Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment

DE-FE0026087

MID-ATLANTIC U.S. OFFSHORE
CARBON STORAGE RESOURCE
ASSESSMENT PROJECT

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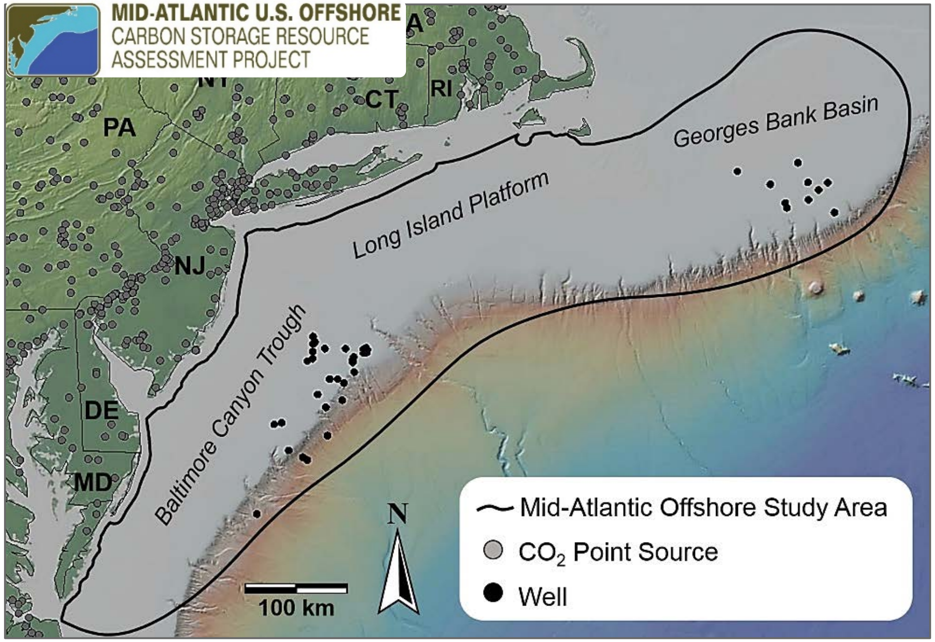
U.S. Department of Energy
National Energy Technology Laboratory
Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting
August 26-30, 2019

Presentation outline

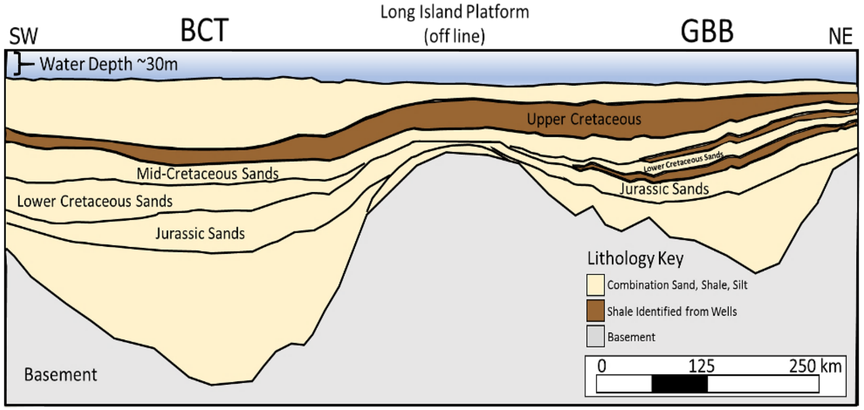
- Project Overview & Org.
- Technical Status
- Accomplishments
- Lessons Learned
- Synergy Opportunities
- Project Summary



Study Area: ~171,000 km^2 (44 wells)

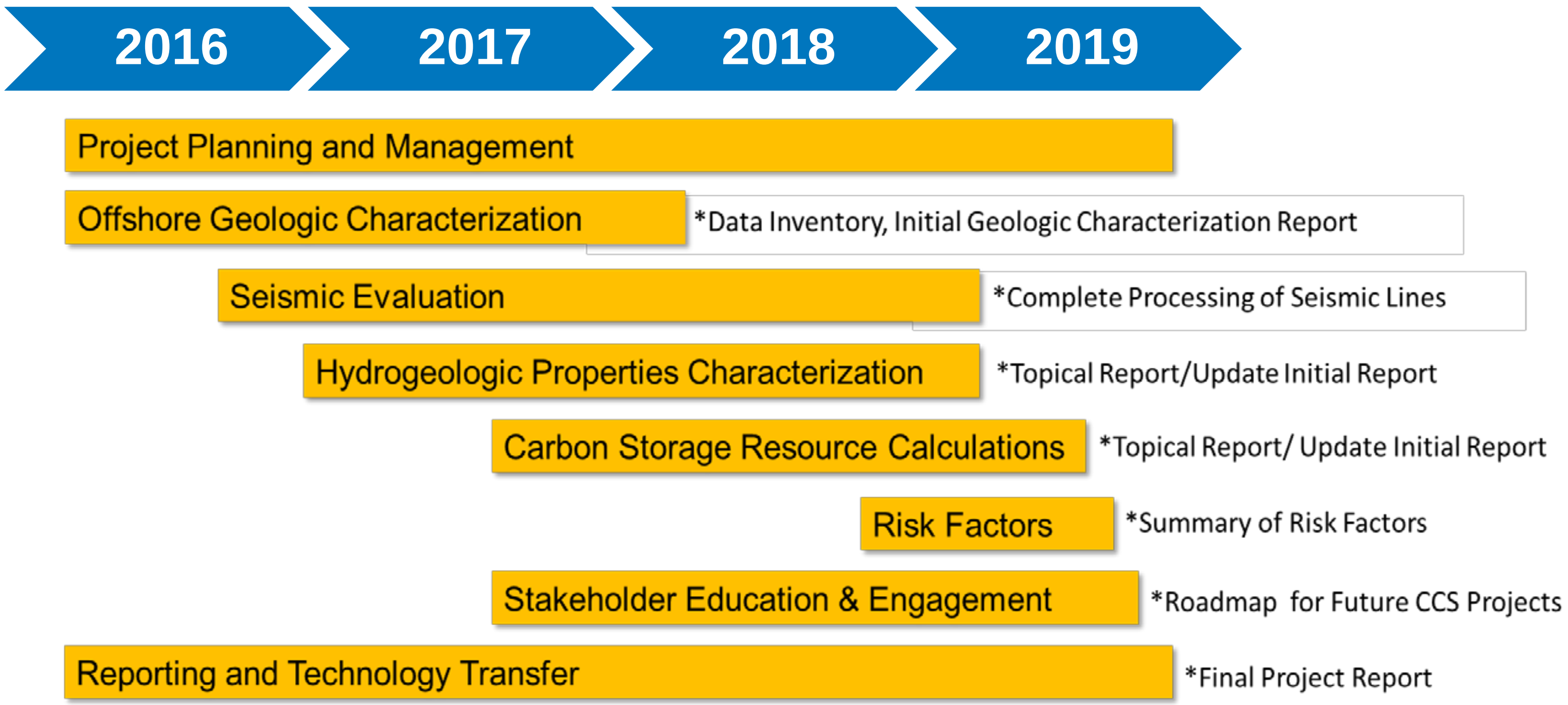
- Georges Bank Basin (GBB)
- Long Island Platform
- Baltimore Canyon Trough (BCT)

Focused on saline sand reservoirs and seals  **~800 - 3000 m deep**



Technical Status

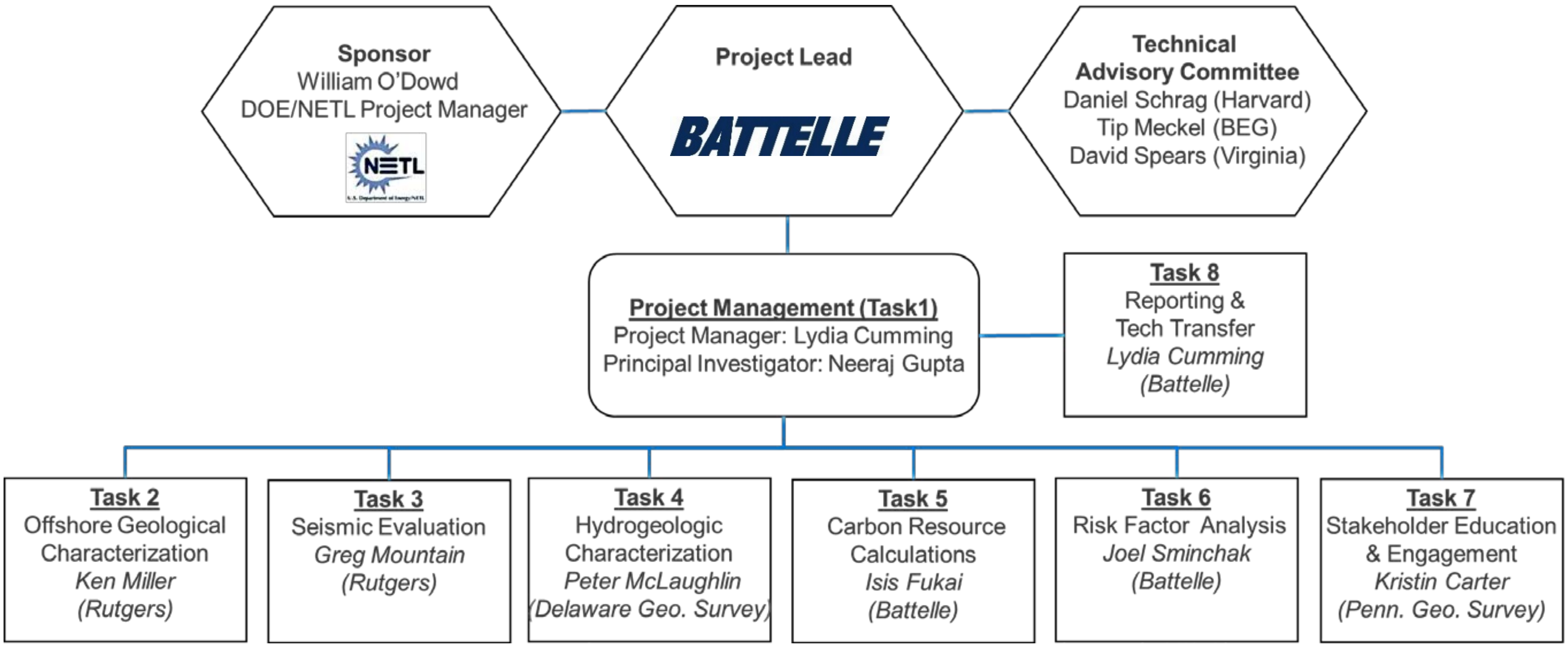
- Objective = Complete systematic C-Storage Resource Assessment of the U.S. Mid-Atlantic offshore coast region.
- Technical scope has been completed. Final Technical Report Submitted August 13, 2019.



*Key milestone or deliverable

Project organization and team members

- The project consisted of 8 tasks, with a diverse team of experts responsible for project implementation



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Project team – collaborating seamlessly across multiple institutes

- **Lamont Doherty Earth Obs.** - Dave Goldberg, Angela Slagle, Will Fortin
- **Delaware Geol. Surv.** - Pete McLaughlin, Moji KunleDare, June Hazewski, Noam Kessing, David Wunsch
- **Rutgers Univ.** - Greg Mountain, Ken Miller, Stephen Graham, Alex Adams, John Schmelz, Kim Baldwin, David Andreasen, Chris Lombardi (deceased)
- **Maryland Geol. Surv.** - David Andreasen, Andy Staley, Katie Knippler, Richard Ortt
- **Pennsylvania Geol. Surv.** - Kristin Carter, Brian Dunst, Morgan Lee, Ryan Kassak, Danial Reese
- **US Geol. Surv.** - Guy Lang, Uri ten Brink
- **Battelle** - Neeraj Gupta, Lydia Cumming, Andrew Burchwell, Joel Sminchak, Isis Fukai, Kathryn Johnson, Laura Keister, Christa Duffy, Heather McCarren
- **Advisors** – Daniel Schrag (Harvard), Tip Meckel (TX BEG), David Spears (VA Geo. Surv.)

