Subsurface geology for carbon storage across New Jersey and into the offshore region of the Midwest Regional Carbon Sequestration Partnership region

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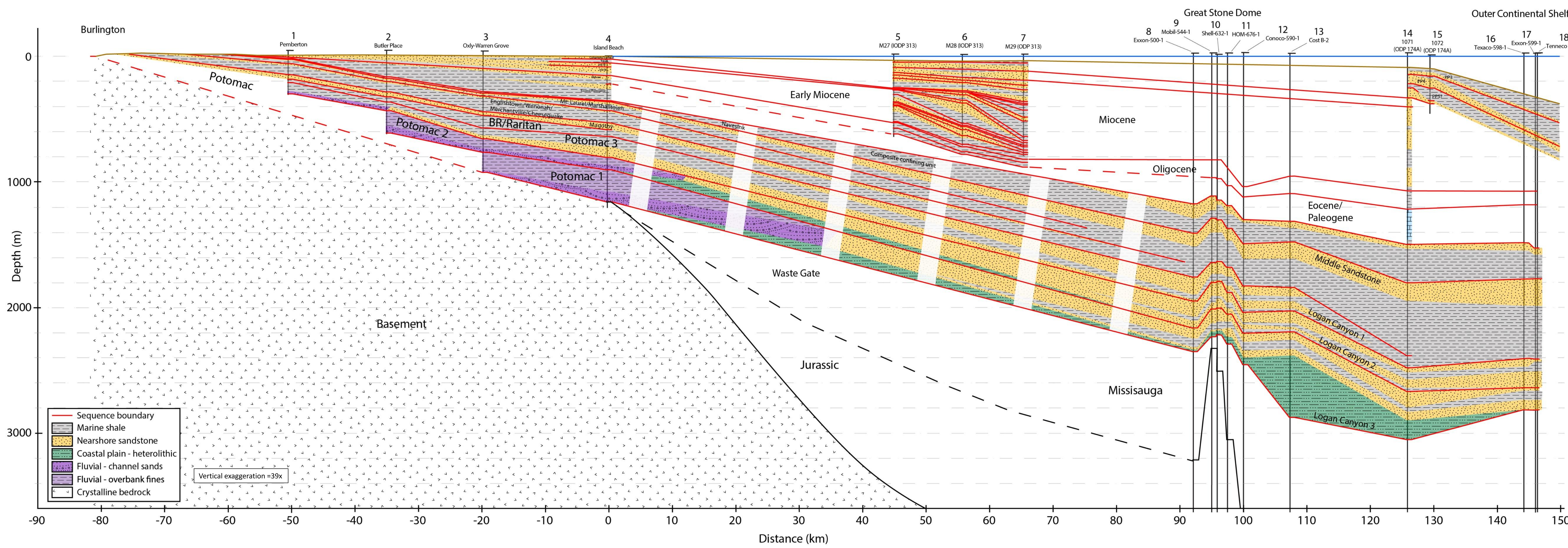
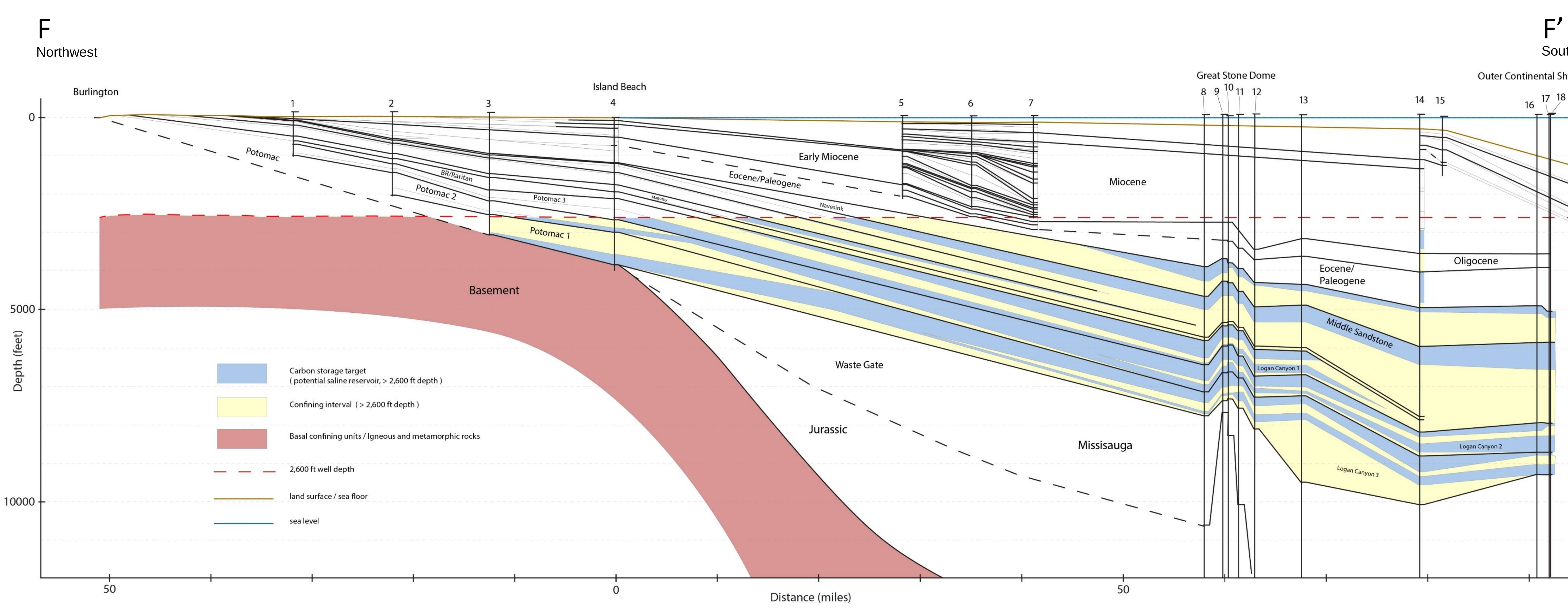
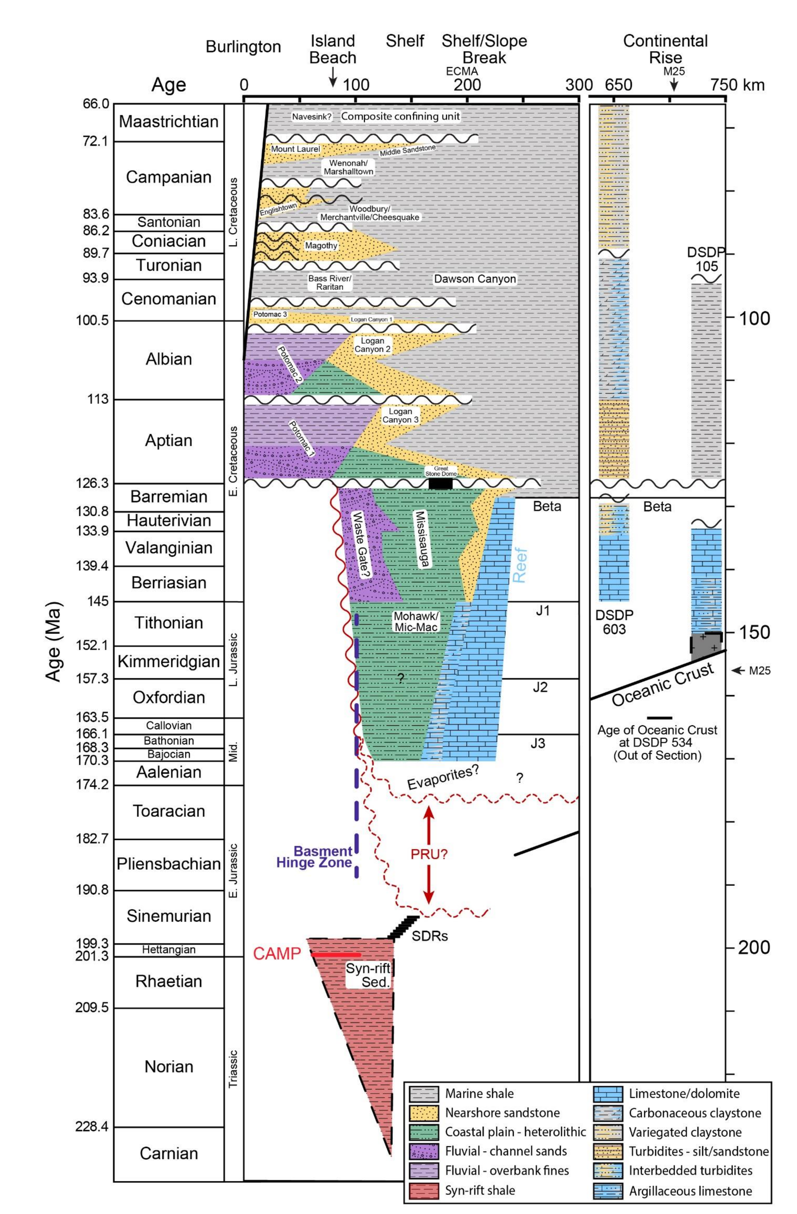




