FINAL REPORT

PRELIMINARY CHARACTERIZATION OF CO2 SEQUESTRATION POTENTIAL IN NEW JERSEY AND THE OFFSHORE COASTAL REGION

Conducted by the Midwest Regional Carbon Sequestration Partnership (MRCSP)

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DISCLAIMER

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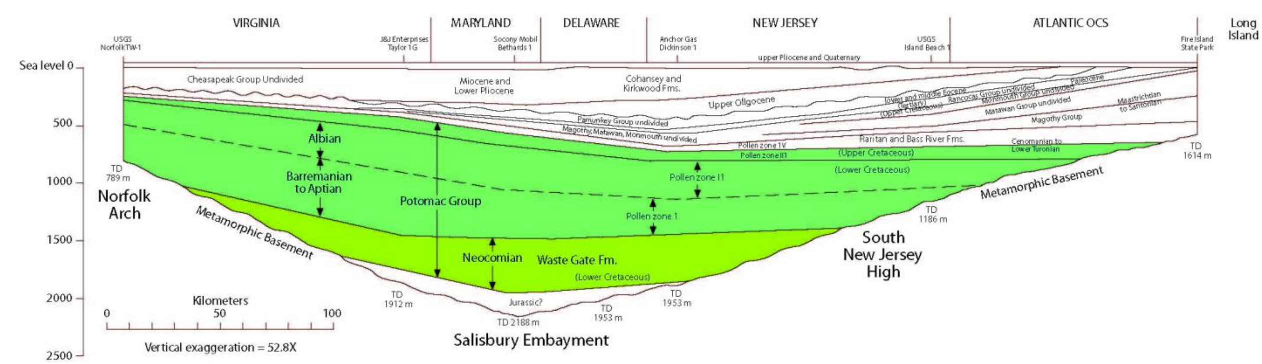

New Jersey Geological Survey

STATE OF NEW JERSEY
Chris Christie, *Governor*

Department of Environmental Protection
Bob Martin, *Commissioner*

Geological Survey
Karl Muessig, *State Geologist*

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

The mission of the New Jersey Department of Environmental Protection (DEP) is to assist the residents of New Jersey in preserving, sustaining, protecting and enhancing the environment to ensure the integration of high environmental quality, public health and economic vitality.

NEW JERSEY GEOLOGICAL SURVEY

The mission of the New Jersey Geological Survey (NJGS) is to map, research, interpret and provide scientific information regarding the state's geology and ground-water resources. This information supports the regulatory and planning functions of DEP and other governmental agencies and provides the business community and public with information necessary to address environmental concerns and make economic decisions.

Cover illustration: Cross section of coastal plain strata between Maryland and New Jersey

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GLOSSARY OF TERMS

2D	two-dimensional
3D	three-dimensional
ACAD	AutoCAD
AMCOR	Atlantic Margin Coring Project
BCT	Baltimore Canyon Trough
BGR	German Federal Institute for Geosciences and Natural Resources
cdp	common depth point
CO_2	carbon dioxide
COST	continental offshore stratigraphic test
DSDP	Deep Sea Drilling Project
DWG	AutoCad drawing
DXF	drawing exchange files
ESP	expanding spread profile
GE	Google Earth
GIS	geographic information system
ID	unique identifier
IODP	Integrated Ocean Drilling Program
JPEG	picture file type
KMZ	zipped KML files
mbsf	meters below seafloor
mcs	multichannel seismic
MRCSP	Midwest Regional Carbon Sequestration Partnership
MSL	mean sea level
MSU	Middle Sandstone Unit
Mt	million metric tons
NAD83	1983 North American Datum
NJGS	New Jersey Geological Survey
NJSPC	New Jersey State Plane Coordinate System
NJSPCF	New Jersey State Plane Coordinate System in U.S. feet
ODP	Ocean Drilling Program
shrimp	sensitive high resolution ion microprobe
TD	total depth
TIN	triangulated irregular network
USGS	U.S. Geological Survey

EXECUTIVE SUMMARY

The New Jersey Geological Survey, in conjunction with Rutgers University, has completed its preliminary characterization of geological sequestration potential in the state of New Jersey and adjacent offshore region including the continental shelf and slope in support of the Midwest Regional Carbon Sequestration Partnership (MRCSP). The geology of New Jersey and its offshore region is diverse, encompassing the Coastal Plain, offshore continental shelf and continental slope, Piedmont (Newark basin), and Highlands, Valley and Ridge. Each of these unique geologic settings was evaluated in terms of its suitability for geologic carbon dioxide (CO_2) sequestration.

Based on our preliminary characterization, the main geologic sequestration options in New Jersey are the numerous deep, saline, sandy formations found in the New Jersey Coastal Plain and adjacent continental shelf and slope. These formations are thick, with burial depths >800 m, a necessary criteria for supercritical storage of CO2. Additionally, these formations are capped by thick low permeability confining beds required to isolate CO2 in the sequestration target formation. The Potomac Formation is the deepest unit in the Coastal Plain and our preliminary studies document that it appears suitable for sequestration of supercritical CO2: it is saline, attains sufficient depth south of Island Beach, and is in proximity to several large anthropogenic CO2 point sources. The Potomac Formation is subdivided into three units from youngest to oldest: Potomac unit 3, Potomac unit 2, and Potomac unit 1. The Potomac unit 3 sands are too shallow to be considered a sequestration target, except in southeastern Cape May County where the top of the sand is below 800 m. The Potomac unit 2 sands are a potential target in southeastern New Jersey in Cape May County, and parts of Atlantic and Cumberland Counties, though our data are too sparse to fully evaluate its distribution and thickness. The Potomac unit 1 sands present the most likely target for sequestration. This unit is very sandy but discontinuous, is hydrologically isolated from shallow fresh water aquifers, and has the capability to store and absorb significant volumes of CO2. The range of total CO2 storage in the three sand units – Potomac units 3, 2, and 1, is 57 - 283 Mt (million metric tons).

Initial studies of the offshore New Jersey continental shelf and slope suggest three sand bodies provide the most likely targets for geological sequestration within the Logan Canyon and the Missisauga equivalents. The offshore Logan Canyon sands can be subdivided into an upper and lower sand. The upper sand is likely equivalent to the onshore New Jersey Potomac unit 3 sands. The lower Logan Canyon sand is correlative with the onshore Potomac unit 2 sand.
The Missisauga Formation appears to be the equivalent of the onshore Potomac unit 1 sand. Future work in seismic and borehole correlation using existing data will aid in refining these preliminary correlations. The potential range of CO2 storage in these three units is 150 – 750 Mt.

The Stockton Formation, within the Mesozoic Newark basin, has some potential based on preliminary data that are far from conclusive. It exceeds 800 m depth in about 2/3 of the area of the basin, with a thickness varying from 150 to 1,400 m based on cross sectional analysis. Due to a lack of deep data, hydrologic parameters and lateral continuity of target lithologies is speculative. Initial results show porosities ranging from 6 to 10 percent in select sands from data limited to two locations in New Jersey and two in adjoining Pennsylvania.

Cambrian to Devonian sedimentary formations in the Valley and Ridge have experienced several deformational episodes with associated elevated temperatures which have reduced their CO2 sequestration potential. However, no deep data exists to truly characterize their hydrologic parameters at depths sufficient to sequester CO2 in the critical state.

The Highlands is dominated by high grade Mesoproterozoic and Neoproterozoic metamorphic units that lack any primary porosity or permeability. Water wells indicate that only secondary fractures account for the water-bearing zones. As such, this region is not a candidate for CO2 sequestration.

Future studies are needed to address the extent, continuity and properties of potential sequestration formations in the New Jersey Coastal Plain and adjacent offshore region. New Jersey is collaborating with Rutgers University and with New York and Maryland to address the offshore region. In addition, the U.S. Department of Energy is supporting new coring and data collection in the New York part of the Newark basin. Results of these studies may suggest additional work in adjacent parts of the basin in New Jersey.

1.0 CHARACTERIZATION OF THE CARBON DIOXIDE STORAGE POTENTIAL BENEATH THE NEW JERSEY COASTAL PLAIN

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1.1 Introduction - Onshore Sequestration

The regional geology, geological history, and available data from the New Jersey Coastal Plain are reviewed in the context of geological sequestration of carbon dioxide. Thick, porous sediments with burial depths >800 m and confined by relatively impermeable mudrocks/muds are potential targets for supercritical storage of CO_2. Such sediment exists beneath the New Jersey Coastal Plain and there are several reasons for considering their sequestration potential:

(1) Tectonism in the onshore New Jersey Coastal Plain is limited. Extensive coring of the Coastal Plain shows that accommodation was dominated by simple thermal subsidence, sediment loading, and compaction. Limited faulting occurs in the New Jersey Coastal Plain, though seismic profiles and correlation of deep wells reveal growth and basement faults that do not penetrate upper strata or the surface.

(2) There are thick confined saline sand units in near proximity to CO_2 sources.

(3) Coastal Plain strata are generally arranged into sand and confining unit clay packages that are predictable using sequence stratigraphy.

(4) The lower to lowermost Upper Cretaceous Potomac Formation is the deepest unit in the Coastal Plain and our preliminary studies document that it appears suitable for sequestration of supercritical CO_2: it is saline, attains sufficient depth south of Island Beach, and can be reached by drilling near the coast at a moderate cost.

(5) The Potomac unit 2 (P2) is traceable throughout the Coastal Plain. The basal P2 sands appear traceable, though their character varies. The P2 sands appear to vary in thickness from 37 to 225 ft. in the wells we studied, though the identification of this unit is often uncertain, as discussed above. The P2 may be a sequestration target though our data are too sparse to fully evaluate its distribution and thickness.

(6) The Potomac unit 1 (P1) sands present the most likely target for sequestration. The unit is very sandy but discontinuous, and is hydrologically isolated from shallow fresh water aquifers and has the capability to store and absorb significant volumes of CO_2.

1.2 Geologic Background

A survey of the United States has identified the U.S. Atlantic Coastal Plain as one of approximately a dozen potential targets for carbon sequestration (http://www.beg.utexas.edu/environqlty/co2seq/). The mid-Atlantic margin, specifically the New Jersey coastal plain and offshore, has been intensively studied with 12 continuously cored onshore boreholes as part of Ocean Drilling Program (ODP) Legs 150X and 174AX (Miller et al.,

2005) and offshore multi-channel seismic profiles and shelf-slope drilling by ODP Leg 150 and 174AX, (e.g., Mountain and Miller, 1994; Monteverde et al., 2008) and shelf drilling by IODP (Integrated Ocean Drilling Program) Expedition 313 (http://publications.iodp.org/preliminary_report/313/index.html) (Fig. 1.1). In this portion of the report, we focus on the onshore New Jersey Coastal Plain (Fig. 1.2).

The New Jersey Coastal Plain is a relatively flat physiographic province separated from the Atlantic Ocean to the east and the Piedmont and Newark basin to the west by the fall line. The Coastal Plain is the onshore portion of a classic passive margin that formed following Triassic-Early Jurassic rifting (Fig. 1.3; Grow and Sheridan, 1986). Post-rift tectonics have been dominated by simple thermal subsidence, sediment loading, and flexure (Watts and Steckler, 1979; Reynolds et al., 1991). The Coastal Plain contains Lower Cretaceous to Holocene strata that dip gently (<1°) seaward and thicken downdip. Jurassic strata have not been identified in the Coastal Plain, although very thick Jurassic strata occur offshore in the Baltimore Canyon Trough (Fig. 1.3). Deposition first began in the region now occupied by the Coastal Plain in the Cretaceous when the crust attained sufficient flexural rigidity for offshore thermal subsidence and loading to cause accommodation onshore (Watts, 1982), a process dubbed thermoflexural subsidence (Kominz et al., 1998). Coastal Plain sediments are primarily unconsolidated siliciclastic sands and muds that were deposited in fluvial to shelfal (neritic) environments, with a strong deltaic influence in the Cretaceous and in the Miocene (Owens and Sohl, 1969; Owens and Gohn, 1985; Sugarman et al., 1993). Paleowater depths generally increased from the middle to Late Cretaceous (Fig. 1.4, Browning et al., 2008), attaining maximum water depths onshore in the early Eocene. A general regression occurred over the last 50 million years and upper Miocene-Holocene strata are primarily marginal marine to non-marine. Cretaceous strata are accessible in both subsurface boreholes and as weathered outcrops (Fig. 1.1), but most of the Cenozoic record is derived from subsurface boreholes where strata are thicker, more marine, and fossiliferous.

Tectonism in the onshore New Jersey Coastal Plain is limited. Extensive coring of the Coastal Plain (Fig. 1.4; summaries in Miller et al., 2005, Browning et al., 2008, and Kulpecz et al., 2008) shows that accommodation was dominated by simple thermal subsidence, sediment loading, and compaction. Limited faulting occurs in the New Jersey Coastal Plain, though seismic profiles and correlation of deep wells reveal growth and basement faults (e.g., Brown et al., 1972; Sheridan et al., 1991) that do not penetrate upper strata or the surface (Sheridan et al., 1988). The middle Atlantic Coastal Plain from northern North Carolina to New Jersey is underlain by a series of alternating crystalline basement embayments and arches (e.g., from south to north: Cape Fear Arch, Albemarle Embayment, Norfolk Arch, Salisbury Embayment, South Jersey High, and Raritan Embayment; Fig. 1.5). Differential movement of these embayments and arches has occurred, though the mechanisms are poorly understood: “wrench tectonic faulting” (Brown et al., 1972), regional warping of “rolling basins” (Owens et al., 1997), flexural effects of sediment loading (Pekar et al., 2003; Browning et al., 2006), or other mechanisms including intraplate stress. Differential subsidence between Delaware and New Jersey has been quantified as <30 m during the Miocene (Browning et al., 2006). Though non-thermal tectonism has occurred, the stratal patterns can be explained primarily by simple tectonism (thermal, loading) and sea-level changes (Miller et al., 2005). However, facies changes within sequences reflect changes in accommodation (including effects of sea level and subsidence) and sediment supply (e.g., Posamentier, et al., 1988; Reynolds, et al., 1991).

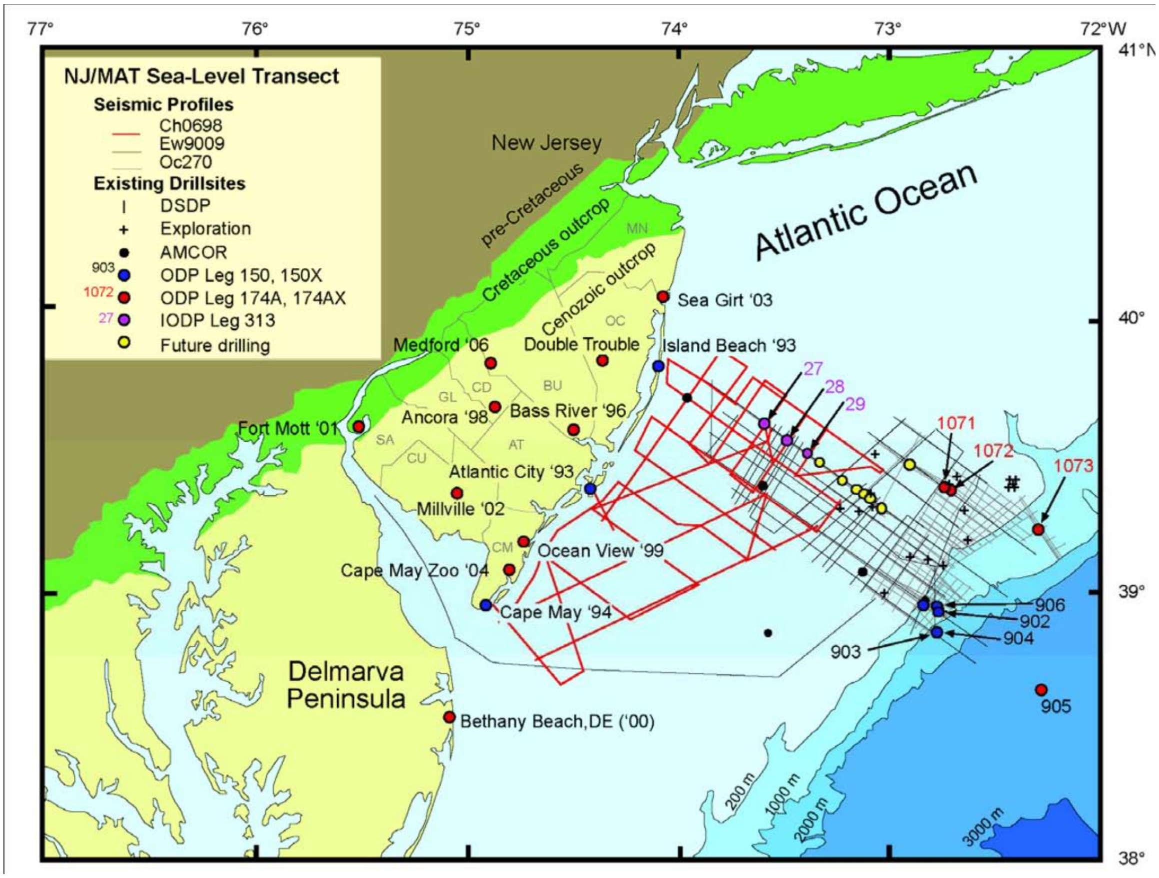

Figure 1.1. Mid-Atlantic Margin Location Map Showing Existing Deep Sea Drilling Project (DSDP), Atlantic Margin

Coring Project (AMCOR), Ocean Drilling Program (ODP), and the Integrated Ocean Drilling Program (IODP) coreholes. Also shown are multichannel seismic data from Ewing (EW9009), Oceanus (Oc270), and Cape Hatteras (Ch0698) cruises. MN = Monmouth County, OC = Ocean County, BU = Burlington County, CD = Camden County, GL = Gloucester County, AT = Atlantic County, SA = Salem County, CU = Cumberland County, CM = Cape May County.

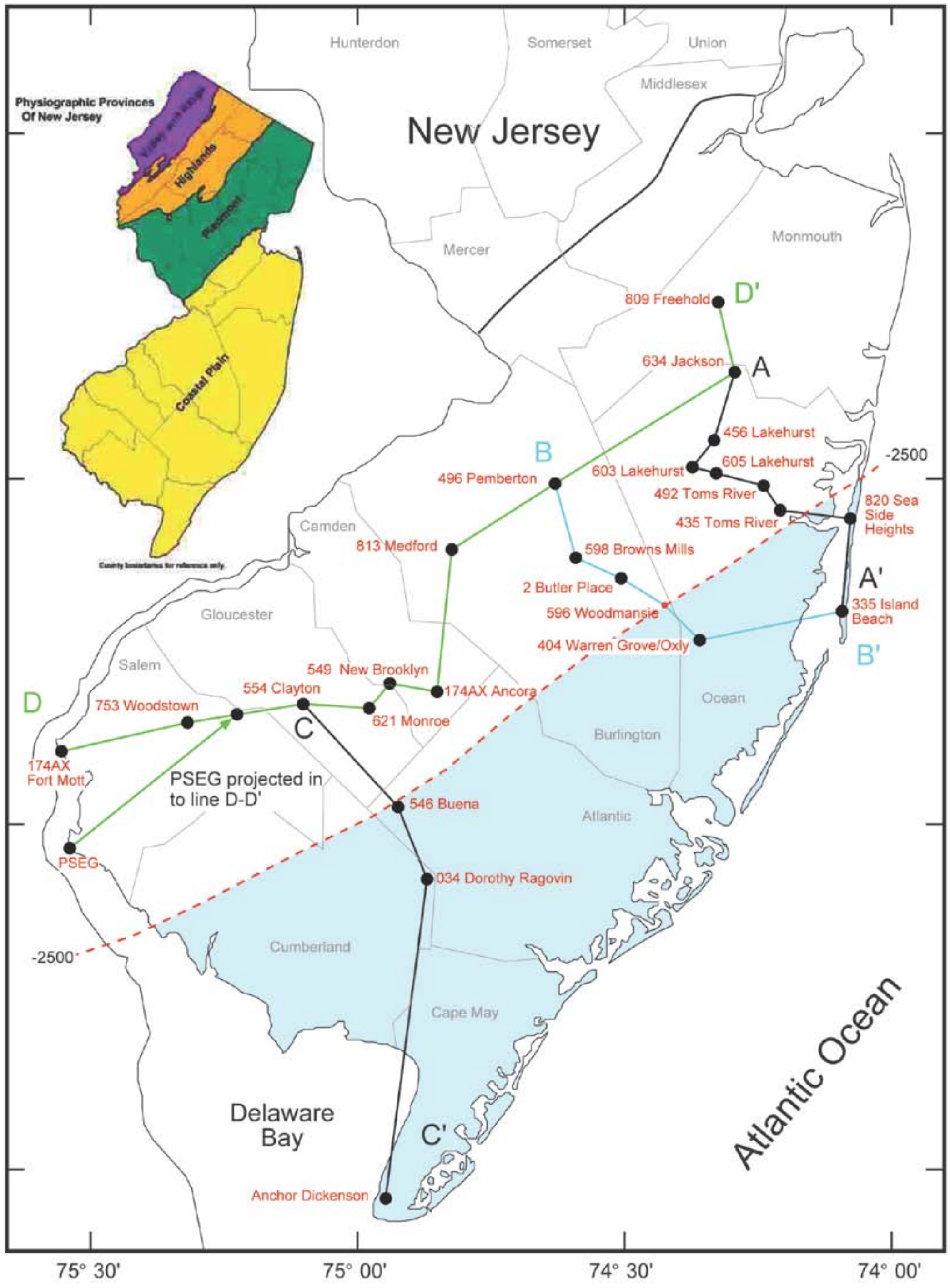

Figure 1.2. New Jersey Coastal Plain Location Map Showing Wells Used to Construct Cross Sections

(Figs. 1.11-1.14), structural contour maps (Figs. 1.15-1.22), and isopach maps (Figs. 1.23-1.25). A-A', B-B', C-C', D-D' refer to cross sections in Figs 1.11-1.14, respectively

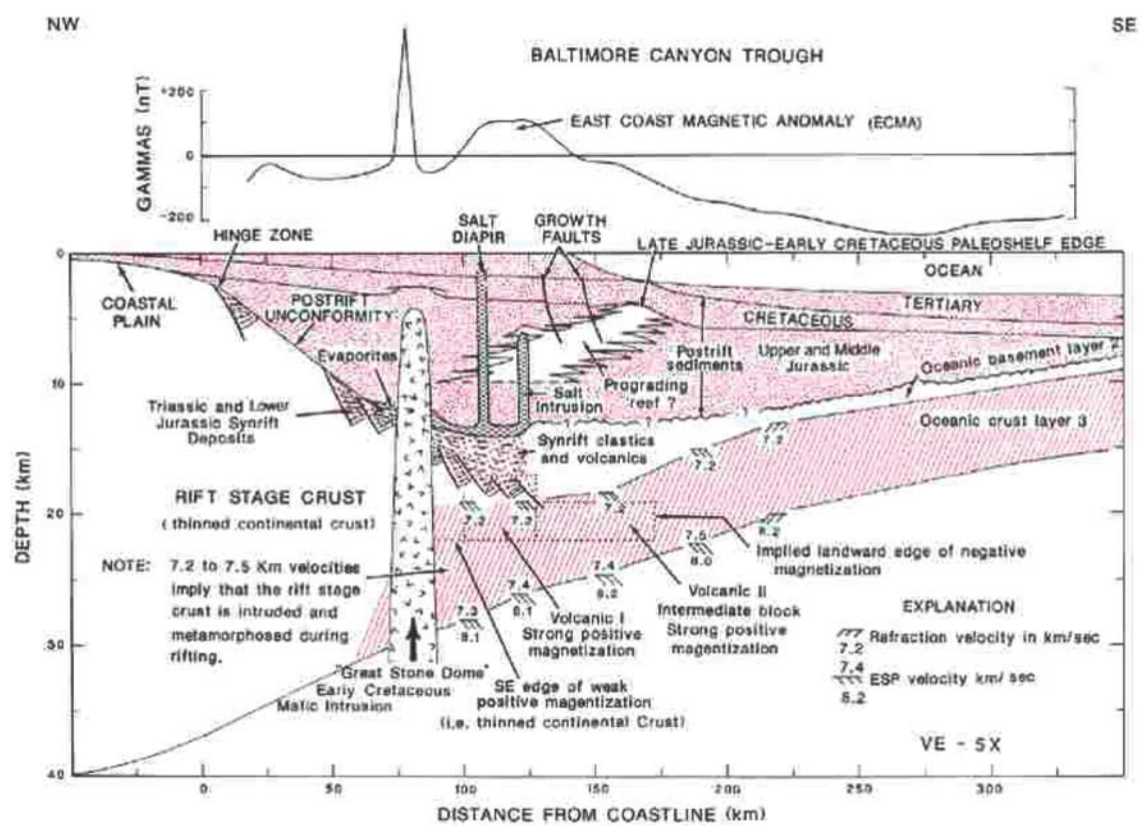

Figure 1.3. Cross Section Through the Baltimore Canyon Trough (from Grow and Sheridan, 1988)

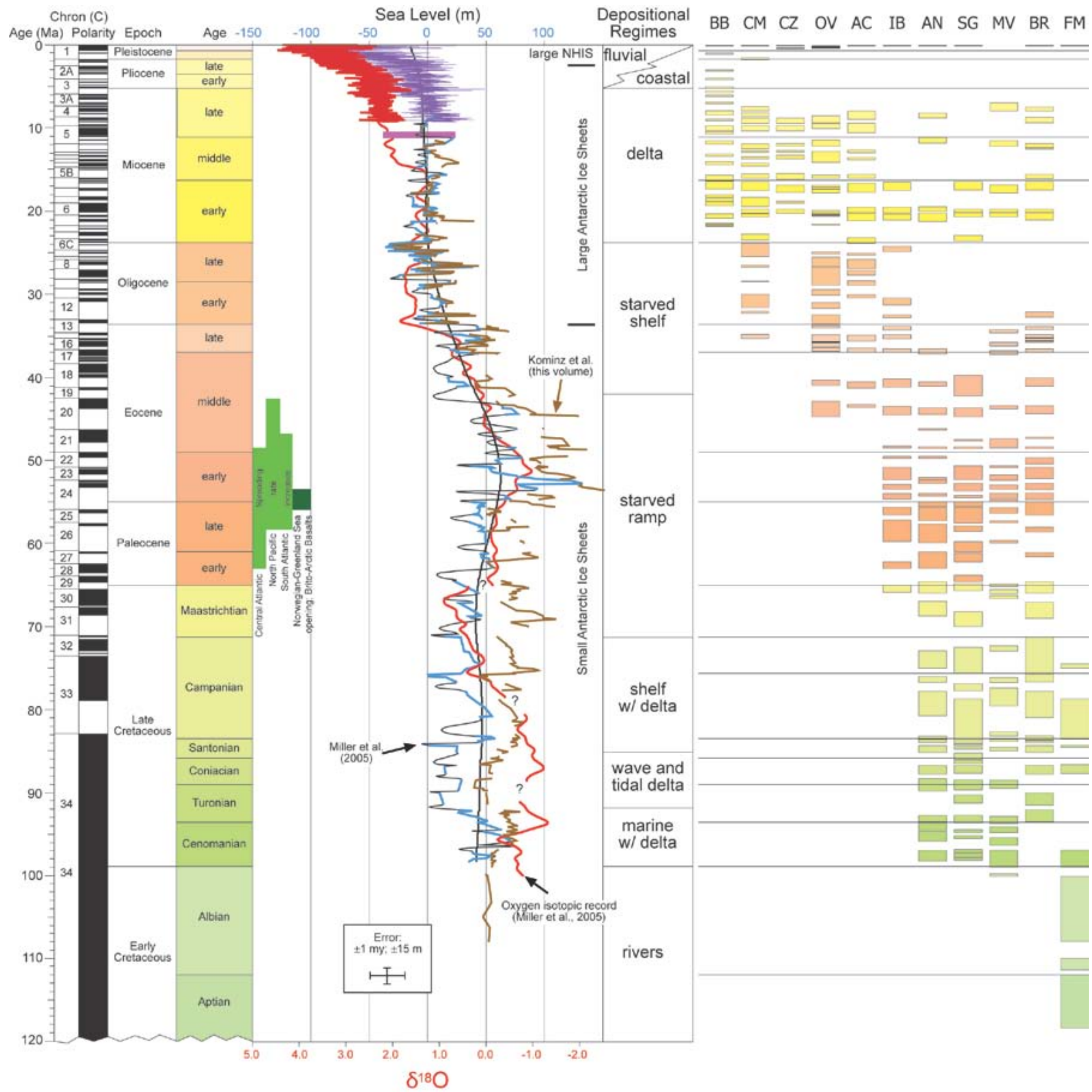

Figure 1.4. Distribution of Sediments in Sequences as a Function of Time. Sea level curve in bluefrom Miller *et al.* (2005). Sea-level curve in brown from Kominz *et al.*, (this volume). Red oxygen isotopic curve from Miller *et al.* (2005). BB-Bethany Beach core, CM-Cape May core, CZ-Cape May Zoo core, OV-Ocean View core, AC-Atlantic city core, IB-Island Beach core, ANAncora core, SG-Sea Girt core, MV-Millville core, BR-Bass River core, FM-Fort Mott core. See Fig 1.1 for locations. NHIS-Northern Hemisphere Ice Sheets. From Browning et al. (2008).

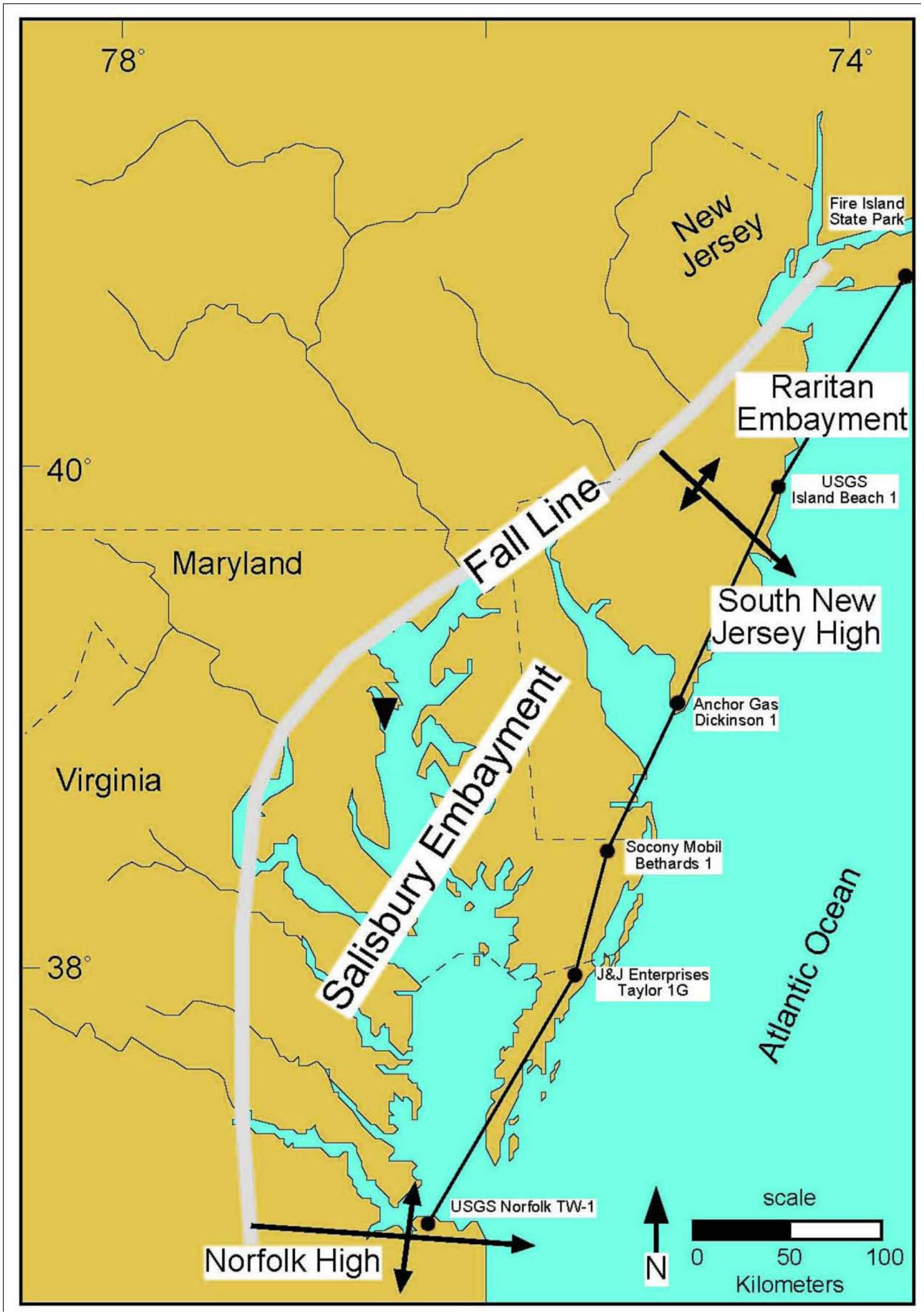

Figure 1.5. Embayments and Troughs of the U.S. Mid-Atlantic Margin After Browning et al. (2006).

Position of the fall line shown as a gray line. State boundaries are dashed.

Coastal Plain strata are generally arranged into sand and confining unit clay packages that are predictable using sequence stratigraphy (e.g., Sugarman et al., 2005). The advantage of using Coastal Plain sediments for carbon sequestration includes the presence of thick confined saline sand units and their proximity to CO_2 sources. Disadvantages include the fact that most sands in the Coastal Plain are too shallow to maintain a supercritical state. The target for carbon sequestration is sands with burial depths greater than 750-900 m (greater than ~2,400 – 3,000 ft.; Fig. 1.2), which onshore entirely comprises the non-marine to marginal marine Potomac Formation.

1.3 The Potomac Formation

The lower to lowermost Upper Cretaceous Potomac Formation (named by McGee, 1886) is the deepest unit in the Coastal Plain and our preliminary studies document that it appears very suitable for sequestration of supercritical carbon dioxide: it is saline downdip of its outcrop (DePaul et al., 2009), attains sufficient depth south of Island Beach for carbon dioxide to be stored in a supercritical state, and can be reached by drilling near the coast at a reasonable cost (Figs. 1.1, 1.3). In Maryland and Virginia, coeval sediments are mapped as the Potomac Group including the Potapsco, Arundel, Patuxent, and Waste Gate Formations (see summary in Wickstrom et al., 2005). The coarse grained lowermost unit, the Waste Gate Formation of Hansen (1984) has received considerable attention for carbon sequestration (Wickstrom et al., 2005). It is not clear if the Waste Gate Formation is represented in New Jersey, though it was correlated to New Jersey by Olsson et al. (1998). Correlations between Maryland and New Jersey will be the subject of future studies. Here we focus on characterizing the lithology and mapping of units within the Potomac Formation in the subsurface of the New Jersey Coastal Plain. Correlations between the onshore Potomac Formation and coeval offshore sands are discussed below.

The Potomac Formation was deposited in fluvial (Glaser, 1971) and fluvial-deltaic (Owens and Gohn, 1985) environments and the following summary was derived from a recent study by Browning et al. (2008). During the time of its deposition, New Jersey experienced a warm subtropical climate with deep weathering (Wolfe and Upchurch, 1987) and received abundant sediment from the Appalachian Mountains. Most of the terrestrial sediments accumulated on a heavily vegetated delta plain (Sugarman et al., 2004) with extensive lowlands and active and abandoned distributary channels dominated by fluvial processes (Fig. 1.6). The delta plain regime is typically divided into two distinct subenvironments: the upper delta plain and the lower delta plain. The upper delta plain is that portion of the delta plain that is above high tide and is not influenced by the ocean and thus contains fresh water deposits (Fig. 1.6). Lower delta plains are affected by fluvial and/or tidal processes (rarely by waves) and thus contain brackish water deposits. The upper delta plain is distinguished from the lower delta plain by greater soil development. Some of the sands in the Potomac Formation may reflect slight marine influences of the delta front, the area where river currents enter the basin and the sediments are dispersed by basinal processes (Fig. 1.6).