BATTELLE It can be done · Rutgers · Maryland Geological Survey · USGS science for a changing world · Delaware Geological Survey · Pennsylvania Geological Survey · Lamont-Doherty Earth Observatory · Harvard University Center for the Environment · Bureau of Economic Geology · Virginia Department of Mines Minerals and Energy

Task 2 - Geologic Characterization

Large coordinated group effort completed to categorize & preserve offshore samples & data for geologic characterization in 3 sub-regions: Georges Bank Basin (GBB); Long Island Platform; Baltimore Canyon Trough (BCT)

Sample Inventory

- ~2,300 core samples
- ~5,000 thin-sections
- ~97,000 drill cuttings

Data Compilation

- 2,500 logs in well database
- Over 1,000,000 ft. of log data digitized
- 5,973 porosity and 5,729 permeability core data points* from 184 reports

*Includes all raw & derived entries reported at all depths for 41 out of 44 wells in the study area

1: sandstone **2:mudstone**

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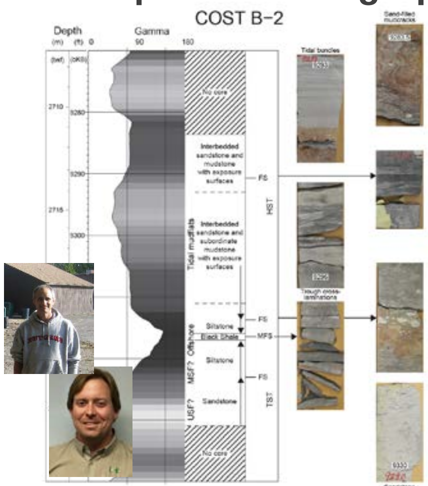
Task 2 - Geologic Characterization

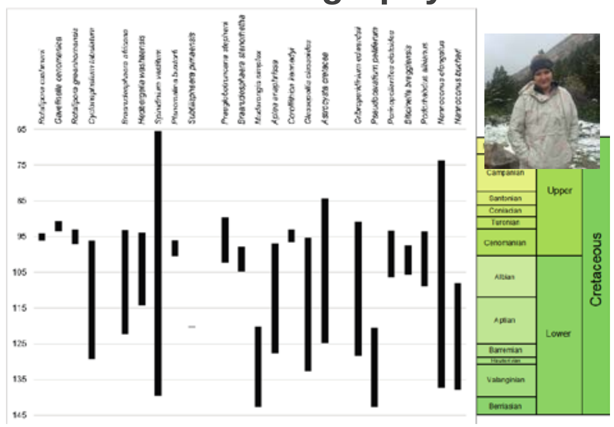
- Data used to integrate sequence stratigraphy, sequence boundaries, log interpretation, onshore-offshore correlation, paleogeography, & seismic interpretations (no small task!).

Sequence Stratigraphy



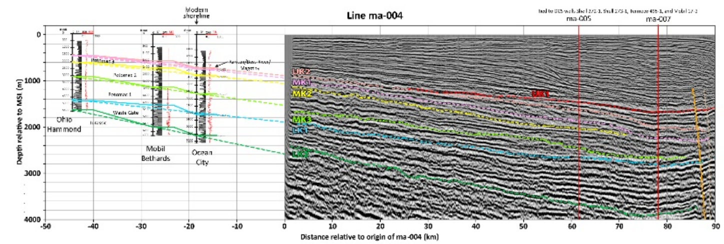
(Miller et al., 2018)

Biostratigraphy



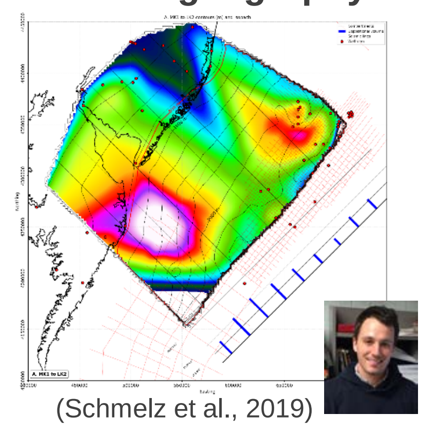
(Jordan et al., in prep. 2019)

Onshore-Offshore Correlation



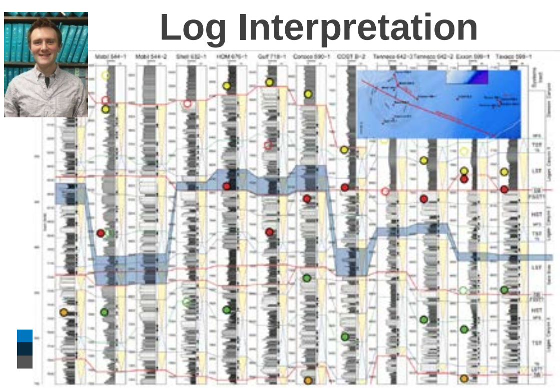
(Quinn et al., 2019)

Paleogeography



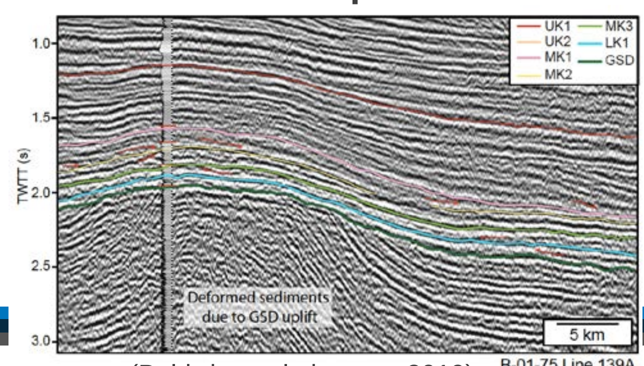
(Schmelz et al., 2019)

Log Interpretation



(Graham, 2019; Lombardi, 2017)

Seismic Interpretation

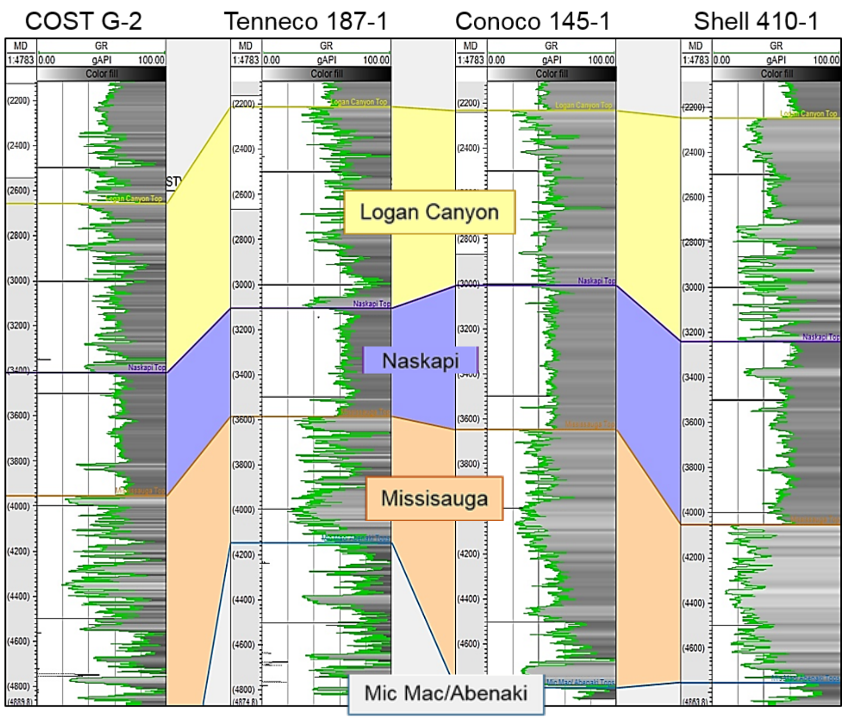


(Baldwin et al., in prep. 2019)

Task 2 - Geologic Characterization

- Geologic characterization of deep saline formations & caprocks completed to define the geologic storage framework.

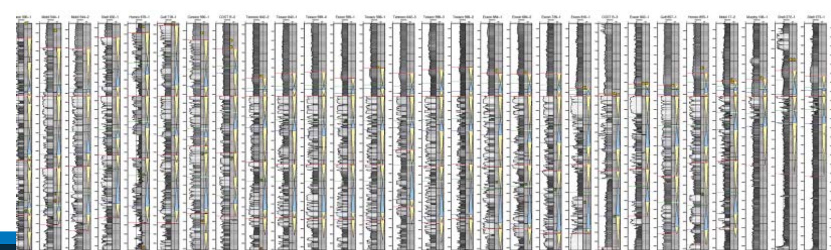
Lithostratigraphic & sequence stratigraphy integrated to define storage zones



Identified **three** potential storage targets and **four** regional caprocks

Age	Seal or Reservoir	Formation Name*	Depth (ft.)	Thickness (ft.)
Upper Cretaceous	Seal	Dawson Canyon	996 – 6,831	556 – 3,128
	Reservoir	Logan Canyon	2,208 - 9,561	174 - 2,227
Lower Cretaceous	Seal	Naskapi	3,022 – 10,557	49 – 1,481
	Reservoir	Missisauga	3,583 - 10,639	553 - 4,542
Upper Jurassic	Seal	Mic Mac	4,116 - 13,591	331 - 13,591
	Reservoir	Mohawk	4,924 - 15,082	5,274 - 7,742
	Base/Seal	Mohican/Iroquois	≥ 9738	-

Tops picked for all 44 wells in study area



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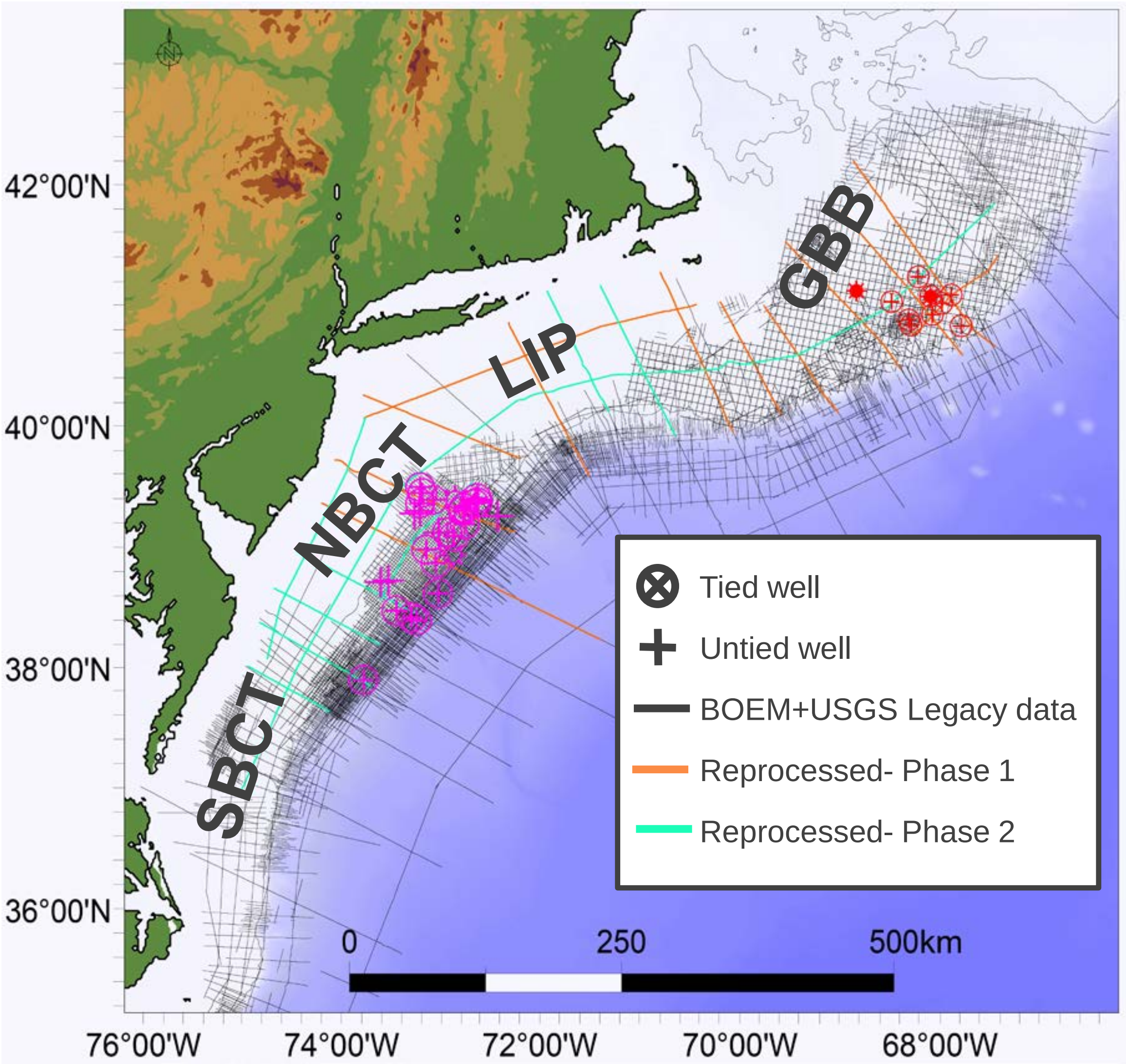
Task 3 – Seismic Evaluation

- Seismic data was reprocessed and used to constrain formation geometry, continuity, and geologic structures
- 4,000 km of USGS legacy data from 1970s (21 seismic lines)
- Of 39 wells, 33 were tied to seismic



