and calcareous shale interval from 2800 to 4900 ft during the drilling of the COST GE-1 well, may indicate significant fracturing [10]. At the COST GE-1 well, reports indicate that the presence of impermeable beds could serve as seals for CO_2 entrapment. The thick shales and calcareous shales between 3600 and 5700 ft, as well as thinner shales and anhydrite beds in the deeper parts of the section, are the best potential seals (Fig. 12). However, no sandstones above the depth of 5700 ft were recovered in either the conventional or sidewall cores. The carbonate rocks in this section are highly porous chalks, but their permeability is very low.Nevertheless, chalks with low permeability values are highly productive in the North Sea [10].

Carbonate-cemented, feldspathic, glauconitic sandstones at a depth of 5800 ft, suggest a major regression, if not a hiatus, between the shallow-water restricted-shelf carbonates and the overlying fine-grained open-marine limestones. This observation is supported by bio-stratigraphic data [10]. The depth interval from about 5700 to 7200 ft in the COST GE-1 well contains a varied shallow marine sequence of generally medium grained calcarenites, dolomite, and anhydrite, with significant amounts of quartz sandstone, pyrite, and glauconite. Common rock types include oolites, fossiliferous calcarenites, dolomite, micrite, and anhydrite.

Based on this stratigraphic analysis, it appears that the most suitable reservoir rocks for CO_2 sequestration are within restricted shelf carbonates with high primary and secondary porosity and good permeability occurring between 5700 and 7200 ft. It has the best permeability encountered below 1000 ft in the COST GE-1 well. This depth interval (5700 and 7200 ft),dominated by sandstone,shows porosities that vary widely and unsystematically with depth from 25% to 30% (perhaps due to variation in diagenesis), and the permeability is as high as 4000 mD. Although characterized by good porosity, the fine-grained limestones above 5700 ft arelikelytoo impermeable to make them candidates for reservoir rocks unless they are widely fractured or contain undetected permeable horizons. Data suggest that the rocks between 1000 to 5700 ft have a permeability of 3 mD or less [10]. Porosity values calculated from well logs shows an irregular patternperhaps due to cementation and facies changes. However, COST GE-1 well shows a clear decrease of porosity with depth down to about 5700 ft; Fig. 10(A). Plottingthe porosity versus depth for the upper portion of the COST GE-1 well, see Fig. 11 (A and C), shows that the fine-grained carbonatesappear to behave similarly to chalks with respect to porosity modification.Some of these carbonates are not strictly true chalks because of their argillaceous matrix.

The porosity and permeability depth relationship for the upper 5700 ft of the COST GE-1 well indicates that Upper Cretaceous section has a porosity range of 12% to 23% from 3500 ft to about 5500 ft; however, the approximate matrix permeability is in the range of 0.15 to 0.6 mD. Plots of porosities and permeabilities as a function of depth from conventional and sidewall cores from the COST GE-1 well [23]. Fig. 11(A) shows that very high porosities (25 to 40%) are encountered in the Cenozoic age chalks in the 1000 to 3000 ft depth interval, and the corresponding permeabilities for these fine-grained limestones are predictably low [23].

Five reservoirs and their associated seals were identified as potential sinks in the Upper Cretaceous section (Fig. 12 and Table 3). The two significant storage reservoirs for CO_2, which considered limestones with significant interbedded sandstone, shales and dolomite [10], are sealed by thick sediments of mainly shale interbedded by limestone.

These two reservoirs, named “A” and “B”, are illustrated in Fig. 12. The trapping mechanism, an overlying caprock or seal, is stratigraphic trapping through lateral facies changes [10]:

(1) Reservoir “**A**” is located between 5320 to 5600 ft, and sealed by about 725 ft. thick shale.

(2) Reservoir “**B**” is located between 5760 to 5950 ft and sealed by 160 ft thick shale. A significant potential for CO_2 storage occurswhere high values of primary and secondary porosity account for much of the best permeability encountered in the Upper Cretaceous section at the well COST GE-1. This reservoir is interrupted at the middle by a thin layer of shale between depths 5870 and 5900 ft which could serve as anadditional seal.

In these intervals, the porosity range is from 20 to 30% especially after 5500 ft, and the permeability range is 1 to 447 mD.

Table 3 Summary of prospective reservoirs and seals for CO_2 sequestration in Upper Cretaceous strata of the Southeast Georgia Embayment [10].

Potential CO_2 Storage	Lithology	Depth (ft)	Porosity in percent or level	Permeability (mD)	Recommended
Seal X	Shale, micrite/limestone, mica, chert	3500-3570 ft	moderate	1.7	Low
Reservoir X	Argillaceous limestone, soft and calcarenite, biomicrite, limestone	3570-3750 ft	19.1	3.5	Low
Seal Y	Very fine calcareous Siltstone	3750-4000 ft	fairly porosity	3	Low
Reservoir Y	Micrite (limestone), chert, biomicrite, quartz sand, loose	4020-4170 ft	19.1	3.5	Medium
Seal Z	Clay, shale	4170-4250 ft		0.1	High
Reservoir Z	Micrite/LS,dolomite, biomicrite	At 4360 ft	23.2	0.1	Low
Seal A	Shale, fine bedding	4400 to 5500 ft at 4906 ft	23.5 %	0.1	High
Reservoir A	Siderite,some pyrite quartz, limestone	5400 to 5580 ft	High porosity 17-23%	3.5 to 447 mD	High
Seal B	Calcareous shale, fine-med silt, and biomicrite	5580-5720 ft	Poor-fair porosity 12%	less permeable, clayey sequence	High
Reservoir B	Sandstone, quartzose silt, dolomite loose sand, coal, siltsone	5720-5950 ft	Moderate-high porosity 19-30.1 %	3.5 to 447 mD	High