We divided the Potomac Formation into three units. Initially, pollen studies were used to recognize Zones I, II, and III (Doyle and Robbins, 1977) in the Potomac Formation, representing the Barremian to lowermost Cenomanian (~120-98 Ma). Three units (Potomac 1, 2, and 3) were tentatively identified in the Potomac Formation based on continuous cores obtained at Fort Mott

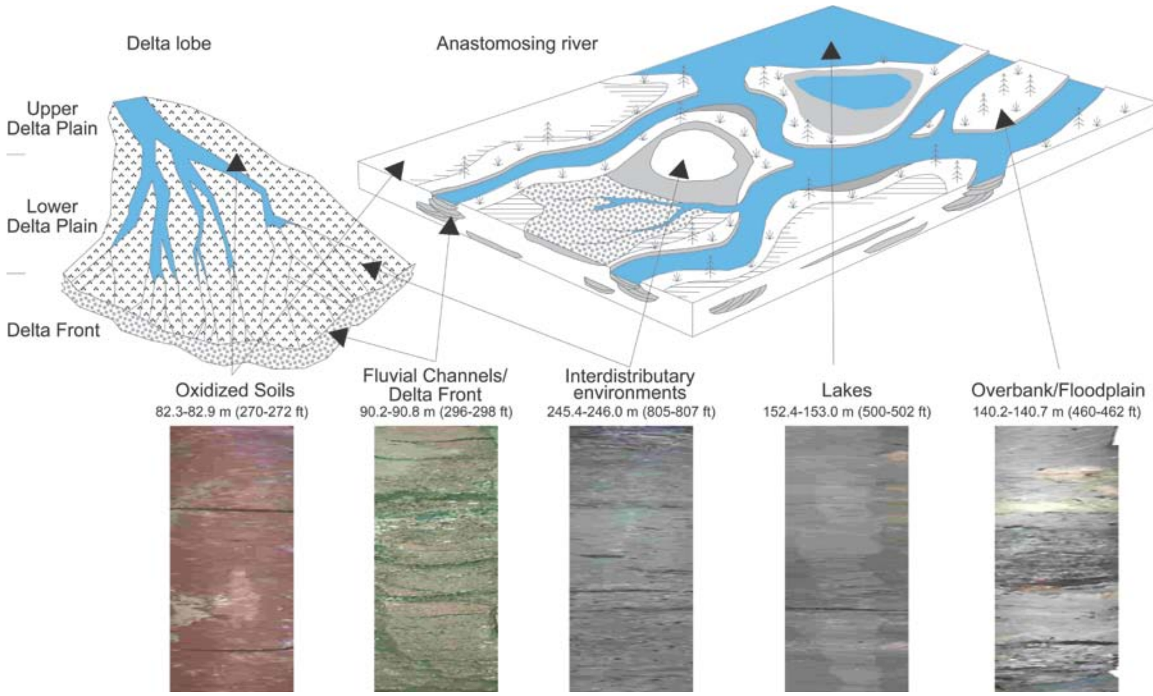

Figure 1.6. Depositional Models for the Potomac Formation After Browning et al. (2008).

Facies model for anastomosed river sedimentation modified from Miall (1996). Facies model for delta plain sedimentation modified from Elliott (1986). Photographs are examples of each facies in core from given levels in the Fort Mott borehole.

(Fig. 1.7; Sugarman, et al., 2004); each unit is associated with a pollen zone and named after the zone. Unit P3 is the uppermost unit, while unit P1 overlies basement (though definite basement was not reached in the corehole, basement maps (Fig. 1.10) suggest it was narrowly missed). In the Fort Mott corehole, upper units P3 and P2 have sands at their bases, overlain by thick confining beds (Fig. 1.7).

Most of the Potomac Formation from the Fort Mott corehole is interpreted to represent anastomosed river environments in a delta plain (Fig. 1.6; summary in Browning et al., 2008). Anastomosed systems are streams that are divided into multiple coexistent channels that have stable islands or bars separating the channels (Smith and Smith, 1980). One problem of interpretation is the degree to which there was marine influence on the majority of the Potomac sediments. Thick sand units (generally 50 - 100 ft.) in the Potomac Formation are generally interpreted to represent fluvial channel deposits, though a delta front environment cannot be excluded, as discussed below. Sediments in the Potomac Formation in the Fort Mott borehole are dominated by mottled red and bluish gray soils developed in an overbank setting with the different colors indicating varying degrees of oxidation during soil making processes (Retallack, 1990). Gleyed soils are bluish/gray, due to waterlogging, and the resultant loss of iron compounds and oxygen deposited in small lakes and marshes. Marshy wetlands typically contain gleyed soils. Lateritic red soils formed under conditions of stability and intense weathering represent overbank deposits on the banks of streams and in between adjacent channels. Sands in the Potomac Formation at Fort Mott consist of fining upward successions deposited in fluvial channel environments.

The Medford corehole (Fig. 1.1) provides another detailed view of the Potomac Formation and the following is derived from the recent Medford Site Report (Sugarman et al., 2010). Three Potomac units were identified in the Medford corehole: Potomac units 1, 2, and 3 (Lower to Upper Cretaceous; ?Barremian-lower Cenomanian; Fig. 1.8). While the Potomac has been successfully subdivided in the Coastal Plain using a palynological zonation, most of the samples from Medford yielded meager spore and pollen preservation, and many samples were essentially barren. The youngest Potomac subdivision, Potomac unit 3 (P3) is a thick section of fluvial sediments that is informally subdivided into two units (Fig. 1.8). The upper unit consists of two distinct fluvial channel sand bodies that are sandwiched between lignitic sandy clays and clays that were deposited in adjacent overbank, swamp and oxbow-lake environments. The lower unit has a ~25 foot thick paleosol and fluvial facies are present to the base of the sequence. Potomac unit 2 (P2) is tentatively subdivided into two units (Fig. 1.8). The upper unit contains predominantly medium to coarse grained fluvial channel sands overlain by levee and overbank silt and clay. The lower unit similarly fines upward from fluvial channels at the base to overbank deposits on top. Potomac unit 1 is sand dominated with two thin clay beds deposited in braided stream environments, with the coarsest beds possibly representing colluvium (Fig. 1.8). The Medford corehole is along strike and updip of Fort Mott; it differs in being very sandy relative to the finer grained Potomac Formation at the latter (Fig. 1.8). The Fort Mott and Medford coreholes provide excellent tie points for correlating the Potomac Formation and its informal units throughout the onshore Coastal Plain using well logs.

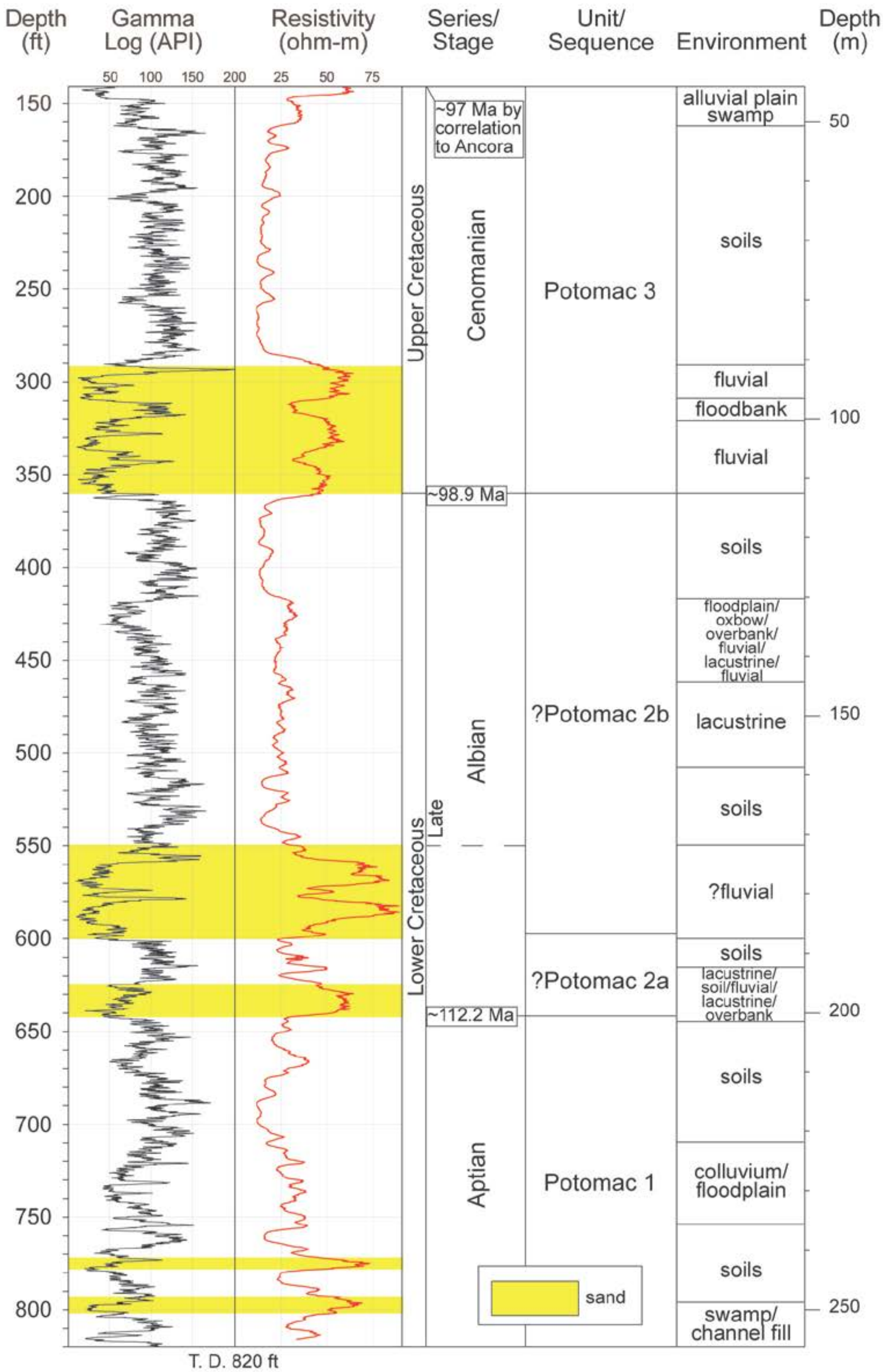

Figure 1.7. Stratigraphy of the ODP Leg 174AX Fort Mott Corehole After Browning et al. (2008).

Gray areas in the gamma and resistivity log columns indicate aquifers.

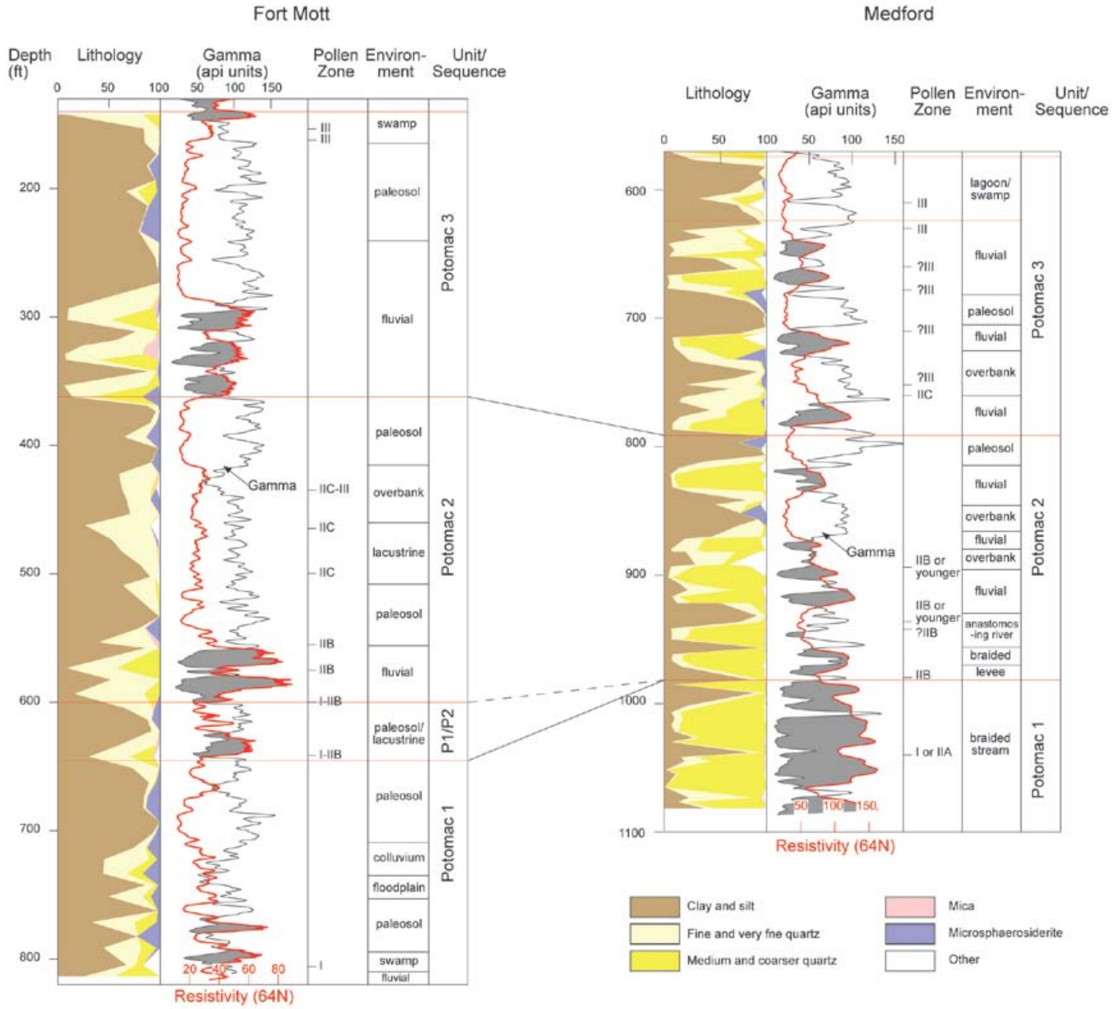

Figure 1.8. Correlation of the Potomac Formation in the Fig. 1.1 Fort Mott and Medford Coreholes After Sugarman et al. (2010).

1.4 Upper Cretaceous Formations

Upper Cretaceous formations mapped through the Coastal Plain are largely marine, and have been extensively studied for sea-level history (Olsson et al., 1988; Sugarman et al., 2005; Miller et al., 2003, 2004, 2005; Browning et al., 2008), as summarized here (Fig. 1.4):

1) The Cenomanian-early Turonian was dominated by marine sediments of the Bass River Formation with minor deltaic influence associated with long-term sea-level rise;

2) The late Turonian through Coniacian was dominated by non-marine fluvial, wave and tidal delta systems of the Magothy Formation associated with long-term sea-level fall (Kulpecz et al., 2008);

3) The Santonian-Campanian consisted of marine deposition under the influence of a wave-dominated delta associated with a long-term sea-level rise and increased sediment supply; several formations reflect transgressive basal deposit (Merchantville, lower upper Englishtown, and Marshalltown Formations), medial prodelta silty clays (Woodbury, medial upper Englishtown, and Wenonah Formations), and upper delta front and nearshore sands (lower Englishtown, upper part of the upper Englishtown, and Mount Laurel Formations); and

4) Maastrichtian deposition consisted primarily of glauconite sand and clay of the Navesink and Red Bank Formations on a starved, ramp shelf environments associated with very high sea-level. These units were previously mapped through the Coastal Plain using well-log correlations (Zapecza, 1989; Owens et al., 1998; Kulpecz et al., 2008; Sugarman and Monteverde, 2008). In this study, we expanded the log database used by Kulpecz et al. (2008) who mapped the upper Cretaceous.

1.5 Chronostratigraphic Correlations

We developed a Jurassic-Cretaceous correlation chart linking onshore and offshore sequences (Fig. 1.9). This figure is a work in progress. The ages of the Santonian-Coniacian and Cenomanian to lower Turonian strata are well constrained onshore by biostratigraphy and Sr-isotope stratigraphy on continuous cores (summary in Browning et al., 2008). The age of the upper Turonian-Coniacian Magothy Formation and the Potomac Formation are poorly constrained by pollen biostratigraphy. Offshore age correlations are discussed below, though in general the ages are coarse since they are based on well cutting samples.

1.6 Well-Log Correlations

As saline sand units within the Potomac Formation below ~2,400 - 3,000 feet (~750 - 900 m) are potential onshore sequestration targets, we focused on compiling data from deep wells to develop a stratigraphic framework for the New Jersey Coastal Plain. The NJGS has researched and assembled all lithologic and geophysical logs of deep wells located within the Coastal Plain or southern part of New Jersey. At present, there are 56 wells in the database. The majority of these logs are paper copies that required digitization and preservation into the LAS format standard (e.g., US Geological Survey [USGS] Ragovin 1, Warren Grove-Oxly, and Anchor-Dickenson 1

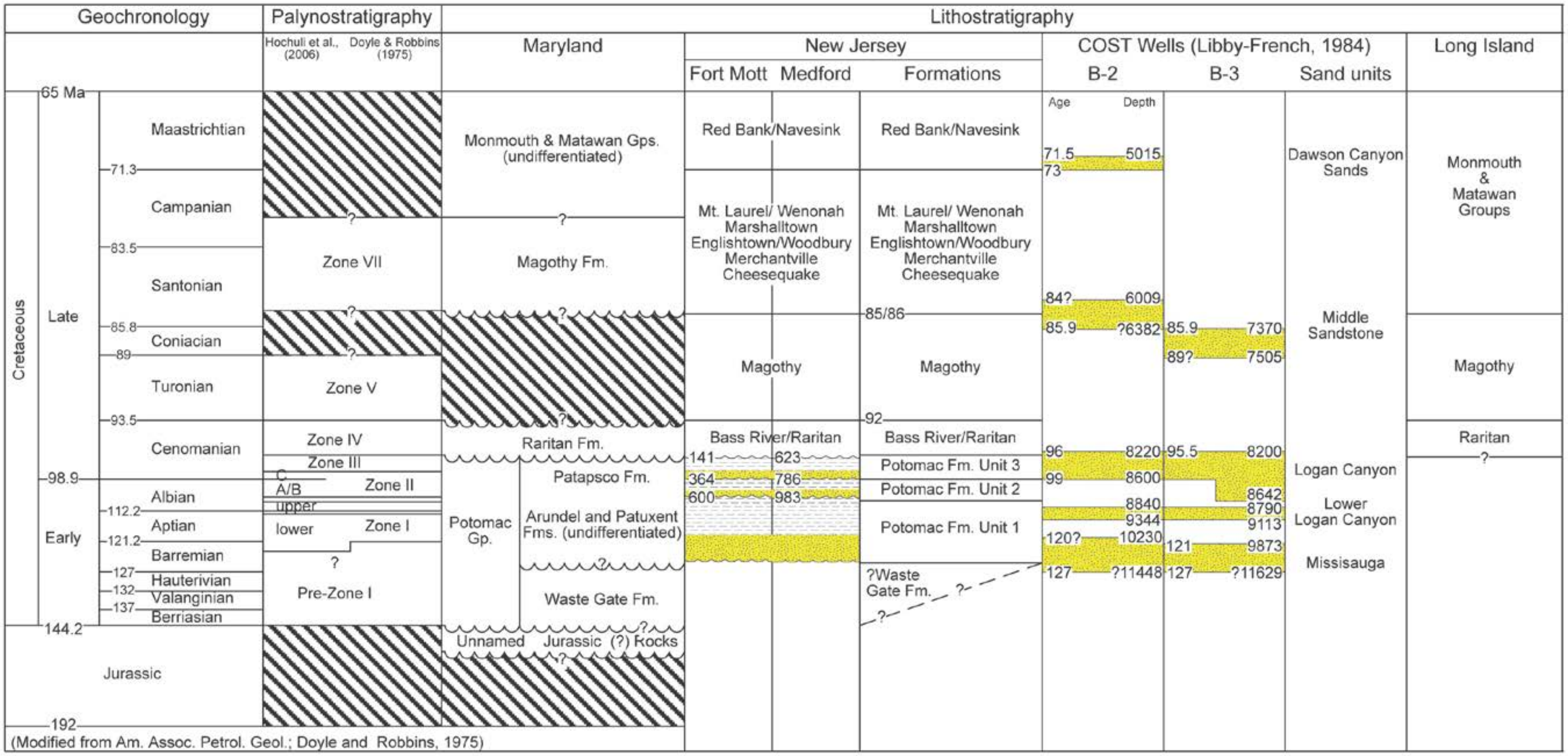

Figure 1.9. Summary Correlation Chart of Cretaceous Sediments in the Atlantic Coastal Plain Between Long Island, New Jersey, Maryland and the Offshore COST B-2 and B-3 Boreholes

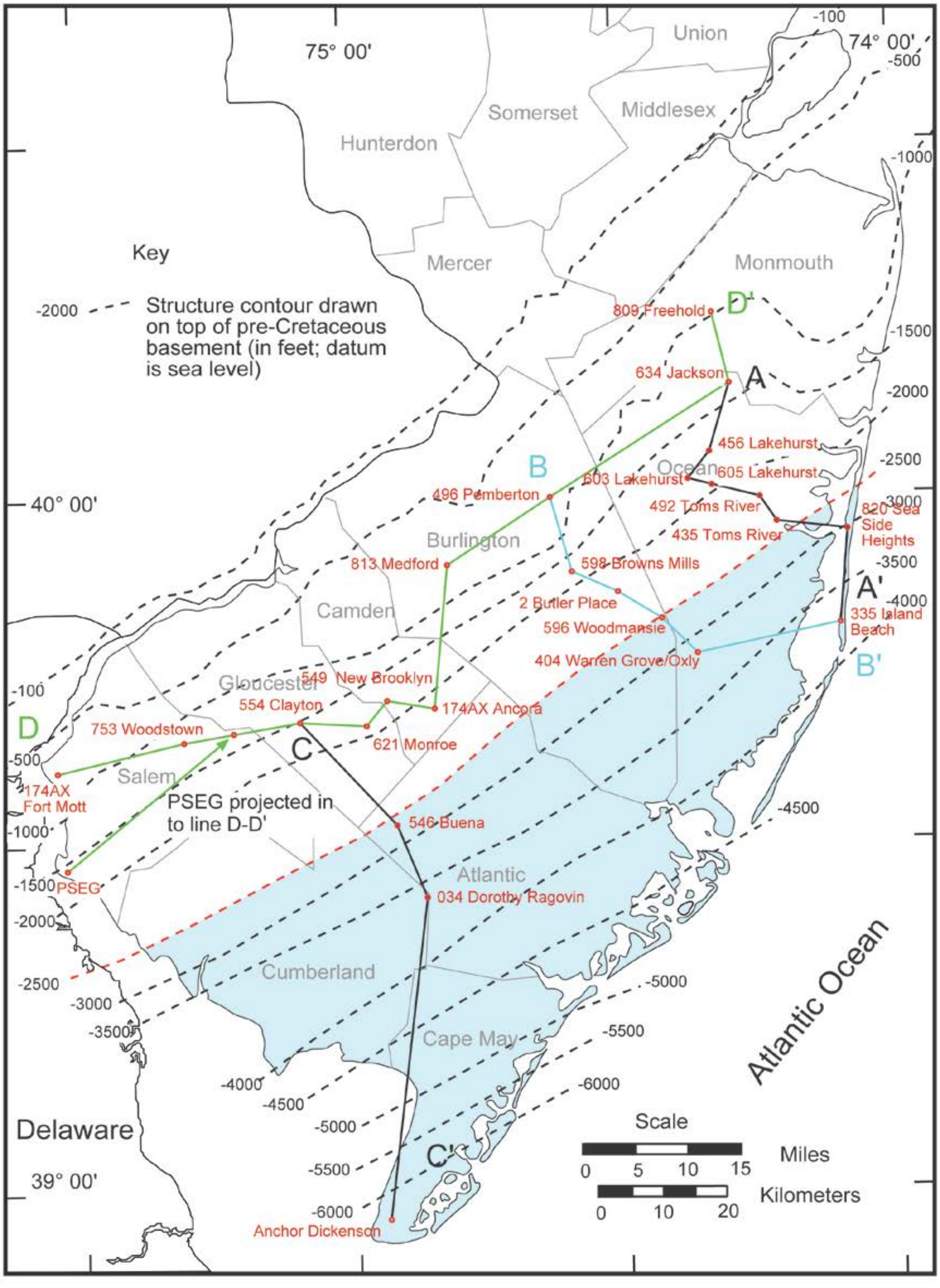

Figure 1.10. Structural contour map on top of pre-Cretaceous basement showing wells used in this study.

Modified after Volkert et al. (1996).

wells). Geophysical logs including gamma, spontaneous potential, resistivity, long and short normal and induction generally comprise the suite used for groundwater studies. Older wells may only have spontaneous potential and single point resistivity. Coverage is better in the southwestern and northern section of the Coastal Plain where the target formations lie at shallower depths. Progressing eastward, formation analysis is less controlled due to lower density well coverage until reaching the coastline where only a few wells intersect the target formations.

We selected 25 well logs (Fig. 1.2) for this study to construct four well-log cross sections (Figs. 1.11 – 1.14). The wells were used to construct structural contour maps (Figs.1.15 – 1.22) as follows: Point files of well locations were labeled with depth to selected surfaces and inputted into ESRI ArcMap 9.x. Wells that did not totally penetrate select horizons were given null values so as not to adversely influence contour generation. Using the 3-D analyst module within ArcMap, the point data was converted to a 2-D surface (raster). These surfaces were contoured using a kriging with a spherical semi-variogram model. All cell sizes were set to a 2,000 ft. grid. Contouring did not use any exaggeration in depth. Contours were connected to surface elevations of the surfaces in question. Structural contour maps were compared with previous efforts (Zapecza, 1989; Kulpecz et al., 2008); these previous efforts had greater number of wells updip, but lack the deepest wells that place constraints on the Potomac Formation. They were used to check contouring of the updip locations. The structural contour maps confirm that only the P3, P2, and P1 sands reach sufficient burial depth for sequestration (750 - 900 m; ~2,400 – 3,000 ft.) onshore. Therefore, isopach maps were created for the three sands contained within these units. Because of the limited number of deep holes, the isopach maps (Figs. 1.23 – 1.25) were hand contoured.

Three dip (A-A’, Fig. 1.11; B-B’, Fg. 1.12, and C-C’, Fig. 1.13) and one updip strike (D-D’, Fig. 1.14) cross sections were constructed. Limited pollen data (Table 1.1) and published age interpretations (Brown et al., 1972; Poag, 1985) were used to guide the correlations. In general, a gamma log spike at the base of the Navesink Formation (base Maastrichtian) and low gamma/high resistivity values of the Magothy Formation are readily identifiable on most logs and provide a means of registering deeper units.

Correlations of the Cenozoic to post-Magothy Upper Cretaceous sections were limited and done primarily to ground truth deeper correlations. Unconfined sands of the undifferentiated Kirkwood-Cohansey aquifer system lie at the top of wells except at updip locations where they are cut out. The Shark River and Manasquan Formations have relatively low gamma values despite the fact that they are dominantly clay-silt as shown by low resistivity values and numerous existing coreholes that sampled these units; the exception is a very sandy upper Shark River’s Toms River Member. The Vincentown and Hornerstown Formations were lumped and the sand of the Vincentown Formation was not mapped. The Navesink sequence(s) is generally thin; in the underlying Marshalltown sequence, we did not break out the Mount Laurel. We correlated sands of the upper Englishtown sequence where possible, though we combined the lower Englishtown Formation sands, Woodbury Clay, and Merchantville Formation greensands into the Merchantville sequence. The thin Cheesequake Formation and sequence was not identified for this report.

As noted, the Magothy Formation is present throughout the study area, and is relatively thick (generally ~30 m/100 ft.). This unit is well-confined by the fine-grained Upper Cretaceous to