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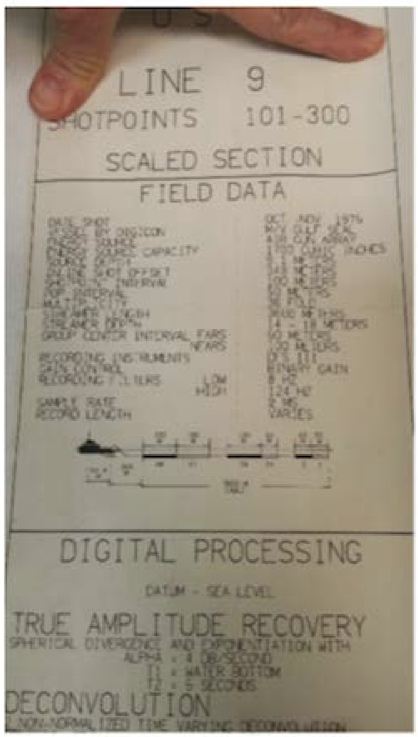
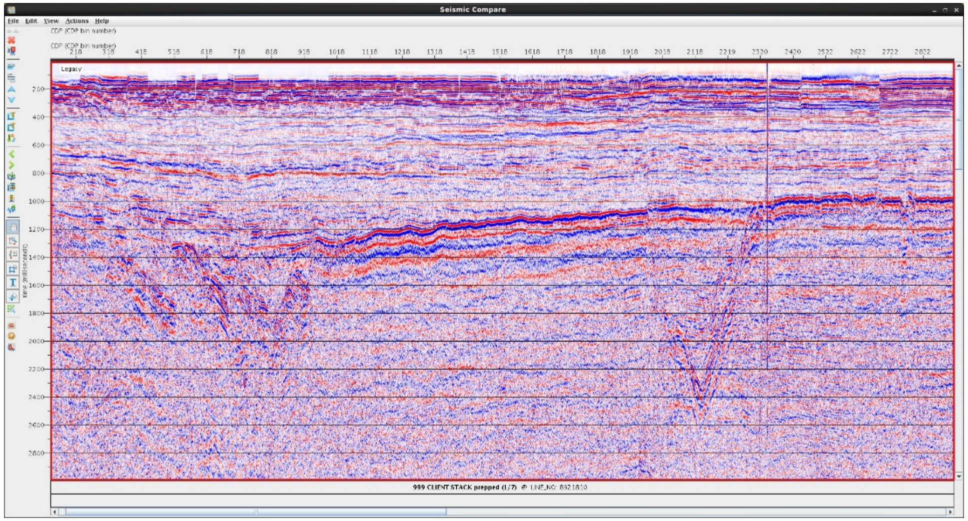
Task 3 – Seismic Evaluation

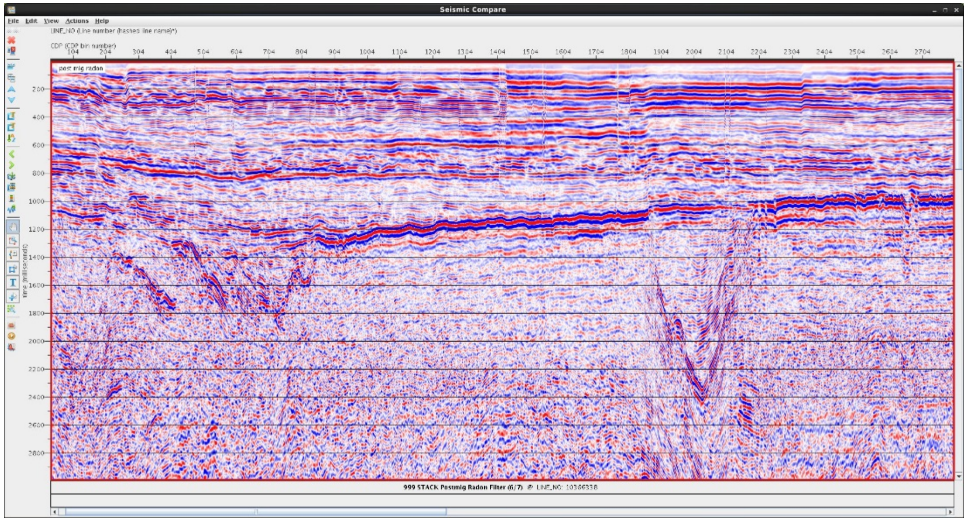
Original data info record



Before reprocessing



After reprocessing



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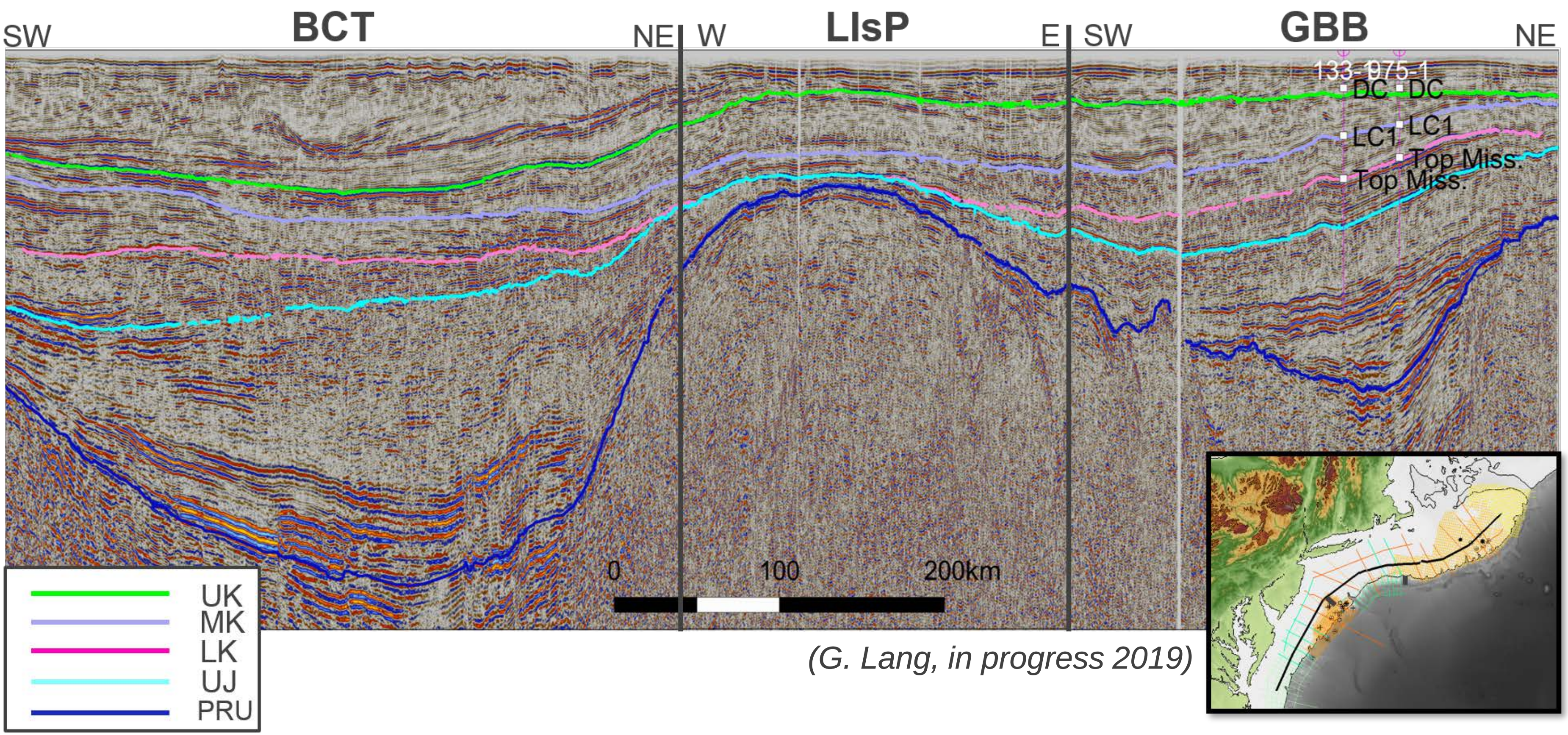
Task 3 – Seismic Evaluation

USGS Line 12 – "the game changer"



(G. Lang, in progress 2019)

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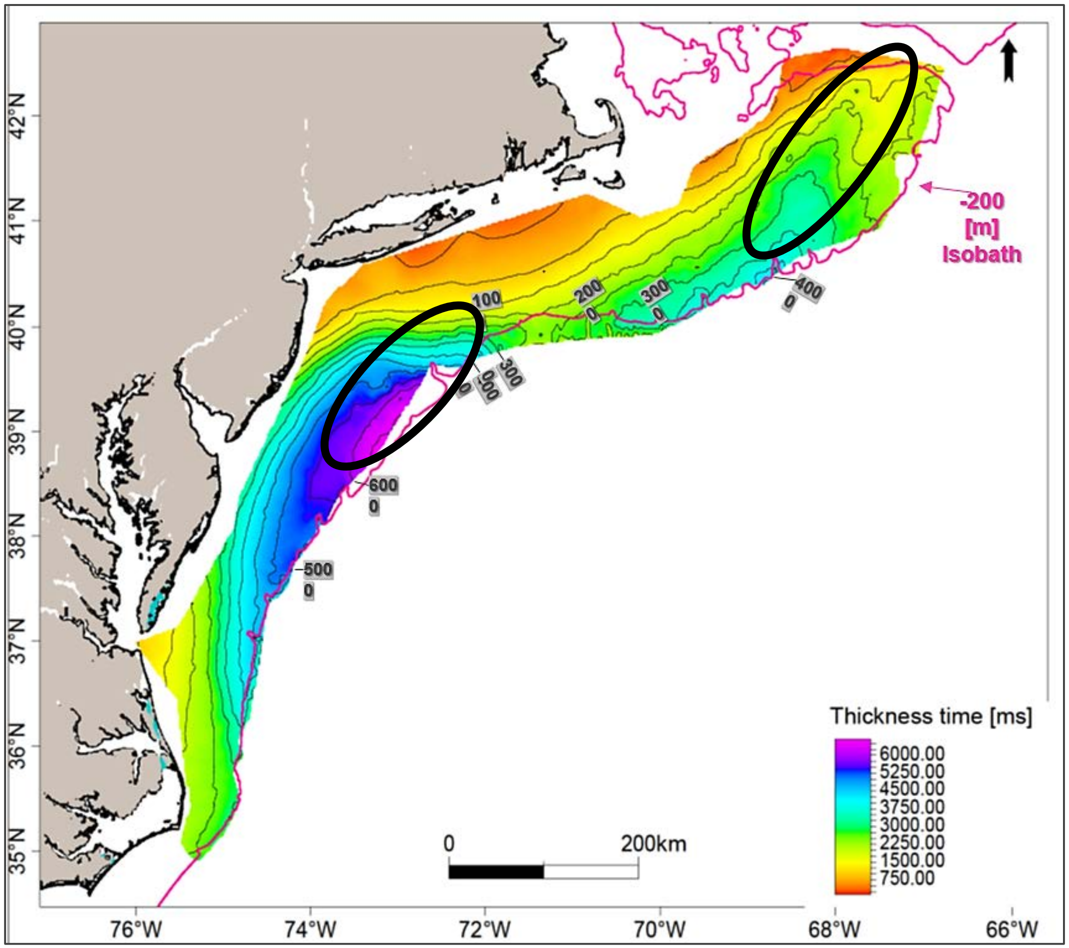
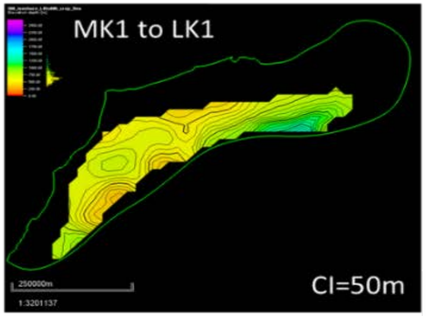
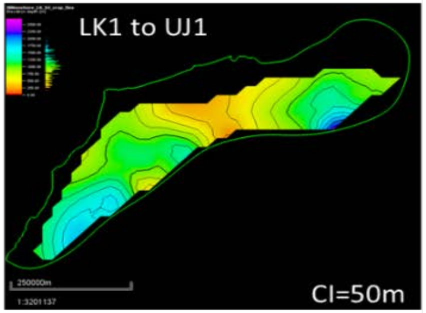
Task 3 – Seismic Evaluation (cont.)

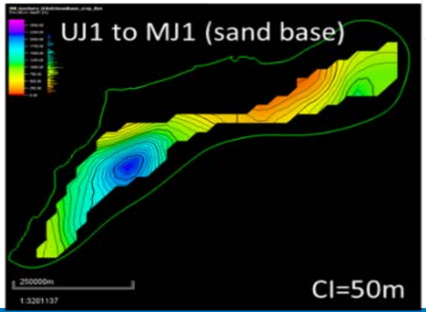
- Maps generated to constrain formation geometry and continuity.



Isochore Thickness Maps







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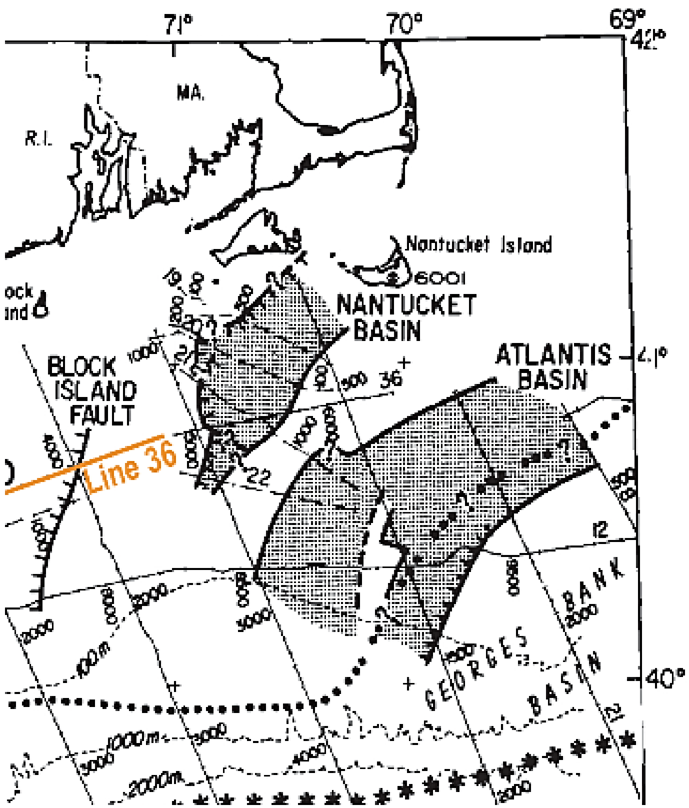
Task 3 – Seismic Evaluation (cont.)