F-F' cross section showing units identified by interval type for purposes of carbon storage. Units are marked as regional and local potential storage targets and confining units. Units are identified below the 2,600 ft depth line, which is an estimate where CO_2 is in a dense super-critical phase.



Stratigraphic column showing ages of sediment on the cross section.

Explanation

Cross section F-F' is ~230 km in extent and begins offshore from the Delaware River (near Burlington NJ), crosses the modern shoreline at Island Beach, NJ, and continues SE offshore to the shelf/slope. The section depicts much of the tectonostratigraphic evolution of the mid-Atlantic continental margin and highlights the geological formations that are potential carbon storage reservoirs. The basin coevolved with the margin as a whole, and the geology represents aspects of: 1) the Proterozoic to Paleozoic compressional phase that formed the foundation of the margin; 2) a Mesozoic rifting phase and extensional separation of the North American and African plates; and 3) a post-rift sedimentation phase that has generated the reservoir and seal systems that comprise promising carbon storage targets. Of the post-rift sedimentary rocks, the Lower to mid-Cretaceous Waste Gate, Potomac, and Logan Canyon Formations are particularly promising carbon storage reservoirs (Hansen, 1982; Miller et al., 2017, 2018; Schmelz et al., 2019; Sugarman et al., 2011). The Jurassic strata and are too deep (diminishing porosity and permeability) and Cenozoic sedimentary rocks are too shallow (insufficient pressure for supercritical storage) for consideration. The nearshore-to-onshore Waste Gate and Potomac Formation strata appear to be favorable targets, considering their high bulk sand content and thickness (Miller et al., 2017), but there are risks associated with up-dip confinement and connectivity of the channel sands. The offshore sandstones of the Logan Canyon Formation, deposited in estuarine, delta front, and prodelta paleoenvironments are "world class" reservoir targets (Miller et al., 2018; Schmelz et al., *in press*). Although the nature of their position offshore likely comes at a higher cost (Rubin et al., 2015), there are formation pressure management incentives to storing CO_2 offshore (Schrag, 2009). Additionally, cultural, political, and economic advantages exist when implementing industrial activity away from major population centers (Schmelz et al., *in press*).

Crystalline basement was likely formed during the Grenville orogeny approximately 1.025 Ga according to the measurements in the Anchor Dickenson well (~100 km south of Island Beach). Taconic (Late Ordovician, ca 450 Ma), or Alleghenian (Carboniferous to Permian; ca. 325-260 Ma) structures presumably lie offshore or elsewhere in the region. The accretion of Proterozoic to Paleozoic terranes during the Taconic and Alleghenian orogenesis was followed by Late Triassic/ Early Jurassic rifting (Klitgord et al., 1988; Seton et al., 2012; Withjack et al., 1998). Sediments were deposited in two sets of northeast trending rift basins during the rift phase (ca. 230-198 Ma in this region; Schlische et al., 2003; Withjack et al., 1998), one landward and one seaward of the basement "hinge zone" (Fig. 1; Manspeizer and Cousminer, 1988). The rift basins or syn-rift sedimentation are not depicted here, but are potential carbon storage targets. The post-rift sedimentation that produced the sedimentary rocks shown in this cross-section are younger than the Central Atlantic Magmatic Province (CAMP; Blackburn et al., 2013) volcanics (~201.6-200.5 Ma) and overlying lowermost Jurassic (ca. 200-198 Ma) lacustrine syn-rift sediments. The best, albeit poorly-constrained, age estimate for the diachronous Post Rift Unconformity (PRU) horizon that separates the syn- and post-rift sedimentary rocks across the margin (Withjack et al., 1998) is approximately ~175 Ma (Klitgord et al., 1988; Klitgord and Schouten, 1986).

