# Potential on-shore and off-shore reservoirs for $CO_2$ sequestration in Central Atlantic magmatic province basalts

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**Identifying locations for secure sequestration of $CO_2$ in geological formations is one of our most pressing global scientific problems. Injection into basalt formations provides unique and significant advantages over other potential geological storage options, including large potential storage volumes and permanent fixation of carbon by mineralization. The Central Atlantic Magmatic Province basalt flows along the eastern seaboard of the United States may provide large and secure storage reservoirs both onshore and offshore. Sites in the South Georgia basin, the New York Bight basin, and the Sandy Hook basin offer promising basalt-hosted reservoirs with considerable potential for $CO_2$ sequestration due to their proximity to major metropolitan centers, and thus to large industrial sources for $CO_2$. Onshore sites are suggested for cost-effective characterization studies of these reservoirs, although offshore sites may offer larger potential capacity and additional long-term advantages for safe and secure $CO_2$ sequestration.**

Eastern United States | greenhouse gas | Jurassic | lavas | rift

In recent years, scientific interest in targeting geological reservoirs for $CO_2$ sequestration in order to stabilize our increasing greenhouse gas concentrations in the atmosphere has been growing. Among these targets, the injection of industrial $CO_2$ into deep saline aquifers or depleted oil and gas reservoirs with large potential storage capacity and geographic ubiquity are common choices (1–5). Several basalt and ultramafic rock reservoirs also have been proposed in a variety of tectonic settings, including, for example, midoceanic islands (6, 7), deep-sea basalt crust (8), and continental flood basalts (9). The effectiveness of any of these reservoirs depends strongly on the storage capacity, retention time, reservoir stability, and the risk for leakage (10, 11). Basalt and ultramafic sequestration targets provide unique advantages over other geological storage options due to their potential for chemical reaction of injected $CO_2$ with the host formation to produce stable, nontoxic $(Ca^{++}, Mg^{++}, Fe^{++})CO_3$ void-filling minerals. In nature, the same processes occur in association with serpentinization and surface weathering in ultramafic and mafic rocks exposed to water, the breakdown of silicates into clays, and the precipitation of carbonates (12, 13). Such geochemical conversion decreases the risk of leakage over the long term, so long as sufficiently large volumes of $CO_2$ can be stored in these formations and retained long enough to allow for the chemical reactions and mineral precipitation to occur (14, 15). Several pilot injection projects in basalt rock provinces are currently underway—such as the CarbFix project in Iceland (6) and the Columbia River plateau in the United States (9)—that will provide critical new information about the injectability and rates of $CO_2$–water–rock reactions in basalt-hosted reservoirs.

Several additional challenges remain for geological sequestration in basalt aquifers, including (*i*) adequate availability of $H_2O$ in the subsurface to allow for mineral carbonation, (*ii*) sufficient flow and outlet for water displaced by injected $CO_2$, and (*iii*) assured integrity of cap rocks for $CO_2$ to remain buried for long periods of time. $CO_2$ sequestration in sediments below the seafloor (16) may offer potential solutions to these additional issues that are more problematic on land. Deep-sea aquifers are fully saturated with seawater and typically capped by impermeable sediments. The likelihood of postinjection leakage of $CO_2$ to the seafloor is therefore low, reducing the potential impact on natural and human ecosystems (8). Long after $CO_2$ injection, the consequences of laterally displaced formation water to distant locations and ultimately into the ocean, whether by engineered or natural outflow systems, are benign. For more than a decade, subseabed $CO_2$ sequestration has been successfully conducted at >600 m depth in the Utsira Formation as part of the Norweigan Sleipner project (17). The Central Atlantic Magmatic Province (CAMP) basalt formations formed during rifting of the Pangea supercontinent (18, 19) and are present near the highly industrial US and western European coastlines. In this study, we further consider the viability of continental flood basalts as potential targets for geological $CO_2$ sequestration (9)—specifically identifying CAMP basalts in both onshore and near-shore locations along the eastern North American seaboard.

## In Situ Mineral Carbonation

Mineral carbonation involves the chemical combination of $CO_2$, water, and metal cations to form carbonates. Oelkers et al. (6) recently summarized the chemistry of mineral fixation of $CO_2$, and Matter and Kelemen (13) highlight the geochemical potential of various basalt and ultramafic formations for $CO_2$ sequestration. Takahashi et al. (20) present a general geochemical model for mineral carbonation in basalt and suggest that mineralization rates may be rapid. Shaef et al. (21) show that dissolution and precipitation reactions in basalt samples tested under laboratory conditions can vary considerably, depending on the glass content and composition of the host minerals. Matter et al. (22) suggest that fracture porosity and connectivity in the basalt aquifer influence the in situ rates, which will differ significantly from those measured in the laboratory. Carbonate precipitation may also reduce in situ porosity and permeability within basalt aquifers over time (6).

