Geology (and policy) matters: The challenging case for carbon storage, U.S. Mid-Atlantic margin

Kenneth G. Miller, J.V Browning, R.E. Kopp, Y. Fan-Reinfelder

Department of Earth & Planetary Sciences

Institute of Earth, Oceans, and Atmospheric Sciences

REI Symposium
May 3, 2017

Environmentalists, Coal Companies Rally Around Technology To Clean Up Coal: NPR Morning Edition, May 1 2017
Solution: All of the above

Energy stabilization wedges Pacala & Socolow (2011)
Carbon Capture from large point sources

1,000 stationary sources account ~30% of global CO₂ emissions

Pre-, Post-, or Oxyfuel capture, compression, and pipe away

Post-combustion: capture CO₂ solvent/membrane

Pre-combustion: gasify coal/biomass/CH₄ burn H₂

Oxyfuel: burn in O₂ with flue gas H₂O and CO₂

Negative CO₂ if use Bio-energy with carbon capture and storage (BECCS) or air capture (e.g., Klaus Lackner)

CCS = carbon capture and storage/sequestration

Carbon storage options:

1) Biological storage
   - (re)forestation
   - aquatic biomass
   0.4 Gt/yr Pacala & Socolow (2011)

2) Geological storage
   - inject CO$_2$ into ocean (a very bad idea)
   - accelerated weathering (see Keleman & Matter)
     http://www.ldeo.columbia.edu/gpg/projects/carbon-sequestration
   - subsurface storage of supercritical CO$_2$
     ~1.5 Gt/yr Pacala & Socolow. 300 power plants

Madin, Oceanus, 2010

Should We Inject Carbon Dioxide into the Deep Ocean?
Study finds that some seafloor life may be harmed by high CO$_2$ levels

By Kate Maller / Originally published online December 22, 2009 / In print Vol. 4, No. 1, Jan. 2010
TOPICS: OCEAN ACIDIFICATION
Carbon sequestration: Supercritical storage

Advantage of injecting CO₂ in supercritical state
Increases volume that can be stored in a reservoir
Supercritical state @ pressure >8 Mpa (80 bars), T >32°C
Compress to supercritical and store > 800 m burial depth

Requires a reservoir and seal (Geology matters)
Geological Storage supercritical CO$_2$

Overview of Geological Storage Options
1. Depleted oil and gas reservoirs
2. Use of CO$_2$ in enhanced oil and gas recovery
3. Deep saline formations — (a) offshore (b) onshore
4. Use of CO$_2$ in enhanced coal bed methane recovery
5. Deep unmineable coal seams
6. Other suggested options (basalts, oil shales, cavities)

EOR

https://www.ipcc.ch/report/srccs/
Geology Matters: Geological Storage CO$_2$

Reverse Petroleum 101

Seal = “Caprock”
Confining Unit
Impermeable
“tight” shales

Reservoir:
porous (20-30%),
permeable (>100 mD)
sandstones, limestones
saline water reservoirs
(not potable water)

https://www.epa.gov/climatechange/carbon-dioxide-capture-and-sequestration-overview
U.S. Mid-Atlantic region for CCS

one of ~dozen suitable U.S. targets identified strata sufficiently deep, porous, permeable, & hydraulically isolated from fresh aquifers several major CO$_2$ producers in this region.

http://www.beg.utexas.edu/environqlty/co2seq/
1 NJ & 1 Delaware coal power plants suitable

Map courtesy of GeoMappApp produced by REI summer intern A. Kulpecz

Miller et al. (2017)
J. Sedimentary Research
Future onshore possibilities

Indian River power plant Delaware Thick (6500 ft to basement) Waste Gate/Potomac I target Politically less difficult than NJ

BL England, Beesley’s Pt., NJ
Onshore coastal plain storage

Miller et al. (2017)
J. Sedimentary Research
Onshore storage in Waste Gate and Potomac I Sands

After Sugarman et al. (2011) updated by Miller et al. (2017)
Onshore storage in Waste Gate and Potomac I Sands

After Miller et al. (2017)
Correlations by REI summer intern C. Walsh
Onshore CO$_2$ storage capacity $\sim$21 Gt C