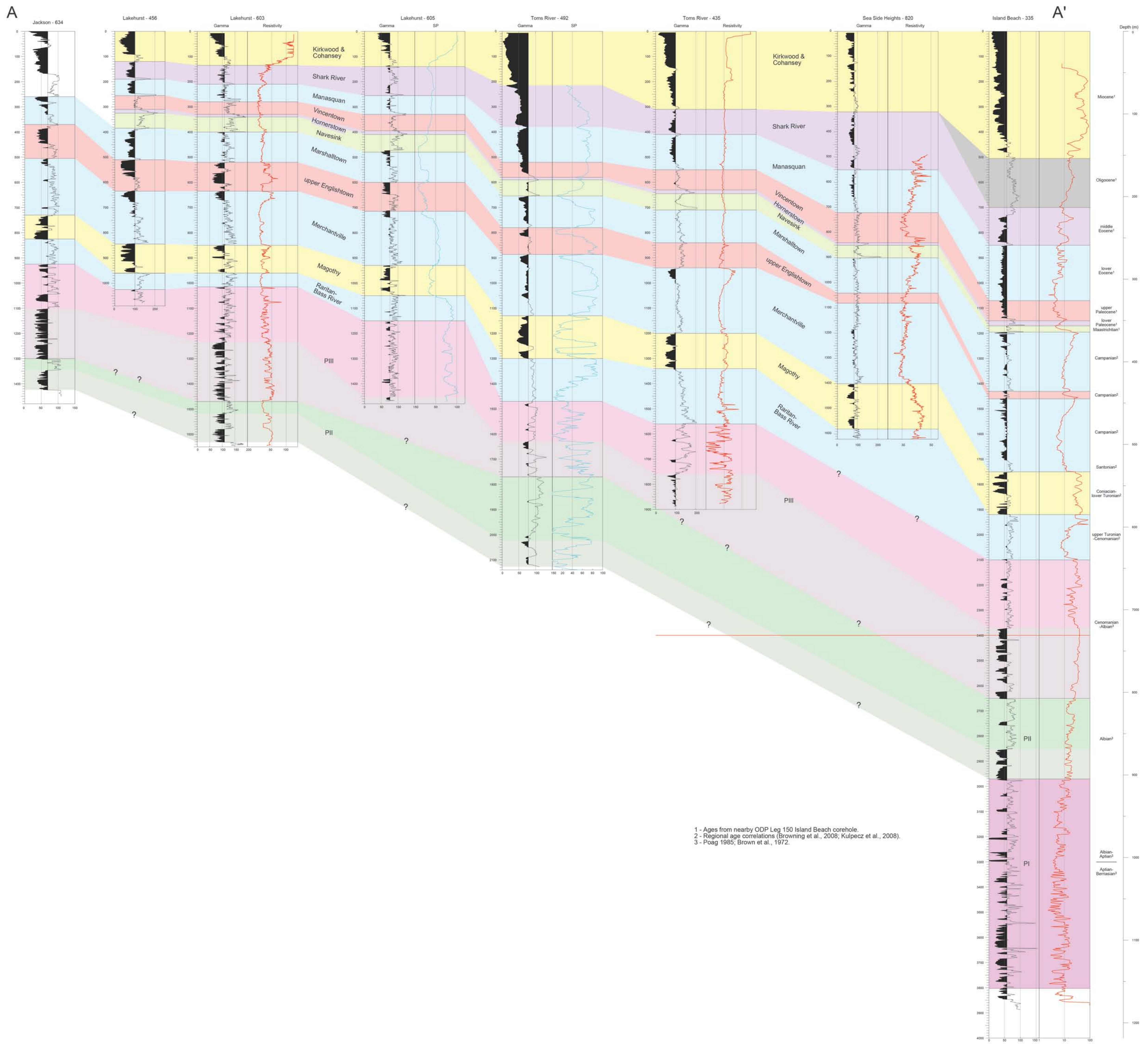

Figure 1.11. A-A' Norther Dip Cross Section, Freehold-Island Beach

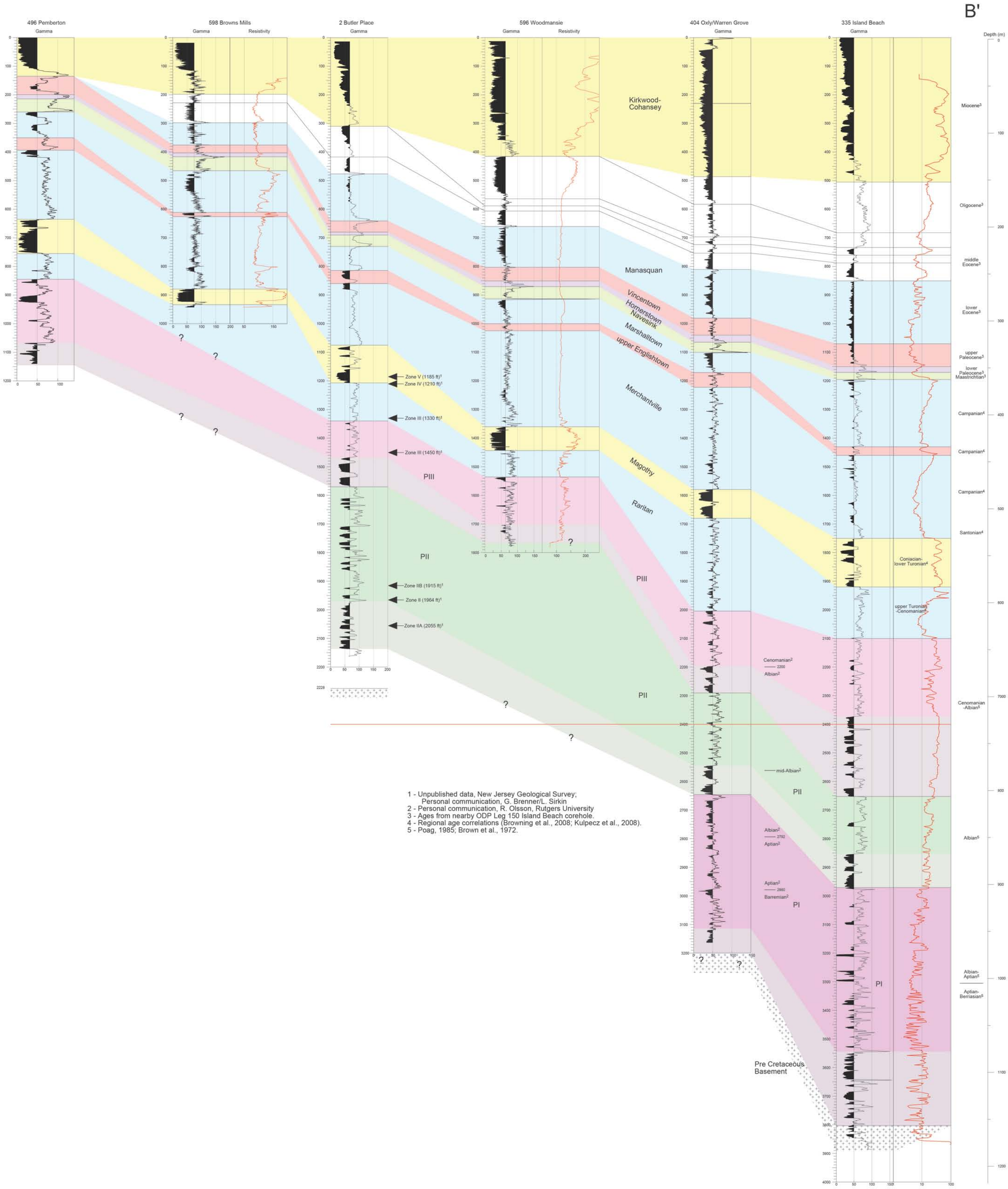

Figure 1.12. B-B' Central Dip Cross Section, Pemberton-Island Beach

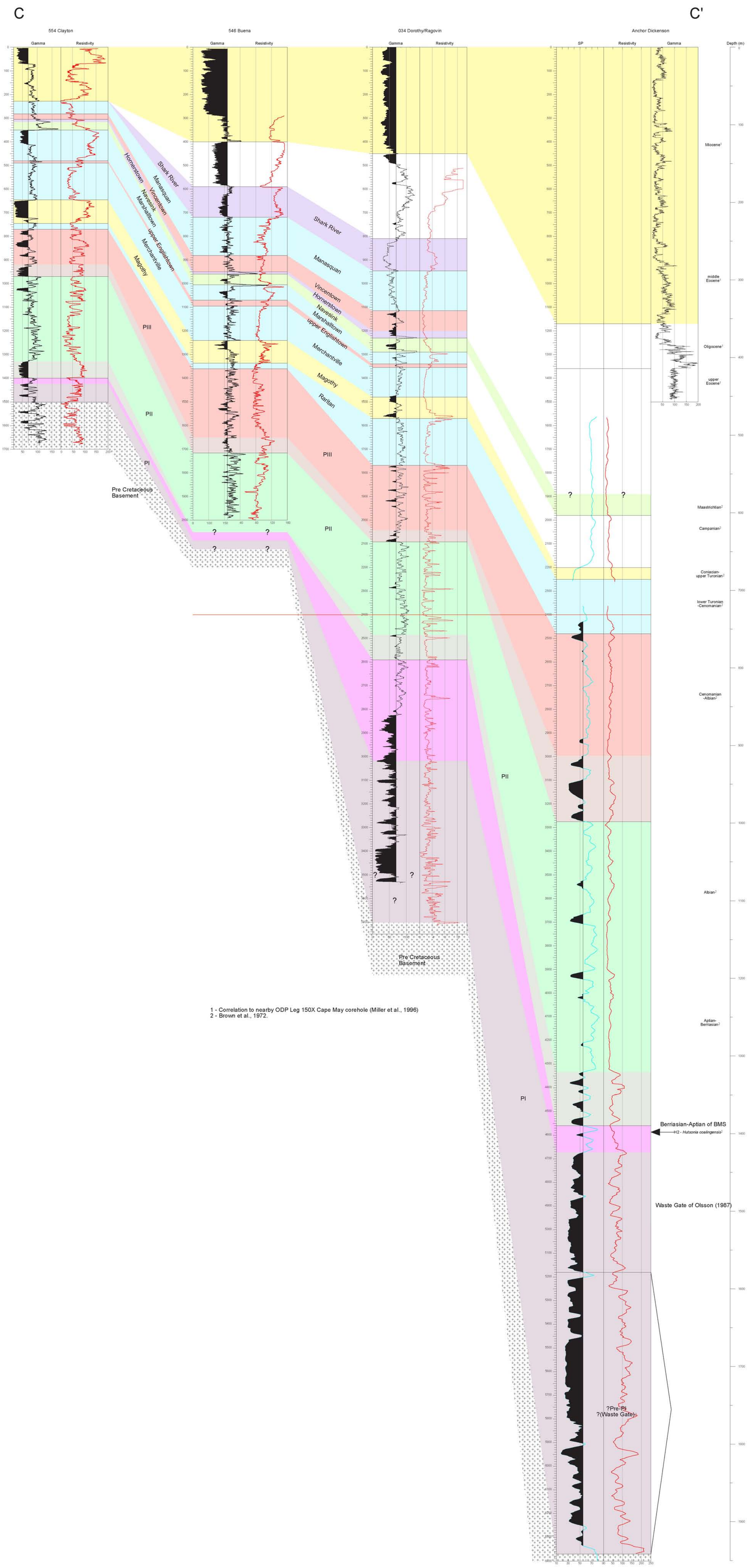

Figure 1.13. C-C' southern dip cross section, Clayton-Anchor Dickenson

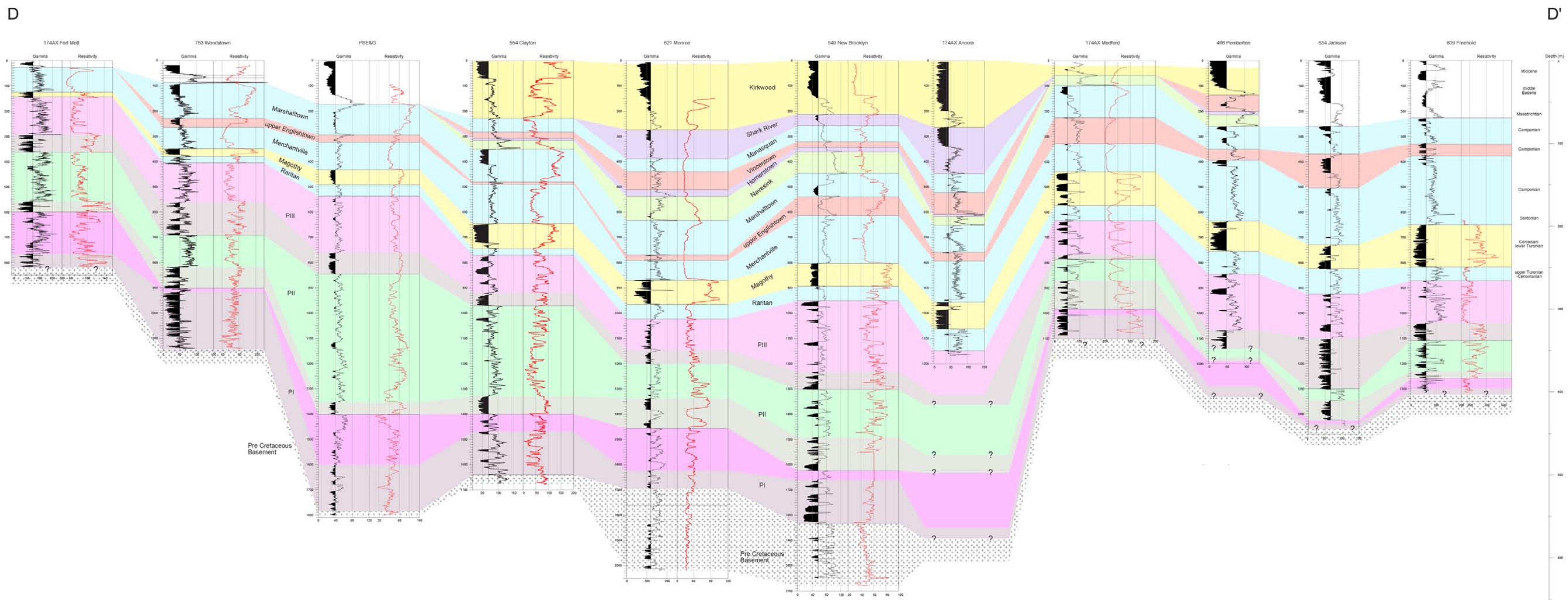

Figure 1.14. D-D' strike cross section Leg 174AX Fort Mott-Freehold

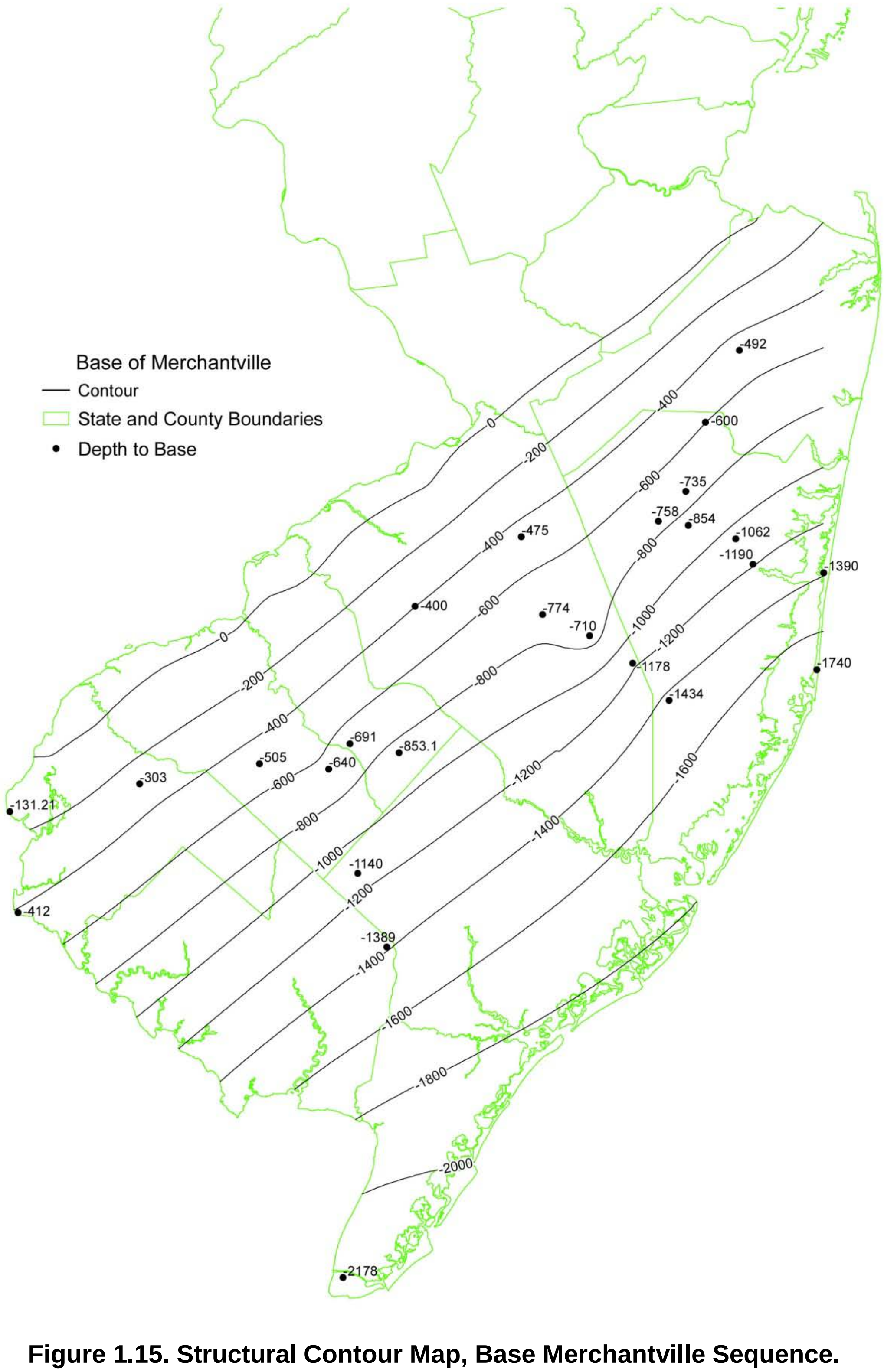

Figure 1.15. Structural Contour Map, Base Merchantville Sequence.

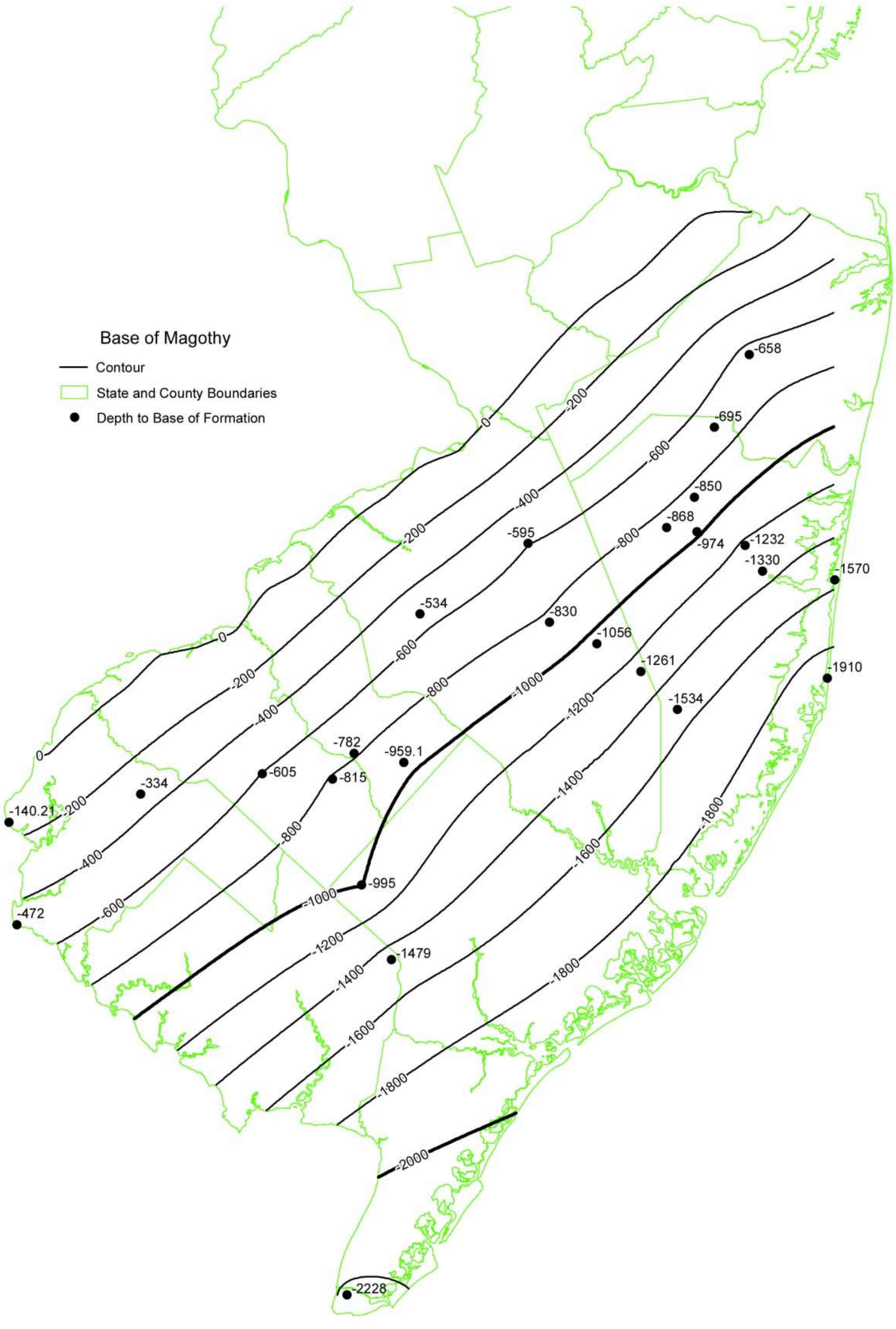

Figure 1.16. Structural Contour Map, Base Magothy Sequence.

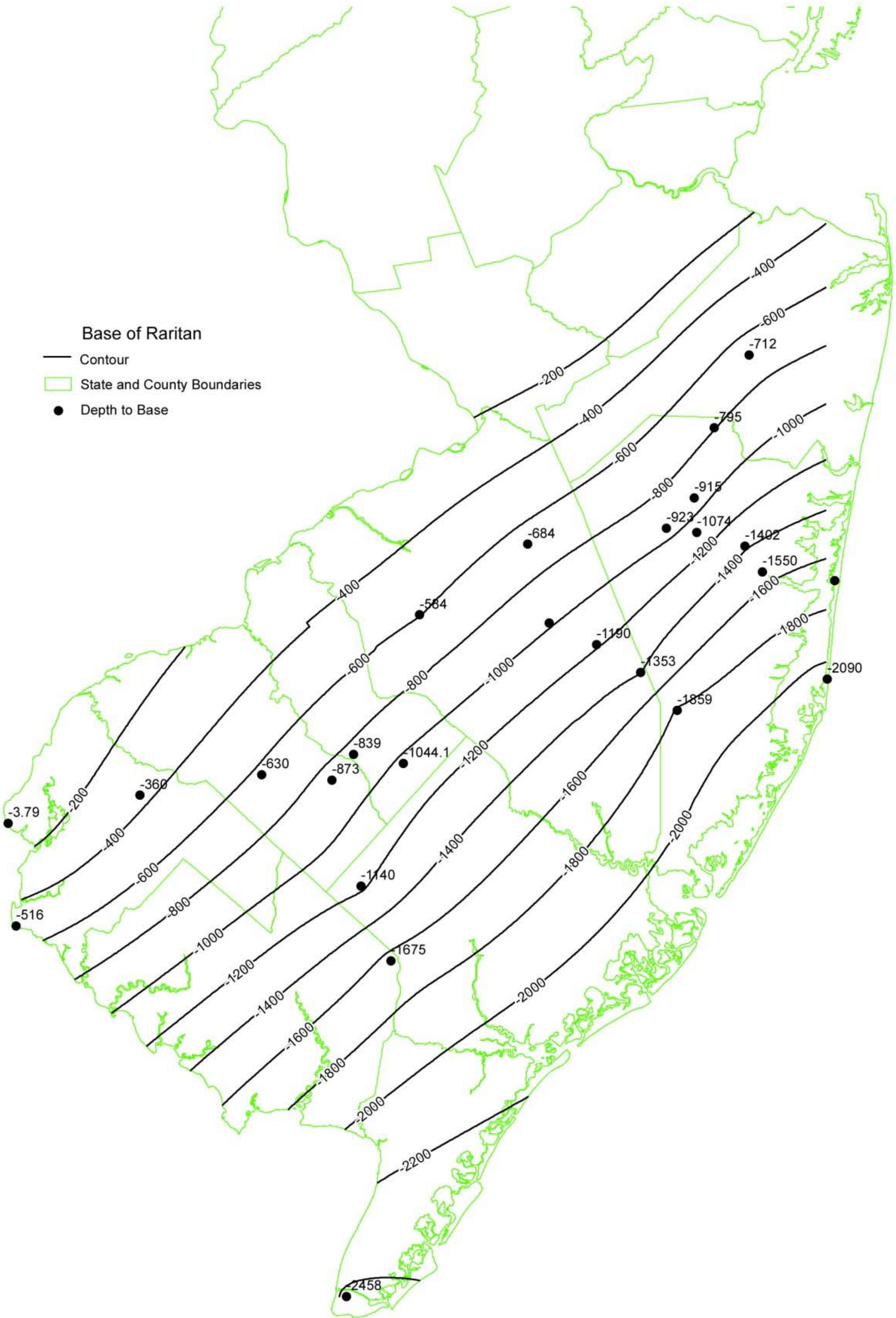

Figure 1.17. Structural Contour Map, Base Raritan Sequence.

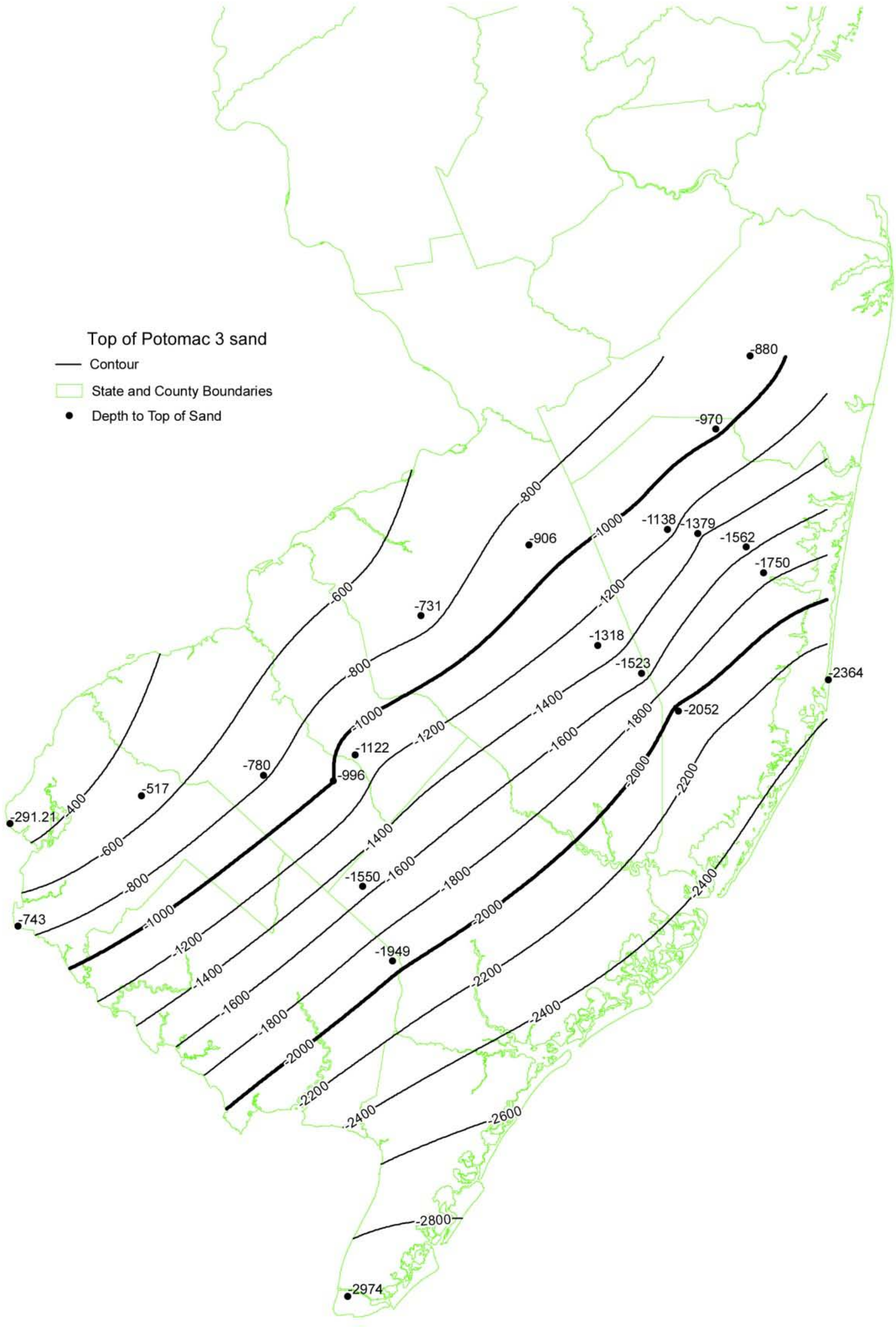

Figure 1.18. Structural Contour Map, Top of P3 Sand.

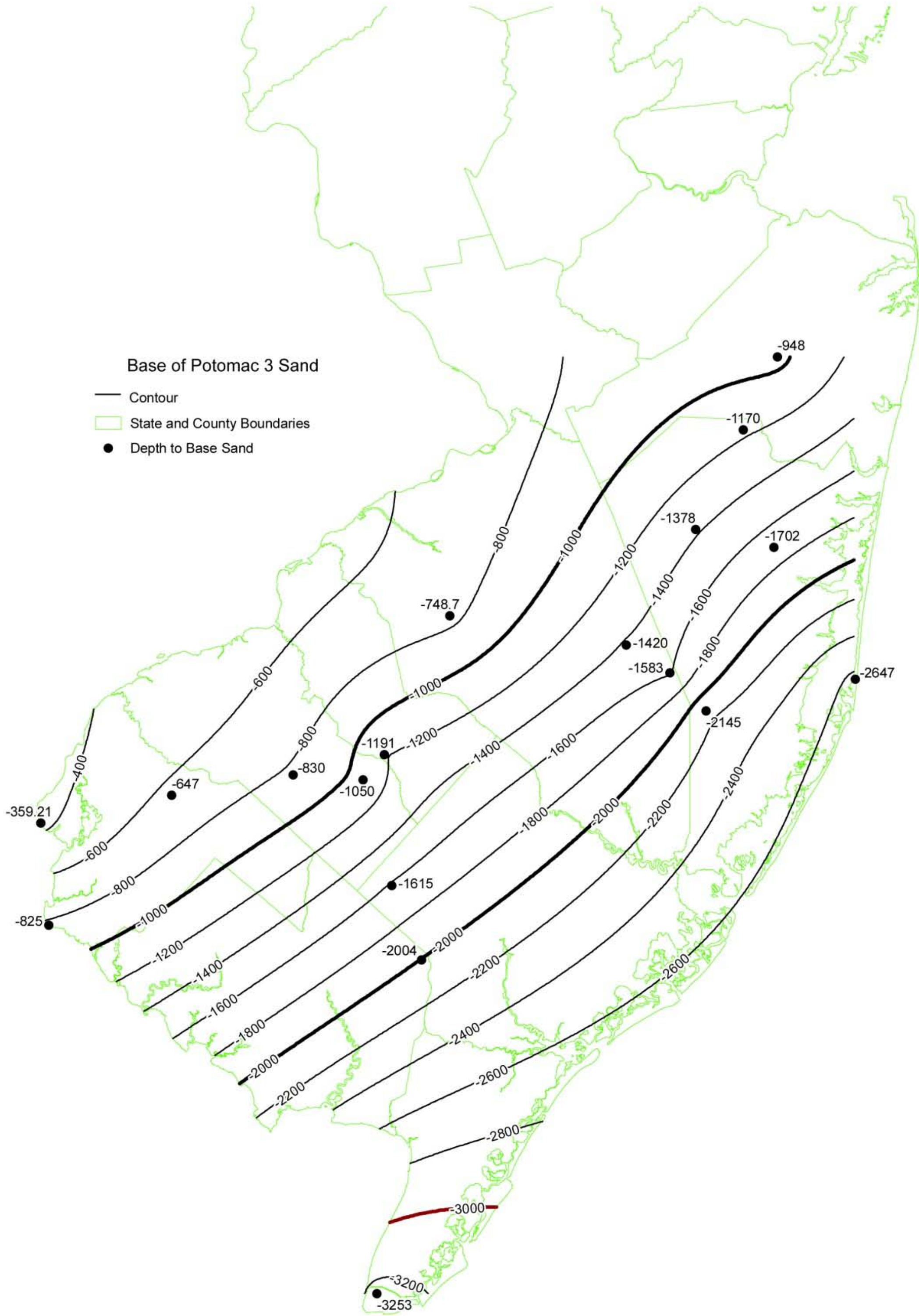

Figure 1.19. Structural Contour Map, Base of P3 Sand.

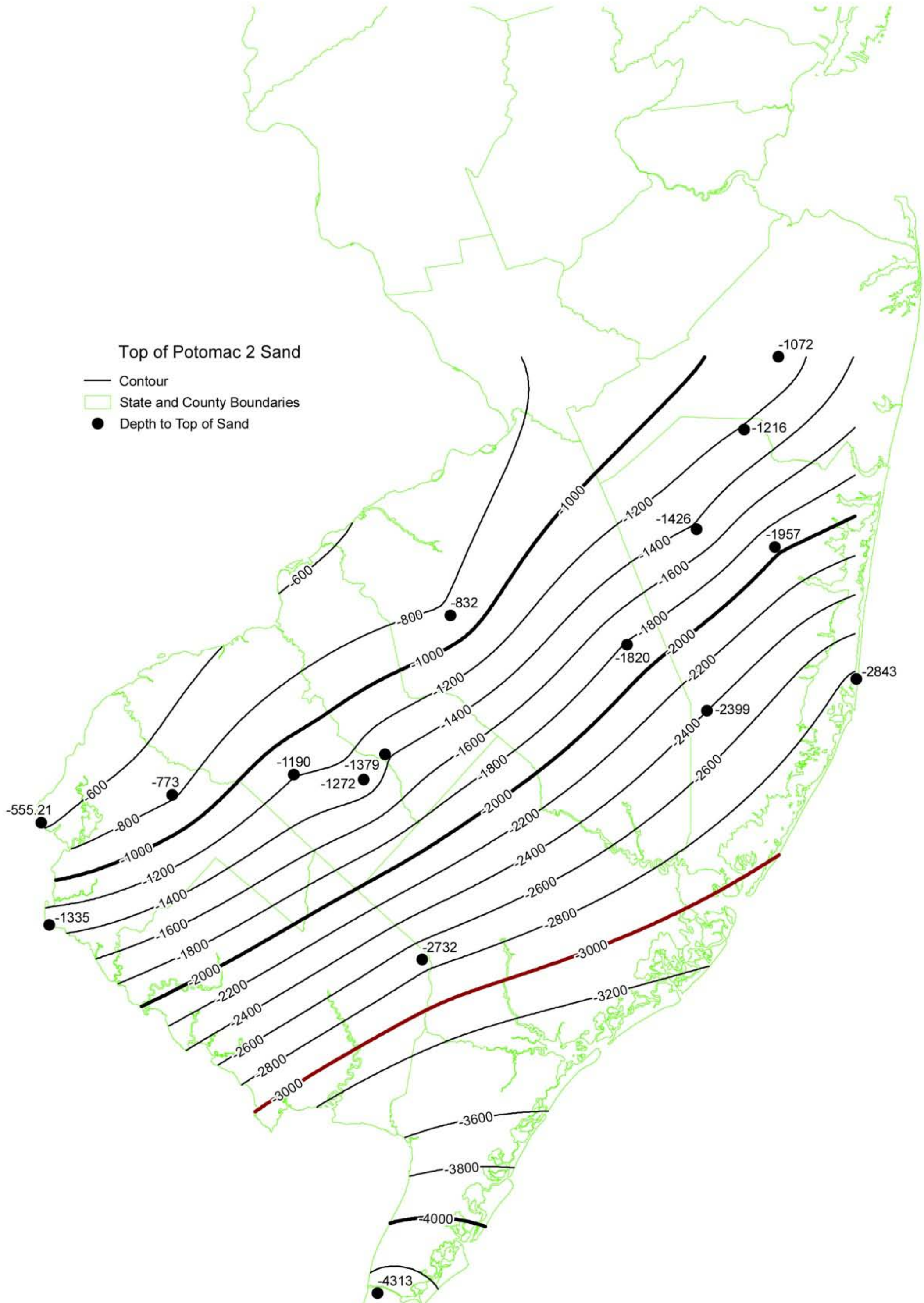

Figure 1.20. Structural Contour Map, Top of P2 Sand.

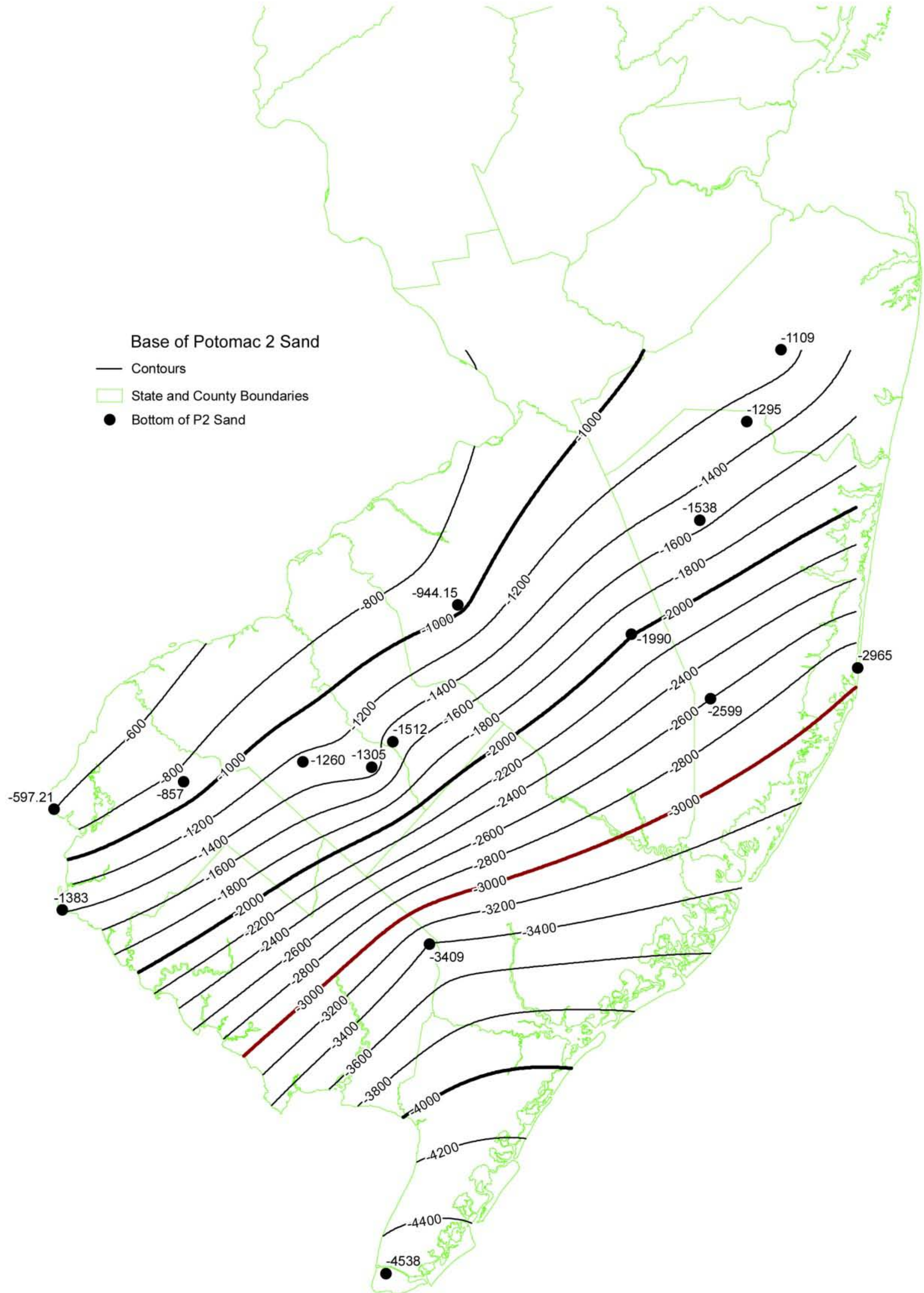

Figure 1.21. Structural Contour Map, Base of P2 Sand.