Field injection tests at basalt sites are essential to evaluate these processes in each potential environment, however, only one in situ experiment has been conducted in a basalt aquifer to date. Matter et al. (23) conducted a small-scale injection experiment in the Palisades sill (CAMP diabase in Newark Basin) to investigate the in situ rates of reaction using dissolved $CO_2$ at low partial pressures. They demonstrated large decreases in $Mg^{++}$ and $Ca^{++}$ concentration in recovered water samples within 200 h of injection and suggested that two processes, mixing between the injected solution and aquifer water and the release of cations from water–rock dissolution, neutralized the introduced carbonic acid. In situ precipitation rates were not measured in

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this experiment, however, and laboratory results from Shaef et al. (21) indicated that the most rapid precipitation rates among several flood basalt samples were for those from the Newark Basin. If large and secure geological reservoirs are identified and tested in flood basalts in close proximity to major industrial centers, such as the CAMP basalt formations along the US east coast, enormous volumes of $CO_2$ could be permanently stored and sequestered by mineral fixation.

## Central Atlantic Magmatic Province

Along the eastern North American seaboard, numerous onshore and offshore basins hold thick sequences of continental sediments that were deposited during the Triassic and Jurassic. These basins parallel the margin of the US east coast and, along with basins on the African and European conjugate margins, were transected by a huge magmatic event in the Early Jurassic (≈201 Ma) that included radiating dike swarms, associated sills and plutons, and massive volumes of basalt flows presently dispersed on four continents (18, 19, 24, 25). Fig. 1 illustrates the current-day extent of CAMP basalt formations. Marzoli et al. (18) suggest that the CAMP was the largest Large Igneous Province in the world, and although mostly eroded now, the original CAMP lava flows may have been equal in volume to the Siberian or Deccan traps but distributed more widely ($\approx 11\ \mathrm{M\,km}^2$). CAMP flows individually tend to have similar basalt geochemistry and to be thick (as much as 200-m thick per cooling unit) (26, 27).

Within the major rift basins along the US eastern coast, CAMP basalt flow formations have been identified as being synchronous (19, 28). Several studies (18, 28, 29) provide evidence that the emplacement for CAMP basalts began ≈202 Ma, recently updated to 201.5 Ma (30), and show similar transected stratigraphy and igneous mineralogy across the basins. Many flood basalts such as the CAMP and the Columbia River plateau basalts are emplaced during phased eruptive events. This results in a stacked sequence of basalt flows with different thicknesses sometimes separated by sedimentary interbeds. The boundaries between successive flows are usually highly vesicular and represent intervals that have undergone rapid cooling as each flow comes in contact with an underlying one and, importantly, the atmosphere or water above. This often creates highly fractured and brecciated intervals at the bottoms and especially the tops of flow unit boundaries as compared with their interiors. Fig. 2 illustrates a schematic of a flow-top and interior sequence and actual core images recovered across a flow boundary from the Orange Mountain basalt in the Newark Basin. The interior of some flows are densely fractured as well, notably the thick lower Preakness Basalt in the Newark Basin (Fig. 3). Not only is this fracture pattern spread throughout the known geographic extent of this flow, it is present in other basins, specifically in correlative flows within the Deerfield, Hartford, and Culpeper basins (27).

In the continuously cored Orange Mountain basalt, high vesicular porosity is observed at the flow tops; dense, low-porosity, and low-permeability basalt is evident in the flow interior. The flow-top boundaries of flood basalt sequences are potential injection reservoirs for $CO_2$ sequestration, sealed above and below by thick impermeable flow-interior basalt and often by interbedded sedimentary units. Within the CAMP, the best-studied basalt formation is the Orange Mountain basalt due to the availability of complete drill cores and logs in the Newark Basin, extensive outcrops, and other geophysical data. Flow-top boundaries similar to the Orange Mountain basalt formation are proposed here as potential targets for $CO_2$ sequestration. Highly fractured flow interiors such as in the Preakness basalt are another potential target, but quantitative data are thus far lacking.