The oldest post-rift sedimentary rocks are likely 25 million years younger than the CAMP (Middle Jurassic offshore and Upper Jurassic onshore). However, the age of the oldest preserved post-rift sediments is uncertain because the wells do not penetrate the basement (buried beneath as much as 16 km of sediments) across large swaths of the margin. The presence of Lower Jurassic post-rift strata (cf., Klitgord et al., 1988; Manspeizer and Cousminer, 1988) is questionable, and there are few samples of Middle to lower Upper Jurassic strata. The earliest Jurassic post-rift sedimentation was likely evaporite precipitation into a nascent Atlantic basin. The evaporites are deeply buried and there are only a few seismically observable salt structures offshore New Jersey (Baldwin et al., 2017). The evaporite regime was succeeded by a fringing carbonate platform that was subsequently buried in the mid-Cretaceous period by siliciclastics (Jansa, 1981).

The Upper Jurassic and Lower Cretaceous siliciclastic sediments, deposited landward of the fringing reef, have been described as the Mohawk, Mic-Mac, and Missisauga Formations and are equivalents of the Scotian shelf (Poag, 1985). These continentally sourced sediments interfingered with Upper Jurassic and Lower Cretaceous carbonates of the Abenaki and Verrill Canyon Formation equivalents that are comprised of the progradational reef positioned beneath the modern outer continental shelf (Poag, 1985). Onshore, the Neocomian (Berriasian-Hauterivian) sediments of the Maryland and New Jersey Coastal Plain record the fluvial deposition of the Waste Gate Formation (Doyle, 1982; Hansen, 1982; Miller et al., 2017). The Waste Gate Formation pinches out, to the south of this cross section, onshore between the Anchor Dickenson well and Island Beach. However, there are equivalent sediments to the Waste Gate Formation present offshore from Island Beach (Baldwin et al., 2017; Schmelz et al., *in press*), and the evidence from sediments in the subsurface of the Maryland and southern New Jersey Coastal Plain (Doyle, 1982; Hansen, 1982; Miller et al., 2017) indicate that they are likely to be siliciclastic. The Waste Gate Formation is equivalent to the heterolithic Missisauga Formation identified in the wells located on the mid- to- outer-continental shelf (Libby-French, 1984; Schmelz et al., 2019). While the Upper Jurassic siliciclastics are likely to be too deeply buried to be considered viable carbon storage reservoir targets, the channel sands of the Waste Gate, and equivalents could represent a significant storage reservoir (Miller et al., 2017), particularly when combined with the fluvial sands of the overlying Potomac Formation.

The Potomac Formation of the New Jersey Coastal Plain is comprised of facies associated with an anastomosing river system (Browning et al., 2008) and, offshore, they can be correlated with the Logan Canyon (LC) Formation equivalent of the Scotian shelf (Libby-French, 1984; Poag, 1985; Miller et al., 2018; Schmelz et al., 2019). The Logan Canyon Formation was divided into upper and lower units by Libby-French (1984). These are separated by a shale-prone unit dubbed the Sable Shale. Using sequence stratigraphic methods and noting inconsistencies in the biostratigraphic correlations across wells, Miller et al. (2018) established that the Logan Canyon Formation is three distinct depositional sequences, the LC3 (oldest), LC2, and LC1 (youngest). Each of these sequences possessed a lowstand systems tract (LST) of interbedded silts and sands, a shaly transgressive systems tract (TST), and a sand-prone highstand systems tract (HST). In total, there are 5 to 7 sand-prone zones that represent potentially excellent reservoir units. The best targets are associated with the highly porous and permeable HSTs of the LC3 and the LC2 sequences. Brown et al. (2011) tested the suitability of these units for injection with CO_2 by creating a reservoir model that characterized fluid flow and pressure buildup in response to CO_2 injection. No issues were identified with an injection rate of 6 Mt/year. These formations are more sand-prone in the vicinity of the Great Stone Dome, and grade into shale down dip and to the south of this cross-section transect (Baldwin et al., 2017, in review; Miller et al., 2018; Schmelz et al., 2019).