$21 \text{ Gt C} (= 77 \text{ Gt CO}_2)$ equivalent to 0.6 to 2.4 years of current U.S. emissions

After Miller et al. (2017)

$$GCO_2 = A_t H_g \phi_t \rho_{CO_2res} E_{saline} \quad (1)$$

GCO$_2$ mass of CO$_2$ storage resource in Gt C

- $\rho_{CO_2res}$ density of CO$_2$ under reservoir conditions
- $\phi$ formation total porosity (assumed 20% here)
- $A_t$ is the total area of the formation
- $H_g$ is the gross thickness of the prospective formation
- $E_{saline}$ is the storage efficiency factor (% of the total formation fluid displaced) low (1%), intermediate (2.5%) high (4%) (DOE/NREL, 2010).

Mean reservoir depths are $\sim$1500 m, geothermal gradient = 23°C/kms
Good storage location: Thick, porous sands & confining beds <10,000 ft (3.4 km, lo porosity below)

Preliminary estimates offshore storage 22-87 Gt (Monteverde et al., 2011)

Doesn't conflict with oil and gas resources: No CH$_4$ in Logan Canyon Sands, most of Mississauga

Avoids public perception concern of storage beneath populated area (Not Under My Backyard; Van Noorden, 2010)

Mitigates concerns regarding earthquake stimulation: (Zoback and Gorelick, 2012): supercritical CO$_2$ into the poorly indurated Logan Canyon will not exceed lithostatic pressures and cause fracturing and earthquakes
MRCSP onshore New Jersey to Maryland: onshore reservoirs and traps and previous MRCSP onshore work: Miller, Browning, Thornburg

Geological evaluation offshore new project:
Log-sample evaluation of offshore reservoirs and traps
Northern BCT: Chris Lombardi, Miller, Schmelz
Eastern Georges Bank Basin: Stephen Graham
Southern BCT: John Schmelz

Seismic Evaluation: Mountain, Miller Baldwin, Schmelz, Graham, Adams
Rutgers focus: BCT & GBB sand reservoirs and shale seals

- Baltimore Canyon Trough (BCT)
- Georges Bank Basin (GBB)

Georges Bank Basin

Baltimore Canyon Trough (= Basin)
Well log transects: GSD & OCS

Continental Offshore Stratigraphic Test (COST) B-2 well industry-government consortium; Scholle (ed.) 1980

Miller et al. submitted “Back to Basics” (B2B)
COST B-2 Core

Ground truth

Register downhole logs to cores

Look at vertical changes on logs to infer sequences (unconformity bounded units)

Arrows point in fining direction
COST B-2 sequences

Logan Canyon 3 sequences (1 is the youngest)

Sequences predict sands are correlatable
Individual beds or most parasequences are not traceable, but sand prone appear at same level and and likely connected reservoirs

High porosity (>30%)

High permeability (>1000 mD)

Excellent reservoir

Sands are confined not only by overlying sequences, but by thick shales

Miller et al. submitted (B2B)
Sequences & biostratigraphic correlations

Miller et al. (in review)
Sequence stratigraphy informs reservoirs and seals
Lithocorrelation violates sequences & biostrat

Sable Shale of Libby French (1981) separating up & lo Logan Canyon placed both above and below basal LC1 sequence boundary, though generally LST of LC2 (note section hung on top LC2)
Seismic profiles “sonograms of the Earth”

Allows recognition of geometry of strata (layers)
Identification of sequences provides increased prediction
Map the units
Recognize faults that would be potential hazard
Slide from K. Baldwin
Geology is ready offshore Mid-Atlantic

✓ Good reservoirs
✓ Good seals
✓ Local CO$_2$ point sources

What next?

What are the political and economic challenges in previous & current projects?