## Newark Rift Basin

Cores and in situ geophysical measurements in the Newark Basin illustrate the fractured and porous nature of basalt in CAMP flows, which are the thickest among known flood basalt provinces. Three flow units have been identified in this area—upper, middle, and lower units of the Orange Mountain basalt (31). In Fig. 4,

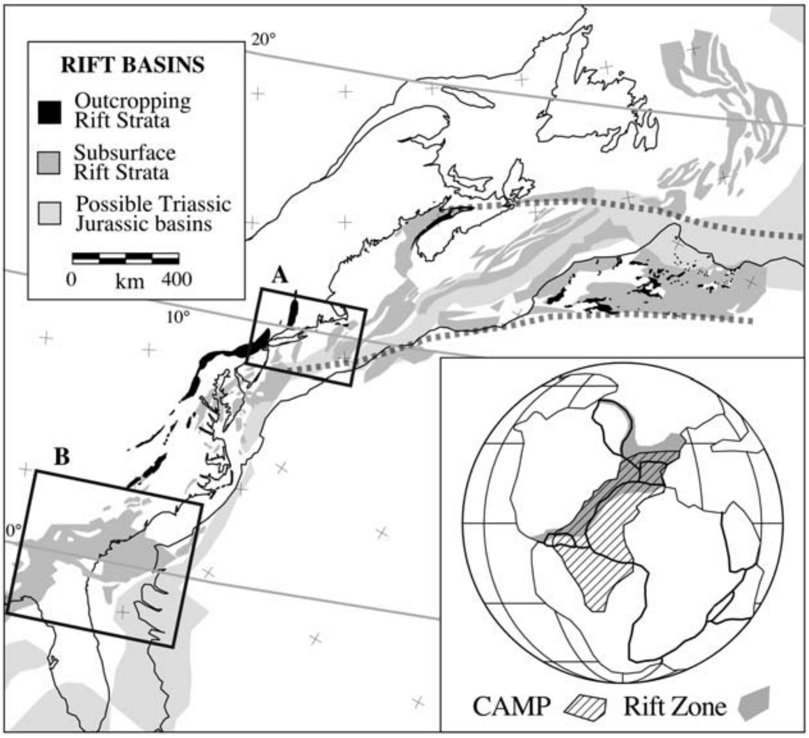

Fig. 1. Distribution of rift basins in eastern North America and Morocco and the distribution of the CAMP flood basalt, modified from ref. 19. Dotted lines represent major strike slip fault zones. Detail areas (*Inset A* and *B*) are discussed in the text.

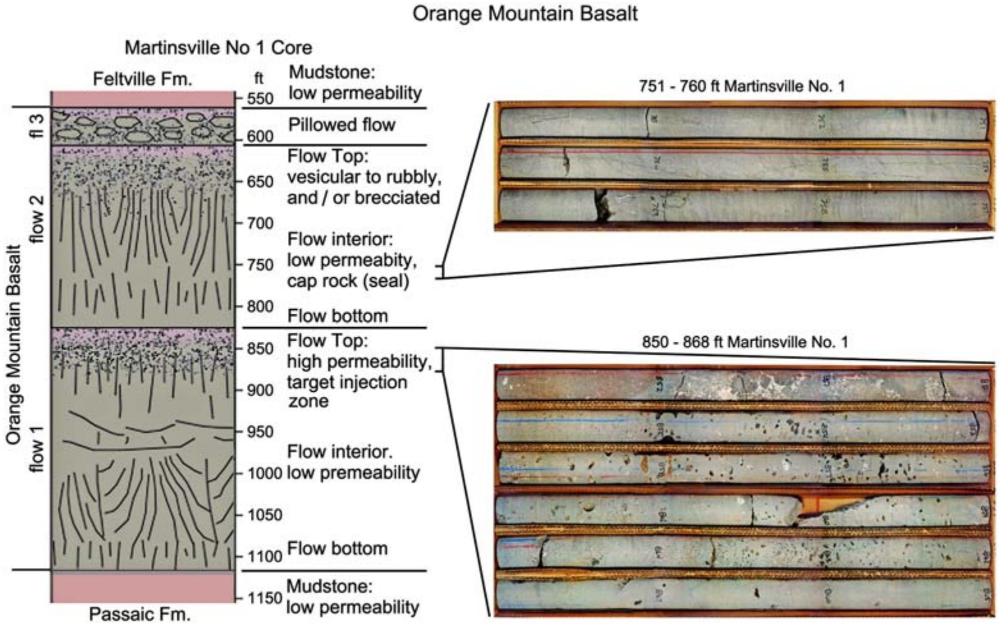

**Fig. 2.** Schematic profile of multiple flow units and core photographs from the Orange Mountain basalt, modified from ref. 28. Flow-top boundary zones show considerable vesicular and rubbly pore space as compared to the dense, low-porosity flow interior. Scales are presented in original measurement units (i.e., core depth in feet).