For estimation of CO_2 storage capacity, a theoretical approach based on the DOE-NETL equation [31] was used to estimate the saline reservoir storage capacity. It estimates CO_2 storage capacity (G_{CO2}) based on the following expression:

$$G_{CO2}= A \times h \times \emptyset \times \rho \times E,$$

where:

A: total area covered by target reservoir and seal,

h: Reservoir thickness,

∅: Reservoir porosity

ρ: Density of supercritical CO_2,

E: CO_2 Storage efficiency factor

Regional CO_2 storage capacity is estimated using the interpolated surfaces with geographical total area of 19×10^{10} m^2. The average reservoir thickness is about 263 ft (80 m). This estimate depends on the regional thickness map for the prospective reservoir. The average porosity values, from the core, within the reservoir interval is 15%. A density of 700 kg/m^3 was used for supercritical CO_2 [6]. The storage efficiency factor *E* is an important source of uncertainty for capacity assessment. It reflects a fraction of the total pore volume that will be occupied by the injected CO_2. For saline formations, their storage efficiency coefficients range between 1.41 and 6.0% over the P_{10} and P_{90} percent probability range. Comparing with different methods, efficiency factors ranging between 1.2 and 4.1% over the P_{10} and P_{90} percent probability range. Therefore, storage efficiency value is 2.0%, which represents the probability level P_{50}, inthelimestone lithology, using Monte Carlo method [32].

Locally, CO_2 storage capacity is estimated with high confidence for the offshore Southeast Georgia Embayment, which is reasonably covered by seismic lines and wells data. The geographical total area that covers the two significant potential reservoir, named A and B, is 15.9×10^9 m^2 (Fig. 12). The total net thickness of the two significant reservoirs is about 470 ft (143.3 m) determined from the well logs. The average porosity value, from the core data, within the two reservoirs is 25.83%. Therefore, the CO_2 storage capacity is approximately 31.92 GT regionally. The local storage capacity for the two significant reservoirs in the Southeast Georgia Embayment provides 8.79 GT of that amount.

7. Conclusions

To summarize, this research is the first assessment of Upper Cretaceous strata for offshore CO_2 storage resource capacity in the southeastern United States outer continental shelf. It provides an integrated description and reliable subsurface evaluation of the top and base of Upper Cretaceous section and predict some potential reservoirs for CO_2 geologic storage regionally and locally within the offshore of Southeast Georgia Embayment. Also, seismic reflectors and stratigraphic units, containing reservoirs or sinks that might be suitable for effective CO_2 storage, were identified. To get accurate interpolation, the structure and thickness maps were created for the top and base of Upper Cretaceous section and the top of reservoirs using specific boundaries (polygons).

The study identified five potential reservoirs and seals. Two of them, discussed in detail, are considered to be the significant compartmented storage in the study area for CO_2 with high quality and integrity. These two main prospects are located at depths between 5320 to 5600 ft and 5660 to 5950 ft at the COST GE-1 well. All CO_2 storage criteria are met in these intervals, most notably high porosity and permeable stratigraphic traps that are capped by thick seals.

Because the Southeast Georgia Embayment has been extensively covered with seismic surveys and wells, the structure maps of the lateral extent of the main reservoir and sealing rock were created locally with high confidence. Therefore, Southeast Georgia Embaymentis a strong candidate for CO_2 sequestration in the Atlantic offshore and the existing deep exploratory wells can be exploited in developing CO_2 sequestration.

This research investigates the hypotheses and answers the research questions that are mentioned in the introduction. Smyth et al. (2008) estimated that the Upper Cretaceous strata at the Carolinas offshore has storage capacity of 16 GT, but this study indicates that the Upper Cretaceous formations have an even greater CO_2 storage capacity than that. It is estimated to be 31.92 GT regionally, and 8.79 GT of that amount represents the local storage capacity for the two significant reservoirs in the Southeast Georgia Embayment. This is the first time CO_2 storage capacities have been quantified in the study areas. The potential sinks are overlain by low-permeability seal layers. There are distinct porosity and permeability regimes that are widely distributed, especially in the lower part of the Upper Cretaceous section, and are influenced by depositional environments and lithologic composition. Also, the results indicate that the Upper Cretaceous units consist of moderate to highly compartmented stratigraphic systems. This helps increase the storage capacity. The research hypotheses were suitable for CO_2 sequestration assessment of the Upper Cretaceous section at the study areas. The limitations of this study are due to the sparsity and asymmetric distribution of the well data regionally. This caused an uncertainty with the regional extent and the integrity of the seal and reservoir.

This research is the first assessment of Upper Cretaceous strata foroffshore CO_2 storage resource in the southeastern United States outer continental shelf. The results are an important step for further studies in the future. The research integrates the available data to provide an assessment of the Upper Cretaceous section. Two main reservoirs were introduced with regional and local estimates for the significant storage capacity. Since the offshore South Georgia Embayment has a significant storage capacity and is covered reasonably by seismic surveys and exploratory well data, it is qualified as a candidate for CO_2 injection. The study suggests directions for future work to include:

(1) Digitize the exploratory wells data professionally,

(2) Build a database of the wells of the Atlantic offshore,

(3) Resampling 2D seismic lines tocreate a 3D volume, which will help to conduct seismic inversions. and

(4) Create a regional velocity model (to provide the correct depths for the structures as well as the potential reservoirs and seals).

This will lead to a more complete assessment of formation evaluation and geologic characterization for CO_2 storage resources.

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