The Upper Cretaceous of the BCT is characterized by a number of transgressive/regressive cycles subdivided into predominantly deltaic depositional sequences on the Mid-Atlantic Coastal Plain (Browning et al., 2008; Miller et al., 2004). These sequences were deposited during a 107-year scale transgression, represented by deepening paleo-water depths in the Baltimore Canyon Trough (Olsson et al., 1988; Poag, 1985). The deepest water depths in the Baltimore Canyon Trough (Olsson et al., 1988; Poag, 1985) coincide with a major global flooding event at the Cenomanian-Turonian boundary (Haq, 2014; Haq et al., 1987; Miller et al., 2005). This deepening produced the retrogradational nature of the Logan Canyon sequences (Miller et al., 2018), in addition to the overlying shale-prone Dawson Canyon Formation equivalent (Libby-French, 1984). Onshore, this unit correlates to the Bass River and Raritan Formations of the New Jersey Coastal Plain. Furthermore, the younger Maastrichtian strata are deposited during a second long-term rise in sea-level that ultimately culminates with a regional sea-level peak in the Eocene (Miller et al., 2005). Developed, at least in part as a response to these Upper Cretaceous RSL highs, a shale-prone "composite confining unit" (Zapecza, 1989) forms a viable regional capstone for the primary carbon sequestration targets, onshore and offshore. This "composite confining unit" includes the Dawson Canyon Formation equivalent, located offshore.

There is one regionally persistent sand-prone unit within the Dawson Canyon Formation, called the Middle Sandstone (Libby-French, 1984). It may be equivalent with any of several onshore sand units identified on the New Jersey coastal plain, from the Coniacian Magothy to the Campanian Mount Laurel Formation. This sandstone unit is buried deep enough to potentially store CO_2 beneath the outer continental shelf. Onshore, while there are a number of sand-prone units stratigraphically above the Cenomanian-Turonian Bass River Formation, none of them is deep enough for storage of supercritical CO_2. Consequently, confinement up dip would need to be carefully assessed if the Middle Sandstone was to serve as a storage reservoir.

References

Baldwin, K., Miller, K. G., and Mountain, G. S., Delineating Mid-Cretaceous Seismic and Well-logSequences to Assess Carbon Storage Potential in the Northern Baltimore Canyon Trough, in Proceedings The Geological Society of America 129th Annual Meeting, Seattle, WA, October 23 2017.

Blackburn, T. J., Olsen, P. E., Bowring, S. A., McLean, N. M., Kent, D. V., Puffer, J., McHone, G., Rasbury, E. T., and Et-Touhami, M., 2013, Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province: Science, v. 340, no. 6135, p. 941-945.

Brown, A. L., Berlin, E. H., Butsch, R. J., Senel, O., Mills, J., Harichandran, A., and Wang, J. T. M., Carbon Capture and Sequestration: Ascertaining CO2 Storage Potential, Offshore New Jersey, USA, in Proceedings Offshore Technology Conference2011, Offshore Technology Conference.

Browning, J. V., Miller, K. G., Sugarman, P. J., Kominz, M. A., McLaughlin, P. P., Kulpecz, A. A., and Feigenson, M. D., 2008, 100 Myr record of sequences, sedimentary facies and sea level change from Ocean Drilling Program onshore coreholes, US mid-Atlantic coastal plain: Basin Research, v. 20, no. 2, p. 227-248.

Doyle, J., 1982, Palynology of continental Cretaceous sediments, Crisfield geothermal test well, eastern Maryland, pt. 2: in: Waste Gate Formation: Maryland Department of Natural Resources, Geological Survey Open-File Report, p. 82-02.