Targets
Logan Canyon & Mississauga Formations

Libby French (1984)
Sleipner Project, Norwegian North Sea (Statoil)
CCS since 1996
The Sleipner area gas field Central North Sea, Norway sector

CO₂ content of “wet” gas 4-9%

Statoil spurred by carbon tax to capture & store CO₂ in a saline reservoir

Injection rate of almost 1 Mt/yr

reservoir Utsira Formation (sandstone) at 800-1,100 meters
A Plan for U.S. Emissions to Be Buried Under Sea

By KATE GALBRAITH
Published: April 17, 2009

In an ambitious proposal to counter global warming, an upstart power developer wants to build a coal-fired electric plant on the outskirts of New York City that would capture its emissions of carbon dioxide and pump the pollutant 70 miles offshore. The gas would be injected into sandstone a mile beneath the ocean floor in the hope that it would stay there for eons.

Experts have thought for years that capturing the emissions from power plants will be a crucial technology for limiting climate change. But high cost projections and scientific uncertainty have meant that progress on the technique has been limited, even as the effects of global warming are starting to be felt around the world.

Welcome to SCS Energy

SCS Energy is a private power plant development company that prides itself on exceeding investor’s expectations. We concentrate on high value projects that lead the industry in environmental stewardship and climate change mitigation.
• Build new Linden coal plant, very high efficiency (can’t retrofit; loss ~25%; need high 40% efficiency plant, need infrastructure of trains, power lines)
• 90% capture
• 500 megawatt plant, 5 MtCO$_2$/year (plan to store 200 Mt)
• First large scale commercial power plant w/ CCS
• 3-5 b$ of private capital (no government $)
• Business plan: make fertilizer/H$_2$ fuel at night
The locations of the pipeline and injection well area are based on an interpretation of the image and have not been geo referenced.

Courtesy of D. Schrag
Social-Political Reactions Towards of PurGen’s Deployment

- Opposition from key local officials, grassroots activists in Linden, and several statewide environmental groups who opposed the plant on environmental justice and public health grounds
  - A CCS plant burns 25-40% more coal
  - CO₂ leakage: Not Under My Backyard (NUMBY)
- Economic Feasibility
  - an unfavorable economic environment for coal
- Failure of expected federal climate change legislation
- Political Aspects
  - Opposition from the governor
  - Environmentalists protesting for cleaner energy
Also Cancelled: SCS EOR in California

The Project

Hydrogen Energy California (HECA) is a clean and reliable alternative energy solution that will provide significant economic and environmental benefits to Kern County and the State of California, while advancing California’s long term climate strategy.

As one of the first projects of its kind, HECA will bring together safe and commercially proven technologies into a single, multi-purpose operation that will generate a stable and predictable new source of clean, low-carbon electricity using hydrogen; minimize greenhouse gases released into the atmosphere; capture, store and utilize carbon dioxide (CO2) for enhanced oil recovery; and produce a much needed local source of low-carbon fertilizer.
Other projects under construction: largest Gorgon

Gorgon field NW Australia “wet” (14% CO₂) gas field
Project plans to inject 1 Mt Carbon/year
Cost $2 billion, Australian government $60 million

Source: Chevron

carbon dioxide injection project
the world’s largest commercial-scale carbon dioxide injection project

FORBES 2016 “Tillerson says Exxon is also involved in a third of worldwide projects to capture and sequester carbon dioxide.”
Captured CO₂ used to enhance production at the West Ranch oil field, from ~300 to 15,000 barrels per day.

190m$ Clean Coal Power Initiative Program

**Petra Nova**, Paris, TX Generating Station commercial-scale post-combustion carbon captures more than 90% of CO₂ sequestration of 1.6 Mton/yr

**Petra Nova EOR political reality**

Kemper Project, Mississippi
EOR 100 m$ pipeline to Denbury and Tellus oil fields

Lignite-fired electrical generating station using gasification & capture
President Obama's Climate Plan "clean coal"
DOE 270 m$ grant & 13 m$ tax credits
Cost of $2.4 billion increased to $7.1 billion due to cost overruns
Project management issues delayed May 2014 opening

Working project: Boundary Dam, Saskatchewan

Operational July 2014; first plant to capture carbon on an industrial scale
Sells CO₂ for EOR in Weyburn Field to offset costs
Costs: 1.4 b$C, 240 m$C Canadian government