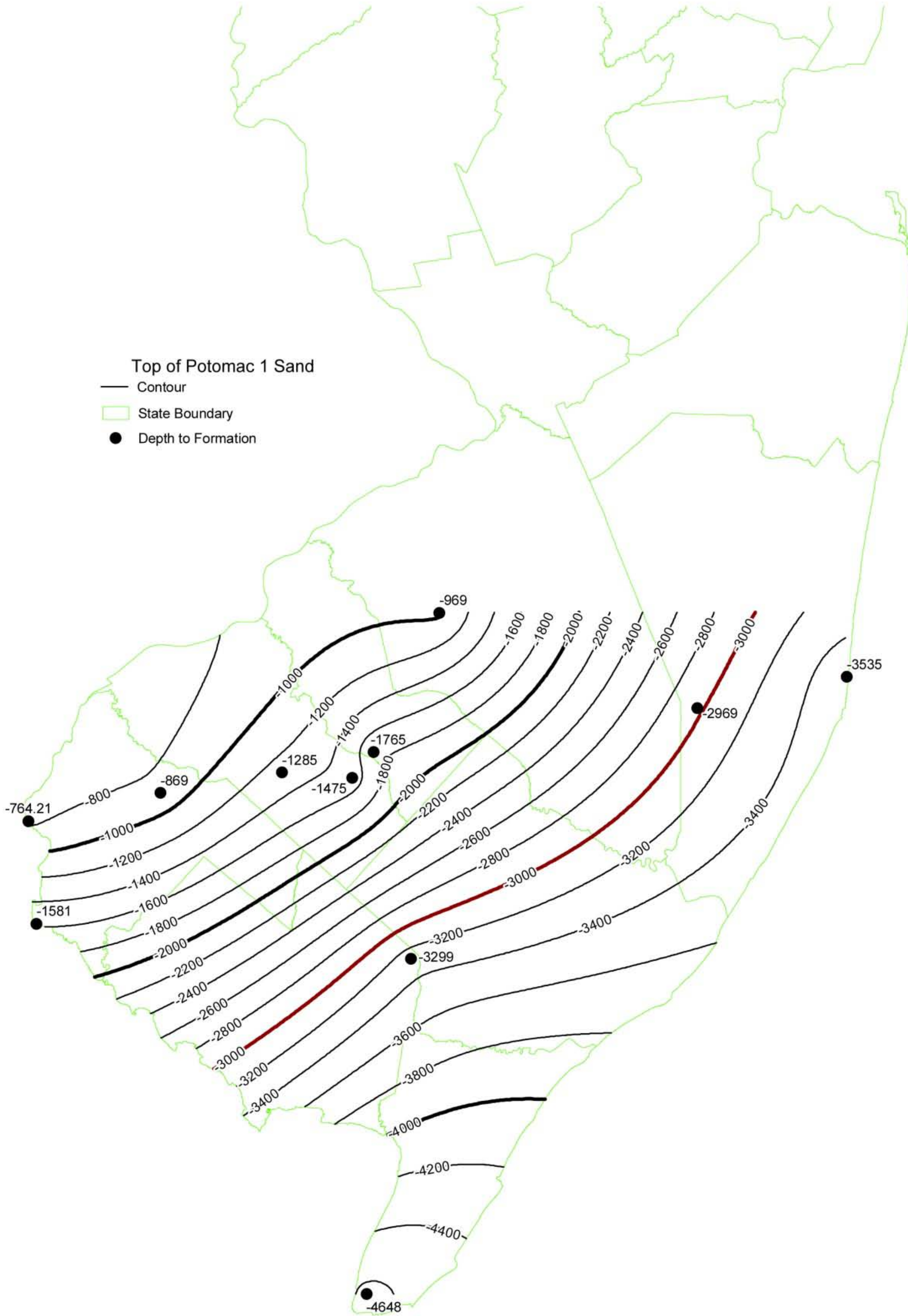

Figure 1.22. Structural Contour Map, Top of P1 Sand.

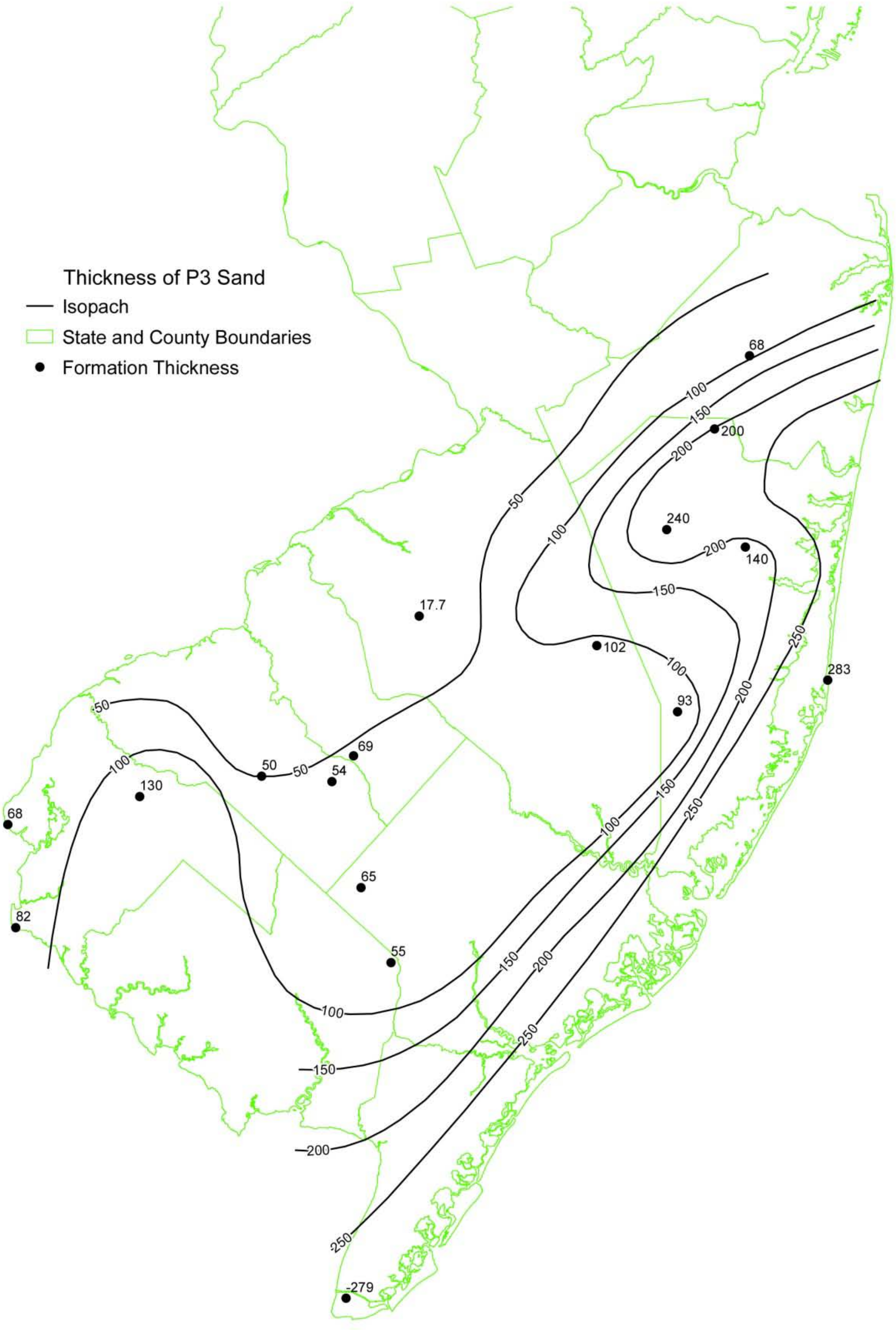

Figure 1.23. Isopach Map of P3 Sand.

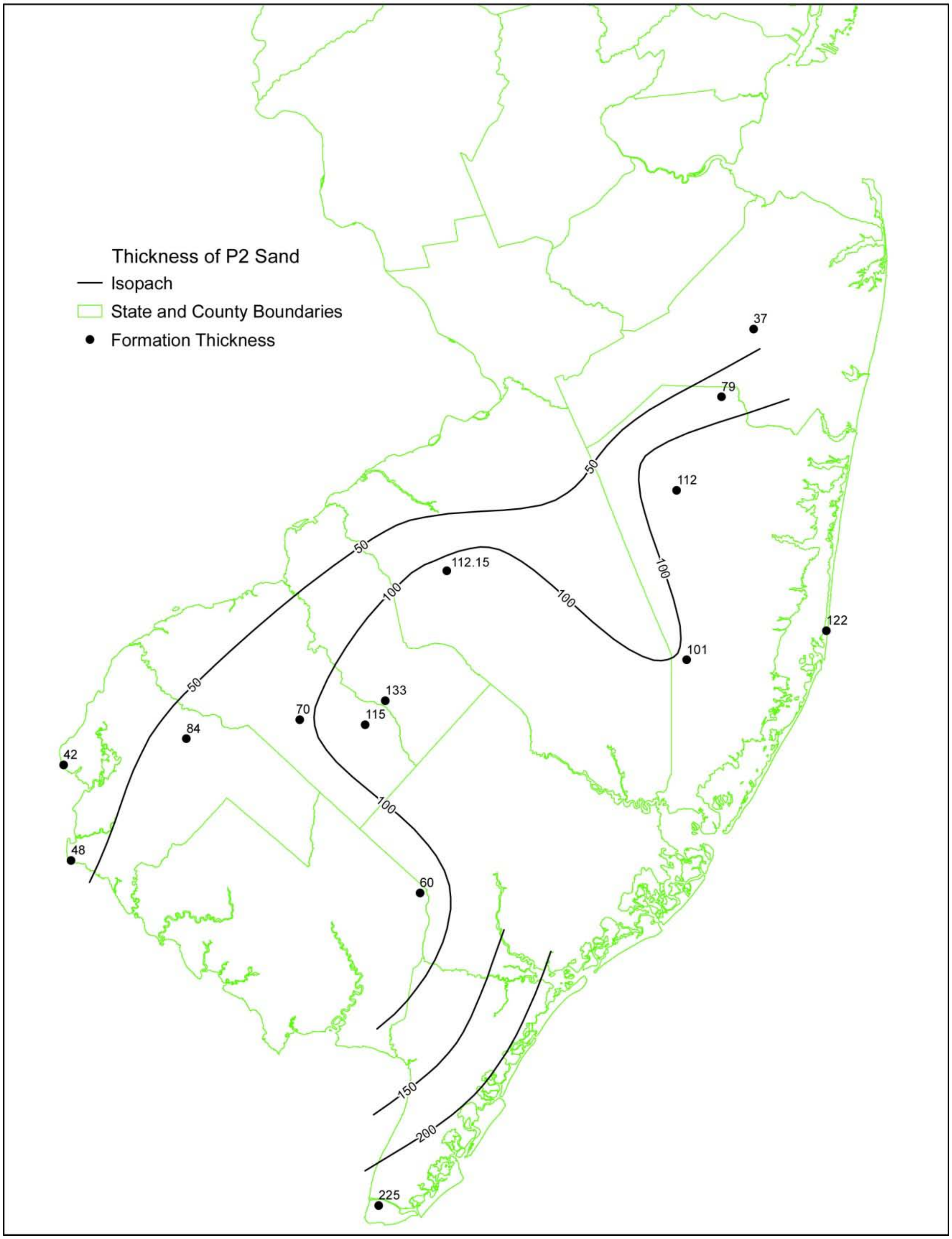

Figure 1.24. Isopach Map of P2 Sand.

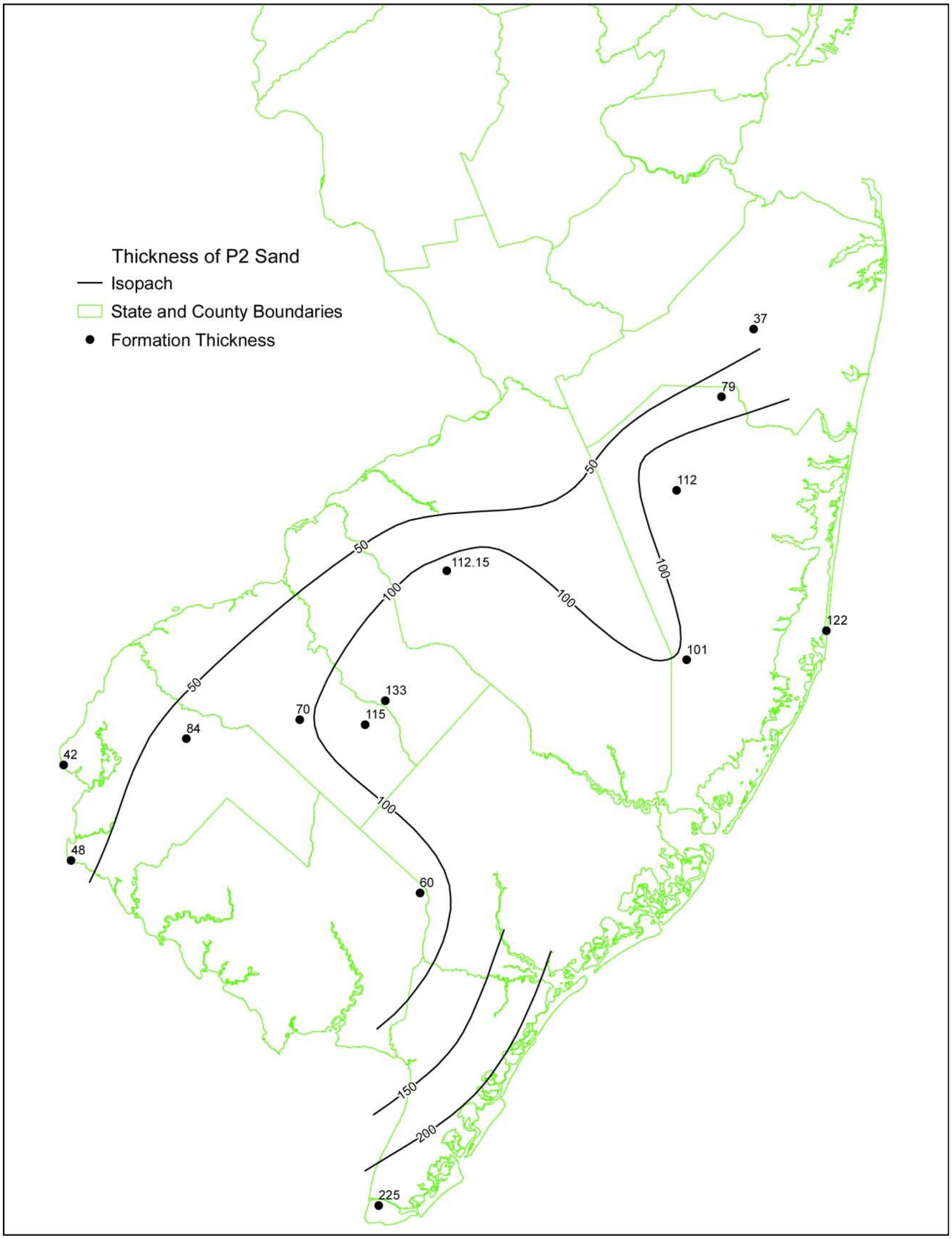

Figure 1.25. Isopach Map of P1 Sand.

Table 1.1. Unpublished Pollen Data From Selected Deep Wells

Location	Depth	Zone	Comment
Butler Place	1185	V	very sparse
	1210	IV	
	1270		few Cretaceous spores
	1330	III	
	1450	III	
	1750	barren	
	1915	IIB	
	1964	II	
	2055	IIA	numerous spores
New Brooklyn Park	1012	III, maybe V	
	1050	V	one specimen
	1143	barren	
	1148	barren	
	1237		no advanced forms
Oxly 1	2080	VII?	very sparse
	2320	III?	very sparse
	2700	III, IV?	very sparse
	3000	I?	very sparse
Oxly 1A	1870		tr. Pollen; shells
	1990	III?	tr. Pollen; shells
	2190		tr. Pollen; shells
Anchor Gas Ragovin	3108		Barren
	3282	IIB (maximum age)	Very sparse
	3396	transition III	
	3553	IIB?	Very sparse
Toms River Chem	1506	II?	sparse
	1620	III	
	2099	IIB	abundant spores and pollen
Lakewood	1525	VII	Excellent Recovery

Paleogene muds and mudstones. However, at no point in the onshore New Jersey Coastal Plain does this unit reach the critical depth of 2,400 ft./750 m required for sequestration (Fig. 1.16) and thus is not considered further here. Offshore equivalents of the Magothy Formation may prove suitable because they lie at progressively deeper burial depths downdip. Even in downdip locations (Island Beach and Dorothy Ragovin), the Magothy appears to be primarily sand based on gamma log intensities (Figs. 1.11 – 1.13), though the most downdip location (Anchor Dickinson Cape May) lacks suitable log data for evaluation.

The Potomac unit 3 (P3) has proven to be remarkably traceable both downdip (Figs. 1.11 – 1.13) and along strike (Fig. 1.14). In particular, the basal P3 sands can be correlated along strike from Fort Mott across the entire Coastal Plain to Freehold (Fig. 1.14). Across the strike section, the gamma logs display very similar patterns. Thickening and thinning of the P3 sands occurs along strike on the South Jersey High (Figs. 1.14, 1.23), but the basal P3 sands are observable at all sections. These P3 sands are ~50 ft. thick updip on the South Jersey High and thicken downdip to nearly 300 ft. at Island Beach and Anchor Dickenson/Cape May (Fig. 1.23). As noted, the widespread distribution and apparent continuity of the P3 sands does not readily fit a fluvial origin but is consistent with a delta front environment (Sugarman et al., 2005). The P3 sands might be a target for sequestration though they do not exceed burial depths of 3,000 ft. in the Coastal Plain (Fig. 1.18). The only location where the depth of the top of the P3 sands exceed 2,400 ft. is in the Cape May peninsula and the most shoreward portion of Atlantic and southern Ocean Counties (Fig. 1.18). This region could be considered for carbon sequestration in the P3 given that opportunities exist for also sequestering in the deeper P2 and P1 sands.

The P3 sands are lowermost Cenomanian (Fig. 1.9) and appear to correlate with the offshore Logan Canyon unit 3a sands, another potential sequestration target (see Section 2 - offshore). The physical continuity of these units is discussed briefly below (see Section 2 - offshore) and will be the subject of future studies.

The Potomac unit 2 (P2) is mappable throughout the Coastal Plain. Additionally, the basal P2 sands appear continuous in our study area, although its geophysical well-log character varies. On dip section A-A’ (Fig. 1.11), the P2 sands form a single blocky/boxcar character updip with a confining layer clay above this sand. Downdip on A-A’ there are two distinct blocky P2 sands both at Lakehurst and Toms River 492, separated by a clay-silt bed; this package is overlain by a confining clay-silt bed. At Island Beach, there appears to be three sand beds. A double blocky pattern occurs downdip at Oxly/Warren Grove, but the character changes updip to Butler Place where there are several discontinuous sands separated by clays. It is possible that some of the section identified as P2 sand here could be Potomac unit 1 (P1) sands; identification of the P2 sands at Butler Place is dependent on pollen data (table 1.1) based on cuttings and must be considered preliminary. Correlation of the P2 sands on C-C’ is uncertain (Fig. 1.13). At the Anchor Dickinson/Cape May well, there appear to be two sand units based on the resistivity log, similar to other downdip sections. However, correlation to the Dorothy/Ragovin well is uncertain. Pollen data (Table 1.1) suggest very thick (~700 ft.; ~200 m) P2 sands. However, pollen are sparse and the cuttings samples from this hole clearly suffer from caving (with glauconite and shells extensively caved into the red paleosols of the Potomac; unpublished drillers log). Thus, the pollen assignments were not followed and the base of the P2 sands was placed at 2,900 ft. at a sand/confining bed contact.

Updip the P2 sands vary considerably along strike. In the updip strike section D-D' (Fig. 1.14), the P2 sands vary from one distinct blocky sand body (e.g., Clayton) to numerous sand bodies. This variability is consistent with core data from Fort Mott and Medford indicating deposition in a fluvial, likely anastomosing river environment (Sugarman et al., 2004). Downdip, the continuity of the P2 sand in each of the wells might indicate a delta front environment as the sand is dispersed over a relatively large area.

The P2 sands appear to vary in thickness from 37 to 225 ft. (Fig. 1.24) in the wells we studied, though the identification of this unit is often uncertain as discussed above. The P2 may be a sequestration target though our data are too sparse to fully evaluate its distribution and thickness.

The P2 sands are assigned to pollen Zone II. They are likely Albian in age though Hochuli et al. (2006) suggested that they may extend into the basal Cenomanian. Offshore correlations of this unit are uncertain. They may correlate with the lower Logan Canyon sands, another sequestration target (see Section 2 - offshore). The physical continuity of these units is discussed briefly below (see Section 2 - offshore) and is the subject of future studies.

Thick Potomac unit 1 (P1) sands present the most likely target for sequestration in the New Jersey Coastal Plain. In updip wells, the P1 exhibits great lithologic variability (Fig. 1.14). In the Medford corehole (Figs. 1.8, 1.14) it consists of thick (100 ft.), pebbly coarse sands with a blocky log pattern interpreted as a braided stream deposit. Similar blocky log patterns occur at New Brooklyn and Woodstown (Fig. 1.14). In contrast, the well logs of Monroe, Clayton, and PSE&G (Fig. 1.14) show lower gamma log values for the P1 unit implying much less sand content. In the Fort Mott corehole, the P1 is a muddy sand in its lower part and muddy at the top (Fig. 1.7), intermediate in character between the sandier and muddier sections along strike (Fig. 1.14).

The P1 was only sampled downdip in four downdip wells. At Island Beach, the basal P1 sands are 260 ft. thick and display several blocky sands separated by thinner clays based on the gamma log (Fig. 1.12). The top of the sands are at ~3,550 ft./1,080 m and are likely candidates for sequestration. Traced updip to the Oxly well (Fig. 1.12), where their top is at 3,115 ft., the P1 sands appear to be thin and perhaps finer grained. Thus, they appear to be confined updip by the P1 clays and overlying confining units. As noted above, differentiation of the P1 and P2 sands is difficult in the Ragovin well (Fig. 1.13), though the P1 sands below 3,400 ft. provide a potential sequestration target. The section from 3,400 - 2,900 ft. at Ragovin appears to be sandy and tentatively assigned to the P1 unit (Fig. 1.13). However, log quality is poor for this section and the cutting samples suffer from extensive caving. At Anchor Dickinson/Cape May, the P1 sands are remarkably thick (~1,700 ft.) and display 8 - 12 thick blocky log units separated by comparatively thin mud units (Fig. 1.13).

Potomac unit 1 was assigned to Pollen Zone I at Fort Mott. Pollen Zone I is assigned to the lowermost Albian to Barremian (Hochuli et al., 2006). Correlations of this unit are uncertain although it appears to correlate with the offshore Missisauga sands and the Arundel-Patuxent Formations of the Potomac Group of Maryland (Fig. 1.9).

The thick blocky sands of the P1 at Cape May were correlated to the Waste Gate Formation in Maryland by Olsson et al. (1988). The Waste Gate was assigned to pre-Zone I (Hansen, 1984), which is Neocomian in age (lower Lower Cretaceous; Berriasian to Barremian). The age of this unit in the downdip Anchor-Dickenson/Cape May, Ragovin, Oxly, and Island Beach wells are uncertain. Poag (1985) assigned this unit to Aptian-Berriasian at Island Beach, Olsson (personal communication) assigned it to the Albian to Barremian at Oxly, and Brown et al. (1972) assigned the top of P1 at Anchor-Dickenson/Cape May to Berriasian-Aptian. The age is poorly constrained and in fact may be as old as uppermost Jurassic (Olsson et al., 1997; Fig. 1.26). Future work will focus on evaluating the relationship of the thick P1 sands from Island Beach to Cape May with the Waste Gate Formation in Maryland and intervening sections in Delaware and with offshore sections.

1.7 Suitability as a CO_2 Injection Target or Seal Unit

The Potomac Formation is unconformably overlain by the silts and clays of the Raritan/Bass River Formations, which forms a confining bed. The overlying Magothy Formation and other sands are present upsection, but in general the Upper Cretaceous to Paleogene comprises several confining units. The Potomac Formation is well confined downdip. The fundamental question is: Do the downdip Potomac Formation sands beneath the coast communicate updip where they outcrop along the Delaware River? The answer to this is that the discontinuous nature of the sands, particularly within the P2 and P1 units, very likely precludes significant updip migration.

The P1 sands provide potential targets for sequestration. The P2 sands are thinner and less continuous. The P1 sands comprise a thick, predominantly sand package, but as in the Waste Gate Formation, individual sandy units and confining beds are likely discontinuous (Hansen, 1984). The lower part of the P1 sands that are tentatively equivalent to the Waste Gate Formation pinch out and do not outcrop. Thus, as noted by Hansen (1984) the complex sand-confining beds of these units is not an issue: they are hydrologically isolated from shallow fresh water aquifers and have the capability to store and absorb significant volumes of CO_2.

1.8 A Preliminary Estimate of CO_2 Storage Capacity

A preliminary estimate is made following four steps.

Step 1: We calculated the volume of the three sand units (P1, P2, and P3) using simple geometric shapes (Fig. 1.27). Only the volumes below 800 m (supercritical depth of CO_2) are considered. The volume of the P3 unit is calculated as the difference between two pyramids, one based on the top of P3 and the other on the base of P3, below -800 m elevation. The volume of the P2 and P1 sands are obtained similarly. The results are ~380, ~780, and ~1700 km^3 for P3, P2, and P1 units, respectively. Because these units contain multiple interbedded silts and clays, we multiply the total volumes above with the estimated fraction of sand, which is at least 70 percent for the Potomac Group (Zapecza, 1989). The final sand volumes are shown in the first block of Table 1.2.

Step 2: We converted aquifer volumes to pore volumes, based on the range of porosity observed for sands. Freeze and Cherry (1979) reported a range of 25 percent to 50 percent porosity for surficial sands. We reduced these values slightly to 20 percent - 40 percent to reflect the compaction at depth. These values (low = 0.2, mid = 0.3, and high = 0.4) are used to calculate the pore volume for each of the sand units (block 2 in Table 1.2). Hansen (1984) provided information regarding

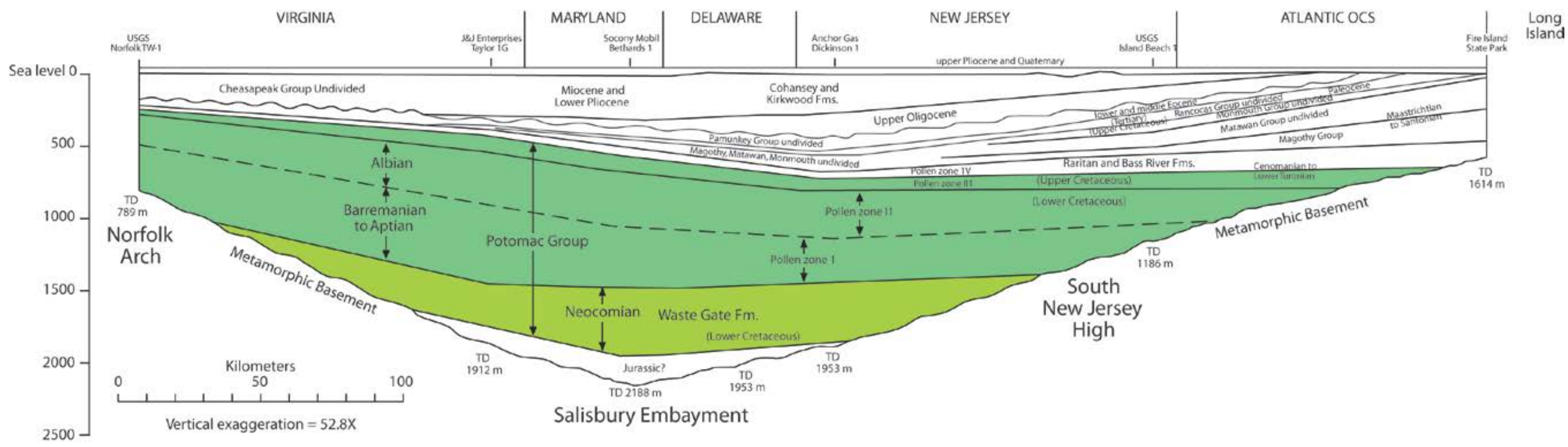

Figure 1.26. Cross section of Coastal Plain strata between Maryland and New Jersey (after Olsson et al., 1997). Locations of boreholes are in Fig. 1.5. Note that Fire Island State Park is shown slightly west of its actual location.

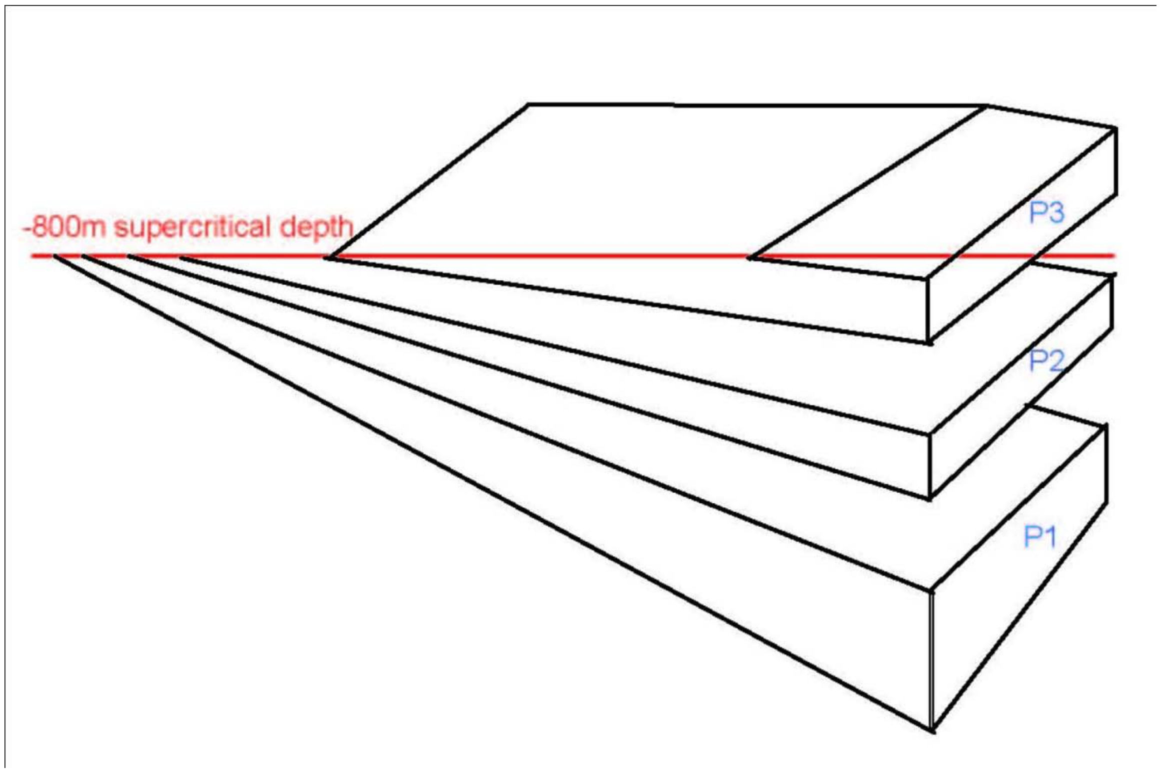

Figure 1.27. Schematic of Aquifer Volume Calculation

Table 1.2. Calculation of CO_2 storage for the New Jersey Coastal Plain Potomac Formation (onshore)

Aquifer Unit	Aquifer Volume	Pore Volume (km^3) *			CO_2 Volume (km^3) ~ 20% Pore **			CO_2 Volume (km^3) ~ 35% Pore			CO_2 Volume (km^3) ~ 50% Pore			CO_2 Mass (million tonne), 20% Pore			CO_2 Mass (million tonne) ~ 35% Pore			CO_2 Mass (million tonne) ~ 50% Pore		
	(km^3)	low (0.2)	mid (0.3)	high (0.4)	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high
P3	270	54	81	108	11	16	22	19	28	38	27	41	54	8	11	15	13	20	26	19	28	38
P2	550	110	165	220	22	33	44	39	58	77	55	83	110	15	23	31	27	40	54	39	58	77
P1	1200	240	360	480	48	72	96	84	126	168	120	180	240	34	50	67	59	88	118	84	126	168
Total	2020	404	606	808	81	121	162	141	212	283	202	303	404	57	85	113	99	148	198	141	212	283

* Range of sand porosity based on Freeze and Cherry (1979), 0.25-0.45, with a 5% reduction considering compaction at below 800m depth. Here we evaluate low, mid, and high values.

** Based on IPCC (2005) report on CCS, supercritical CO_2 only displaces 20-50% of pore space. Here we evaluate low, mid, and high values.

*** Assuming 0.7kg/m^3 density at supercritical state (IPCC, 2005). The result is in million metric ton (or million tonne, or Mt) porosity in the lower Potomac (Waste Gate Formation) of eastern Maryland. He reported that porosities generally range from 19 to 27 percent, within the range we consider here.

Step 3: We converted pore volumes to potential CO_2 volumes. Studies in the IPCC (2005) report that only 20 percent - 50 percent of the pore volume can be displaced by injected CO_2 due to the fact that supercritical CO_2 is not miscible and has higher viscosity than the native pore fluid (saline groundwater), so that it does not move as a piston to replace the entire pore fluid but moves as thin fingers and only occupies a fraction of the pore space. Using the low (20 percent), mid (35 percent), and high (50 percent) values, we obtain the potential CO_2 volumes as shown in table 1.2 (block 3), for each of the 3 porosity values.

Step 4: We converted CO_2 volumes to mass. Assuming that supercritical CO_2 has a density of 0.7 kg/m^3, we obtain the mass of CO_2 in Mt as shown in Table 1.2 (block 4) for each of the 3 porosity values. The range of total CO_2 storage in the three sand units is 57 - 283 Mt. These estimates are illustrated in Figure 1.28 below for the range of porosity and CO_2 displacement.

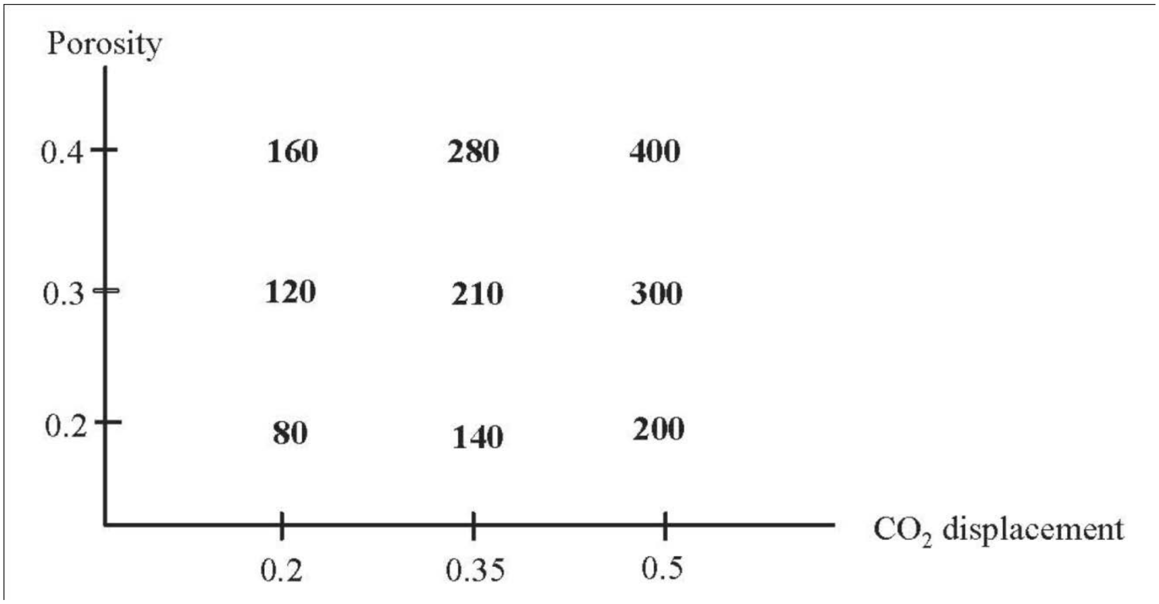

Figure 1.28. Total CO_2 Storage Capacity (numbers in matrix, in Mt) in the Context of Uncertainty in Porosity and Fraction of CO_2 Displacement of Native Fluids.

1.9 References

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2.0 CHARACTERIZATION OF THE CARBON DIOXIDE STORAGE POTENTIAL BENEATH THE CONTINENTAL SHELF AND SLOPE OFFSHORE NEW JERSEY

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2.1 Introduction - Offshore Sequestration

Thick, porous sediments with burial depths >800 m required for supercritical storage and confined by impermeable mudrocks/muds are potential targets for the geologic sequestration of CO_2. Such formations exist beneath the continental shelf and slope offshore New Jersey (Fig. 1.1 and Fig. 2.1). There are several reasons for considering their sequestration potential:

1) High Early Cretaceous sedimentation rates and simple tectonic history of the Atlantic margin (Steckler and Watts, 1982) resulted in thick, widespread mid-Cretaceous sands that have retained relatively high values of permeability (Scholle, 1977, 1980);
2) Recent studies confirm that high Late Cretaceous global sea level (Miller et al., 2005) resulted in fine-grained confining beds that potentially seal sequestration reservoirs now found onshore as well as offshore (Fig. 1.4);
3) There is little evidence of major faulting, rotation, or other structural disturbances that could have caused pathways for leakage of sequestered CO_2;
4) A substantial number of seismic profiles, exploration wells, and regional studies on this margin already exist (Fig. 2.1; e.g., Hathaway et al., 1976; Poag, 1977, 1978, 1980, 1985, 1987; Kidwell, 1982, 1988; Olsson et al., 1987; Greenlee et al., 1988, 1992; among others).