the middle/lower basalt units are shown as measured by in situ geophysical well logs near Martinsville, NJ (32). Porosity profiles are computed from density and neutron measurements as well as from core samples. Cores were subsampled over the flow boundary and measured using He-pyncnometry to obtain bulk and grain density estimates for comparison with the logs. These data provide the minimum porosity of each sample, assuming that He invades all of the connected pore space. Very little chemical alteration is observed by above-baseline natural gamma ray measurements, and the borehole conditions were consistent through most of this interval (32). Neutron porosity data are erroneously high over the interval due to the presence of clay minerals that increase the neutron count. Importantly, the interflow interval from 830–880 ft indicates elevated porosity measurements—a factor of two or more greater than the overlying and underlying flow interiors—and reaches a porosity value of 20% in the log and 10% on core samples. Note, however, that core measurements do not sample the fracture porosity or large void space (secondary porosity) in most formations and often underestimate the measured in situ porosity. The best estimate of porosity in the interflow zone is greater than the core estimates and likely averages 15%. The interpretation of these data suggests massive basalt flow interiors bounded by fractured flow tops and porous interflow contact zones typically occur between the CAMP flows.

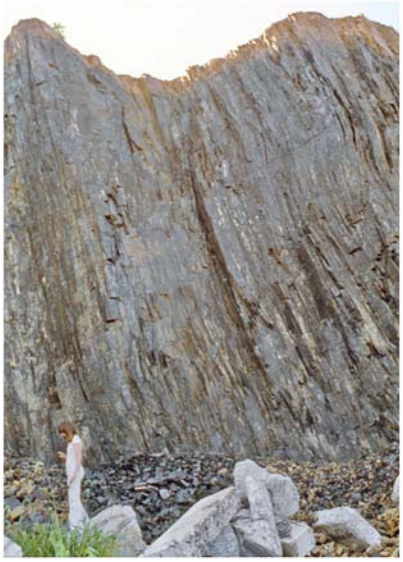

**Fig. 3.** Photograph of the highly fractured Preakness basalt in the Newark Basin. Photograph courtesy of author (PEO).

## Offshore Long Island Rift Basins

Along the eastern North American seaboard, the early Atlantic rifting also generated a series of offshore basins filled with Mesozoic sediments, previously identified by seismic, gravity, and magnetic surveying. Hutchinson et al. (33) mapped four buried rift basins on the Long Island platform, extending from the New York Bight to Nantucket, and each extending more than 1,000 km$^2$ in area and filled with >800 m of sediments (Fig. 5*A*). Hutchinson and Grow (34) identified a postrift fault northwest of the buried New York Bight basin, with no specific evidence of recent activity, but suggest that this relic fault may be associated with the origins of the Mesozoic rift basins along the coastline. Maguire et al. (35) investigated a similar, smaller off-shore basin near Sandy Hook, NJ. The Sandy Hook and New York Bight basins have been proposed to be offshore extensions of the basalt-hosting Hartford rift system and are thus potential locations of buried CAMP flow basalts. Maguire et al. (35) conducted a modeling study of the Sandy Hook basin and predicted that basalt exists under several hundred meters of flat-lying sediments. These deposits have never been drilled or dated, however their proposed existence explains seismic reflections observed across the basin as well as gravity and magnetic anomalies in the region. Maguire et al. (35) hypothesized that these buried basalt flows are associated with the eastern extent of the CAMP intrusion and synchronous with the Orange Mountain basalt flows. Similar gravity and magnetic anomalies in the New York Bight basin could be explained by buried basalt flows that exist under a thick Triassic–Jurassic sediment pile, and associated faults, although the early seismic surveys did not adequately resolve these deep