- New data processing capabilities and seismic inversion techniques were used to improve

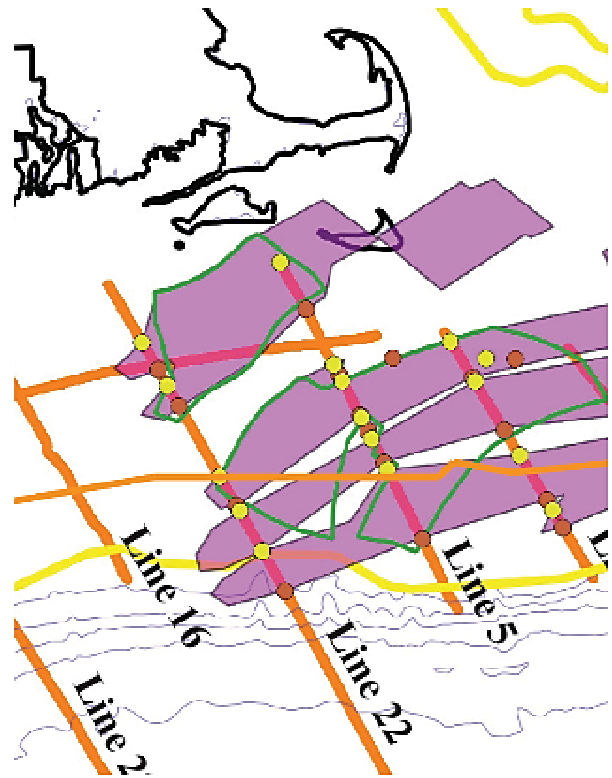
Larger, more continuous basins yield greater CO_2 storage potential

Legacy Processing



Map from Hutchinson et al., 1986

Modern Processing



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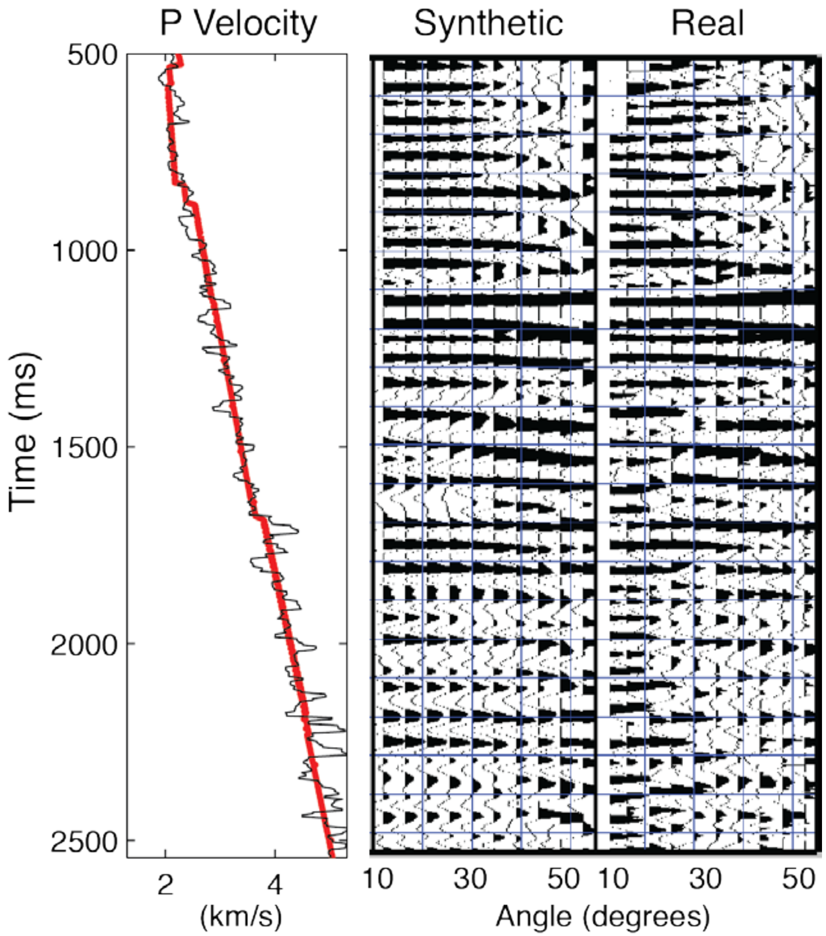
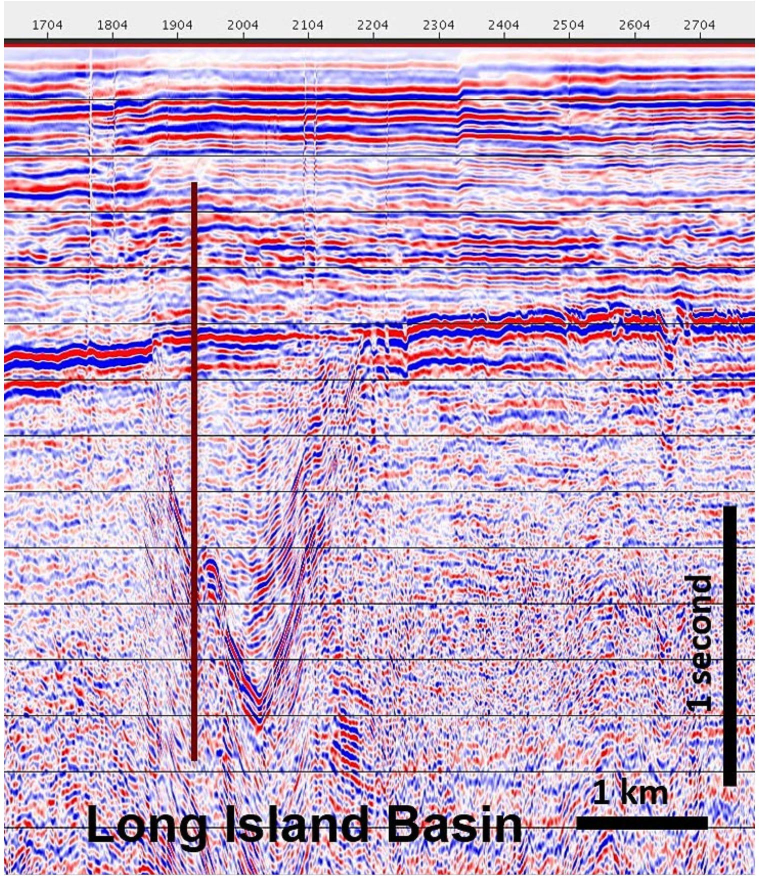
Task 3 – Seismic Evaluation (cont.)

- Seismic inversion provides virtual well control points where there are few or no wells to confirm rock properties.





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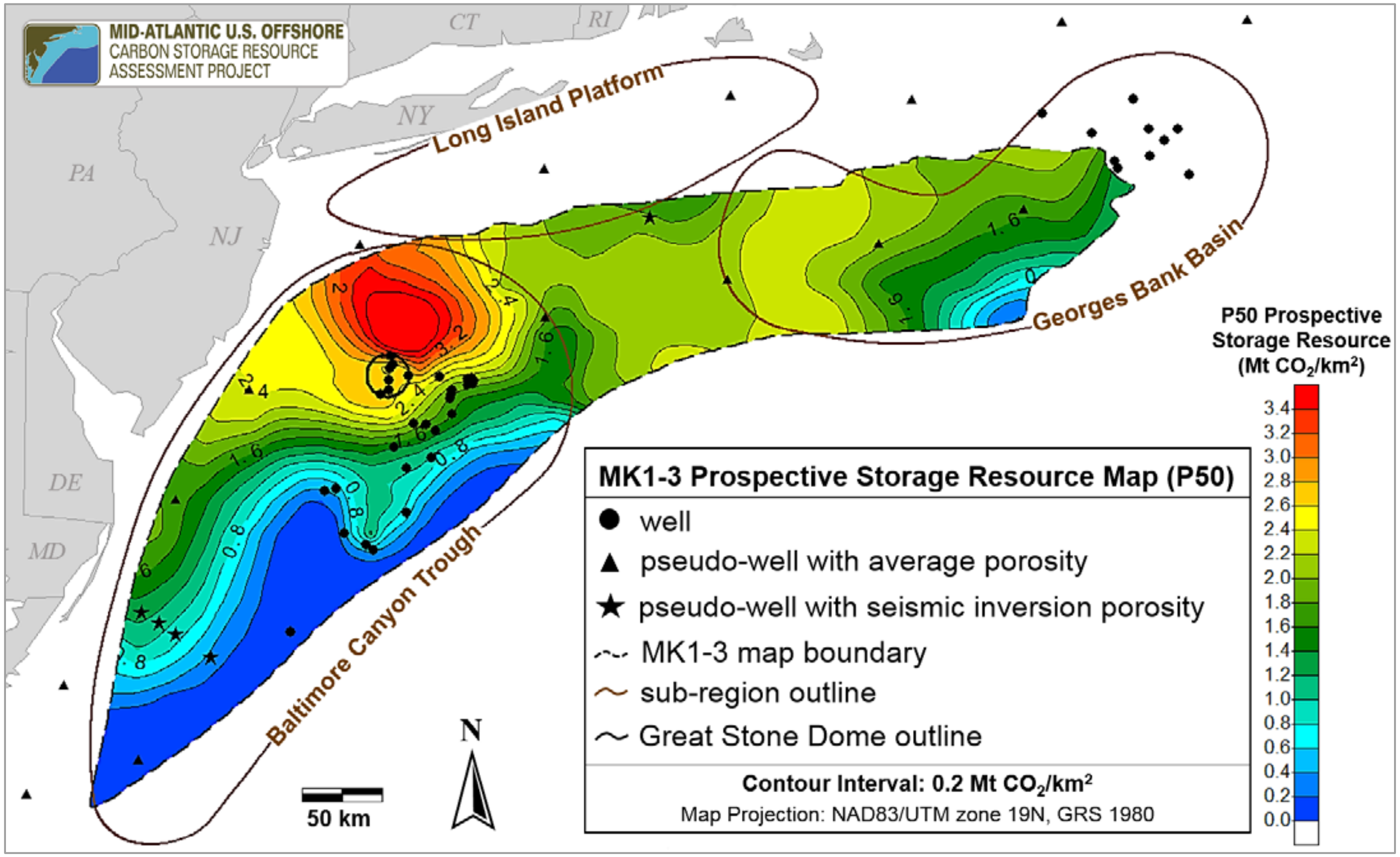
Task 3 – Seismic Evaluation (cont.)

- Well control points or pseudo wells important for Long Island Platform and Georges Bank Basin, and Western Baltimore Canyon Trough.



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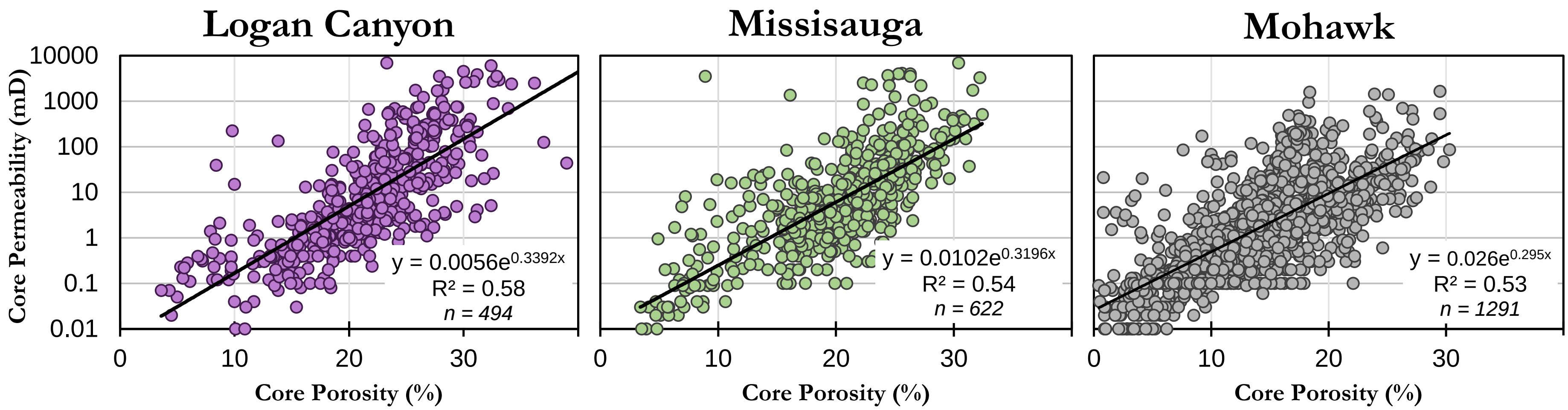
Task 4 – Hydrogeologic Characterization (Cont.)

- Hydrologic and petrophysical properties of offshore deep saline formations and caprocks supplemented with new tests on core/cuttings.