In this section, we review the regional geology, geological history, and available data of the U.S. mid-Atlantic margin (from the Coastal Plain to the continental slope) in the context of geological sequestration.

2.2 Geologic Background

The New Jersey continental shelf and slope is part of a classic passive margin that contains the thickest sedimentary record of the entire eastern U.S. coastline (Fig. 1.3). Rifting and subsequent separation from what is now Northwest Africa occurred during the Late Triassic-earliest Jurassic (ca. 230-190 Ma), forming a series of onshore and offshore rift basins (e.g., Grow and Sheridan, 1988; Olsen et al., 1996). Seafloor spreading began prior to the Callovian (~165 Ma); Middle Jurassic, (Sheridan, Gradstein et al., 1978), with the likely opening beginning off Georgia, ca. 200 Ma, and progressing northward off the mid-Atlantic margin (Withjack et al., 1998). This south to north "zipper" rifting is associated with a diachronous post-rift unconformity that separates active "rift-stage" deposits (strongly influenced by syndepositional, large and rapid tectonic uplift and subsidence) from more passive margin "drift-stage" deposits that accumulated in an ever-widening and deepening basin open to the ocean. Post-rift history has been dominated by simple

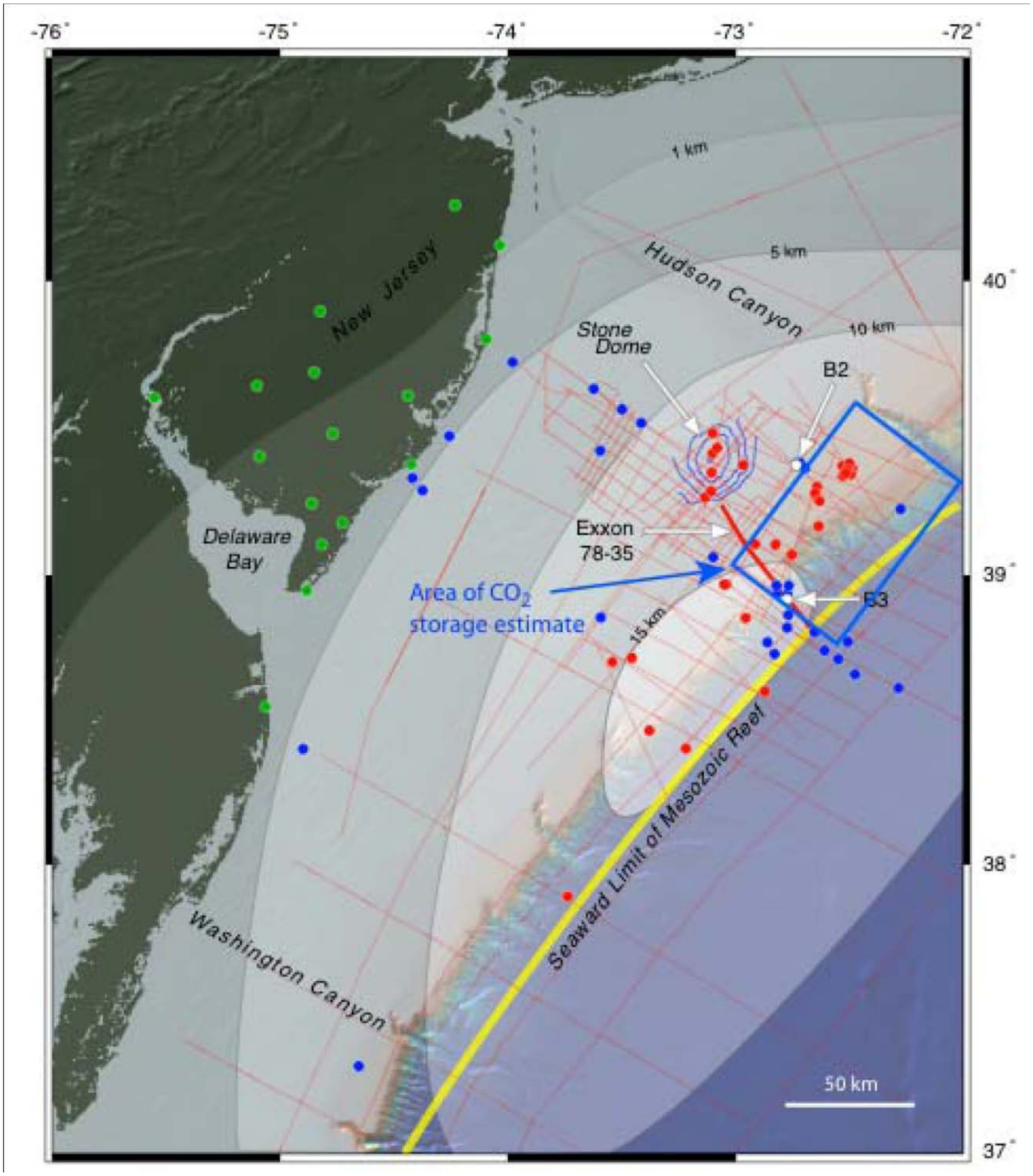

Figure 2.1. Available Offshore Seismic and Well Data Along the Mid-Atlantic States Between Hudson and Washington Canyons.

thermal subsidence, sediment loading, lithospheric flexure, compaction, and sea-level changes (Watts and Steckler, 1979; Reynolds et al., 1991; Kominz et al., 1998, 2008; Miller et al., 2005). However, local normal faulting (minor except for several large growth faults beneath the modern outer continental shelf), rare salt diapirism, and a single Early Cretaceous igneous intrusion (the Stone Dome, Fig. 1.3) locally complicate the otherwise simple tectonic passive margin post-rift history (Poag, 1985).

Thick post-rift sediments (up to 16 km) accumulated along the mid-Atlantic region in an offshore basin termed the “Baltimore Canyon Trough” (BCT, Fig. 1.3). In general, the Mesozoic section of the BCT contains thick coarse-grained units confined by thick muds and mudstones. The Jurassic section is composed of thick (typically 8-12 km), shallow-water limestones and shales that are restricted to the offshore BCT (Fig. 1.3). A barrier reef complex fringed the margin from the Jurassic until the middle Cretaceous and now is buried beneath the upper continental slope (Jansa, 1981; Poag, 1985, Fig. 1.3). Long-term global sea-level rise plus thermal subsidence and flexural bending of the crust beneath the Coastal Plain led to progressive widening of the BCT during the earliest Cretaceous (ca 120-140 Ma; Olsson et al., 1987). River input to the shelf overwhelmed the carbonate platform that had existed throughout the Jurassic, and resulted in moderately thick (~2-3 km) offshore Cretaceous strata containing several major Cretaceous sand bodies. Due to their porosities, permeabilities, and total storage volume, these are carbon sequestration targets, as described below.

An Upper Cretaceous (Campanian) sand, equivalent to the Dawson Canyon formation of the offshore eastern Canadian Scotian Basin (Libby-French, 1984) is apparently finer grained and less suitable for sequestration. After these Late Cretaceous pulses of sand, accumulation rates in the BCT were generally low-moderate during the deposition of Upper Cretaceous to Paleogene siliciclastic and carbonate fine-grained sediment (Poag, 1985). The latter provided a thick, regional “cap”, or confining unit. A major switch from carbonate ramp deposition to starved siliciclastic sedimentation occurred in the earliest Oligocene in response to global and regional cooling (Miller et al., 1997). Sedimentation rates increased dramatically in the late Oligocene to Miocene (Poag, 1985) due to an increased input from the hinterland (Poag and Sevon, 1989; Pazzaglia and Gardner, 1994) and resulted in thick sand bodies arrayed as prograding and aggrading units beneath nearly the entire modern shelf. These deposits were cored in the nearshore regions in 2009 by IODP Expedition 313 (G.S. Mountain, co-chief scientist) as archives of global sea-level change. While they have potential for carbon sequestration, they were not sampled in the CO_2 stability zone (i.e., all holes were less than 800 m subbottom penetration). Perhaps farther offshore at greater burial depths, these units will provide presently unknown sequestration opportunities.

2.3 Sequestration Targets

At the temperatures predicted by the regional geothermal gradient of 25°C/km, liquid carbon dioxide is stable below 800 meters sub-seafloor (mbsf). We began our investigation by searching below this depth for high-porosity/permeability formations of sufficient thickness in both the COST (Continental Offshore Stratigraphic Test) B-2 and B-3 records (Scholle, 1977, 1980; Poag, 1985). Two Lower Cretaceous sands provide the most likely targets for geological sequestration offshore. Lower Cretaceous sands have been termed the Missisauga (Neocomian-Albian) and

Logan Canyon (Albian-Cenomanian) equivalents, according to correlations to stratigraphic units named on the eastern Canadian Scotian Margin (Libby-French, 1984).

The offshore Logan Canyon sands are likely equivalent to the onshore New Jersey Potomac Sequence 3. At Fort Mott, NJ, these sands are assigned to Pollen Zone III (~ lower Cenomanian) and at Ancora, NJ to nannofossil Zone CC9 or older (lower Cenomanian to Albian). Offshore, at the COST B-2 well, Poag (1977) reported Zone UC3 (= *Rotalipora reicheli* zone; ~ mid Cenomanian) and Zone UC2 (= *R. globotruncanoides* Zone; lower Cenomanian) from the upper Logan Canyon equivalent, establishing that it is Cenomanian and correlates with the Potomac 3 sequence onshore. At the COST B-3 well, the upper Logan Canyon is also Cenomanian (Poag, 1985). (Note that this disagrees with preliminary correlations of the sands at COST B-2 as Albian; plate 2 in Open-File Report 79-1159). The lower Logan Canyon sands are Albian at both COST B-2 and B-3 (Poag, 1977, 1985) and thus correlate with the Potomac 2 sands onshore (Fig. 1.9). At present we know that the top of the Cenomanian offshore ends abruptly with an overlying, relatively thick unit of deltaic mudstone that would provide a good seal inhibiting upward migration of liquid carbon dioxide pumped into the underlying Cenomanian sands.

The second target sands correlate to the Missisauga Formation (Neocomian-Aptian) of the eastern Canadian margin (Libby-French, 1984) and to the Potomac 1 sands (Fig. 1.9, table 2.1; Sugarman et al., 2004). However, while the exact relationship between the onshore and offshore sands needs to be evaluated to establish the relative continuity or isolation of these units, it is clear that in both settings the sands of the Logan Canyon and Missaugua provide sequestration potential.

There is a modest amount of publically available seismic survey, drill core and borehole log data offshore the mid-Atlantic states. We have access to a great deal of this information as well as studies based on it. We have collected some of it in past research projects, and we've begun to evaluate the potential for seabed sequestration of carbon dioxide. The following summarizes our progress to date.

2.4 Available Geologic Samples

The Baltimore Canyon Trough has been drilled for several purposes on many occasions (Fig. 2.1). The Atlantic Slope Project was a reconnaissance effort by a consortium of oil companies in 1967 (Weed et al., 1974; Poag, 1978; Sites 13-15 offshore New Jersey; Sites 22 and 23 offshore Delmarva Peninsula), and was followed by the US Geological Survey in 1976 leading the Atlantic Margin Coring Project (AMCOR) on the slope and shelf (Hathaway et al., 1979; NJ offshore sites 6009, 6010, 6011, 6020, and 6021 and offshore Delmarva Peninsula sites 6007, 6008). Both projects comprised open-hole drilling with penetration limited to 330 m sub-bottom. Several more open-hole targets were drilled on the slope during DSDP (Deep Sea Drilling Project) Legs 11, 93, 95, and ODP 150. ODP Leg 174A and IODP Expedition 313 both drilled on the shelf, but with the maximum penetration of 757 mbsf, none of the sites provide direct evaluation potential for carbon sequestration targets.

Figure 2.1 shows the available well and wireline log data that are available. The well data are from many different sources, collected over the last four decades, with a range of usefulness to the current project:

Table 2.1. Hydrogeologic Units at COST B-2 and B-3 wells and Correlation With the Lithologic Units Defined by Libby-French (1984).

LITHOSTRATIGRAPHY						HYDROLOGIC UNITS							
UNITS DEFINED BY LIBBY-FRENCH, 1984	Depth to Units (ft) (Libby-French, 1984)		Depth to Units (ft) (our interpretation)		ONSHORE EQUIVALENTS	Average Depth Below Seafloor (ft)		Total Thickness (ft)		Total Thickness of Sand (ft)		% sand beds in unit	
	COSTB2	COSTB3	COSTB2	COSTB3		COST B2	COST B3	COST B2	COST B3	COST B2	COST B3	COST B2	COST B3
Dawson Canyon	5000 (1524)	5400 (1646)	5015 (1528)	absent	Mount Laurel								
Bottom of Dawson Canyon	-	-	5107 (1556)	absent	Mount Laurel								
Middle Sandstone Unit	5920 (1804)	6695 (2040)	6009 (1831)	7370 (2246)	Magothy Fm.	5807.5 (1770)	4709.5 (1435.5)	373 (114)	135 (41)	194.86 (59.4)	89.06 (27.2)	52.24	65.97
Bottom of Middle Sandstone Unit	-	-	6382 (1945)	7504 (2287)	Magothy Fm.								
Logan Canyon (Upper Sandstone)	8220 (2505)	8200 (2499)	8220 (2505)	8200 (2499)	Potomac Fm. Unit 3	8022 (2445)	5693 (1735)	380 (116)	442 (135)	96.88 (29.5)	224.85 (68.5)	25.49	50.87
Sable Shale Member	8635 (2632)	absent	8600 (2621)	8642 (2634)									
Logan Canyon (Lower Sandstone)	8840 (2694)	absent	8840 (2694)	8790 (2679)	Potomac Fm. Unit 2	8704 (2653)	6223.5 (1897)	504 (153.6)	323 (98.5)	309.78 (94.4)	63.88 (19.5)	61.46	19.8
Naskapi	9680 (2950)	8800 (2682)	9344 (2848)	9113 (2777)									
Missisauga	10230 (3118)	9905 (3019)	10230 (3118)	9873 (3009)	Potomac Fm. Unit 1								
Mic Mac	11340 (3456)	11630 (3545)	11448 (3489)	11629 (3544)									
Abenaki	absent	12550 (3825)	absent	12160 (3706)									

1) Open hole 6021 (~1,000 ft.), sporadically cored sites drilled by the USGS during its AMCOR project in 1976;

2) Two stratigraphic test wells, the outer shelf COST B-2 and slope wells produced cutting samples, wireline logs, and sidewall cores (Scholle 1977; 1980). We have obtained electronic files of downhole log data from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE). Cores, washed and unwashed cuttings, thin sections and slides are warehoused at the Delaware Geological Survey;

3) Thirty-two exploratory wells (Libby-French, 1982; Prather, 1991) were drilled in the Baltimore Canyon Trough between 1975 and 1983. Exploration efforts focused along three trends: (1) structural features entirely on the modern continental shelf (28 wells), particularly the Great Stone Dome (Fig. 2.1); (2) the carbonate shelf margin (3 wells); and (3) a shelf-margin deltaic complex (1 well). Logs, sidewall samples, and cores similar to those of the COST wells are also accessible from BOEMRE. Cores, washed and unwashed cuttings, thin sections and slides are warehoused at the Delaware Geological Survey;

4) Roughly 1 dozen holes drilled by the scientific drilling community during DSDP Legs 11, 93, 95, ODP Legs 150 and 174A, and IODP Expedition 313 are publically available; all of the latter are open hole, frequently logged, nearly all continuously cored, but like the AMCOR holes, few reach deep enough to be of immediate relevance to the stable sequestration of liquid carbon dioxide.

We have obtained and analyzed well logs from the COST B-2 and various other wells and discuss the results below.

2.5 Available Seismic Data

Figure 2.1 shows the survey data on which we will base our assessment. The multichannel seismic reflection profiles are from several sources:

1) Reconnaissance-scale (i.e., 10's of km between adjacent survey lines, cross-shelf distribution, 10-km sub-seafloor penetration but low resolution) profiles collected by the USGS during the 1970's;

2) Regionally focused (i.e. outer shelf, slope and continental rise) and higher resolution profiles collected in 1979 by the German Federal Institute for Geosciences and Natural Resources (BGR) in cooperation with the USGS;

3) Reconnaissance-scale profiles collected by the Exxon Production Research Company in the 1970's and provided to us in a collaborative study in 1990;

4) Modest resolution data (120-channel, tuned airgun array, 3 km penetration) collected by us with roughly 5 km line spacings in 1990 aboard the *R/V Ewing*; and

5) Three high-resolution surveys (48-channel, shallow-towed GI airgun data with 1 km penetration and line spacing from 2 km to as close as 150 m in locations of proposed

ODP and IODP drill sites) collected by us between 1995 and 2002 using the *R/V Oceanus*, *Cape Hatteras*, and *Endeavor*.

Accurate measurement of seismic velocities beneath the seabed is needed to estimate thicknesses of possible sequestration intervals as well as their depths below the seabed. To date we have consulted three sources:

1) Expanding-spread profile (ESP) measurements at five specific locations collected during the LASE experiment (Keen et al., 1986) in 1981;
2) Sonic log and check shot time-to-depth conversions prepared at the COST B-3 well; and
3) Stacking velocities that accompany the BGR profiles along the outer shelf.

Because of their proximity to the area of interest in this study and our familiarity with how the measurements were derived, thus far we have relied exclusively on the latter, as described below. All of the track lines and drill site locations in Figure 2.1 are available in ASCII-coded text-only files comprising longitude, latitude, common depth point for the former and longitude and latitude for the latter.

2.6 Seismic Interpretation

BGR line 218 (Fig. 2.2) runs within a few tens of meters of the COST B-3 well. We decided to use its stacking velocities in deriving a regionally applicable time-to-depth conversion to enable correlations between profiles (acoustic travel time) and profiles (depth below sea level). Other choices were ESP measurements made at five specific locations or the time-to-depth curve based on sonic log and check-shot data and published with the COST B-3 report. The closest ESP data are 10 km from B-3 and thought not to be ideal for correlations at this location. The reported velocity data from B-3 provides little detail in the upper 800 mbsf and no opportunity for us to evaluate.

Nineteen stacking velocities computed every 1 km along BGR line 218 were examined. After manipulation to account for the effect of travel through a water column of variable depth, the smoothed two-way time below seafloor vs. depth below seafloor relationship shown in Figure 2.3 was developed. This was used to calculate the depths to sequestration targets between 8,250 and 9,000 ft. below the seafloor at the COST B-3 where it is crossed by Exxon line 78-35 at cdp (common depth point) 2,763. We are more confident of this pick of the top of the primary target sequestration zone than the base. The former is a reasonably continuous reflector of moderate amplitude; the latter is much more difficult to trace along any given profile. Hence, we are confident of our ability to track the top of a potential sequestration interval, but (at this stage) less so of our ability to evaluate its thickness. We have traced this Cenomanian top along a network of profiles extending away from COST B-3 (where their top is 8,200 ft. bkb) and using the same time-to-depth conversion, find this depth also matches Cenomanian upper Logan Canyon sands in the COST-B2 well (8,220 - 8,600 ft. bkb).

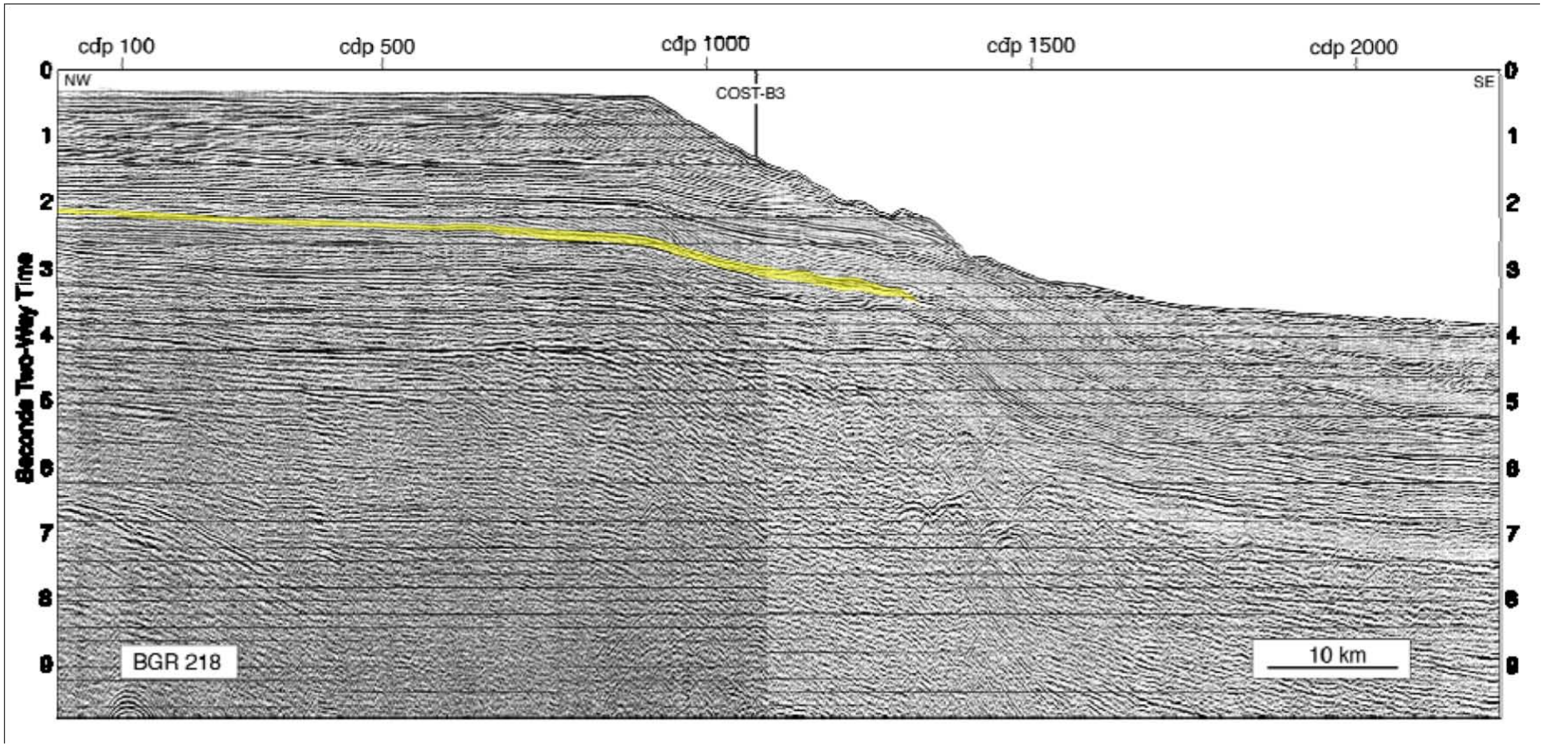

Figure 2.2. BGR Line 218 Passing Within a Few 10s of Meters of COST B-3 at 893 m Water Depth on the Continental Slope.

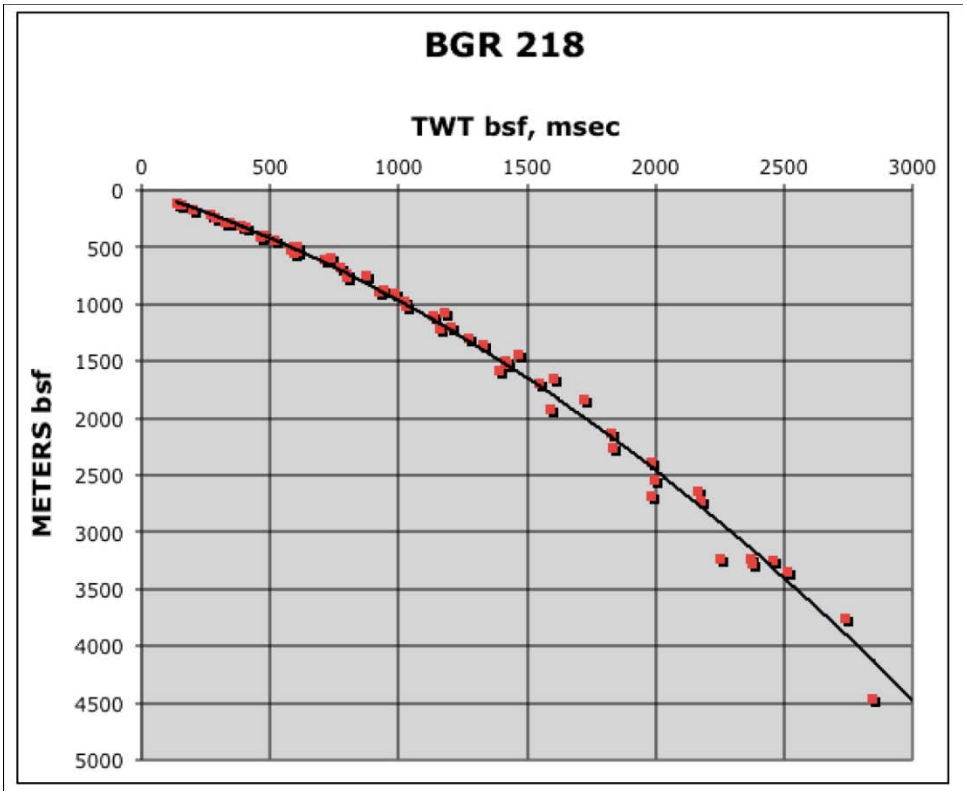

Figure 2.3. Two-Way Time vs. Meters Below Sea Floor Relationship Derived From Stacking Velocities Used to Process the BGR Line 218 in the Vicinity of the COST B-3 well.

2.7 Importance of True Depth Evaluation

The actual depth to a seismic reflection can be substantially different from what might appear obvious in a casual appraisal of a display shown in two-way travel time. As an example, Figure 2.4 shows Exxon line 78-35 with tracings of the seafloor plus top (and likely base) of the target Cenomanian sand displayed in time as well as depth. In time (Fig. 2.4, upper) the Cenomanian top (red tracing) becomes abruptly deeper when traced seaward from the shelf to the slope (near cdp 3,000). In actual depth (Fig. 2.4, lower), it's clear that while this surface is indeed steadily deepening, there is no abrupt change at the shelf/slope transition. Of course, the deceiving aspect of the time display is the effect of abrupt lateral changes in the 'average' velocity to a reflector when comparing a column that is mostly sediment (velocity of 2 km/sec or greater) versus a column on the slope that may be mostly seawater (velocity = 1.5 km/sec). When considering actual thickness between deeply buried surfaces (Fig. 2.4, lower), things can be quite different than would seem when displayed only in travel time. The shoaling of the possible base of the Cenomanian sands (yellow tracing) near cdp 3,200 is due to the early cementation and minimal compaction of the underlying carbonate structure known to exist at this location at about 3,500 - 4,000 m total depth. This contrasts markedly with the compaction of correlative sediments in the back-reef/lagoonal/carbonate platform environment that occurred beneath the Cenomanian sands near cdp 3,900.

An interesting question is how soon after burial did this 'structuring' take place? If very early, before or at least during the deposition of the Cenomanian sands, we might expect seaward thinning of Cenomanian sands and perhaps onlap onto the supposed reef. Alternatively, if post-reef units like the Cenomanian will go right over the reef as blankets of uniform thickness, well after deposition and burial, this would provide an indication that our 'base of the Cenomanian' has perhaps been misidentified. Since these units are the target sequestration sands, resolving this question will be very important.

2.8 Well-Log Correlations

In phase I, we obtained and interpreted downhole logs from the COST wells B-2 (91 m water depth on the shelf) and B-3 (819 m water depth on the slope). The following logs were plotted: natural gamma ray, resistivity, neutron porosity, and density porosity; for COST B-3, we included spontaneous potential (SP) and conductivity (Fig. 2.5). Based on log character, three basic lithologies were recognized: (1) sands associated with low gamma ray values, resistivity values that increase from shallow focus to deep focus sensors, and increases in neutron porosity and density porosity log values; (2) shales associated with high gamma and high neutron density and low neutron density; and (3) intermediate sandy shale/shaley sand associated with log values intermediate to those of the other two lithologies. We used published age control (Fig. 2.5) (Scholle, 1977, 1980; Poag, 1977, 1985; Sikora and Olsson, 1991) and applied the lithologic terminology of Libby-French (1984). These interpretations will be refined in Phase III by developing a well-log transect using industry wells, implementing a sequence stratigraphic approach to the logs looking at stacking patterns, and by evaluating seismic profiles.

The Dawson Canyons sands are found only at COST B-2 (5,015 – 5,107 ft.; all depth are in feet below kelly bushing [90 ft. above sea level]), where they are reported as uppermost Cretaceous

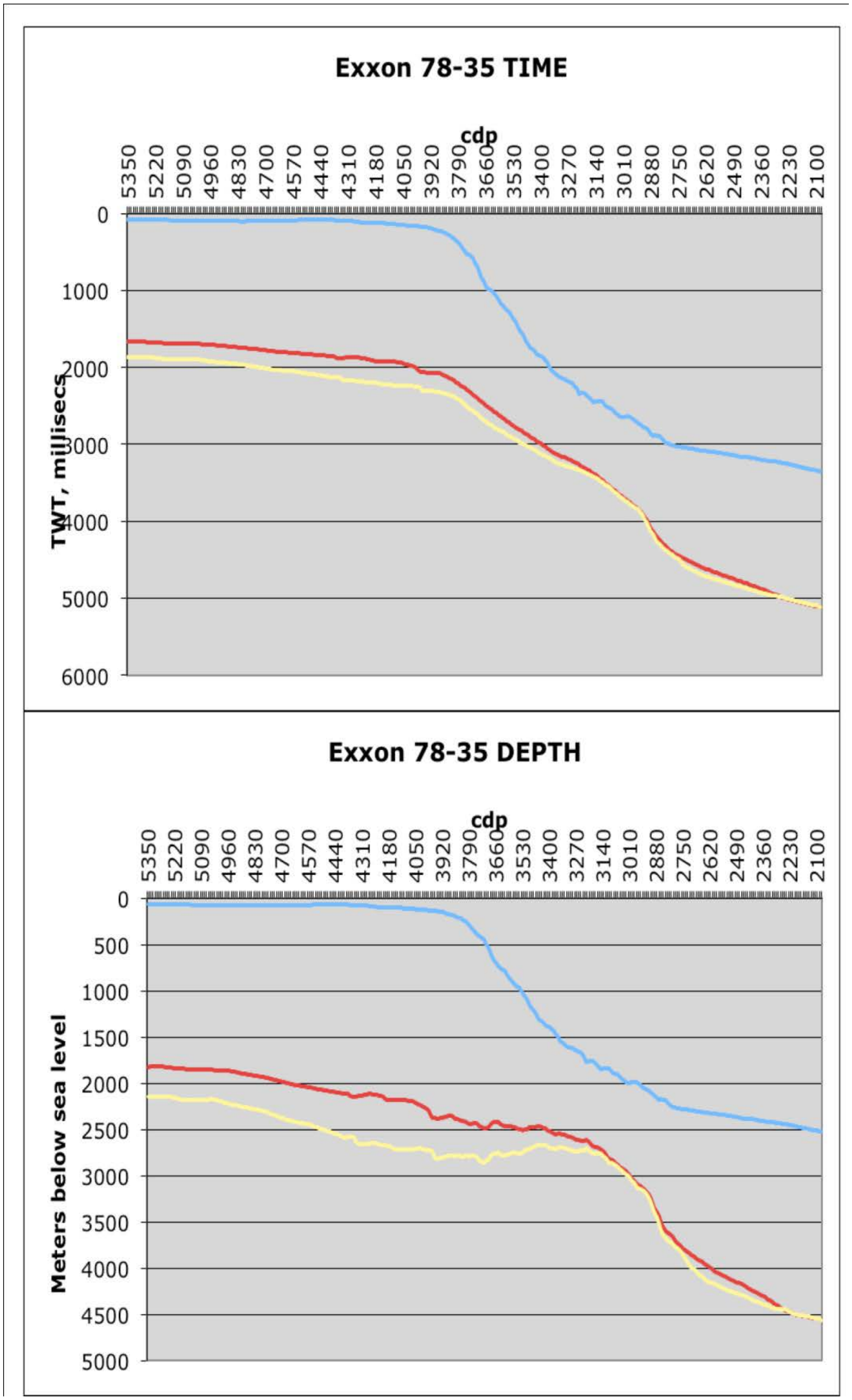

Figure 2.4. Tracings of Seafloor, the Top and the Possible Base of the Cenomanian Interval Along Exxon Line 78-35.

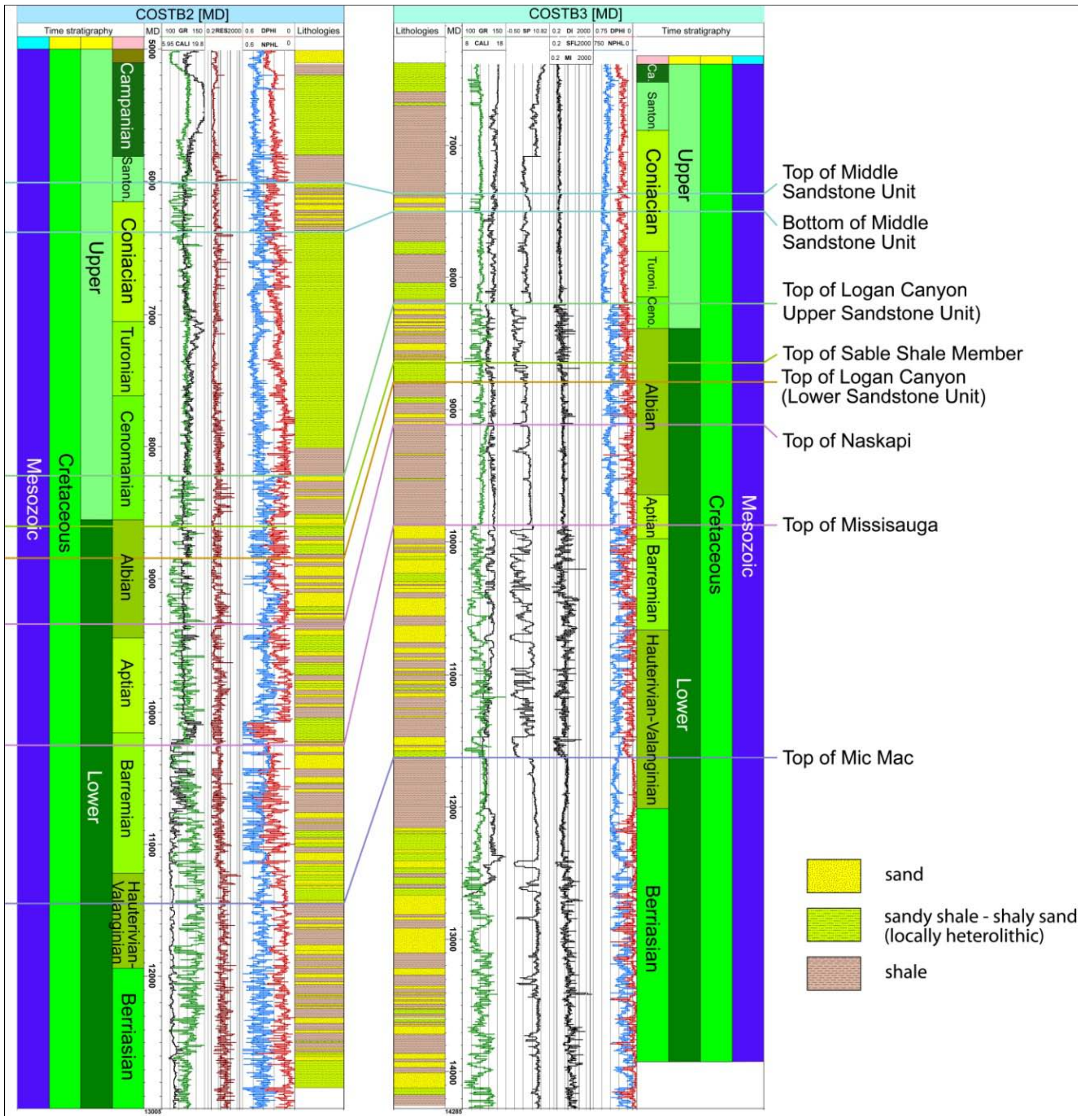

Figure 2.5. Well-Log Correlation From COST B-2 to B-3.