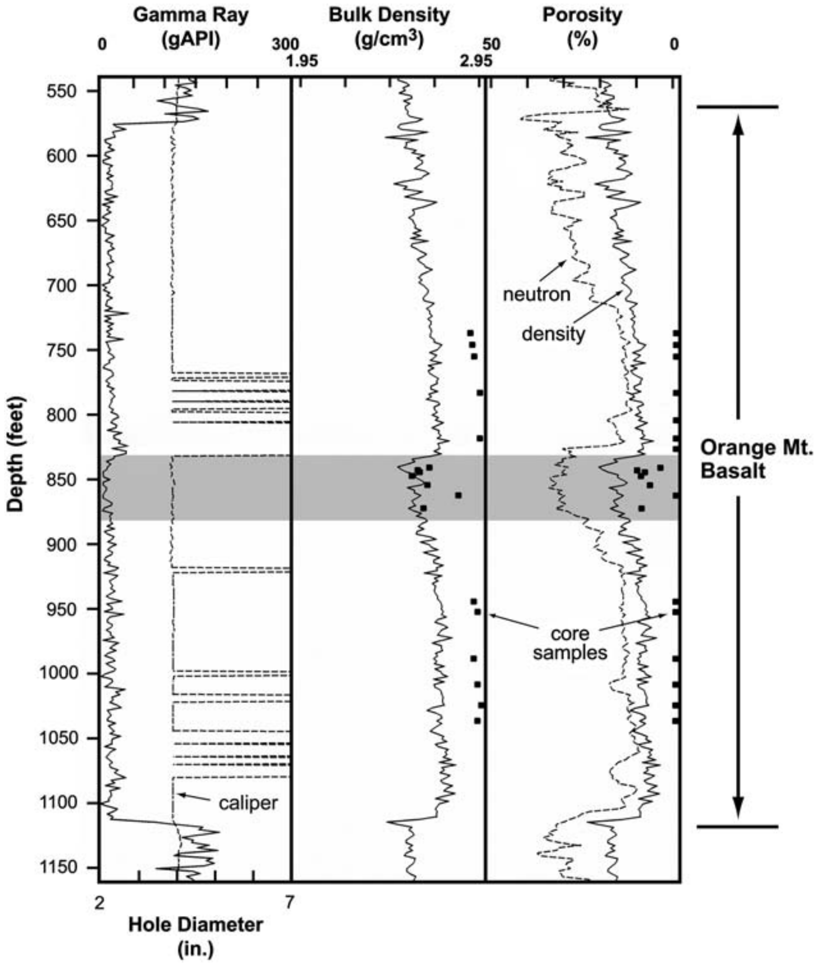

**Fig. 4.** Geophysical log profiles through lower, middle, and upper flows of the Orange Mountain basalt. Density and porosity profiles indicate an increase from ≈10% to 20% porosity over the 15-m (50-ft) thick flow-top boundary zone, which amounts to $\approx 2.25 \times 10^6$ $m^3$ open pore volume per $km^2$. Scales are presented in original measurements units (i.e., log depth in feet and hole diameter in inches).

features (34, 35). Drilling in the Nantucket basin also sampled basalt flows of the CAMP (36).

CAMP extrusives both onshore and offshore were contemporaneous, formed episodically, and contain interflow zones like those observed in the Orange Mountain basalt, potentially providing a buried storage reservoir with considerable flow-top boundary porosity. In subocean locations, flow tops would be seawater filled and capped by dense basalt as well as fine-grained and clay-rich sediments, both advantages for secure storage and rapid carbonation of injected $CO_2$. For example, considering the small Sandy Hook basin off of New Jersey and assuming that basalt flow-top boundary zones have average bulk porosity of 15% and extend over one-third of its area, we estimate that 7 $km^3$ of basalt flow-top volume and ≈1 $km^3$ of potential pore volume could be available for $CO_2$ storage in this basin alone. This amounts to a total volume of pore space for injection of up to