Well name	Permeability		Porosity (plug)	Grain density (plug)	Thin section	XRF	XRD	SEM
	(probe)	(plug)						
Conoco 145-1					1	1	1	
COST B-2	17	15	15	15	18	15	17	5
COST B-3	12	6	6	6	13	13	13	4
COST G-1	8	4	4	4	7	5	6	2
COST G-2	3	2	2	2	2	2	2	
Exxon 599-1	2	1	1	1	3	4	3	
Exxon 684-1	10	4	4	4	10	10	8	4
Exxon 684-2	1	1	1	1	1	1		
Mobil 544-1	12	1	1	1	12	11	12	1
Shell 273-1	2				2	2	1	
Shell 372-1	2				2	1	1	
Shell 586-1	2	1	1	1	1	1	1	1
Shell 587-1	1				1	1	1	
Shell 632-1	3	1	1	1	3	3	3	
Shell 93-1	1				1	1	1	
Texaco 598-1	3	3	3	3	3	3	3	1
Texaco 642-1	2	1	1	1	2	2	2	
Totals	81	40	40	40	82	76	75	18

Task 4 – Hydrogeologic Characterization

- Hydrologic and petrophysical properties of offshore deep saline formations and caprocks were cataloged and characterized



Core porosity and permeability data indicate offshore deep saline formations of interest have storage reservoir potential

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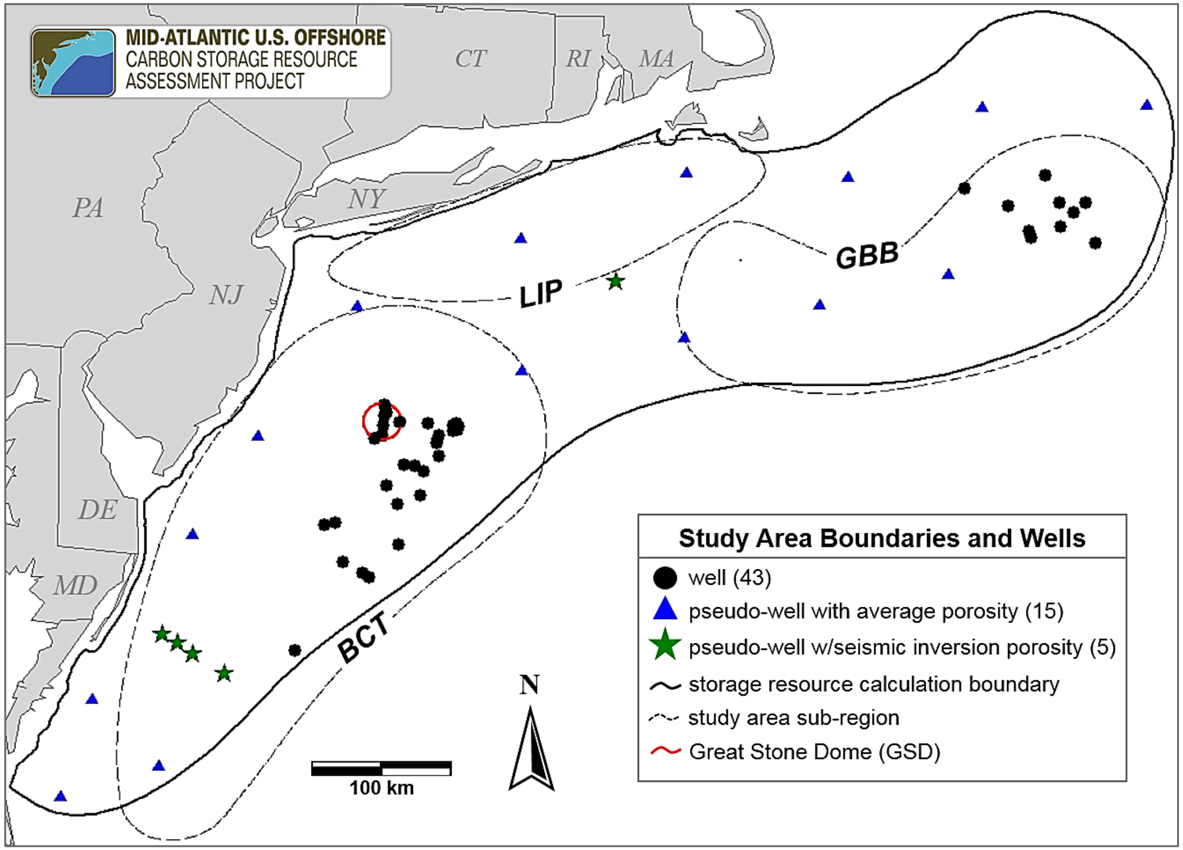
Task 5 – Storage Resources

Objective: systematically quantify and evaluate geologic CO_2 storage resources in the Mid-Atlantic U.S. offshore study region

Approach:

1) Data integration and mapping
2) Regional-scale volumetric storage resource calculations
3) Local-scale dynamic injection and storage simulation



*Sanguinito et al., 2016; https://edx.netl.doe.gov/organization/co2-screen

Task 5 – Storage Resources (cont.)

Potential Deep Saline Storage Zones: Middle Cretaceous Logan Canyon sandstone (MK1-3); Lower Cretaceous Missisauga sandstone (LK1) and Upper Jurassic Mohawk sandstone (UJ1)

Screening Criteria:

1) Formation depth > 1,000 m to ensure supercritical CO_2 storage, minimize soft-sediment deformation risk
2) Caprock to prevent vertical CO_2 migration
3) Hydrogeologic traps to prevent lateral CO_2 migration

Period	Epoch	~Age (Ma)	Seismic Surface	Storage/ Confining Zone	Formation
Cretaceous	Upper	86	UK1		Dawson Canyon
				UK1	
		100	MK1		Logan Canyon
	Middle		*MK2*	MK 1-3	*Logan Canyon 2*
			MK3		*Logan Canyon 3*
	Lower	126	LK1		Missisauga
				LK1	
		139	LK2		Mic-Mac
				LK2	
Jurassic	Upper	152	UJ1		Mohawk
				UJ	
	Middle	164	MJ1		Mohawk ss base

not to scale

caprock (shale)
storage zone (sandstone)
approximate/inferred

Offshore storage zones and caprocks defined by chrono-, litho-, and seismic sequence stratigraphy (Baltimore Canyon Trough)

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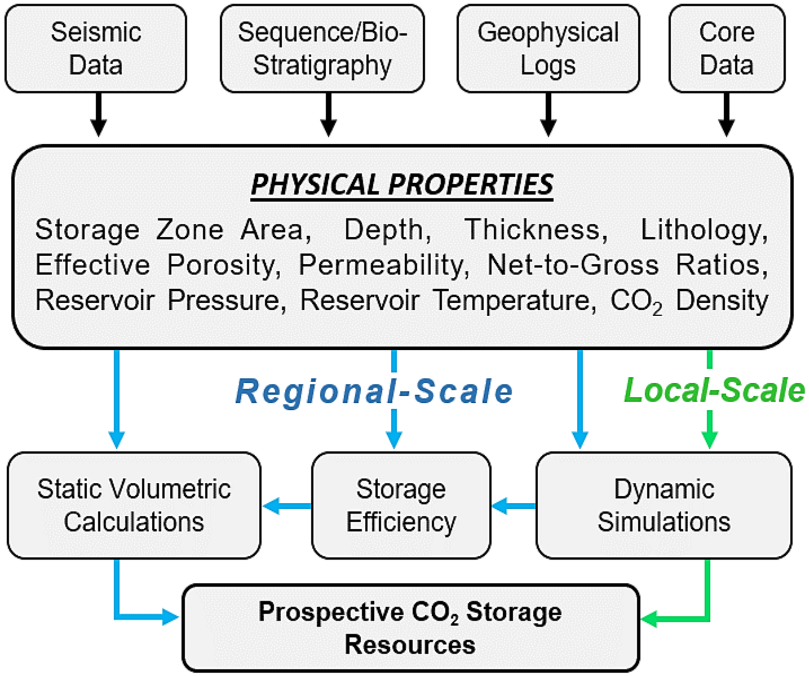
Task 5 – Storage Resources (cont.)

Data integrated into regional maps to represent reservoir pore volume available for CO_2 storage

Regional-Scale Static Estimates:

- DOE-NETL volumetric method[1] and CO_2-SCREEN Tool[2]
- Total pore volume x storage efficiency: quantity of CO_2 able to be stored
- Grid-based, stochastic; uncertainty defined statistically (e.g. P10, P50, P90)



Schematic showing data input and workflow used for estimating offshore CO_2 storage resources.

Local-Scale Dynamic Simulation: CO_2 injection and storage performance given specific pressure, time, and operational constraints

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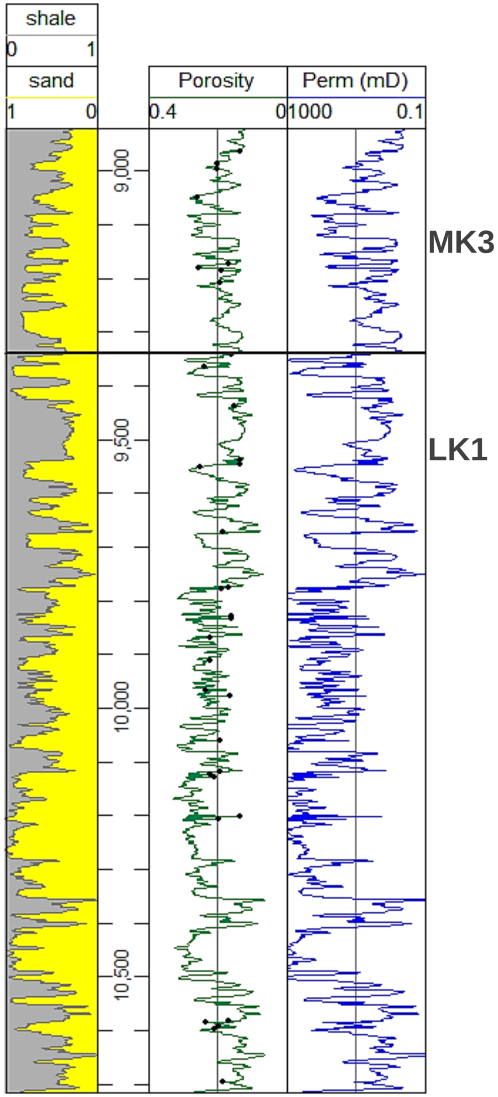
Task 5 – Storage Resources (cont.)

Average porosities: 21 – 29%

Average permeabilities: 45 – 339 mD

Values are within range of those reported for other offshore reservoirs used for commercial-scale CO_2 storage[1]



Regional averages for total storage zone (SS, ≥10 mD)

Storage Zone	Area (km^2)	Thickness (m)	Effective Porosity (%)	Permeability (mD)*	CO_2 Density (kg/m^3)
MK1-3	92,928	181	23	71	815
LK1	117,493	154	26	65	809
UJ1	134,578	211	21	45	796

*geometric mean

Regional averages for net storage zone (SS, ≥100 mD)

Storage Zone	Area (km^2)	Thickness (m)	Effective Porosity (%)	Permeability (mD)*
MK1-3	79,918	55	27	314
LK1	117,102	40	29	339
UJ1	88,372	32	25	264

*geometric mean

1. Norwegian Petroleum Directorate (2011; 2013)

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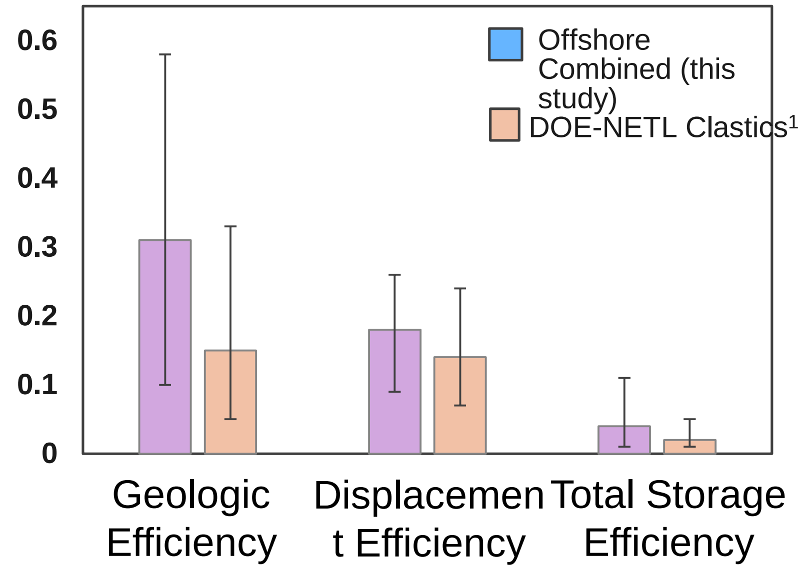
Task 5 – Storage Resources (cont.)