Hansen, H., 1982, Hydrogeologic framework and potential utilization of the brine aquifers of the Waste Gate Formation, a new unit of the Potomac Group underlying the Delmarva Peninsula, pt. 1: Waste Gate Formation: Maryland Department of Natural Resources, Geological Survey Open-File Report, p. 82-02.

Haq, B. U., 2014, Cretaceous eustasy revisited: Global and Planetary Change, v. 113, p. 44-58.

Haq, B. U., Hardenbol, J., and Vail, P. R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, no. 4793, p. 1156-1167.

Jansa, L. F., 1981, Mesozoic carbonate platforms and banks of the eastern North American margin: Marine Geology, v. 44, no. 1-2, p. 97-117.

Klitgord, K. D., Hutchinson, D. R., and Schouten, H., 1988, U.S. Atlantic continental margin; Structural and tectonic framework, in Sheridan, R. E., and Grow, J. A., eds., The Atlantic Continental Margin, U.S., Volume I-2: Boulder, CO, The Geological Society of America, p. 19-55.

Klitgord, K. D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, in Vogt, P. R., and Tucholke, B. E., eds., The Western North Atlantic Region, Volume 1000, Geological Society of America, p. 351-378.

Libby-French, J., 1984, Stratigraphic framework and petroleum potential of northeastern Baltimore Canyon trough, Mid-Atlantic outer continental shelf: AAPG Bulletin, v. 68, no. 1, p. 50-73.

Manspeizer, W., and Cousminer, H. L., 1988, Late Triassic-Early Jurassic synrift basins of the US Atlantic margin, in Sheridan, R. E., and Grow, J. A., eds., The Atlantic Continental Margin: US, Volume I-2: Boulder, CO, The Geological Society of America, p. 197-216.

Miller, K. G., Browning, J. V., Sugarman, P. J., Monteverde, D. H., Andreasen, D. C., Lombardi, C., Thornburg, J., Fan, Y., and Kopp, R. E., 2017, Lower To Mid-Cretaceous Sequence Stratigraphy and Characterization of CO2 Storage Potential In the Mid-Atlantic US Coastal Plain: Journal of Sedimentary Research, v. 87, no. 6, p. 609-629.

Miller, K. G., Kominz, M. A., Browning, J. V., Wright, J. D., Mountain, G. S., Katz, M. E., Sugarman, P. J., Cramer, B. S., Christie-Blick, N., and Pekar, S. F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, no. 5752, p. 1293-1298.

Miller, K. G., Lombardi, C. J., Browning, J. V., Schmelz, W. J., Gallegos, G., Baldwin, K., and Mountain, G. S., 2018, Back to Basics of Sequence stratigraphy: Early Miocene and Mid Cretaceous examples from the New Jersey paleoshelf: Journal of Sedimentary Research, v. 88, p. 148-176.

Miller, K. G., Sugarman, P. J., Browning, J. V., Kominz, M. A., Olsson, R. K., Feigenson, M. D., and Hernández, J. C., 2004, Upper Cretaceous sequences and sea-level history, New Jersey coastal plain: Geological Society of America Bulletin, v. 116, no. 3-4, p. 368-393.

Olsson, R. K., Gibson, T. G., Hansen, H. J., and Owens, J. P., 1988, Geology of the northern Atlantic coastal plain: Long Island to Virginia, in Sheridan, R. E., and Grow, J. A., eds., The Atlantic Continental Margin, U.S., Volume I-2: Boulder, CO, The Geological Society of America, p. 87-105.

Poag, C. W., 1985, Depositional history and stratigraphic reference section for central Baltimore Canyon trough, in Poag, C. W., ed., Geologic Evolution of the United States Atlantic Margin: New York, Van Nostrand Reinhold, p. 217-263.

Rubin, E. S., Davison, J. E., and Herzog, H. J., 2015, The cost of CO2 capture and storage: International Journal of Greenhouse Gas Control, v. 40, p. 378-400.