(Fig. 2.5; table 2.1). A Maastrichtian age has been suggested (Poag, 1985), though correlations based on nannofossils (P. Valentine in Scholle, 1977) indicate a Campanian age. It is very likely that these sands correlate with the onshore uppermost Campanian Mount Laurel Sands based on a very similar well-log pattern (serrated to boxcar sands overlain by a very large gamma log increase). Re-evaluation of the published foraminiferal data indicates that these sands are in fact Campanian. We will obtain picked foraminiferal samples from C.W. Poag to further evaluate the age of this unit.

At COST B-2, a very thick confining unit (5,107 - 6,009 ft.) overlies the Middle Sandstone Unit (MSU) of Libby French (1981), which we interpret as occurring from 6,009 – 6,382 ft. (table 2.1). At COST B-3, the MSU occurs from 7,370 – 7,504 ft. (table 2.1). This unit is Santonian to Coniacian and thus correlates with the Magothy Formation sands onshore (table 2.1) (Sugarman et al., 2005; Kulpecz et al., 2008). Onshore it is an excellent sand, though it lies at a depth that is above the critical threshold burial depth (2,400 - 3,000 ft.) for sequestration (see Coastal Plain, Section 1). At COST B-2 and B-3, about 52 - 66 percent of the MSU section appears to be sand (table 2.1) and it is sufficiently confined and deep for sequestration.

The upper Logan Canyon sands occur at 8,220 - 8,600 and 8,200 - 8,642 ft. at COST B-2 and B-3, respectively (table 2.1). This unit is relatively thick (380 and 442 ft. at B-2 and B3, respectively); at B-3, Scholle et al. (1980) report that this unit has high porosities (>30 percent) and high permeabilities (up to ~800 md). However, not all of the upper Logan Canyon section is comprised of sands. At COST B-2 only 25 percent of the 380 ft. thick section is sand, whereas >50 percent of the 442 ft. thick section at B-3 comprises sand (table 2.1).

The Sable Shale equivalent of Libby-French (1981) confines the lower Logan Canyon sands. At COST B-2, the shales range from 8,600 - 8,840 ft.; Libby-French (1981) did not interpret the Sable Shale at B-3, though we place it at 8,642 - 8,790 ft. based on our well-log interpretations (table 2.1). The shale seems to span the Cenomanian/Albian boundary, though Poag (1985) interprets this boundary as disconformable at both wells. Additional study is needed to further evaluate the age and placement of possible unconformities.

The lower Logan Canyon Sand equivalent occurs from 8,840 - 9,344 ft. and 8,790 - 9,113 ft. at COST B-2 and B-3, respectively (table 2.1). Most of this section is sand at B-2 (>64 percent of the section), but at B-3, the section appears to largely shale out (~20 percent of the section is sand). Limited permeability data for this section at COST B-3 from Scholle et al. (1980) indicate low permeability (<1 md).

The Naskapi Shale equivalent of Libby-French (1981) occurs from 9,344 - 10,230 ft. and 9,130 - 9,873 ft. at COST B-2 and B-3, respectively (table 2.1). These shales confine the Missisauga equivalent sands below. Very limited data for this section at COST B-3 from Scholle et al. (1980) indicate low permeability.

The Missisauga Sand equivalent of Libby-French (1981) occurs from 10,230 - 11,448 ft. and 9,873 - 11,629 ft. at COST B-2 and B-3, respectively (table 2.1). These sands are thick at both sites and thicken and become blockier toward the slope site. One possible concern for sequestration in this unit is the possibility of hydrocarbons, particularly natural gas. Hydrocarbon exploration in this region shows high concentrations of thermogenic methane.

2.9 Sequestration Potential

The COST B-2 and B-3 wells offer preliminary information on the hydrogeologic structure, particularly the presence and thickness of sandy units, in the outer continental shelf and the slope region. Table 2.2 gives the three hydrogeologic units that have substantial sand layers interbedded with shales/mudstone, and their correlation with the stratigraphic and lithologic units defined earlier by Libby-French (1984). Total sand thickness and fraction for each unit are also given.

We estimated the potential CO_2 storage capacity over a 50 km by 30 km area surrounding the two wells (blue box, Figure 2.1). From the mean sand thickness at B-2 and B-3 in table 2.1, we calculated the CO_2 storage capacity in the three units as shown in table 2.2, at three porosity and percentage CO_2 displacement values as in table 2.1 for the onshore study. The procedures and assumptions are the same as in the onshore part of the report.

The estimates in table 2.2 give a range of 14 to 69 Mt of CO_2 storage for the 50 km x 30 km area (blue box in Figure 2.1). The lack of data updip and further south prevents extrapolating this number across the shelf off the NJ coast; this data gap is to be filled in the proposed Phase III study. At present, such an extrapolation would suggest a total storage on the order of 150 to 750 Mt of CO_2 from the Washington Canyon to Hudson Canyon.

Table 2.2. CO2 Storage Capacity in the Magothy, P3 and P2 Units

Aquifer Unit	Aquifer Volume	Pore Volume (km^3) *			CO^2 Volume (km^3) ~ 20% Pore **			CO^2 Volume (km^3) ~ 35% Pore			CO^2 Volume (km^3) ~ 50% Pore			CO^2 Mass (million tonne), 20% Pore			CO^2 Mass (million tonne) ~ 35% Pore			CO^2 Mass (million tonne) ~ 50% Pore		
	(km^3)	low (0.2)	mid (0.3)	high (0.4)	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high
Magothy	116	23	35	46	5	7	9	8	12	16	12	17	23	3	5	6	6	9	11	8	12	16
P3	188	38	56	75	8	11	15	13	20	26	19	28	38	5	8	11	9	14	18	13	20	26
P2	189	38	57	76	8	11	15	13	20	26	19	28	38	5	8	11	9	14	19	13	20	26
Total	493	99	148	197	20	30	39	35	52	69	49	74	99	14	21	28	24	36	48	35	52	69

* Range of sand porosity based on Freeze and Cherry (1979), 0.25-0.45, with a 5% reduction considering compaction at below 800m depth. Here we evaluate low, mid, and high values.

** Based on IPCC (2005) report on CCS, supercritical CO_2 only displaces 20-50% of pore space. Here we evaluate low, mid, and high values.

*** Assuming 0.7kg/m^3 density at supercritical state (IPCC, 2005). The result is in million metric ton (or million tonne, or MT)

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3.0 CHARACTERIZATION OF THE CARBON DIOXIDE STORAGE POTENTIAL OF THE STOCKTON FORMATION IN THE NEWARK BASIN

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3.1 Introduction - Sequestration in the Late Triassic Stockton Formation

A three-dimensional (3D) structural analysis of the Stockton Formation in the Newark basin was undertaken as part of a regional evaluation of potential geological reservoirs for sequestering man-made carbon dioxide that would otherwise be discharged into the atmosphere from power-generating and other commercial industries.

1) This study focused on the Late Triassic Stockton Formation, a sandstone formation that is the oldest and deepest sedimentary unit in the basin.
2) In outcrop, the Stockton Formation has the most primary porosity of any formation in the basin.
3) A three-dimensional computerized framework of the Newark basin (Pa-NJ-NY) was built with maps and cross section interpretations of the stratigraphic position and thickness of the Stockton Formation.
4) These interpretations are largely based on cross section interpretations lacking adequate subsurface control. Publicly available, high quality seismic reflection data are also lacking.
5) The Stockton Formation exceeds 2,500 ft. depth, the minimal burial depth for supercritical storage of CO_2, in about 2/3 of the area of the basin (herein referred to as the areas of interest).
6) In the areas of interest, the Stockton Formation is estimated to range in vertical thickness from about 500 ft. to just over 4,500 ft.
7) Of the total area of interest, about 78 percent of the reservoir volume is located in the eastern region, and mostly in New Jersey. The remaining 22 percent reservoir volume is in the western region, mostly in Pennsylvania.
8) The pore volume calculated for the entire region ranges from 139 to 278 km^3 using porosity values of 5 and 10 percent, respectively.
9) Little is known about how lithologies and porosities in the Stockton Formation vary in the subsurface throughout the basin. What is known comes from two deep oil exploration wells in Pennsylvania, and two deep cores in New Jersey (Nursery and Princeton cores of Olsen and others, 1996), outcrop samples, and shallow core from near the outcrop area. Arkosic sandstone in outcrop gives way to siliceous sandstone in the deep wells.
10) These interpretations are overall, loosely constrained and should be viewed as gross estimates of the depth thickness, and reservoir volume for sequestering carbon dioxide in the Stockton Formation.

3.2 Geologic Background

A three-dimensional computerized framework of the Newark basin (PA-NJ-NY) was built with maps and cross section interpretations of the stratigraphic position and thickness of the Late Triassic Stockton Formation. These interpretations were used to characterize the extent and volume of the formation occurring more than 2,500 ft. below mean sea level (MSL). This sandstone formation is the oldest and deepest sedimentary unit and has the most primary porosity of any formation in the basin. It is therefore being evaluated as a reservoir for sequestering CO_2 gases at shallow depths in the Earth's crust. The structural framework of the Stockton is based on regional bedrock-geology maps, geologic sections, deep rock cores, and hydrocarbon exploration wells. Formation boundaries of five geologic sections in New Jersey are from the 1:100,000 scale geologic sections of Drake and others (1996). Geologic sections in Pennsylvania and New York are based on stratigraphic contacts and faults. Depth and thickness values are extrapolated from New Jersey along strike to the southwest and northeast, respectively. The computerized results are projected into geographic coordinates using a geographic information system (GIS), and then imported into Google Earth (GE) for display and transfer to the public. An outline of the methods used in generating the GIS shapefile themes used in the project follows with discussion of the results.

3.3 Geospatial Coordinate Systems and Source Data

This report is based on regional geological bedrock maps and cross sections of the Newark basin, two deep hydrocarbon exploration wells in Pennsylvania, and two deep core holes (Princeton and Nursery cores) in New Jersey (Fig. 3.1). The information was compiled using the 1983 North American Datum (NAD83) and the New Jersey State Plane Coordinate (NJSPC) System. Distance units are in US feet (NJSPCF), and vertical coordinates are referenced to the National Geodetic Vertical Datum of 1983. The geology is based on the regional bedrock mapping of Fisher and others (1970), Berg and others (1980), Drake and others (1996), and Owens and others (1998). The New Jersey part is at the 1:100,000 scale whereas those for Pennsylvania and New York are at the 1:250,000 scale. Updating of the geology mapped in New Jersey is based on unpublished 1:24,000-scale maps of the area between Flemington and Princeton mapped by the NJ Geological Survey. Two-dimensional lines of mapped faults in Pennsylvania and New York were also downloaded (Fisher and others, 1970; Berg and others, 1980) and merged with faults of New Jersey (Fig. 3.1). The bedrock coverage for Pennsylvania and New York was projected from Universal Transverse Mercator projections and meter units of the respective states into NJSPCF using the ArcView GIS computer software by Environmental Systems Research Institute. Geology shapefiles were transformed to geographic coordinates (decimal degrees) using an ArcView projector scripts, and then converted to Google Earth (GE) KMZ (zipped kml files) files for sharing.

The two deep hydrocarbon-exploration wells are the Cabot and Parestis wells (Fig. 3.1). The Cabot well was drilled by the North Central Oil Company in 1985 at an elevation of about 480 ft. to a total depth (TD) of 10,490 ft. Drilling penetrated the lower Passaic, the entire Lockatong formations before ending in the Stockton Formation (Written communication from John Harper, 2010). The Parestis well was drilled by Eastern Exploration Company in 1988 at an elevation of about 350 ft. to a total depth of about 6,712 ft. (Written communication from John Harper, 2010). Crystalline basement was reached at a depth of about 6,680 ft. Table 3.1 lists the depth and

Figure 3.1. Bedrock Geologic Map of the Newark Basin Showing Formations and Lithologies.

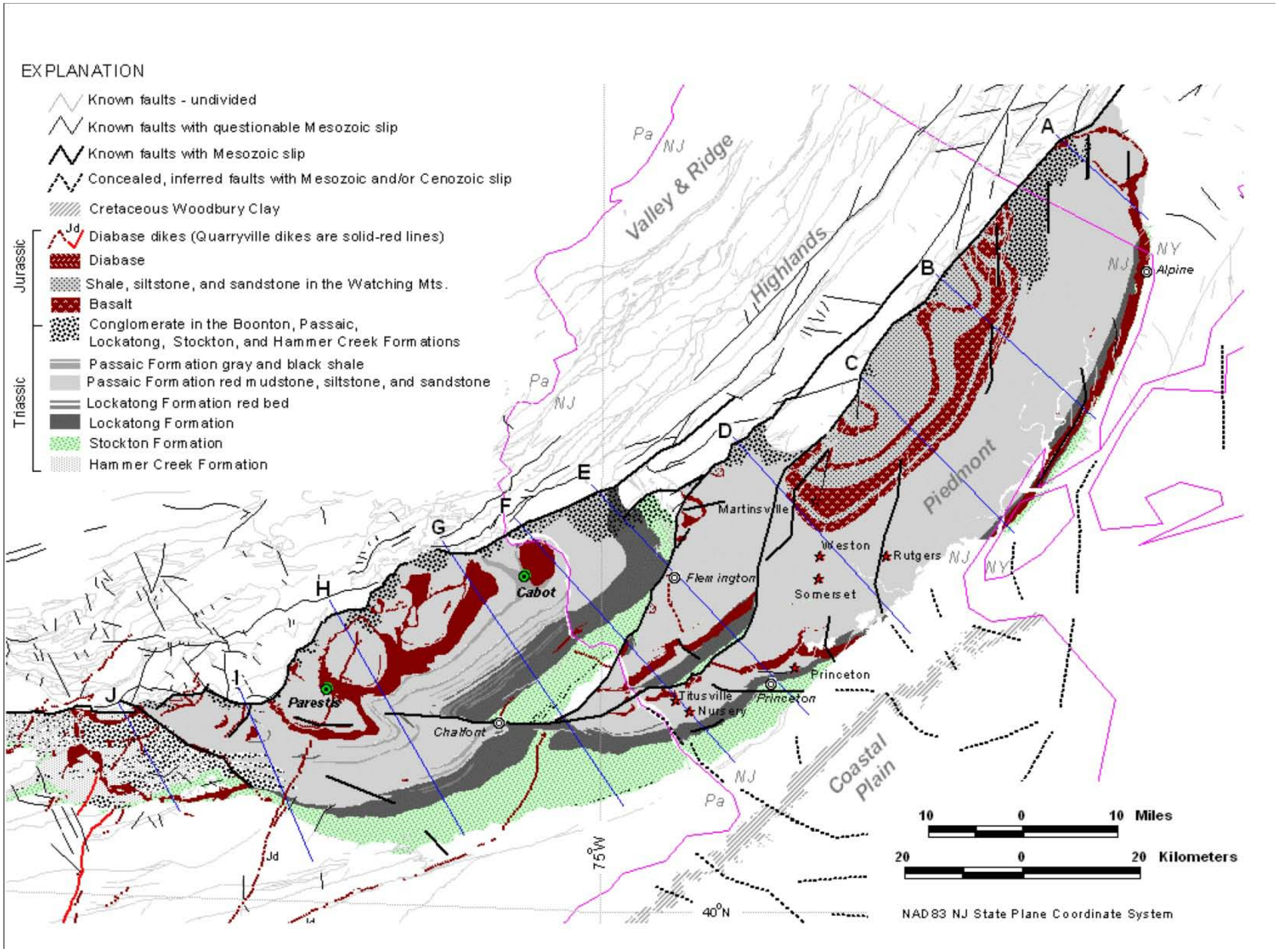

Table 3.1. Measurement Points, Coordinates, and Values of the Depth and Thickness of the Stockton Formation in the Newark Basin.

ID	XCOO RDYCOORDDEPTH	VERTHCK
A1	616244 844 897 133 74	0
A2	618064 843 161 127 04	3562
A3	628686 833 559 876 6	3075
A4	638882 824 269 451 2	2069
A5	647465 816 390 100 0	1302
B1	553125 764 936 223 63	0
B2	555957 762 355 217 39	4589
B3	580895 739 632 159 96	3370
B4	600815 721 481 909 7	2813
B5	616243 707 424 264 3	1289
B6	620193 703 796 100 0	1103
C1	514061 703 537 227 35	0
C2	517082 700 491 219 71	4548
C3	522209 695 323 210 61	4214
C4	536714 680 702 167 11	4037
C5	556816 660 439 848 3	2961
C6	574565 642 510 100 0	2122
D1	433791 679 329 723 0	0
D2	437232 675 525 710 1	1801
D3	448386 663 197 655 0	2001
D4	451080 660 219 715 4	2212
D5	455192 655 673 137 32	0
D6	457709 652 891 137 06	3799
D7	463202 646 656 135 38	3967
D8	468829 640 599 163 33	3900
D9	484490 623 287 133 77	3826
D10	505054 600 556 611 5	3344
D11	515468 589 046 100 0	2237
E1	365843 641 896 177 0	0
E2	367727 640 032 226 9	1608
E3	369513 638 153 272 6	1587
E4	383354 623 524 165 4	2789
E5	387278 619 333 412	3430
E6	395321 611 000 629 9	0
E7	396332 609 939 570 7	1936
E8	400182 605 885 105 48	0
E9	400966 605 060 955 2	1945
E10	402387 603 565 116 33	1563
E11	404831 600 944 106 23	4091
E12	418230 586 880 447 6	4338
E13	424696 580 074 100 0	4050
E14	433725 570 570 790 5	0
E15	435417 568 789 687 6	4272
E16	447974 555 571 100 0	3950

ID	XCOORDYCOORDDEPTH	VERTHCK
F1	313752 633 174 715 2	0
F2	321717 624 319 851 2	2458
F3	333786 610 902 534 0	2960
F4	345287 598 117 380 1	3344
F5	352588 589 972 100 0	3423
F6	367052 573 920 213 1	0
F7	368765 572 016 100 0	4082
F8	372188 568 206 703 7	0
F9	376129 563 802 695 2	5190
F10	385817 553 069 100 0	4167
F11	392818 545 277 955 7	0
F12	394043 543 924 819 9	4524
F13	400415 536 831 340 0	3672
F14	406770 529 744 100 0	3663
G1	274857 614 956 916 5	0
G2	281671 604 964 107 17	2565
G3	291976 589 936 848 3	2074
G4	303771 572 980 530 5	2321
G5	314395 557 138 100 0	2689
G6	326153 539 932 175 7	0
G7	334088 528 389 215 4	3257
G8	338400 522 161 100 0	3126
H1	209844 583 665 517 9	0
H2	217940 569 550 436 9	1268
H3	226204 555 140 600 6	1538
H4	236826 536 620 546 6	1772
H5	243140 521 229 915 8	2054
H6	257234 501 038 379 9	2674
H7	263065 490 866 100 0	2713
I1	161218 526 501 925 5	0
I2	163580 521 232 807 9	1090
I3	169636 506 993 512 1	1090
I4	176332 491 288 100 0	1207
J1 935	47 524621 7844	0
J2 976	81 517413 7650	1090
J3	105183 504 355 281 1	1028
J4	109291 497 033 840	1029
Parestis	200604 549 009 524 0	1090
Cabot	310376 611 503 816 0	1840*

Notes: Depth values are to the top of the formation measured from mean sea level.
VERTHCK – Vertical thickness of the formation.
* Partially penetrated thickness.

thickness of the Stockton from unpublished consulting reports prepared for the drilling companies by private consultants and provided to the NJ Geological Survey from the Pennsylvania Geological Survey (Written communications from John Harper, 2010). The locations for the wells are approximate, and are based on address searches for the land owners where the named wells were drilled. Two deep core holes drilled for the Newark Basin Coring Project (Olsen and others, 1986) also reached the Stockton Formation. The Nursery core (Fig. 3.2) was drilled at an elevation of 155 ft. and reached the top of the unit at a depth of about 3,177 ft. The Princeton core was drilled at an elevation of about 120 ft. and penetrated the top of the Stockton Formation at a depth of about 834 ft. Neither of these cores penetrated the full thickness of the unit.

3.4 Cross-Section Interpretations

Ten cross sections show the subsurface structure and thickness of the Stockton Formation in the Newark basin (Fig. 3.2). Five sections are from the 1:100,000-scale digital version of the NJ state geological map (Dalton and others, 1999). Four of these, sections B through D, are from the northern bedrock sheet (Drake and others, 1996) whereas section E is from the central bedrock sheet (Owens and others, 1998). Sections B, D, E, and F extend through the basin whereas section C ends slightly short of the southeast side. The four cross sections in Pennsylvania and the one in New York are placed arbitrarily along the width of the basin and spaced about 10 miles apart. A set of map points was digitized along the trace of each section (Fig. 3.2), for measurement of vertical depth and thickness of the formation to be measured. A unique identifier (ID) was assigned to each point and added to table 3.1, along with the respective map (x- and y-) coordinates.

The two-dimensional (2D) GIS shapefile for the section traces, sampling points, stratigraphic contacts, and faults in the basin were exported from an ArcView GIS project and saved as AutoCAD (ACAD) drawing exchange files (DXF). The DXF files were opened and saved as an AutoCAD drawing file that was used for measuring the depth and thickness of the unit in the basin. The section traces were positioned at 0 ft. elevation, representing mean sea level. Raster (JPEG) images of the five NJ sections were imported, scaled, and positioned along the section traces in the ACAD drawing file in order to digitize the formation contacts and faults in profile as a basis for measuring the depths and thicknesses of the unit in the third (vertical) dimension. Complex lines with connected vertices (polylines) were drawn along the stratigraphic contacts from the raster images and placed on a unique file layer. Profile images and the correlative features were registered in 2D map space for the determination of depth and thickness values.

Cross sections of the Stockton Formation in Pennsylvania and New York are based on stratigraphic dips and thicknesses form various sources. A 12^o dip for the southeastern parts of the sections in Pennsylvania is based on a regional cross section by Lyttle and Epstein (1987). The New York cross section is located about 20 miles northeast of the easternmost in New Jersey (Fig. 3.2). Dips of the Stockton in the New York section range from 14^o to 17^o based on dips of 13^o to 20^o W in Alpine, NJ (Fig. 3.2) recorded by H.B. Kummel (NJGS permanent notes). The subsurface geometry of these sections was further constrained by mapped stratigraphic contacts, and from geologic reports on the two exploration wells.

Simple line segments were drawn normal to and downward from the profile trace to the top and bottom of the Stockton Formation for each sample point in each profile. The lengths of these

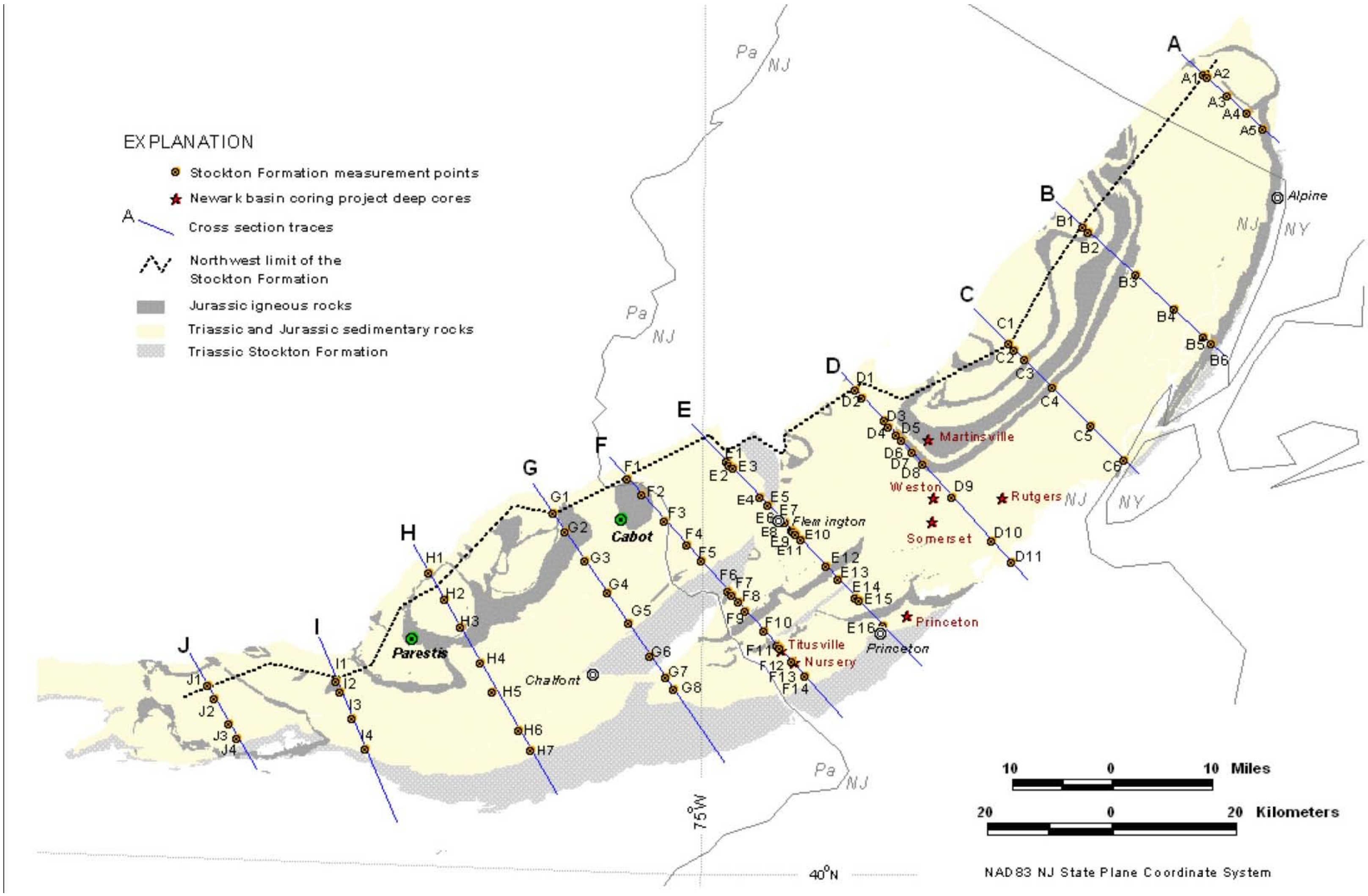

Figure 3.2. Generalized Geologic Map of the Newark Basin Showing the Stockton Formation and Overlying Mesozoic Rocks, Lithology, and Sampling Sites.

respective drop lines were queried in AutoCAD, copied, and recorded in table 3.1 for each measurement point. Table 3.1, is an ASCII, tab delimited text file that was added to an ArcView GIS project for the Newark basin to derive the depth and thickness maps. The northwestern most sample points correspond to locations where the Stockton Formation is estimated to pinch out along border faults in the northwest. A polyline connecting these points for each section (Fig. 3.3) was digitized and saved as a shapefile for the northwestern boundary in the depth and thickness maps. The southeastern most sample points are along section traces where the depth to the Stockton is approximately 1,000 ft. (Fig 3.3 and table 3.1).

3.5 3D Surface Analyses of the Depth, Thickness, and Volume of the Stockton Formation (below 2,500 ft. MSL)

The ArcView GIS 3D Analyst software extension was used to generate triangulated irregular network (TIN) surfaces for elevation of the top of the Stockton Formation below sea level (Figs. 3.3 and 3.4), and for its vertical thickness (Figs. 3.5 and 3.6). A TIN is a set of adjacent, nonoverlapping triangles connecting irregularly spaced points with x, y, and z coordinates. The TIN model provides a data structure for the efficient generation of surface models for the analysis and display of terrain and other types of surfaces (Environmental Systems Research Institute, 1991). TIN surfaces of the depth (Fig. 3.3) and thickness (Fig. 3.5) of the Stockton Formation were used to create polylines connecting points of equal elevation or thickness (isolines) for each surface (Figs. 3.4 and 3.6). The set of isolines representing the depth are called structure contours, and the isolines of equal thickness are called isopach contours.

The structure contours and isopach contours derived here relate to MSL and therefore require the addition of topographic elevations to estimate drilling depths to the top and bottom of the Stockton Formation in the basin. Topographic elevations in the basin range from about 900 ft. above MSL in the northwest to 90 ft. above MSL to the southeast. Mountain peak elevations in the Watchung Mountain region are about 600 ft.

The volume of the Stockton Formation below 2,500 ft. (MSL) was calculated using a second set of TINs that are restricted to the area below 2,500 ft. depth and the northwest limit of the formation (Figs. 3.6, 3.7, and 3.8, and table 3.2). First, two polygons are used to represent the map extent of the Stockton Formation below 2,500 ft. (MSL). Polygons were constructed for the western and eastern parts of the basin using polylines for the northwest limit of the formation (Fig. 3.4) and the -2,500 ft. isolines generated from the TIN for the vertical depth to the top of the formation (Fig. 3.4). The break between the two areas coincides with the Flemington fault zone, a major intrabasin fault that breaks the basin into east and west segments for further evaluation. Figure 3.6 shows the spatial relationship between the planimetric limits of the formation below 2,500 ft. and the first set of depth isolines. The thickness isolines were then clipped to the boundaries of these two polygons (Fig. 3.7). A new set of TINs were then generated for each of the two polygons using the clipped isoline values as the TIN control values (Fig. 3.8). The volume of each TIN surface was calculated using a built-in ArcView function within the 3D Analyst extension for calculating the area and volume statistics for a TIN. The volume was calculated using a flat base of value 0 (ft.) relative to the variable TIN surface elevations.

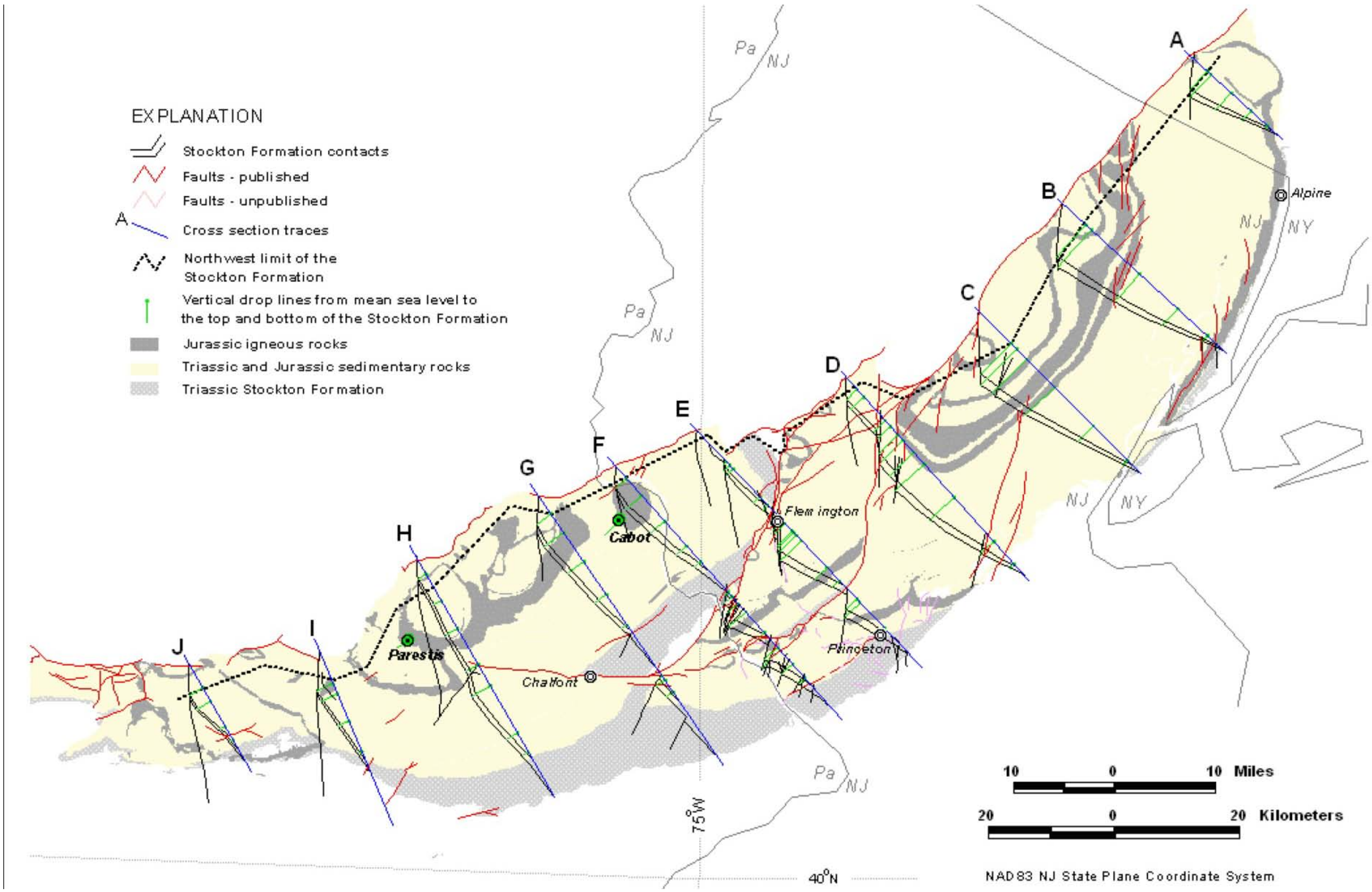

Figure 3.3. Generalized Geologic Map of the Newark Basin Showing the Stockton Formation and Overlying Mesozoic Rocks, Lithology, Faults, and Cross-Section Interpretations

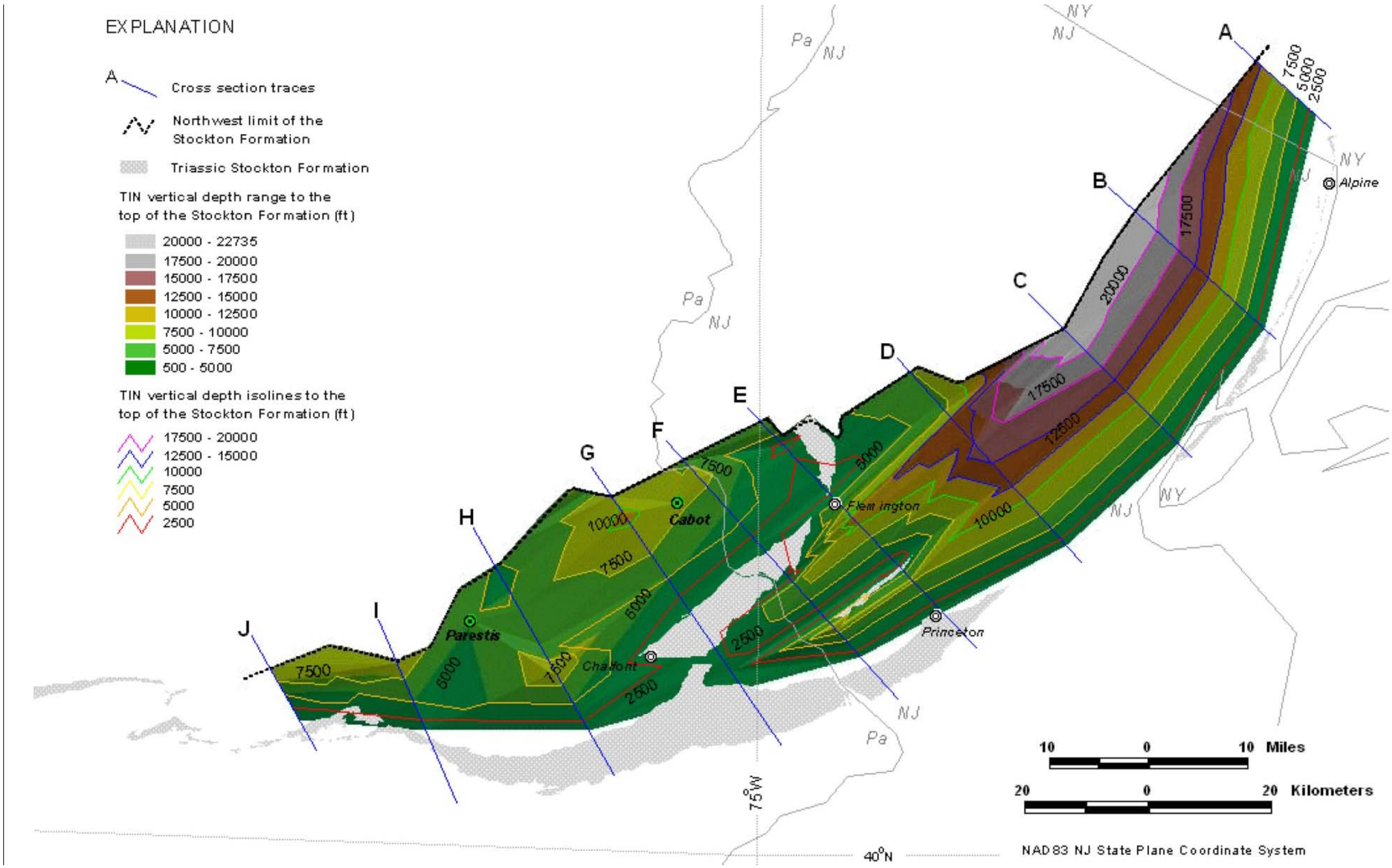

Figure 3.4. Map Showing Depth to the Top of the Stockton Formation (in feet below mean sea level).