Offshore-Specific Storage Efficiencies

- Geologic Efficiency = 10 – 58%
- Displacement Efficiency = 9 – 26%
- Total E_{saline} = 1 – 11%

Higher medians (P50) and larger ranges than storage efficiencies reported for onshore clastic formations

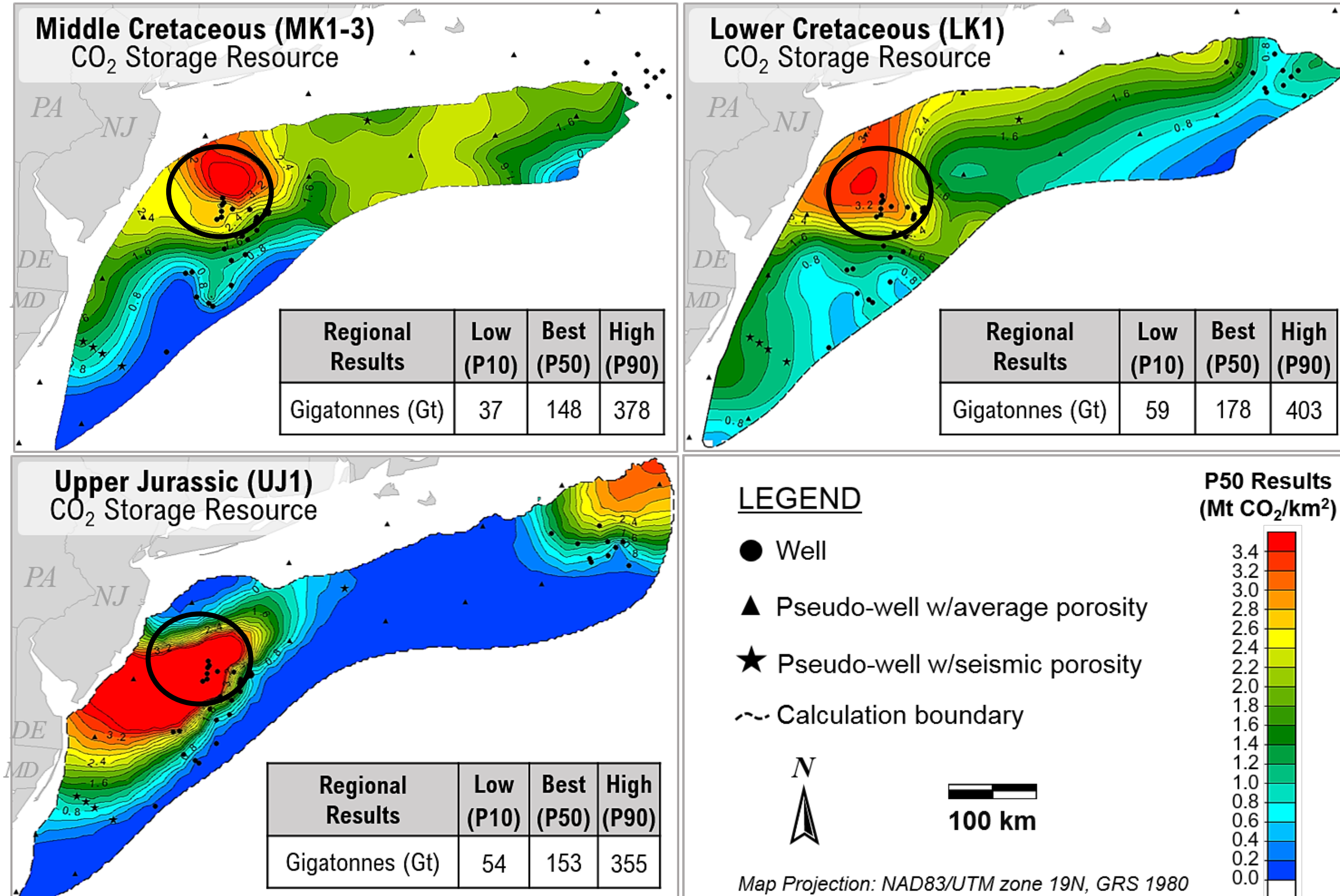
Comparison of Storage Efficiency Results



Storage Zone	Geologic Efficiency			Displacement Efficiency			Total Storage Efficiency (E_{saline})		
	P10	P50	P90	P10	P50	P90	P10	P50	P90
Middle Cretaceous (MK1-3)	0.09	0.36	0.70	0.09	0.18	0.26	0.01	0.05	0.13
Lower Cretaceous (LK1)	0.12	0.36	0.59	*	*	*	0.02	0.05	0.11
Upper Jurassic (UJ1)	0.08	0.19	0.38	*	*	*	0.01	0.03	0.07
Offshore Combined	**0.10**	**0.31**	**0.58**	**0.09**	**0.18**	**0.26**	**0.01**	**0.04**	**0.11**
DOE-NETL[1] Clastics	**0.05**	**0.15**	**0.33**	**0.07**	**0.14**	**0.24**	**0.01**	**0.02**	**0.05**

*Not Analyzed

Task 5 – Storage Resources (cont.)



Middle Cretaceous (MK1-3)

Regional Results	Low (P10)	Best (P50)	High (P90)
Gigatonnes (Gt)	37	148	378

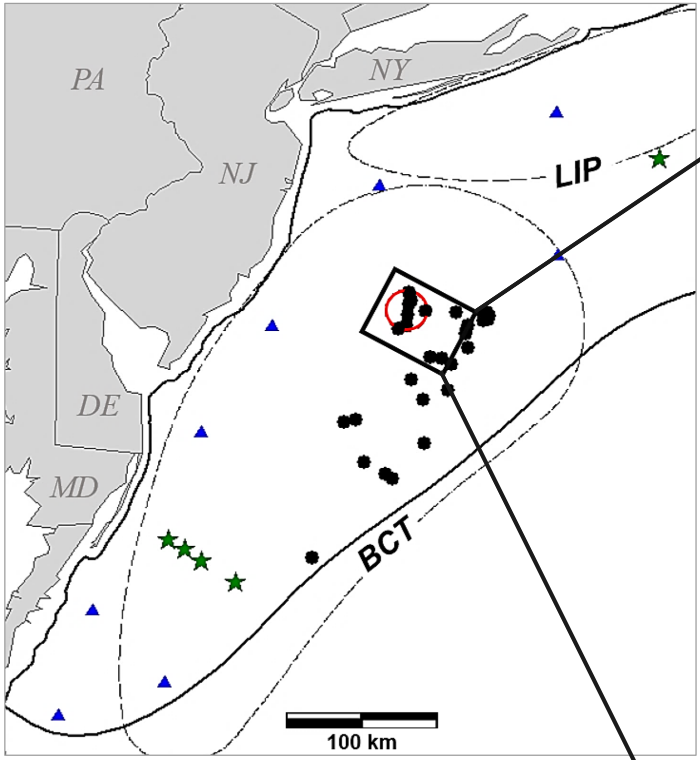
Lower Cretaceous (LK1)

Regional Results	Low (P10)	Best (P50)	High (P90)
Gigatonnes (Gt)	59	178	403

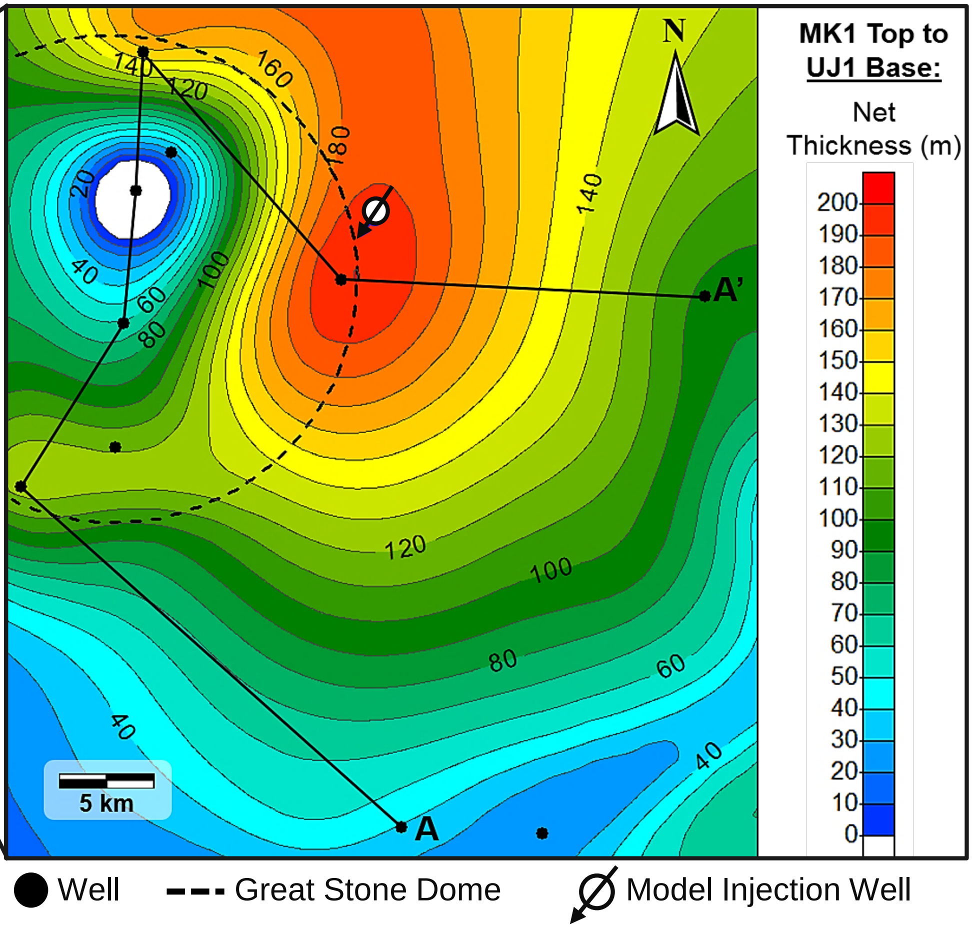
Upper Jurassic (UJ1)

Regional Results	Low (P10)	Best (P50)	High (P90)
Gigatonnes (Gt)	54	153	355

Task 5 – Storage Resource (cont.)



Selected Area: Northern Baltimore Canyon Trough near Great Stone Dome (596 km^2)



- High regional storage resource per unit area (≥ 2.5 $MtCO_2/km^2$)
- Constrained by data from 20 nearby wells w/average spacing ~15 km

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Task 5 – Storage Resource (cont.)

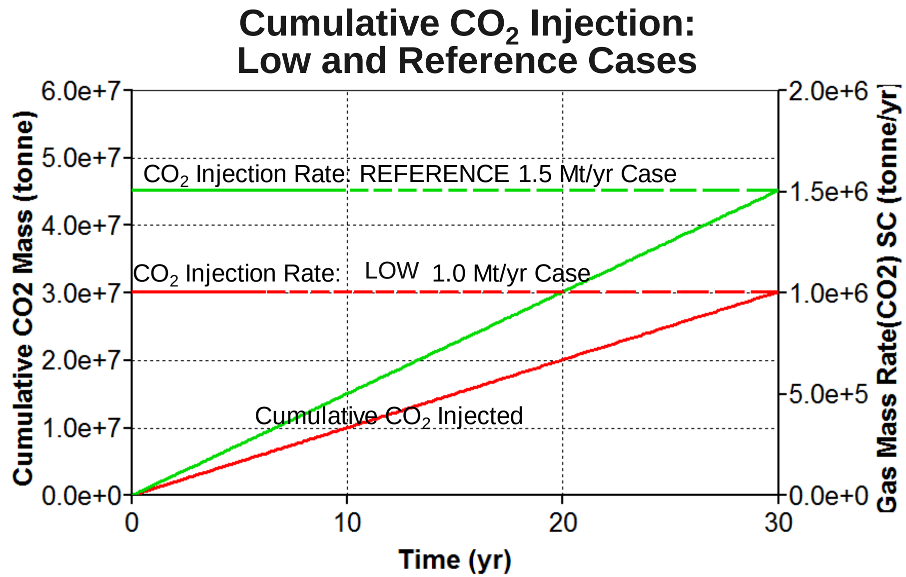
- 3D Site Model: 596 km^2
- Vertical Layers: 35
- Injection Duration: 30 years
- Frac Pressure Gradient: 14.7 kPa/m (0.65 psi/ft)

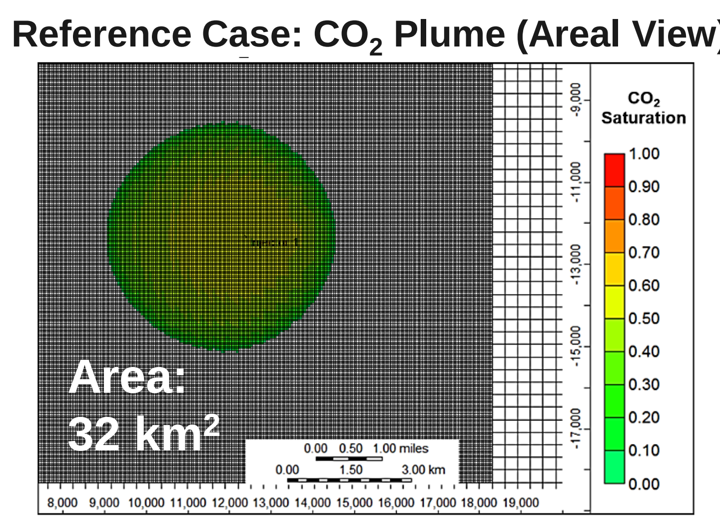
One vertical injection well, three injection rates

Injection Rate (Mt CO_2/year)		Cum. CO_2 Stored (Mt)
High	~1.7	51 Mt
Reference	1.5	45 Mt
Low	1.0	30 Mt

Model injection rates ≈ individual emission rates associated w/majority (96%) of nearby CO_2 sources