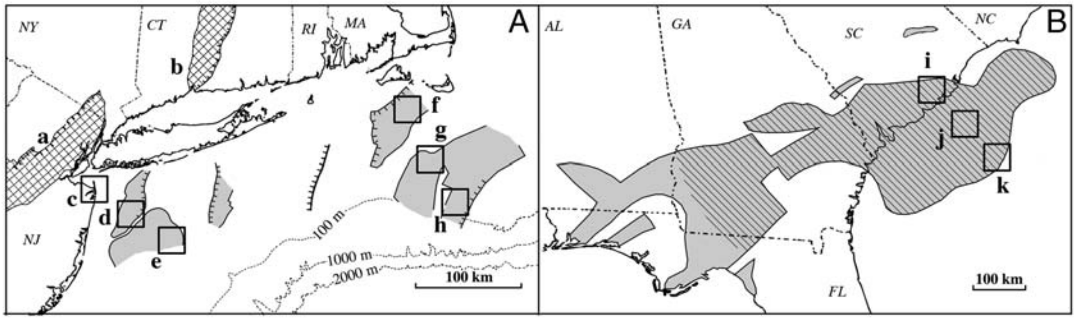

**Fig. 5.** Potential onshore and offshore sites for pilot drilling studies in CAMP basalt along eastern US coastal regions. Black squares indicate initial study areas. Maps refer to inset box locations in Fig. 1. (*A*) Sites located in buried Mesozoic rift basins on the Long Island platform (shaded), modified from ref. 33 and nearby onshore basins (cross-hatched): a, Newark basin; b, Hartford basin; c, Sandy Hook basin; d–e, New York Bight basin; f, Nantucket basin; g–h, Atlantis basin. (*B*) Sites located across the extent of buried basalt (hachured) in the South Georgia Rift basin (shaded), modified from ref. 38: i, location proximal to Clubhouse Crossroads basalt cores; j–k, sites more proximal to seaward-dipping reflectors.

900 Mt of $CO_2$, the equivalent of emissions from three or four 1-GW coal-fired power plants for 40 years. The existence of buried basalt flows in the Sandy Hook basin, and in the other Mesozoic offshore basins, can only be confirmed by high-resolution survey mapping followed by drilling in and around these locations.

### South Georgia Rift Basin

At the southern margin of the eastern United States, the South Georgia Rift basin underlies the coastal plain of South Carolina and Georgia, extending more the 40, 000 km$^2$ and equal in size to the other eastern US rift basins combined (Fig. 5*B*). With much less erosion than its northern counterparts, the stratigraphy of the South Georgia basin appears to primarily contain thick sequences of red beds (37), intrusive diabase sills, and basalt flows (38). The Clubhouse Crossroads basalt flows have been identified on seismic transects and sampled, although incompletely, in three drill cores in South Carolina (39, 40). Olsen et al. (19) summarized radiometric, geochemical, and paleomagnetic dating evidence from these cores and concluded that the basalt flows were synchronous with other CAMP basalts ($\approx$202 Ma). This large basalt unit also has been associated with massive offshore basalts identified seismically as “seaward-dipping reflectors” that were emplaced during the early opening phases of the Atlantic Ocean (41). These features may also be offshore basalts associated with the CAMP, but they have never been drilled or dated.

Based on the US Geological Survey cores in South Carolina, the Clubhouse Crossroads basalt is a 250-m thick series of basalt flows that are chemically similar to CAMP basalts, underlain by rift basin sediments, and overlain by coastal plain deposits and, like other CAMP flows, consist of multiple eruptive events (42); similar properties of the basalt interiors and interflow zones can be anticipated at these sites. Given that the South Georgia Rift basin far exceeds the known area of the other eastern US coastal basins and is buried at greater depths and with thicker sedimentary cover, it has been suggested previously as a potential geological sink for $CO_2$ storage (9, 43). The Clubhouse Crossroads basalt, in particular, may add enormous potential as a secure reservoir for permanent $CO_2$ sequestration in the South Georgia Rift basin. Remaining questions about the timing, structure, and extent of the Clubhouse Crossroads basalt must first be resolved by drilling and experimental investigation in the area. Drilling studies at onshore locations may be a cost-effective means to explore and evaluate these reservoirs prior to evaluating deeper offshore targets.

### Conclusions

The injection of $CO_2$ in CAMP basalt formations offers critical advantages for sequestration that warrant pressing investigation. The flow-top boundary zones in the CAMP basalt provide ample pore space for injection and storage of $CO_2$, and the overlying basalt interiors and conformable as well as overlapping sediment cover will act as impermeable geological caps for long periods of time. Offshore storage locations provide a further advantage of eventually circulating displaced seawater from the reservoir into the ocean with benign effect after completing the injection. Along the eastern US metropolitan coastline, the South Georgia basin, the New York Bight basin, and the Sandy Hook basin offer potential basalt-hosted reservoirs both onshore and near shore, with considerable potential for long-term $CO_2$ injection and sequestration. Further research for $CO_2$ storage and fixation in basalt formations and for characterization of potential sites is essential: initially, to drill and evaluate the geological properties in characteristic basalt formations at cost-effective onshore locations, and second, to conduct pilot injection studies in potential CAMP basalt reservoirs. Offshore areas would require high-resolution survey mapping to identify, and avoid, neotectonic faults that could be reactivated above basalt reservoirs. Several suggested initial study locations, both onshore and offshore, in potential CAMP basalt reservoirs are indicated on Fig. 5. Because of their proximity to major metropolitan centers, and thus to large industrial sources of $CO_2$, these CAMP targets could ultimately provide safe and secure sequestration of carbon at several practical locations.