Strengths
- Strong policy drivers to reduce emission
- Overcame many of the initial challenges:
  - 400 kT captured in Year 1; 800 kT in Year 2
- Cleanest coal-fired power plant in Canada

Weaknesses
- Plagued by problems, cost overruns
- Negative earnings (EBIT)
- Doubled price electricity
- Only 50% stored
- Subsidizing oil extraction
Other (cancelled) projects: Vattenfall

Vattenfall’s Germany failed experiments

Schwarze Pumpe steam generator pulverized coal, 30 MW achieved, ~100% CO₂ capture

Jänschwalde, Germany (scaled up) cancelled due to public opposition and lack of the German Government to delineate the CCS legal framework

CCS research was cut as Vattenfall decreases its R&D budget by 20%. They announced that they will focus on other energy sources as the challenging market conditions limited have spending.
Concerns about earthquake stimulation

Earthquake triggering and large-scale geologic storage of carbon dioxide

Mark D. Zoback\textsuperscript{a,1} and Steven M. Gorelick\textsuperscript{b}
Departments of \textsuperscript{a}Geophysics and \textsuperscript{b}Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO\textsubscript{2} emissions associated with coal-based electrical power generation and other industrial sources of CO\textsubscript{2} [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) Proc Natl Acad Sci USA 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO\textsubscript{2} into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO\textsubscript{2} repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

“We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO\textsubscript{2} into the brittle rocks commonly found in continental interiors.”

Not always true. Geology matters.
Models of injection into Logan Canyon Sands show pressures below failure.

Courtesy of D. Schrag and Schlumberger Carbon Services
10 Years

Courtesy of D. Schrag
50 Years (end of injection)

Courtesy of D. Schrag
60 Years (10 years after injection stopped)

Courtesy of D. Schrag
Conclusions

Geology is ready!

Onshore suitable for storage at Beesley’s Point, NJ and Indian River, DE not feasible due to NUMBY and Green opposition.

The Logan Canyon Sands are a world class target for storage offshore; Could have multiple injection sites on east coast.

Political opposition to geological storage offshore; PurGen plan could be done with natural gas; Greens might not oppose.

Economics not there without a price for carbon.

All current projects are EOR or “wet” gas recovery.
In Memoriam
Christopher J. Lombardi

Chris passed unexpectedly on Nov. 29, 2016 and will be posthumously awarded a Ph.D. in Geological Sciences from Rutgers University May 2017.

Chris had been working with the New Jersey contingent of the Midwest Regional Carbon Sequestration Partnership (MRCSP) for the past 4 years as a graduate student at Rutgers University. He made great strides in the correlation of chronostratigraphy of Mid-Atlantic offshore formations that are being evaluated for carbon storage opportunities. Specifically, his work on the Great Stone Dome and adjacent areas shows that sands targeted for carbon storage are bracketed by sequence boundaries, provided increased confidence in their continuity and seals.
Requirements

Large stationary point source

Reservoir: saline aquifers (not in potable water)

Cap rock: confining bed mudstones

Burial > 800 m deep

Geology matters
Earthquake issues

Earthquakes: injection of fracking fluids into underground disposal wells causes faults to slip. This is what is responsible for Oklahoma’s massive earthquake spike. Yet, same injection in TX does not. Geology matters.

Earthquakes Caused by Human Activity

The maps below show where there has been seismic activity, caused mostly by oil and gas operations. Northern Oklahoma and southern Kansas have been especially hard hit, with an exponential growth in the number of human-caused earthquakes.

So

The New York Times

U.S. Maps Pinpoint Earthquakes Linked to Quest for Oil and Gas

By RICHARD PÉREZ-PÉÑA APRIL 23, 2015

U.S.

New Concern Over Quakes in Oklahoma Near a Hub of U.S. Oil

By MICHAEL WINES OCT. 14, 2015
Current Geologic CO$_2$ Injection Projects

- Commercial-scale & demonstration projects are taking place around the world – USA, Canada, Norway, Spain, Algeria, Australia, China, and Japan
- Most are tied to O&G, disposal of “wet” gas CO$_2$ or EOR

Operational CCS Projects

Source of images: Global CCS Institute
40 Years

Courtesy of D. Schrag