**Max. allowable bottom hole pressure: 31,000 kPa*





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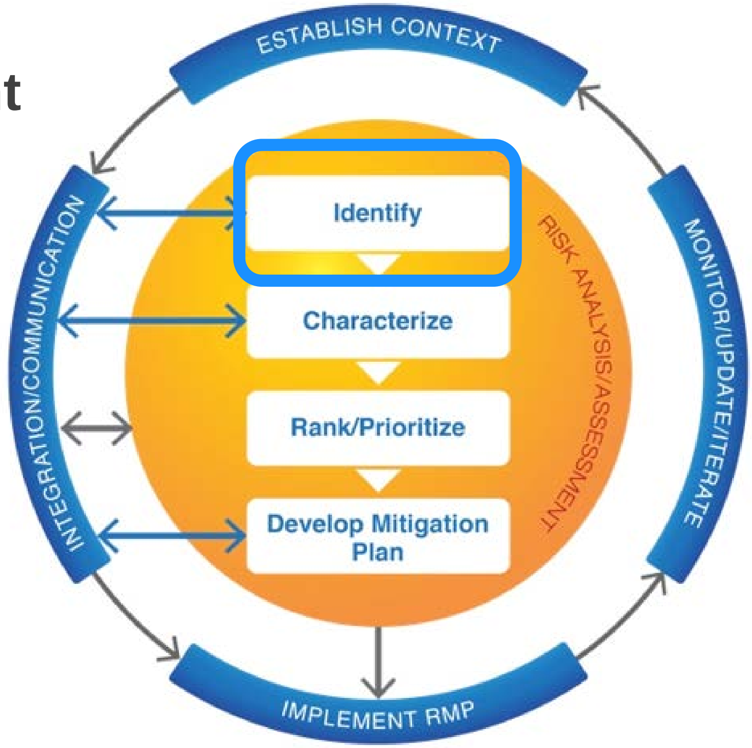
Task 6 – Risk Factors

Objective: Identify technical risk factors in mid-Atlantic offshore areas that may affect CO_2 storage resource estimates:

1. **Geological Risk Factors**
2. **Long Term Storage Risk Factors**
3. **Environmental Factors for Deployment**

Risk factor analysis leverages project team work from other tasks (geotechnical testing, mapping, seismic analysis, database, GIS, log analysis, stakeholder review)

DOE-NETL risk management process (DOE-NETL, 2011)



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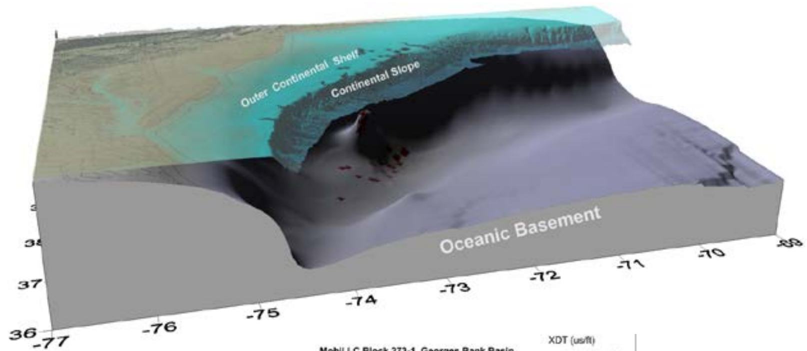
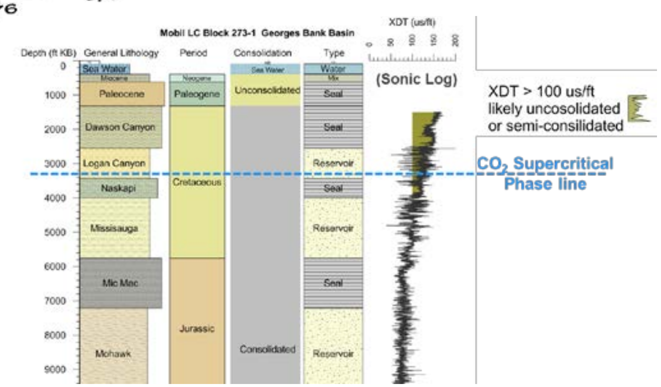
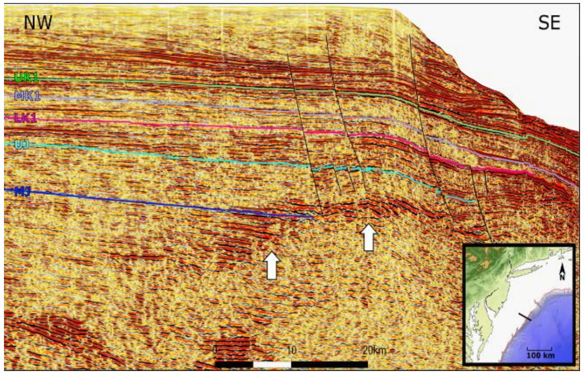
Task 6 – Risk Factors (cont.)

- Draft task summary report was submitted:
  - Area benefits from the large spatial extent, thick sequences of K- and J-age sands, scarcity of wellbores (44 P&A wells), and distance from populated development.
  - No highly critical risk factors identified that would impede CO_2 storage in study areas.
  - Moderate risks include faults and geomechanical stability along the mid-Atlantic <u>slope</u> and reservoir variability
  - Soft sediment deformation identified as a risk factor for semi- or unconsolidated sediments less than 1,000 m deep







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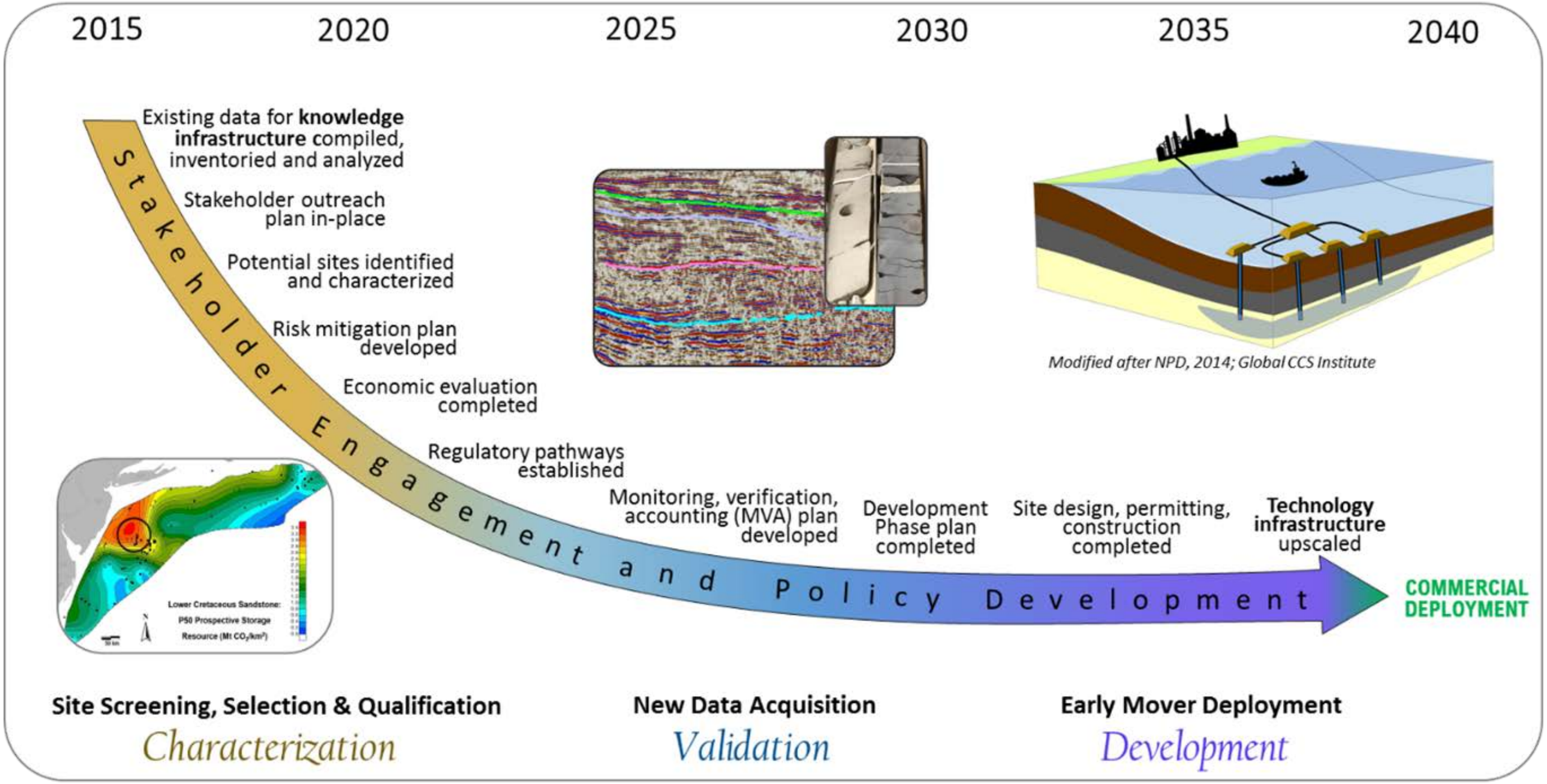
Task 7 – Stakeholder Outreach

The stakeholder outreach task will engaged stakeholders about CO_2 storage resources in the offshore mid-Atlantic



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Task 8 – Technology Transfer

- Technology Transfer has included:
  - ***7 peer reviewed technical articles, 4 M.S. Theses, 1 PH.D., 34 presentations and posters!***
  - 5 outreach pamphlets➔ ➔ ➔ ➔ ➔
  - Annual review meetings (2016, 2017, 2018, 2019)
  - SECARB Annual Stakeholder Briefing
  - CSLF International Workshops on Offshore Geologic CO_2 Storage (2016, 2017, 2018)
  - Conferences and meetings: 2016 CCUS, GHGT-13, GSA (multiple), AAPG (multiple)

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Accomplishments to Date

- Detailed inventory and developed comprehensive database
- Characterized key properties of reservoirs and caprocks, including: depth, thickness, porosity, permeability, sequence stratigraphy
- Completed sample analysis to address data gaps and calibration of existing data
- Completed advanced reprocessing of 4,000 line km of seismic data
- Developed composite seismic lines, zone top surface maps, and zone isopach maps
- Completed analysis of CO_2 storage risk factors in study area
- Offshore Prospective CO_2 Storage Resource complete
- Successful stakeholder outreach workshop with Harvard

Lessons learned

- World class carbon storage resource is present along Mid-Atlantic Offshore Outer Continental Shelf: 150-1136 Gt.
- Uncertainty due to offshore data gaps and data vintage can be addressed via resource classification and use of probabilistic methods to estimate storage
- Integration and correlation of various data sets (core, log, seismic, biostrat) is time-intensive but extremely valuable for constraining statistical distributions of offshore formation properties
- Risk factors include soft sediment deformation, environmental factors, stakeholder support, reservoir variability, and features along continental slope.

Synergy opportunities

Building on preliminary offshore characterization of MRCSP Program

- Atlantic Coastal Plain CO_2 Storage Resources
- Triassic Rift Basins for Long-Term CO2 Sequestration

Collaborating with other DOE Offshore Projects

- Project technical advisors from SOSRA & Gulf Coast Projects

Adding to the international pool of offshore CCS information

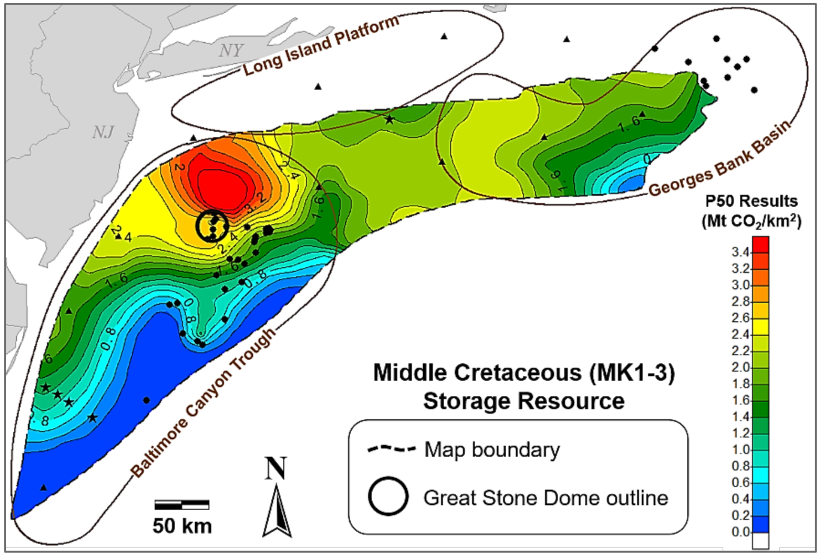
- CSLF International Offshore Geologic Storage Workshops
- Offshore storage stakeholder workshops

Project summary

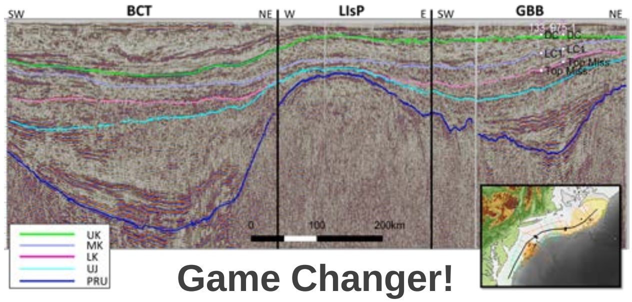
MID-ATLANTIC U.S. OFFSHORE
CARBON STORAGE RESOURCE
ASSESSMENT PROJECT

Key Findings:

- Deep thick saline formations and caprocks identified for potential storage & containment
- Risk factor analysis resulted in a comprehensive list of potential sources of risk and identified site screening criteria specific to the marine environment
- Risk communication is an important element for future CCS applications.