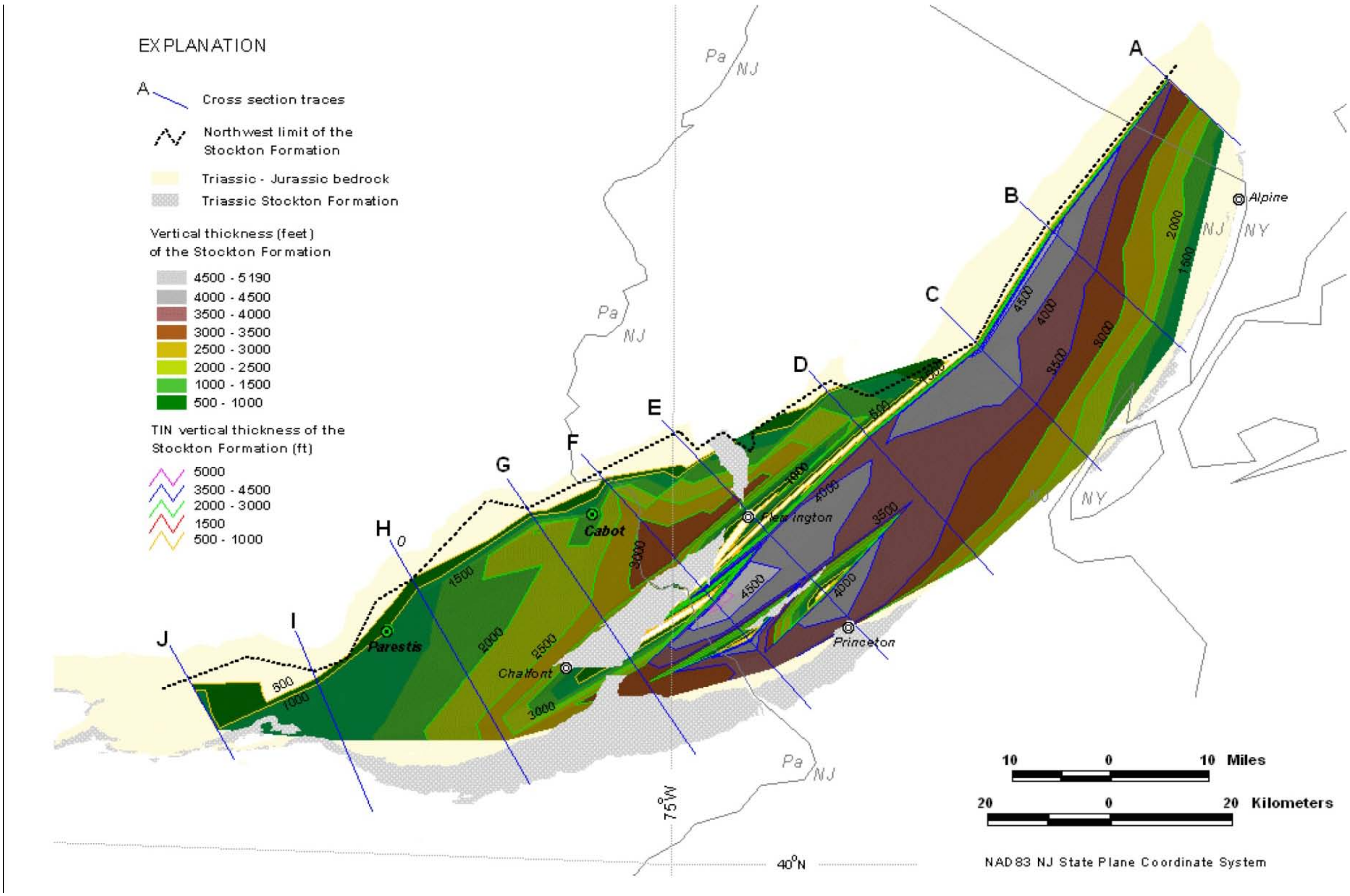

Figure 3.5. Map Showing Thickness of the Stockton Formation

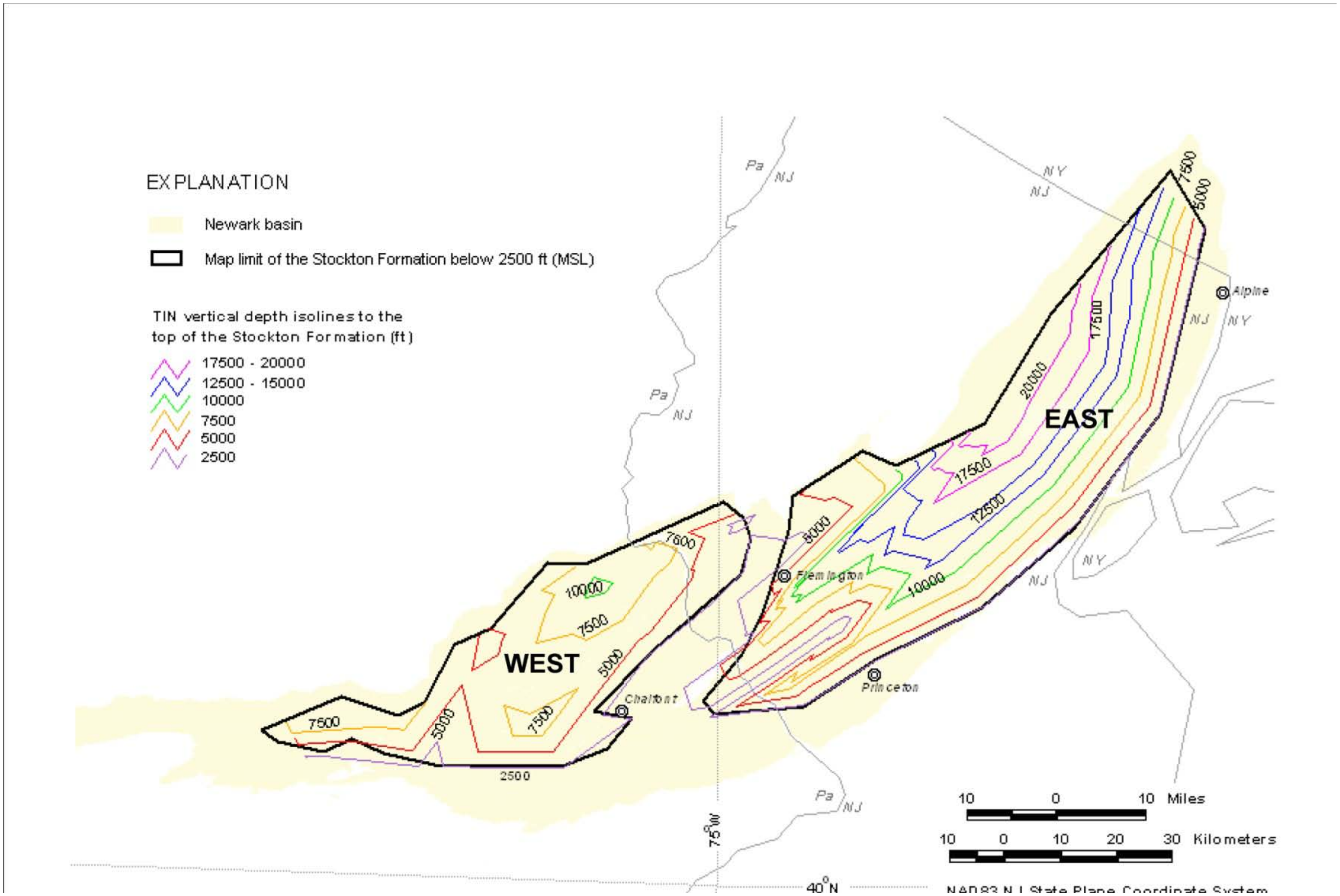

Figure 3.6. Map Limit of the Stockton Formation Below 2,500 ft. (MSL) in the Newark Basin

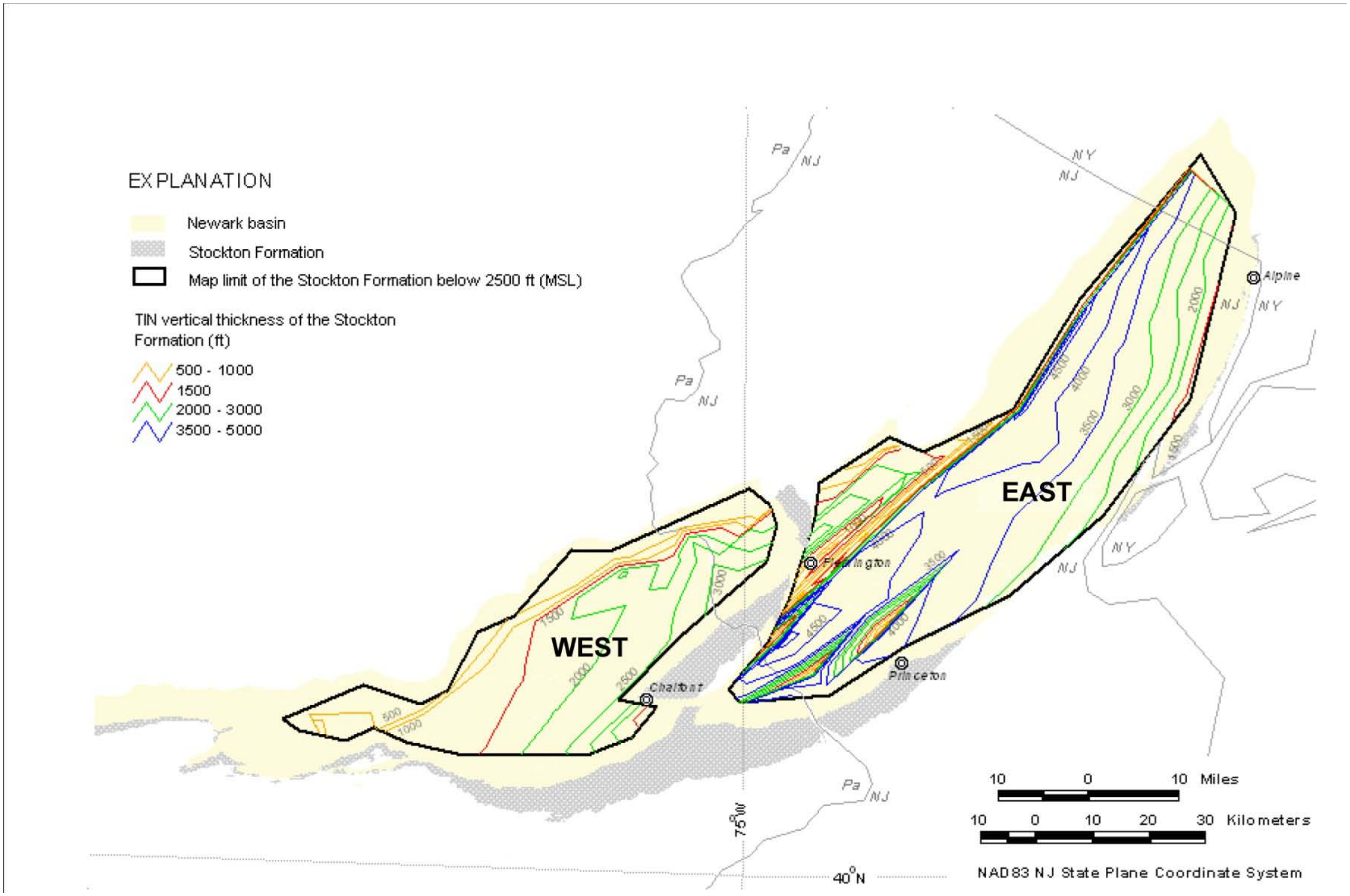

Figure 3.7. Vertical Thickness of the Stockton Formation Below 2,500 ft. (MSL) in the Newark Basin.

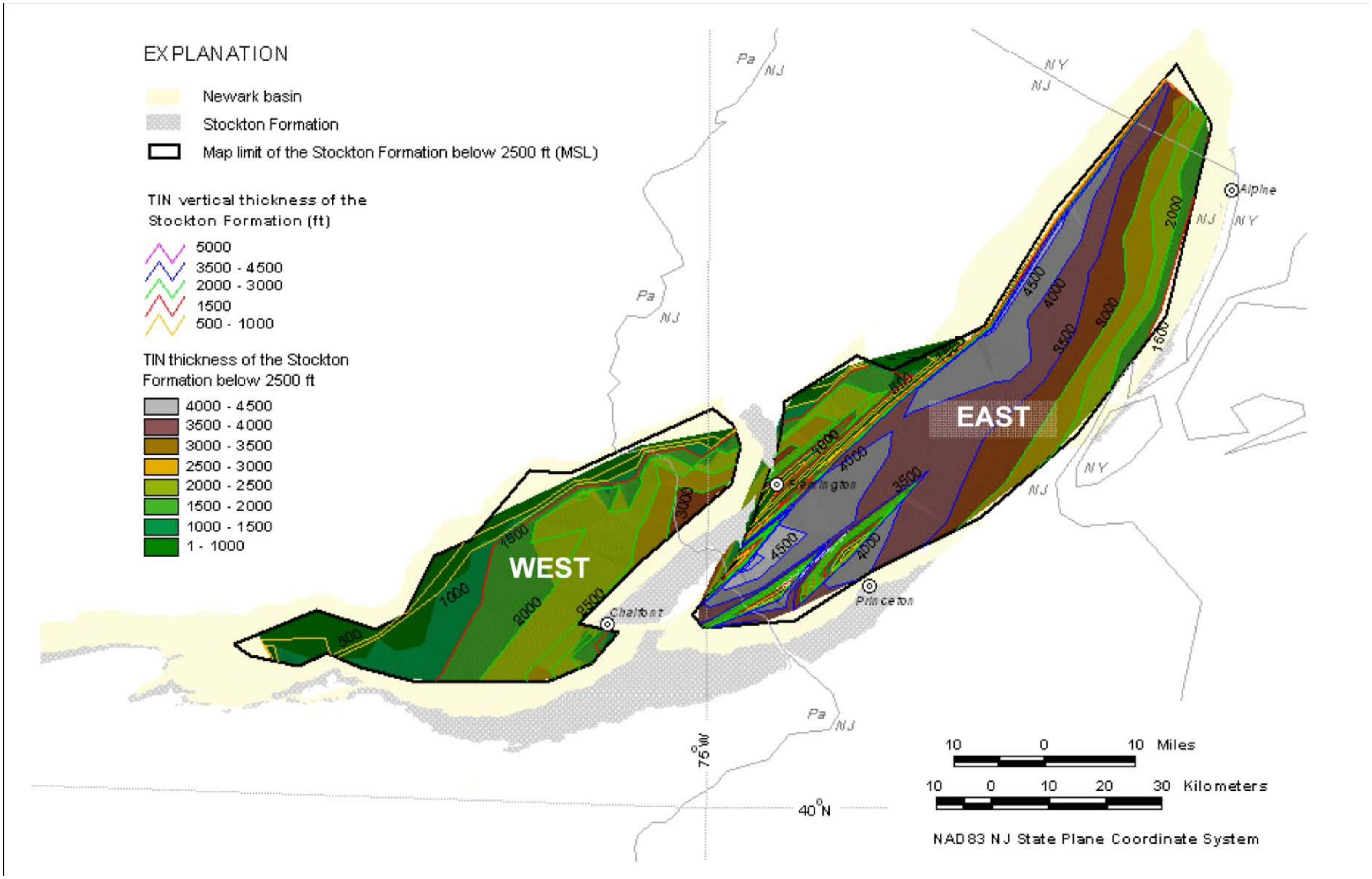

Figure 3.8. TIN Surfaces of the Vertical Thickness of the Stockton Formation Below 2,500 ft. (MSL).

3.6 Discussion

The two deep hydrocarbon exploration wells and two deep cores are the only points providing absolute subsurface control for these interpretations. The Cabot well is located between sample points G2 and F2, whereas the Parestis well is located between sample points H2 and I2, respectively (Fig. 3.2). The report for the Cabot Well divides the sedimentary sequence into upper (2,900 to 6,650 ft.), intermediate (6,650 to 8,650 ft.) and deep (8,650 to 10,490 ft.) intervals. The upper interval is cited as corresponding to the Lockatong Formation, but the top of the Stockton Formation is not explicitly picked. For the purpose of this study, the top of the Stockton is placed at the top of the deep interval, corresponding to a sequence of "fractured shale with thick, low porosity, wet sandstone". Therefore, the depth and thickness values for the Stockton Formation in the Cabot well included in table 3.1 are 8,160 ft. and 1,840 ft., respectively. Note that the depth of 8,160 ft. is derived by subtracting the surface elevation (480 ft.) plus 10 ft. (estimated distance from the kelly bushing to land surface) from the reported top of the deep interval. In the report for the Parestis well, a thickness of 1,950 ft. is cited for the Stockton Formation in the Cabot well, although it is not clear if this is for the vertical (apparent) thickness or the true stratigraphic thickness of the unit. Most of the hydrocarbon shows in the Cabot well were natural gas in the Lockatong Formation at drilling depths of 2,900 to 6,250 ft.

The report for the Parestis well interprets the sandstone-dominated beds at the base of the sedimentary sequence, from about 5,590 to 6,680 ft. depth, as the shallow-water equivalents of the lower Lockatong Formation, and the time-equivalent of the type Stockton Formation as not deposited in the area. Typical Lockatong shale and siltstone sections are reported above the 5,590 ft. depth. The Cabot and Parestis wells are in the same fault block. Therefore, the lower 1,090 ft. of sandstone-dominated beds in the Parestis well are included in the Stockton Formation in this study. Depth and thickness values in table 3.1 for the Parestis well are therefore 5,240 ft. (5,590 ft. depth – 350 ft. land elevation) and 1,090 ft., respectively. The Parestis well report also includes a section titled 'sandstone quality', indicating that the 1,090 feet of sandstone-dominated section contains more than 70 percent sandstone with an average porosity of 6 percent. Another 110 ft. of cleaner sandstone has an average porosity of 7 percent to 10 percent. Other thin sandstone sections have reported porosity of 10 to 12 percent. Zones with porosities exceeding 7 percent are permeable, with flowing salt water. The pore volume calculated for the Stockton Formation uses 5 and 10 percent porosity values (Table 3.2).

Of the two deep cores in the Stockton Formation, the Nursery core is located about 1,500 ft. south of control point F13, whereas the Princeton core is about 2.5 miles northeast of sample point E16 (Fig. 3.2). The top of the Stockton Formation in the Nursery core is ~ 3,022 ft. below MSL. This is about 400 ft. shallower than that for point F13 (3,400 ft.) which is based on the cross-section interpretation. Similarly, the depth value of the Princeton is about 440 ft. below MSL (~834 ft. BLS – 394 ft. surface elevation). Sample point E16 is the farthest southeast on section E, and is 1,000 ft. below MSL. In both instances, the cross-section interpretations overestimate the depth of the Stockton Formation by a few hundred feet more than the core samples. These discrepancies are small and far from the target areas for sequestering CO_2 in deep crustal reservoirs, where depths to the formation top exceed 2,500 ft. below land surface.

Table 3.2 TIN Area and Volume Statistics for the Stockton Formation Below 2,500 ft. (MSL)

Region	Planimetric Area	Volume	Volume	Pore volume at percentage porosity			
				5%	10%	5%	10%
	ft^2	ft^3	km^3	ft^3		km^3	
East	32371915588	9.88326E+13	2799	4.94163E+12	9.88326E+12	140	280
West	16703233699	2.74591E+13	778	1.37296E+12	2.74591E+12	39	78
Total	49075149287	1.26292E+14	3577	6.31458E+12	1.26292E+13	179	358

The tables and figures show that the Stockton Formation is deepest and thickest beneath the Watchung Mountain locality in New Jersey; here formation depth may exceed 20,000 ft. below MSL, and unit thickness may exceed 4,500 ft. (Figs. 3.4 and 3.5). Depths west of Flemington generally are less than 10,000 ft. below MSL, and most are less than 7,500 ft. The Stockton Formation is also relatively shallow and thin in the Pennsylvania part of the basin compared to areas farther northeast (Fig. 3.5). The maximum thickness of the Stockton Formation in the fault blocks west and north of Flemington is thought to be about midway along section F, where it may exceed 3,000 ft. (Fig. 3.5). It exceeds 3,000 ft. in the fault blocks to the south and east of Flemington (Fig. 3.5), where maximum thickness may be as much as 5,000 ft.

TIN surface computation is not precise. Figure 3.7 shows that TIN surfaces locally fall short or extend beyond the polygon boundaries used to generate them due to the irregular shape of the polygons, and the algorithm used for interpolating parameter values during TIN processing. A visual inspection of the results for both areas shows that the area and volume estimates for the west polygon is probably underestimated whereas those for the east are slightly overestimated.

In summary, the Stockton Formation is thought to be present and exceed the minimum target depth of 2,500 ft. for sequestering supercritical CO_2 in about two-thirds of the basin. Of the total area available for potential sequestration, about 78 percent of the reservoir volume is located in the eastern region, mostly in New Jersey. The remaining 22 percent is in the western region, mostly in Pennsylvania. These results are largely based on cross-section interpretations lacking adequate subsurface control. Publicly available, high quality seismic reflection data are also lacking. Little is known about how lithology and porosity of the Stockton Formation vary throughout the basin, other than what is gleaned from the Nursery and Princeton cores, outcrop samples, and shallow core from near the outcrop belts. Outcrops of the Stockton Formation are generally scarce because its high feldspar content has resulted in deep weathering. Accordingly, these interpretations are gross estimates of the depth, thickness, and volume of the Stockton Formation below 2,500 ft. (MSL).

3.7 References

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4.0 CHARACTERIZATION OF THE CARBON DIOXIDE STORAGE POTENTIAL IN THE PALEOZOIC AND PRECAMBRIAN ROCKS OF NEW JERSEY

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4.1 Introduction - Carbon Sequestration in the Paleozoic and Precambrian Rocks

A series of Paleozoic geologic units have been identified in the western part of the MRCSP region (Fig. 4.1) that may have potential as reservoirs for the storage of carbon dioxide. Geologic units of similar age occur in the northern part of New Jersey but present a different lithologic history. The New Jersey formations have been subjected to a much higher degree of deformation, four or five periods of tectonism, than similar-aged units in the western MRCSP research area. While the western MRCSP units can be found at thousands of feet in depth, their correlative units in New Jersey crop out at the surface. Based on these surface exposures and limited data generated from water wells, generally 600 ft. or less, their carbon sequestration potential is extremely low. New Jersey does not have a history of oil and gas exploration to supply either deep borehole or seismic data to adequately characterize the deep structure of these units.

4.2 Geologic Summaries of Units Identified

New Jersey is divided into four physiographic provinces which have distinctive geology and landforms. From the northwest to the southeast they are the Valley and Ridge, Highlands, Piedmont and Coastal Plain provinces (Fig. 4.2). The lateral equivalent of the potential sequestration targets from the western MRCSP are found mainly as surface and relatively shallow subsurface formations in the Valley and Ridge, and as narrow bands in the Highlands Province and the northwestern edge of the Piedmont Province (Fig. 4.3).

4.3 The Precambrian Unconformity Surface

The Precambrian Unconformity Surface has been identified as a potential target in other parts of the MRCSP study area. The Precambrian rocks that occur in the subsurface in most of the MRCSP region are again exposed at the surface in the Highlands.

4.4 New Jersey Highlands

The New Jersey Highlands, and contiguous Hudson Highlands in southern New York and Reading Prong in eastern Pennsylvania, constitute one of the largest Grenville terranes that extend along eastern North America (Fig. 4.4). Mesoproterozoic rocks in the New Jersey Highlands are in fault contact along their eastern border with Late Triassic to Early Jurassic rocks of the Newark basin part of the Piedmont Province. Along the western border of the Highlands, Mesoproterozoic rocks are nonconformably overlain by, or in fault contact with, a passive margin clastic and carbonate shelf sequence of Cambrian and Ordovician age of the Valley and Ridge Province.

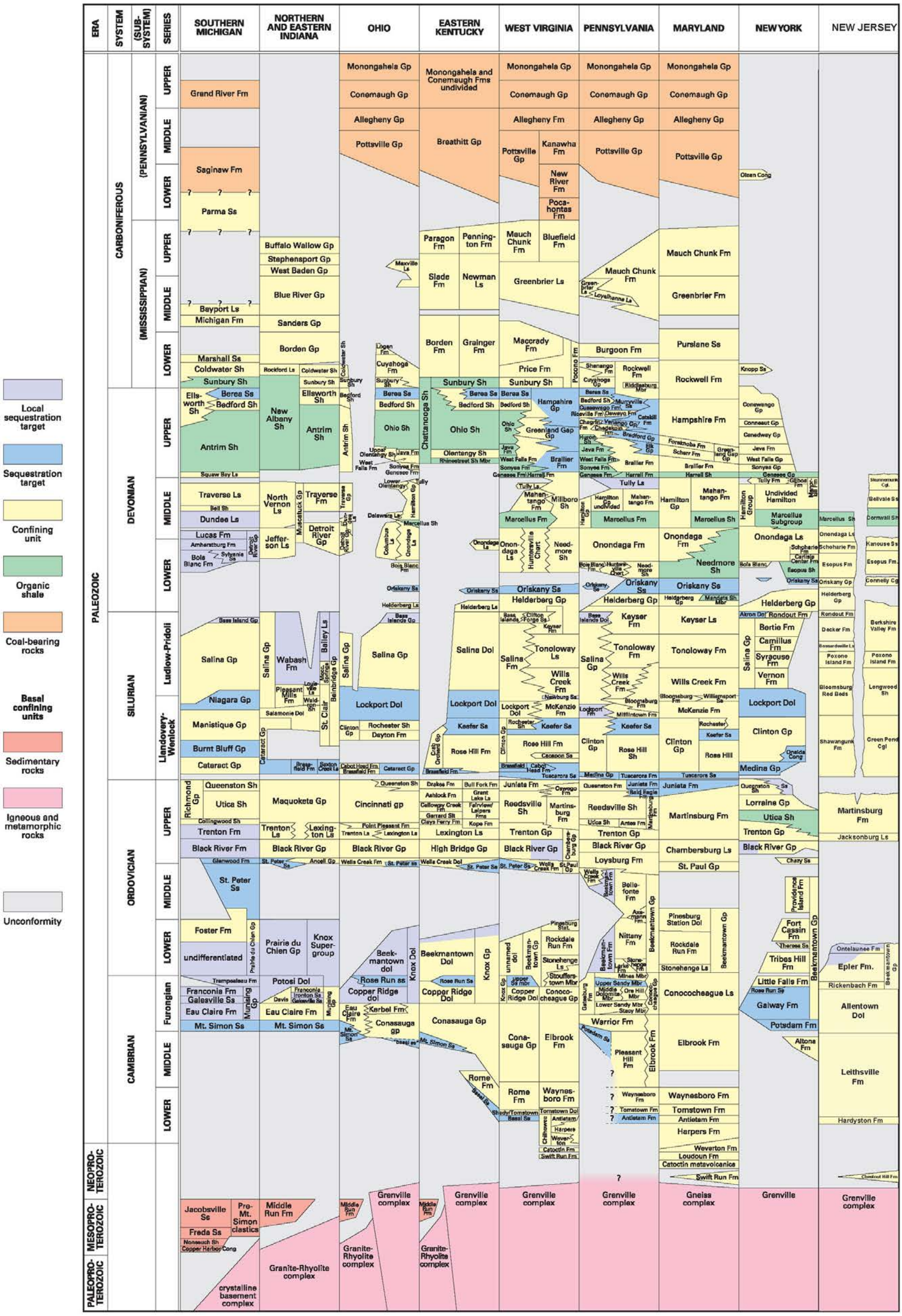

Figure 4.1. Correlation Chart Relating the New Jersey Paleozoic Geologic Units to the Rest of the Region Modified From Wickstrom, et. al., 2005