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1. Bachu S, Gunter WD, Perkins EH (1994) Aquifer disposal of $CO_2$ hydrodynamic and mineral trapping. *Energ Convers Manage*, 35:269–279.
2. Bergman PD, Winter EM (1995) Disposal of carbon dioxide in aquifers in the US. *Energ Convers Manage*, 36:523–526.
3. Hitchon B (1996) *Aquifer Disposal of Carbon Dioxide: Hydrodynamic and Mineral trapping—Proof of Concept* (Geoscience Publishing Ltd., Alberta), pp 1–165.
4. Holloway S (2001) Storage of fossil fuel-derived carbon dioxide beneath the surface of the Earth. *Annu Rev Energ Env*, 26:145–166.
5. Jessen K, Kovscek AR, Orr FM Jr (2005) Increasing $CO_2$ storage in oil recovery. *Energ Convers Manage*, 46:293–311.
6. Oelkers EH, Gislason SR, Matter J (2008) Mineral carbonation of $CO_2$. *Elements*, 4:333–337 doi: 10.2113/gselements.4.5.333.
7. Matter JM, et al. (2009) Permanent carbon dioxide storage into basalt: The CarbFix pilot project, Iceland. *Energy Procedia*, 1:3641–3646 doi: 10.1016/j.egypro.2009.02.160.
8. Goldberg D, Takahashi T, Slagle A (2008) Carbon dioxide sequestration in deep-sea basalt. *Proc Natl Acad Sci USA*, 105:9920–9925 doi: 10.1073/pnas.0804397105.
9. McGrail BP, et al. (2006) Potential for carbon dioxide sequestration in flood basalts. *J Geophys Res*, 111:1–13 doi: 10.1029/2005JB004169.
10. Hawkins DG (2004) No exit: Thinking about leakage from geologic carbon storage sites. *Energy*, 29:1571–1578.
11. Rochelle CA, Czernichowski-Lauriol I, Milodowski AE (2004) The impact of chemical reactions on $CO_2$ storage in geological formations: A brief review. *Geological Storage of Carbon Dioxide*, (Geological Society of London, London), Special Publ, 233, pp 87–106.
12. Seifritz W (1990) $CO_2$ disposal by means of silicates. *Nature*, 345:486 (lett).
13. Matter JM, Kelemen PB (2009) Permanent storage of carbon dioxide in geologic reservoirs by mineral carbonation. *Nat Geosci* www.nature.com/naturegeoscience [online] doi: 10.1038/NGE0683.
14. Gunter WD, Bachu S, Benson S (2004) The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide. *Geological Storage of Carbon Dioxide*, (Geological Society of London, London), Special Publ, 233, pp 129–145.
15. Assayag N, et al. (2009) Water–rock interactions during a $CO_2$ injection field test: Implications on host rock dissolution and alteration effects. *Chem Geol*, 265:227–235.
16. House K, Schrag D, Harvey C, Lackner K (2006) Permanent carbon dioxide storage in deep-sea sediments. *Proc Natl Acad Sci USA*, 103:12291–12295.
17. Herzog H, Eliasson B, Kaarstad O (2000) Capturing greenhouse gases. *Sci Am* 72–79.
18. Marzoli A, et al. (1999) Extensive 200-million year old continental flood basalts of the Central Atlantic Magmatic province. *Science*, 284:616–618.
19. Olsen PE, et al. (2003) Cyclo-, magneto-, and bio-stratigraphic constrants on the duration of the CAMP event and its relationship to the Triasssic-Jurassic boundary. *Am Geophy Un Monograph*, 136:7–32.
20. Takahashi T, Goldberg D, Mutter JC (2000) Secure, long-term sequestration of $CO_2$ in deep saline aquifers associated with oceanic and continental basaltic rocks. *Proc of the SRI Int Sympos, Deep Sea & CO2* (The Ship Research Inst, Mitaka, Japan).
21. Schaef HT, McGrail BP, Owen AT (2009) Basalt-$CO_2$-$H_2O$ interactions and variability in carbonate mineralization rates. *Energy Procedia*, 1:4899–4906 doi: 10.1016/j.egypro.2009.02.320.
22. Matter JM, et al. (2006) Fracture permeability in igneous and metasedimentary rocks: New results from hydraulic testing and geophysical logging in the Newark Rift Basin. *Hydrogeology*, 14:689–699 doi: 10.1007/s10040-005-0456-3.
23. Matter JM, Takahashi T, Goldberg D (2007) Experimental evaluation of in situ $CO_2$-water-rock reactions during $CO_2$ injection in basaltic rocks: Implications for geological $CO_2$ sequestration. *Geochem Geophys Geosy*, 8:Q02001 doi: 10.1029/2006GC001427.
24. May PR (1971) Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in the context of the predrift configuration of the continents. *Geol Soc Am Bull*, 82:1285–1292.
25. Hames W, McHone JG, Renne P, Ruppel C (2003) Introduction. *Am Geophy Un Monograph*, 136:16–32.
26. Puffer JH, Philpotts AR (1988) Eastern North American quartz tholeiites: Geochemistry and petrology, in Triassic-Jurassic rifting; continental breakup and the origin of the Atlantic Ocean and passive margins. *Dev Geotecton*, 22B:579–605.
27. Olsen PE, Smoot JP, LeTourneau P (2007) Field guide to Earth’s largest continental flood basalt province, the CAMP, as expressed in the Culpeper basin, VA. *A fieldtrip*