Next Steps: Complete regional Prospective Storage Resource calculations and additional stakeholder outreach



Game Changer!

Data compiled and results generated as part of this project will help guide future site screening and selection efforts in the study area, address potential technical barriers to offshore CCS, and inform stakeholders, policy & business decisions.

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Appendix Material

Benefit to the program

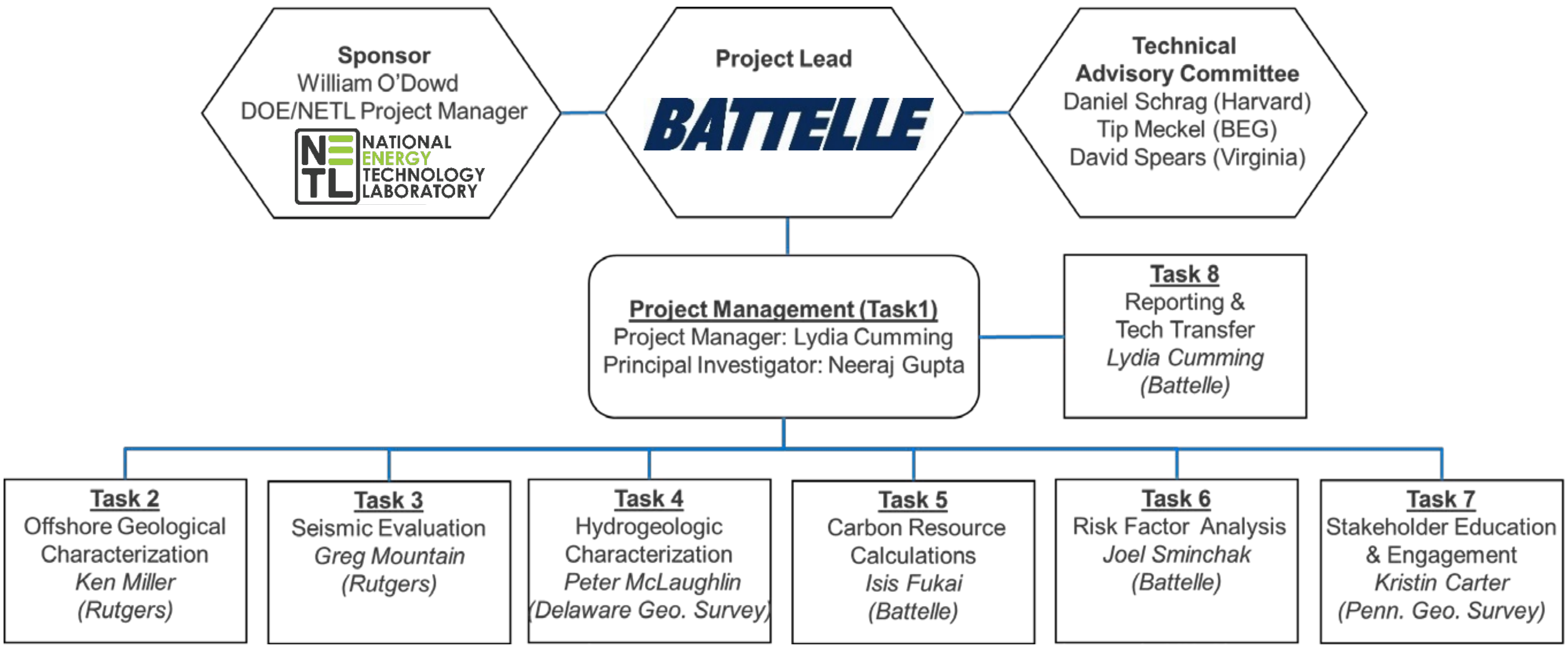
- The project will establish a Prospective Storage Resource Assessment in offshore regions along the mid-Atlantic and northern states in the U.S. The key outcomes include: (1) a systematic carbon storage resource assessment of the offshore mid-Atlantic coastal region, (2) development of key input parameters to reduce uncertainty for offshore storage resource calculations and efficiency estimates, (3) evaluation of risk factors that affect storage resource potential, and (4) industry and regulatory stakeholder outreach to assist future projects.
- Characterization of deep saline formation geologic and hydrologic properties, evaluation of risk factors, and estimation of Prospective Storage Resource at the P10, P50, and P90 percentiles for Mid-Atlantic offshore study area will contribute to the Carbon Storage Program's effort to support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent (Goal).
- The overall workflow and results established by this project along with stakeholder outreach efforts will also aid in development of Best Practice Manuals for Site Screening, Selection, and Initial Characterization; Outreach; and Risk Analysis (Goal).

Project Overview- Goals & Objectives

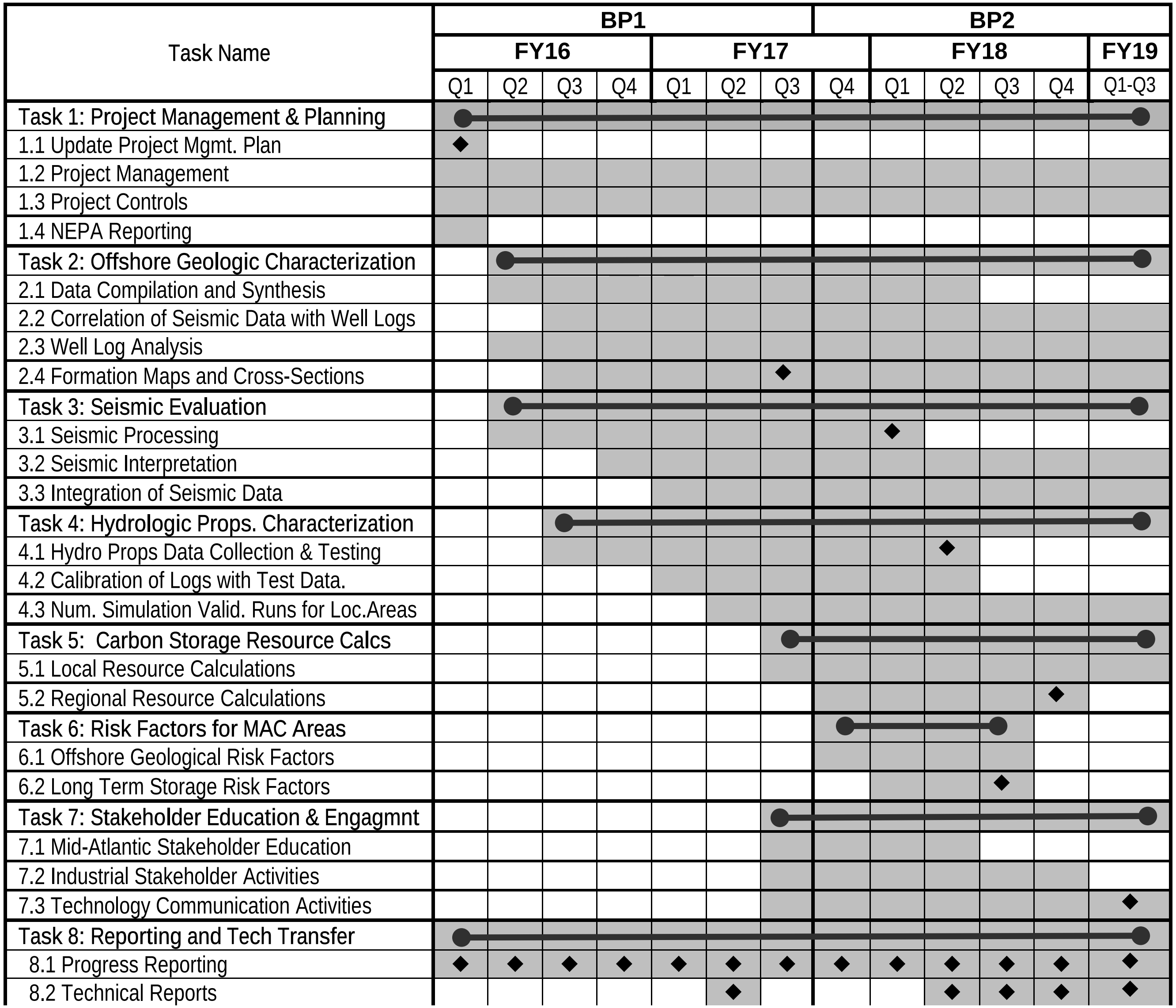
- Objective: Complete a systematic Carbon Storage Resource Assessment of the U.S. Mid-Atlantic offshore coastal region (Georges Bank Basin - Long Island Platform - Baltimore Canyon Trough)

DOE Carbon Storage Program Goal	U.S. Mid-Atlantic Offshore Project Objectives	Success Criteria
Support industry's ability to predict CO_2 storage capacity	Geologic characterization of potential offshore storage zones in the Mid-Atlantic study area	Constrained study to areas with realistic storage potential based on depth and thickness criteria, and presence of CO_2 containment mechanisms
	Use seismic data to better define continuity of offshore deep saline formations and caprocks	Evaluated and selected seismic data for additional processing
	Catalog hydrologic properties of offshore deep saline formations and caprocks	Surveyed available geologic cores for the study area and selected samples to undergo hydraulic tests and laboratory measurements
	Integrate data to estimate Prospective Storage Resource and Storage Efficiency of candidate storage reservoirs	Determined suitable carbon storage resource calculation method and workflow for offshore study area/formations
Develop Best Practice Manuals	Examine risk factors associated with CO_2 storage in the Mid-Atlantic study area	Provide an initial assessment of offshore geological risk factors and long-term CO_2 storage risk factors
	Engage stakeholders to guide future projects	Prepare a stakeholder list and project fact sheet for education and engagement

Organization chart



Gantt chart



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2018	Back to Basics of Sequence Stratigraphy: Early Miocene and Mid-Cretaceous Examples from the New Jersey Paleoshelf	Journal of Sedimentary Research	Miller, K. G. et al
accepted	Onshore-offshore correlations of fluvial-deltaic sequences from the mid-Cretaceous of the southern Baltimore Canyon Trough,	AAPG Bulletin	Schmelz, W.J. et al.
2019	Mid-Cretaceous Paleopedology and Landscape Reconstruction of the mid-Atlantic U.S. Coastal Plain,	Journal of Sedimentary Research	Thornburg, J.D. et al.
submitted	Delineating Mid-Cretaceous seismic and well-log sequences to assess carbon storage potential in the northern Baltimore Canyon Trough,	Geosphere	Baldwin, K.W. et al.
in prep.	Revised age constraints for Barremian to Cenomanian sequences, offshore U.S. mid-Atlantic margin	Geosphere	Jordan, L. et al.
2019	Summary of geologic data from three core holes drilled through the Potomac Group in the Coastal Plain of Cecil County, Maryland: Report of Investigations No. 87, DNR Publication No.	Department of Natural Resources - Maryland Geological Survey, Resource	Quinn, H.A.
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2017	Sequence stratigraphic interpretation of mid-Cretaceous strata from the Great Stone Dome to the continental slope, northern Baltimore Canyon Trough: Implications to sea level and Carbon Capture and Sequestration	Rutgers University, Ph.D. thesis	Lombardi, C.
2019	New Insights on the Mesozoic evolution of the Mid-Atlantic Continental Margin from Integrated Sequence Stratigraphy and Numerical Modeling	Rutgers University, master's thesis	Schmelz, W.
2019	Quantitative Biostratigraphic Analysis of Middle Cretaceous Sequences in Baltimore Canyon Trough, Mid Atlantic U. S. Margin	Rutgers University, master's thesis	Jordan, L.
2019	Georges Bank Basin Stratigraphy: Cretaceous Gamma Log Sequences Correlated with Seismic Data	Rutgers University, master's thesis	Graham, S.

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January, 2016	Sequence stratigraphic framework of the mid-Cretaceous nonmarine Potomac Formation in New Jersey and Delaware	GSA	Denver, CO	Thornburg, J.D. et al.
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May, 2016	Overview of the Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment	CCUS	Tysons, VA	Cumming, L. et al.
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March, 2017	Cretaceous Sedimentation Patterns in the Southern Baltimore Canyon Trough: Correlating the Maryland Coastal Plain to the Continental Rise	SE GSA	Richmond, VA	Schmelz, W.J. et al.
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October, 2017	Cross Sections from the Midwest Regional Carbon Sequestration Partnership: Visualizing Subsurface Carbon Storage Opportunities Across the Central and Eastern United States	GSA	Seattle, WA	Dinterman P. A., et al.
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September, 2016	Carbon Storage Potential at the Great Stone Dome, Northern Baltimore Canyon Trough	GSA	Denver, CO	Lombardi, C. et al
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November, 2016	Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment	GHGT-13	Lausanne, SW	Cumming et al
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December, 2018	Potential for CO_2 sequestration in Rift Basins Offshore the US East Coast: Updated basin extent and composition from pre-stack seismic inversion	AGU	Washington, D.C.	Fortin, W. et al

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