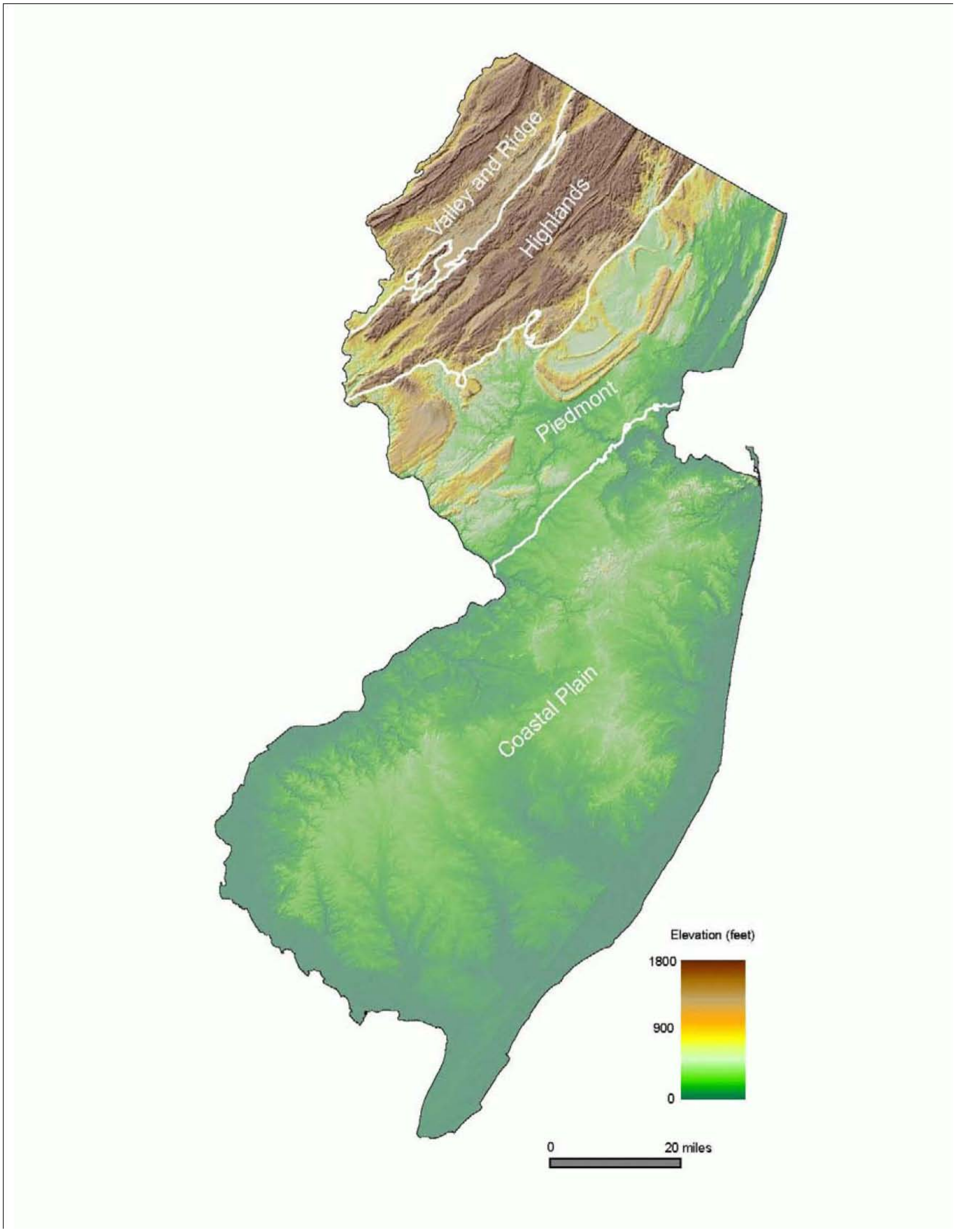

Figure 4.2. Map of the Physiographic Provinces of New Jersey

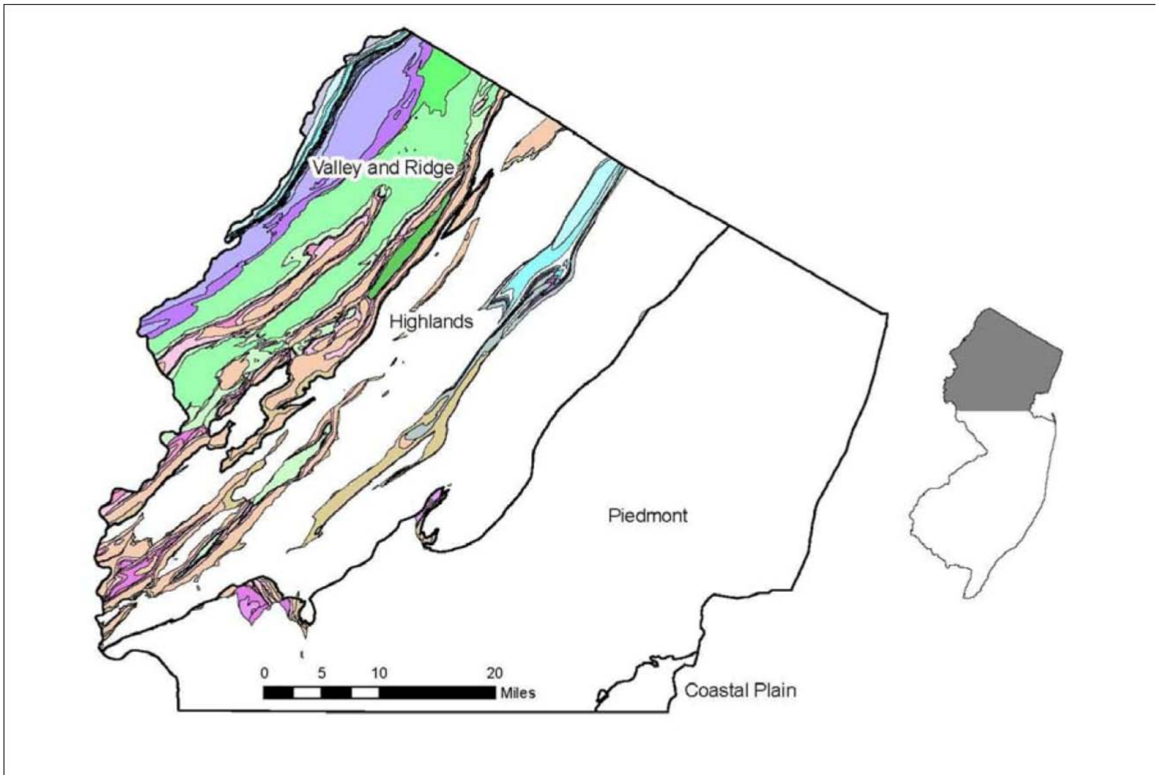

Figure 4.3. Distribution of Paleozoic Units in Northern New Jersey

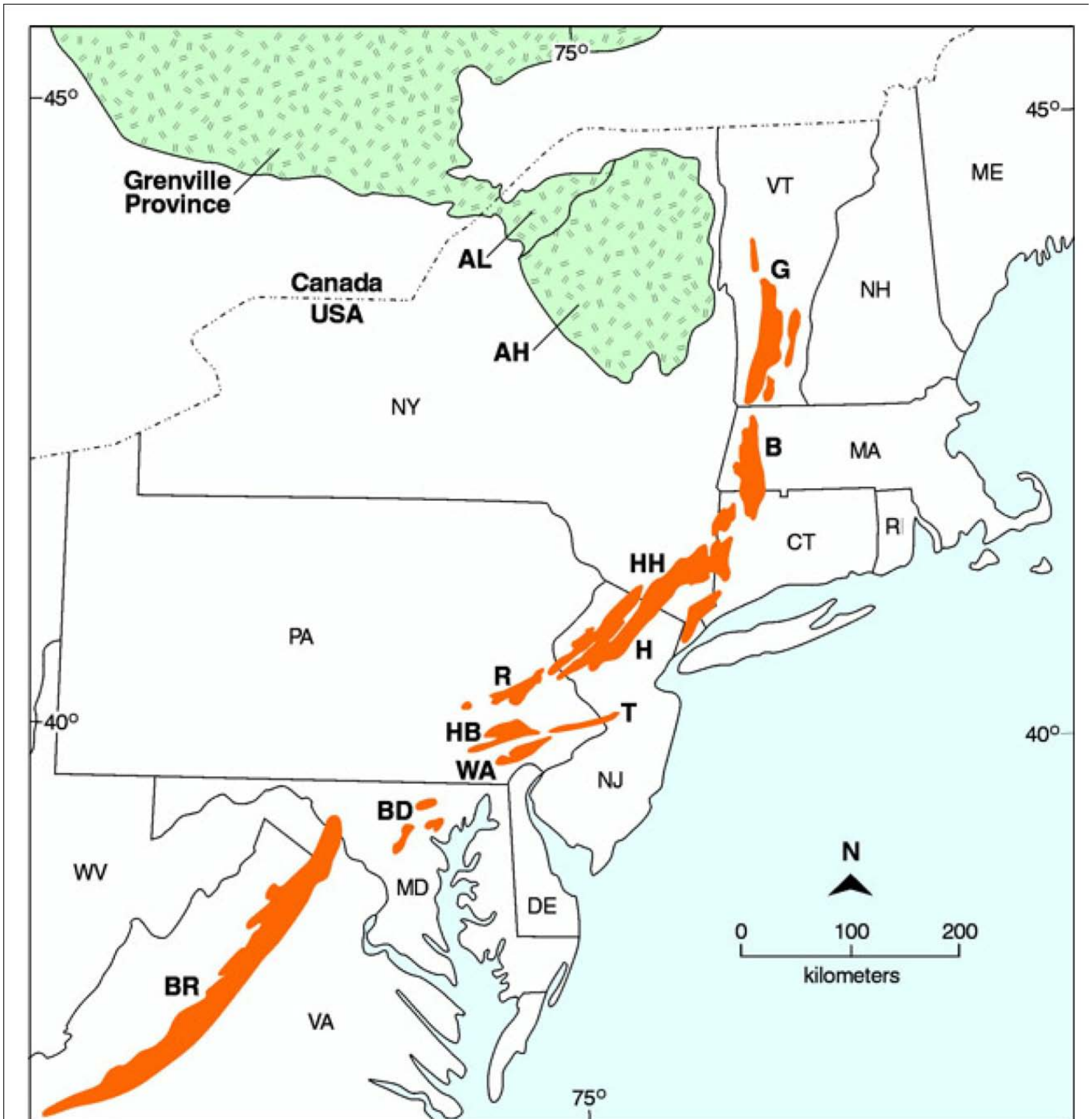

Figure 4.4. Distribution of Mesoproterozoic-age rocks in the central and northern Appalachians (shown in orange). H – New Jersey Highlands

The New Jersey Highlands are underlain by a heterogeneous assemblage of Mesoproterozoic rocks (Fig. 4.5), most of which were metamorphosed to granulite-facies conditions by 1030 Ma during the Ottawan orogeny. These include a regionally widespread assemblage of 1.28 - 1.25 Ga (Volkert et al., 2010) calc-alkaline magmatic-arc plutonic (diorite, quartz diorite, tonalite,) and volcanic (basalt, andesite, dacite, minor rhyolite) rocks that underlie about 30 percent of the Highlands.

Magmatic arc rocks are spatially associated with a supracrustal succession of intercalated metasedimentary gneisses, quartzite, marble, and bimodal volcanic rocks that predominate in the western Highlands where they are as much as 2,100 m thick. Supracrustal rocks underlie about 20 percent of the Highlands. The supracrustal succession is interpreted as having formed in a back-arc basin inboard of the Losee arc above thinned and extended crust (Volkert, 2004). Rhyolite gneiss layers intercalated with Franklin Marble yielded U-Pb SHRIMP (sensitive high resolution ion microprobe) ages of 1.29 - 1.25 Ga (Volkert et al., 2010) that are coeval with calc-alkaline magmatism and arc development.

Calc-alkaline magmatic arc rocks and supracrustal rocks were intruded by widespread granite and related rocks of the 1.18 Ga Byram and Lake Hopatcong Intrusive Suites (Volkert et al., 2010) that underlie about 45 percent of the Highlands. The Byram and Lake Hopatcong Suites are composed of monzonite, quartz monzonite, granite, alaskite, and pegmatite. Various postorogenic felsic intrusive rocks dated at 1019 to 986 Ma (Drake et al., 1991; Volkert et al., 2005) underlie an additional five percent of the Highlands.

The Chestnut Hill Formation of Neoproterozoic age (Drake, 1984; Gates and Volkert, 2004) is composed of locally preserved terrestrial sedimentary siliciclastic rocks metamorphosed to greenschist-facies conditions that were deposited along the rifted eastern Laurentian margin. These metasedimentary rocks occur discontinuously mainly in the western New Jersey Highlands and Reading Prong in southeastern Pennsylvania where they rest unconformably on Mesoproterozoic rocks. The Chestnut Hill Formation is, in turn, overlain nonconformably by the Hardyston Quartzite of Lower Cambrian age.

Wells within the Grenville rocks are mainly for domestic and municipal water usage and as such are generally not deeper than 600 ft. Primary porosity in the Proterozoic rocks of New Jersey is nonexistent. Water well data suggests that fracture porosity and permeability accounts for flow. Proterozic and Neoproterozoic units have limited to no capacity of CO_2 sequestration.

4.5 Paleozoic Rocks of the Valley and Ridge, Highlands and Piedmont Provinces

The Paleozoic rocks (Cambrian to middle Devonian) of the Valley and Ridge Province have been intensely folded and faulted into the long, parallel northeast-southwest trending ridges and valleys characteristic of this province. Resistant sandstone and siltstone layers form the ridges with shale, limestone and dolomite underlying the valleys. There are some anticlinal structures in the Kittatinny Valley Section which may provide small scale traps in the Cambrian and Ordovician rocks, but the Silurian and Devonian rocks occur only on the northwest dipping synclinal limb

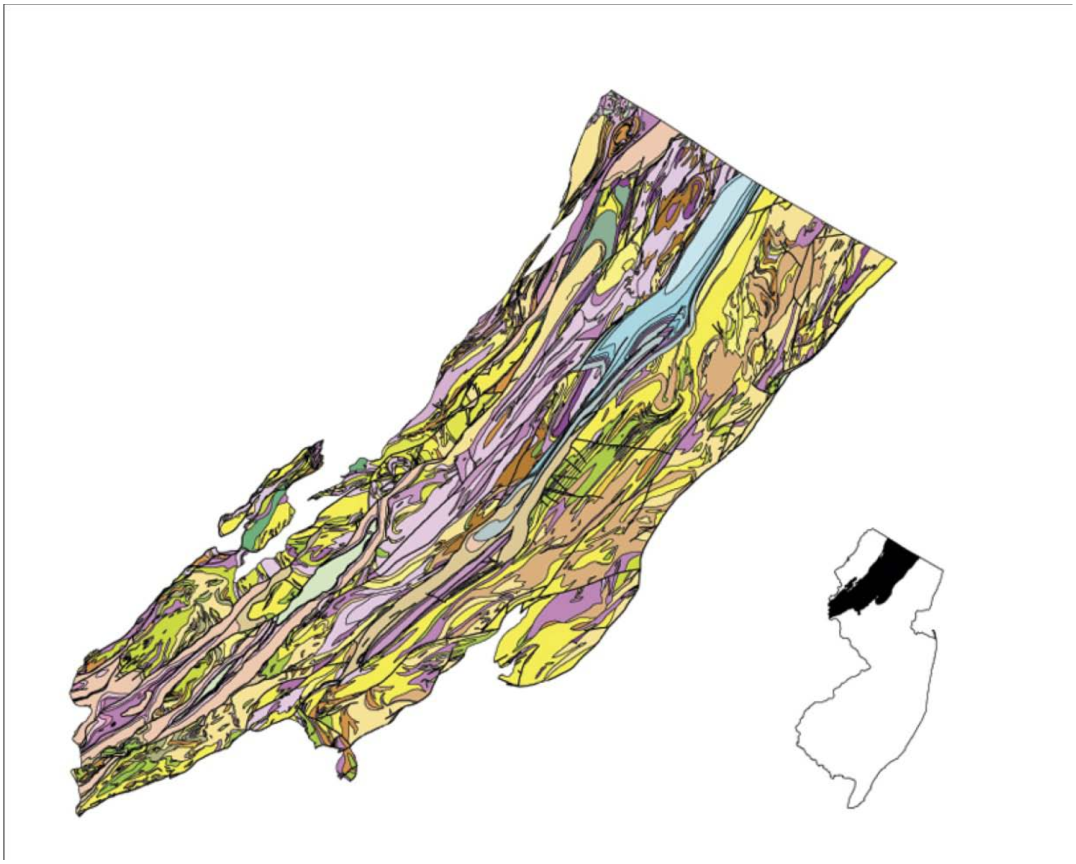

Figure 4.5. Bedrock Geologic Map of Northern New Jersey Showing Geologic Relationships of Completely Folded and Faulted Mesoproterozoic Rocks of the Highlands

that forms the escarpment of the Appalachian Mountain Section of the Valley and Ridge Province.

The Paleozoic rocks of the Green Pond Syncline within the Highlands Province range in age from basal Cambrian up through the Middle Devonian. They are tightly folded into several anticlines and synclines in a narrow linear band, that varies from less than a mile up to about 3.5 miles wide, and are cut by a series of steely dipping faults. Any potential structural traps would likely be too limited in aerial extent to be of use for storage of CO_2.

The Paleozoic rocks along the northwestern edge of the Piedmont Province range in age from basal Cambrian up through the Ordovician and are strongly folded and faulted. Where exposed, they are overlapped by the Triassic conglomerates, sandstones and shales. Water wells within a mile of the edge of the Triassic sediments have penetrated Paleozoic rocks, but there are no deep drill holes or seismic lines further out in the Newark basin to indicate how far out under the basin the Paleozoic rocks may extend and how deep they might be. Even though the basal Cambrian sandstones may be somewhat thicker on the southeast side of the Highlands, the chances of any potential structural traps for storage of CO_2 is speculative at best.

No wells have been drilled in search of oil or gas in any of the Paleozoic rocks of the state so there are no deep porosity and permeability data. Outside of several deep core holes (1,000+ ft.), all the information is from water wells, most of which seldom exceed 650 ft. Information from the large number of water wells in the region indicates certain formations are very good producers of ground water but generally at depths of less than 600 ft. The best ground water producing zones in the entire sequence are in the Cambrian-Ordovician carbonate rocks. Some of the Silurian and Devonian limestone formations may be moderate producers of ground water, but there is little information on those units due to lack of wells since most of the outcrop area of these formations is on federal or state parklands.

Some of the high yielding wells from the Leithsville Formation (Lower and Middle Cambrian) and lower Allentown Dolomite (Upper Cambrian) can exceed 1,000 gallons per minute. The wells in the basal part of the Beekmantown Group (Upper Cambrian to Lower Ordovician) can have high yields that range from about 20 gpm to about 100 gpm. The ground water in these rocks is mainly from the secondary porosity, not primary porosity. The lower Paleozoic rocks of New Jersey have been subject to much higher temperatures, over 300^{o} C (Harris et. al, 1995), than adjoining areas leading to a large amount of recrystallization of the limestones and dolomites.

4.6 Cambrian Basal Sandstone

The basal Cambrian Hardyston Quartzite lies unconformably on the Grenville basement complex in New Jersey. Elsewhere in the MRCSP study area the basal Paleozoic sandstones may be potential targets but are not suitable as targets in New Jersey for several reasons. In New Jersey, the Precambrian unconformity is exposed at the surface exposure and there is some disagreement by various workers on the nature and amount of relief on the surface. Ludlum (1940, p. 18) indicates that it must have been one of low relief, whereas Hague and others (1956, p. 456) suggest it is very irregular. Markewicz and Dalton (1977, p. 7) indicated that the Precambrian surface must have been irregular, with deeply weathered joints, shallow basins and intermediate gently sloping plateaus based on mapping in the 1960's and early 1970's. The unconformity generally dips to the northwest under the lower Paleozoic sedimentary rocks.

The Hardyston Quartzite is extremely variable both laterally and vertically. The lower contact with the Precambrian is generally an arkosic sandstone which locally can grade to a quartz pebble conglomerate. Above the basal beds usually the sandstone becomes finer, more compact and cemented with silica forming an orthoquartzite. Locally the cementing agent can also be iron oxide with some small limonite deposits locally found in the Hardyston. At some locales the Hardyston grades upward through a sandy shale or sandy dolomite and into dolomitic limestone of the overlying Leithsville Formation. Where the Hardyston is less than 10 ft. thick, the upper contact grades from a siliceous quartzite to a siliceous dolomite. The thickness ranges from less than a foot to about 200 ft. with the average being much less than 100 ft.

4.7 Basal Sandstone to Knox-Beekmantown Unconformity

Overlying the Hardyston Formation are dolomitic rocks of the Kittatinny Supergroup (Drake and others, 1996). The Cambrian-Ordovician aged Kittatinny Limestone (Weller, 1900) was subdivided into five mappable formations (Markewicz and Dalton, 1977) with a more informal subdivision used for the new 1:100,000 scale bedrock map of the state (Drake and others, 1996). The difference between the two concerns the breakdown of the Ordovician portion of the sequence. Both publications generally agree on the Leithsville and the Allentown Formations.

The Leithsville Formation, of Middle to Lower Cambrian age, consists of three members; the lower part is a medium- to dark-gray, silty weathering, medium- to coarse-grained, medium- to massive-bedded, rubbly, undulating locally sandy dolomite with scattered white dolomite clots and crystals. Frequent discontinuous large masses and lenses of pyrite and other sulphides can be present in the lower part. The middle part is a cyclic sequence of interbedded medium-gray, very-fine to fine-grained, thin- to medium-bedded dolomite, shaly dolomite and varicolored quartz sandstone, siltstone and shale. The lower and middle parts are likely equivalent to the Shady Dolomite of Virginia (Palmer & Rosanov, 1976; McMenamin et al, 2000). The upper part is a medium- to dark-gray, fine- to medium-grained, medium- to massive-bedded, pitted dolomite. Knots and lenses of chert can be present. The Leithsville ranges from 500 to 800 ft.

The Allentown Dolomite of Upper Cambrian age consists of two members. The lower part is a cyclic sequence of light- to dark-gray, fine- to medium-grained, thin- to medium-bedded dolomite interbedded with shaly dolomite. Ripple marks, cross beds, edgewise conglomerate, mud cracks, oolites, and algal structures are common. The upper part is a light- to dark-gray, fine- to medium-grained, locally coarse, medium- to massive-bedded dolomite. Some minor orthoquartzite beds and thin shaly- to silty-laminae are present with less common edgewise conglomerate, oolites, ripple marks, mud cracks, and algal structures. At the top of the formation are two sequences of steel-gray, thin-bedded quartzite and discontinuous dark-gray chert lenses. The Allentown Dolomite is approximately 1,800 ft. thick. The Upper Cambrian sandstone formations identified farther westward in the MRCSP study area, as potential sequestration targets could be lateral equivalents to the upper Allentown Dolomite.

The Beekmantown Group, of Lower Ordovician to Upper Cambrian age, consists of the Rickenbach, Epler, and Ontelaunee Formations (Markewicz and Dalton, 1977). The Rickenbach Formation has two members and distinct mappable facies. The lower member consists of a light- to dark-gray, thin-to medium-bedded, fine- to medium-grained dolomite with many stringers of sand. The upper member consists of a medium- to dark-gray, aphanitic- to coarse grained, medium-bedded dolomite. Some beds contain floating quartz sand to sand stringers at the base. There are several zones of thin black chert beds, knots and stringers. A distinctive facies within the Richenbach consists of a light gray- to gray, medium- to very-coarse-grained, massive-bedded dolomite with the dolomite grains being very euhedral and surrounded by a clay-like material which can thicken from a few feet to over a hundred feet along strike. The upper contact with the Epler can consist of a massive chert horizon. The Rickenbach ranges in thickness from 150 to 300 ft.

The Epler Formation has three members. The lower member is a light- to dark-gray, very-fine- to medium-grained, massive, laminated dolomite. It grades upward into the middle member that is a laterally variable, light- to dark-gray, aphanitic- to fine-grained, thin-bedded dolomite or siliceous dolomite with local olive- to pink, thin up to 2 inch silicious dolomite to shaly ribs. A lenticular, gray, aphanitic- to fine-grained massive, laminated to ribbed limestone locally occurs. The upper member is a light- to dark-gray, very-fine- to fine-grained, massive, laminated dolomite that is similar in character to the basal member. The Epler ranges in thickness from 350 to 500 ft.

The Ontelaunee Formation has two members. The lower part is a medium- to dark-gray, medium- to very-coarse-grained, massive dolomite which contains a large amount of irregularly bedded and rugose chert. The upper part is a medium- to dark-gray, very-fine- to medium-grained, thin- to massive-bedded dolomite containing scattered chert zones. The Ontelaunee ranges from absent due to erosion to over 350 ft. thick.

Below the Knox-Beekmantown unconformity, in the underlying Ontelaunee, Epler and Rickenbach Formations, paleosolution breccias occur, which if unmineralized, may have a limited potential for storage as in other areas. Since there has been no oil, gas or deep mineral drilling in the Paleozoic rocks of the state, there is no information on the amount of mineralization of these breccias outside what is observed at the surface. These breccias in New Jersey likely have little to no porosity for the same reasons stated earlier.

4.8 Knox-Beekmantown Unconformity to Lower Silurian Unconformity

The Knox-Beekmantown Unconformity in New Jersey separates the lower Ordovician dolomitic units from the middle and upper Ordovician limestones and shales. Markewicz and Dalton (1977) show a relief change of 500 ft. over 15 miles on this surface. The underlying carbonate rocks have evidence of paleo-solution features occurring as much as 400 to 500 ft. below the unconformity. In outcrop, the rubble breccias can be filled with residual soil material and deeper crackle breccias filled with carbonate cement and locally, sulphide minerals. Locally lying atop the unconformity occurs a green dolomitic siltstone, argillite, shale and calcareous. This unit, which can exceed 150 ft. in thickness, locally forms a paleo-sinkhole infilling. In other areas, it has characteristics of a fluvial deposit. This discontinuous unit varies from absent to over 150 ft. thick.

The Middle Ordovician Jacksonburg Limestone consists of a lower "cement limestone" and upper "cement rock" member. The "cement limestone" is a medium- to dark-gray, fine- to coarse-crystalline, fossiliferous, locally high-calcium limestone. A thin- to very-thick dolomite-cobble conglomerate and less abundant limestone-clast conglomerate can also be present. The "cement rock" is a dark-gray- to black, fine-grained, argillaceous limestone with occasional coarse-crystalline limestone beds. The "cement rock" commonly developed a pronounced cleavage. The Jacksonburg ranges from 100 to over 600 ft. in thickness.

The Jutland Klippe sequence, of Middle Ordovician to Upper Cambrian age, is largely shale and sandstone but contains lesser amounts of thin-bedded, fine-grained to aphanitic limestone, dolomite, and pebble conglomerate. This unit is at least 1,500 ft. thick and occurs as several isolated outcroppings along the eastern and southern Highlands boundary where they are onlapped by Triassic and Jurassic units of the Piedmont Province.

The Martinsburg Formation, of Upper to Middle Ordovician age, is a medium- to dark-gray, laminated- to medium-bedded slate, siltstone and less common greywacke sandstone with a turbidite origin. It grades upward into a medium-dark-gray, thin-bedded shale, siltstone and fine-grained sandstone, interbedded with medium- to dark-gray, medium- to thick-bedded and massive quartz and calcareous-cemented sandstone. The total thickness is over 8,000 ft.

4.9 Lower Silurian Medina Group/"Clinton" Sandstone

The Silurian Taconic Unconformity, possibly the correlative of the Cherokee Unconformity in the rest of the MRCSP region, separates the Martinsburg Formation from the Shawangunk and Green Pond Formations. These units would be the equivalents to the Lower Silurian Medina and Clinton Groups.

The Shawangunk (Delaware Valley) and Green Pond (Green Pond Syncline) Formations, of Middle to Lower Silurian age, consists of a light- to medium-gray to light-olive-gray thin- to thick-bedded quartz and feldspathic sandstone, quartzite and quartz-pebble conglomerate. It grades upwards into a light- to medium-gray, greenish-gray, thin- to medium-bedded shale and sandstone. The upper section is a medium- to dark-gray, or dark-greenish-gray, medium- to thick-bedded sandstone and conglomerate with quartz and shale pebbles. The unit is about 1,400 ft. thick.

4.10 Niagaran/Lockport Through Onondaga Interval

The Bloomsburg Red Beds (Delaware Valley) of Upper Silurian age is a grayish- red, thin- to thick-bedded, poorly to moderately sorted siltstone, sandstone and local quartz-pebble conglomerate. The lower part locally consists of a greenish-gray to grayish-red sandstone and siltstone to grayish- red siltstone to mudstone. The unit becomes more shaly toward the top. The Bloomsburg rests conformably on the underlying Shawangunk and is about 1,500 ft. thick.

The Longwood Shale (Green Pond Syncline) of Upper and Middle Silurian age is a dark-reddish-brown, thick bedded shale interbedded with dark red, very thin- to thin bedded sandstone and siltstone. The Longwood Shale is conformable with the underlying Green Pond Formation. The unit is about 300 ft. thick.

The Poxono Island Formation of Upper Silurian age is a greenish-gray- to yellowish-gray, very-fine-grained, thin- to medium-bedded, flaggy dolomite with discontinuous lenses of rounded quartz sand, with local quartz sandstone and argillaceous dolomite beds. The thickness can range up to 600 ft. in the Delaware Valley and up to 275 ft. in the Green Pond Mountain region. The contact with the underlying units is gradational in both regions.

The Bossardville Limestone, which overlies the Poxono Island in the Delaware Valley, consists of a gray- to medium-dark-gray, very-fine-grained, laminated- to thin-bedded limestone to argillaceous limestone. Desiccation columns up to 6 ft. thick occur in the southwest. Thickness ranges from 10 ft. at the New York boundary to over 100 ft. at the Delaware River.

The Upper Silurian Decker Formation is a light- to medium-dark-gray, flaggy to massive, medium- to coarse-grained, fossiliferous limestone locally interbedded with calcareous, quartz-pebble conglomerate, fine- to coarse-grained, calcareous sandstone, siltstone, and arenaceous limestone. Some medium-gray, very-fine-grained dolomite beds also can be present. The Decker ranges from 50 to 80 ft. in thickness.

The Rondout Formation, of Upper Silurian to Lower Devonian age, varies vertically from a lower, medium- to dark-gray, very-fine- to medium-grained, medium-bedded limestone, through a medium-gray, laminated to medium-bedded, argillaceous dolomite, into a medium-dark-gray, fine-grained, medium-bedded, argillaceous limestone to calcareous shale. The total thickness is about 40 ft.

The Lower Devonian to upper Silurian Berkshire Valley Formation in the Green Pond Mountain region is equivalent to the Bossardville Limestone, Decker and Rondout Formations and part of the Helderburg Group in the Delaware Valley. It is a medium-gray to pinkish-gray, very-thin-bedded, fossiliferous limestone, interbedded with a greenish-gray calcareous siltstone and silty dolomite, and less abundant quartz-pebble and limestone-pebble conglomerate. The thickness is 90 to 125 ft. The lower contact with the Poxono Island Formation is conformable.

The Lower Devonian Helderburg Group consists of Manlius Limestone, Coeymans Formation, Kalkberg Limestone, New Scotland Formation, Minisink Limestone and Port Ewen Shale. The uppermost Silurian Manlius Limestone is included in the Helderburg Group (Epstein and others, 1967) although Weller (1903) separated it from the Helderburg based on its gradual contact with the underlying Rondout. It consists of a medium-gray- to dark-bluish-black, thin- to uneven-bedded, flaggy to massive limestone, and local medium-grained limestone with yellowish-gray shale partings. The thickness ranges from 15 to 45 ft.

The Lower Devonian Coeymans and Kalkberg formations is a medium-dark-gray, fine- to coarsely-crystalline, medium- to massive-bedded limestone containing crinoid stems, brachiopods and some chert. It is overlain by a light-gray, quartz-pebble conglomerate, calcareous to limonitic sandstone, to a medium-gray, fine- to medium-grained fossiliferous limestone. The thickness ranges up to about 30 ft. The Coeymans has a maximum thickness of 70 ft.

The New Scotland Formation consists of a lower, medium-gray, fine-grained argillaceous, highly fossiliferous limestone, with chert lenses, knots and irregular beds and an upper dark-gray, very-fine-grained, laminated to thin-bedded, siliceous to slightly calcareous shale containing pods of very-fine-grained limestone and scattered thin beds and lenses of fine-grained argillaceous limestone with some small chert nodules. According to Epstein and others (1972), the New Scotland Formation has a thickness of about 75 ft.; Weller (1903) gives a thickness 160 ft.

The Minisink Limestone is a medium-gray, fine-grained, medium-to massive-bedded argillaceous limestone, fossiliferous and cherty, with lenses of purer limestone. The thickness is about 20 ft.

The Port Ewen Shale, the top of the Helderburg Group, is a medium-gray-weathering, medium-bedded calcareous siltstone, shale, and silty shale. It is about 150 ft. thick.

4.11 Lower Devonian Oriskany Group

The Oriskany Group (Delaware Valley) consists of the Glenarie Formation, Shiver Chert and Ridgely Sandstone. The Glenarie; a medium- to dark-gray, fine-grained, thin- to medium-bedded, silty limestone with local chert, ranges in thickness from 55 to 170 ft. The Shiver Chert is a dark-gray- to-black, medium- to thick-bedded siltstone and shale containing interbedded cherty limestone and chert, ranging in thickness from 0 to 30 ft. The Ridgely Sandstone is a medium-gray, medium- to thick-bedded calcareous, quartz-pebble conglomerate and sandstone, ranging in thickness from 0 to 32 ft. It interfingers laterally with the Glenarie Formation to the northeast.

The Connelly Conglomerate (Green Pond Syncline) of Lower Devonian age is a light-gray- to yellowish-gray thin bedded quartz pebble conglomerate that unconformably overlies the Berkshire Valley Formation. It is about 36 ft. thick.

The Esopus Formation of Lower Devonian age is a light- to dark-gray, laminated- to medium bedded, shaly- to finely arenaceous siltstone intebedded with dark gray mudstone, siltstone and sandstone. In the Delaware Valley the contact is unconformable, but in the Green Pond Syncline it seems to be conformable. The thickness is about 300 ft.

The Schoharie Formation (Delaware Valley) is a medium- to dark-gray, medium- to thick-bedded calcareous siltstone and silty limestone with local ribs or pods of black chert. The lower contact is gradational with the Esopus. The thickness is about 175 ft.

The Kanouse Sandstone (Green Pond Syncline), of Lower Devonian age, is a medium-gray, light-brown and grayish-red, fine- to coarse, thin- to thick bedded sandstone and pebble conglomerate. The unit is about 46 ft. thick and unconformably overlies the Esopus.

The Onondaga (Buttermilk Falls) Limestone, of Middle Devonian age, is a medium-gray, fine-grained, thin- to medium-bedded limestone with nodular and bedded black chert. The name Onondaga is used to the northeast and Buttermilk Falls to the southwest. The unit is about 250 ft. thick. The lower contact with Schoharie Formation is gradational.

4.12 Devonian Organic-Rich Shales

The Marcellus Shale (Delaware Valley), of Middle Devonian age, is dark-gray- to grayish-black, thin- to thick-bedded shale. The lower contact grades downward from a black shale to a limy shale and finally a silty limestone. The thickness in the Delaware Valley is about 900 ft. This is the youngest unit exposed in the Delaware Valley of New Jersey.

The Cornwall Shale (Green Pond Syncline), age equivalent to the Marcellus, is a dark-gray- to black, thin- to thick-bedded shale interbedded with some gray, thin bedded siltstone that is more common in the upper part.

The Bellvale Sandstone, of Middle Devonian age, is a medium-gray, thin- to thick-bedded siltstone and shale interbedded with black- to dark-gray shale. The upper part is a grayish-red to grayish-purple sandstone and quartz-pebble conglomerate. The lower contact with the Cornwall is conformable and placed where shale and sandstone layers are equal. The unit ranges from 1,700 to 2,000 ft. thick.

Middle Devonian Skunnemunk Conglomerate is a grayish-purple- to grayish-red, thin- to thick-bedded conglomerate and sandstone interbedded with a medium-gray, thin-bedded sandstone and greenish-gray and grayish-red, mud-cracked shale. The conglomerate clasts consist of vein quartz, red and green quartzite and sandstone, red and gray chert and red shale and can range up to 6 inches in diameter. The uppermost beds may just reach into the Upper Devonian. This unit is conformable with the underlying Bellvale and is about 3,000 ft. thick.

4.13 Sequestration in Paleozoic Carbonates Below a Major Thrust Fault

In 2009, a site was selected for evaluation as an underground alternative energy storage and power generation facility. Based on preliminary geologic investigations at the water-filled Limecrest Quarry site in Sparta, New Jersey, it was decided to drill three 2,200 foot deep core holes to evaluate the bedrock beneath the quarry since the facility was to be constructed 2,000 feet below the surface.

Most of the quarry is developed in Precambrian Franklin Marble, although the upper quarry benches expose various gneisses that directly overlie the marble, and just west of the quarry rim the lower Paleozoic Hardyston Formation is exposed. The thickness of the Franklin Marble at Limecrest was unknown but based on six 150-foot-deep coreholes drilled beneath the quarry floor in 1997. A minimum thickness of 300 ft. for the marble was determined, whereas further north, the Franklin is over a thousand feet thick. In order to construct the underground facility sound gneissic or granitic rock was required, not marble. Based on geologic mapping of the Sparta area, Drake and Volkert (1993) interpreted exposures of faulted Precambrian gneisses south of the quarry to indicate that the Franklin Marble and gneisses at the quarry had been transported westward over younger Paleozoic rocks, on a thrust fault. They correlated this fault to one about 10 miles further southwest where Baum (1967), based on drilling by the New Jersey Zinc Company, similarly interpreted Precambrian marble and gneiss to be thrust westward over Paleozoic dolomites. However, because Paleozoic rocks immediately west of the quarry appear to be in their correct stratigraphic order, the presence of a major thrust fault is questioned.

Three coreholes were proposed at Limecrest: DR1, on the south side of the quarry; DR2, on the west side; and DR3, on the north side. Drilling of DR2 (2,204 ft.) took place from 7/24/09 until 8/3/09, and DR1 (1,997 ft.) from 8/4/09 until 8/11/09. Based on the results of the first two holes a decision was made not to drill DR3.

Detailed logging of drill core samples from both holes was performed by New Jersey Geological Survey staff. The results of the core logging indicates hole DR2 drilled (top to bottom) 80 ft. of Paleozoic dolomite, and then Precambrian rocks that included 813 ft. of marble and minor granite pegmatite, 430 ft. of gneiss, and 99 ft. of interlayered marble and gneiss before penetrating a thrust fault at a depth of 1,422 ft. About 782 ft. of Cambrian dolomite was encountered beneath the thrust fault. Hole DR1 drilled (top to bottom) Precambrian rocks that included 495 ft. of gneiss, 816 ft. of marble and minor granite pegmatite, and then 282 ft. of interlayered marble and gneiss before encountering the same thrust fault at a depth of 1,593 ft. About 404 ft. of Cambrian dolomite was drilled beneath the thrust fault.

Drilling at Limecrest Quarry ultimately confirmed the presence of a major thrust fault at the western edge of the New Jersey Highlands as proposed by Baum (1967) and Drake and Volkert (1993). Projecting the drill core data from DR2 to DR1 indicates that this thrust fault beneath the quarry dips gently toward the southeast at less than 10^o. Because the dolomite formations drilled beneath the thrust fault in hole DR1 become older with depth, Precambrian gneiss and possibly more marble likely occur beneath the dolomite. However, the geology is further complicated by the interpreted presence of another thrust fault beneath the one that was drilled.

A few miles northeast, in the next valley to the east of the Limecrest Quarry is the abandoned Sterling Hill Zinc Mine where the New Jersey Zinc Company drilled many holes throughout the region and in the mine looking for extensions to the zinc ore bodies. Two 4,500+ foot holes were drilled at both ends of the 2,850 foot level of the mine and neither hole penetrated a thrust fault or lower Paleozoic rocks down to a depth of over 6,000 ft. below the surface. Based on the Limecrest and Sterling Hill Mine drilling, if the western Highlands are significantly thrust over the lower Paleozoic rocks, there is a slim chance of finding suitable structures for the sequestration of CO_2, but this would require the collection of deep seismic surveys as well as exploratory holes about 10,000 ft. deep.

4.14 References

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