*for the 11th annual continental scientific drilling workshop, Arlington, VA* (Drilling, Observation, and Sampling of the Earth's Continental Crust, Salt Lake City), pp 1–45.

28. Whiteside JH, et al. (2007) Synchrony between the Central Atlantic Magmatic province and the Triassic-Jurrassic mass extinction event?. *Palaeogeogr Palaeocl*, 244:3345–367.
29. Kent DV, Olsen PE (2008) Early Jurassic magnetostratigraphy and paleolatitudes from the Hartford continental rift basin (eastern North America): Testing for polarity bias and abrupt polar wander in association with the Central Atlantic Magmatic Province. *J Geophys Res*, 113:1–24 doi: 10.1029/2007JB005407.
30. Schoene B, et al. (2006) Reassessing the uranium decay constants for geochronology using ID-TIMS U-Pb data. *Geochim Cosmochim Acta*, 70:426–445.
31. Puffer JH, Student JJ (1992) Volcanic structures, eruptive style, and posteruptive deformation and chemical alteration of the Watchung flood basalts, New Jersey. *Geol S Am S*, 268:261–277.
32. Goldberg DS, et al. (1984) Well logging results from the Newark Rift Basin Coring Project. *Sci Drilling*, 4:267–281.
33. Hutchinson DR, Klitgord KD, Detrick RS (1986) Rift basins of the Long Island platform. *Geol Soc Am Bull*, 97:688–702.
34. Hutchinson DR, Grow JA (1985) New York Bight fault. *Geol Soc Am Bull*, 96:975–989.
35. Maguire TJ, Sheridan RE, Volkert RA (2004) Geophysical modeling of the northern Apppalachian Brompton-Cameron, Central Maine, and Avalon terranes under the New Jersey Coastal Plain. *Geodynamics*, 37:457–485.
36. Folger DW, Hathaway JC, Chrisopher RA, Valentine PC, Poag CS (1978) Stratigraphic test well, Nantucket Island, Massachusetts. *US Geol Survey Circ*, 773:1–28.
37. Olsen PE, et al. (1991) Rift basins of early Mesozoic age. *Geology of the Carolinas*, ed Horton W 142–170.
38. McBride JH, et al. (1989) Evidences and implications of an extensive early Mesozoic rift basin and basalt/diabase sequence beneath the southeast coastal plain. *Geol Soc Am Bull*, 101:512–520.
39. Rankin DW (1977) Studies related to the Charleston SC earthquake of 1886: A preliminary report. *US Geol Survey Prof Paper*, 1028:1–204.
40. Gohn GS, Houser BH, Schneider RR (1983) Geology of the lower Mesozoic sedimentary rocks in the Clubhouse Crossroads test hole #3, near Charleston SC. *US Geol Survey Prof Paper*, 1313:D1–D17.
41. Holbrook WS, Kelemen PB (1993) Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature*, 364:433–436.
42. Gottfried D, Annell CS, Byerly GS (1983) Geochemistry and tectonic significance of subsurface basalts from Charleston, South Carolina: Clubhouse Crossroads test holes #2 and #3. *US Geol Survey Prof Paper*, 1313:A1–A10.
43. Smyth RC, et al. (2007) Potential sinks for geologic storage of carbon dioxide generated in the Carolinas. *US Bureau of Econ Geol, summary report* 1–14.