Schlische, R. W., Withjack, M. O., and Olsen, P. E., 2003, Relative timing of CAMP, rifting, continental breakup, and basin inversion: tectonic significance, in Hames, W., Mchone, J. G., Renne, P., and Ruppel, C., eds., The central Atlantic magmatic province: insights from fragments of Pangea, Volume 136: Washington, D.C., American Geophysical Union, p. 33-59.

Schmelz, W. J., Miller, K. G., Mountain, G. S., Browning, J. V., and Baldwin, K. E., *in press*, Onshore-offshore correlations of Cretaceous fluvial-deltaic sequences, southern Baltimore Canyon Trough: AAPG Bulletin.

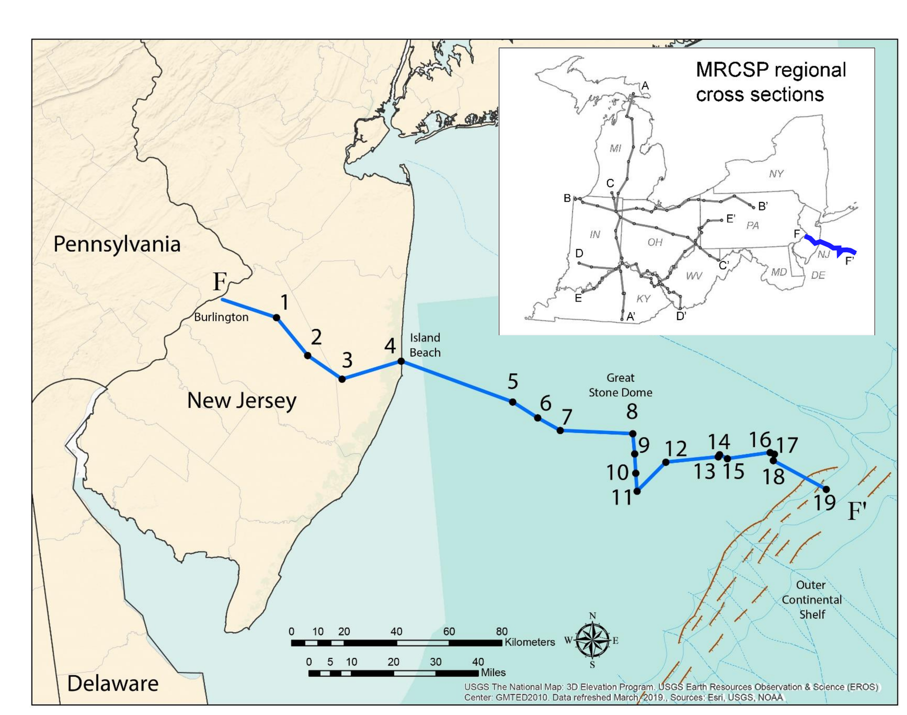
Schrag, D. P., 2009, Storage of carbon dioxide in offshore sediments: Science, v. 325, no. 5948, p. 1658-1659.

Seton, M., Müller, R., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., and Maus, S., 2012, Global continental and ocean basin reconstructions since 200 Ma: Earth-Science Reviews, v. 113, no. 3, p. 212-270.

Sheridan, R. E., Maguire, T. J., Feigenson, M. D., Patino, L. C., and Volkert, R. A., 1999, Grenville age of basement rocks in Cape May NJ well: new evidence for Laurentian crust in US Atlantic Coastal Plain basement Chesapeake terrane: Journal of Geodynamics, v. 27, no. 4-5, p. 623-633.

Sugarman, P., Monteverde, D., Pristas, R., Girard, M., Boyle, J., Miller, K., Browning, J., Fan Reinfelder, Y., Romero, P., and Kulpecz, A., 2011, Characterization of the carbon dioxide storage potential beneath the New Jersey Coastal Plain: Preliminary Characterization of CO2 Sequestration Potential in New Jersey and the Offshore Coastal Region: New Jersey Geological Survey and Battelle.

Withjack, M. O., Schlische, R. W., and Olsen, P. E., 1998, Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America: an analog for other passive margins: AAPG Bulletin, v. 82, no. 5, p. 817-835.



Location of wells in cross section across New Jersey and offshore to the outer continental shelf.