Reservoir and Seal Pairs:

CARBON SEQUESTRATION IN ATLANTIC CANADA

Hayley Pothier
G.D. Wach and M. Zentili
INTRODUCTION

**Basin Suitability**
- Seismicity
- Depth
- Fault intensity
- Geothermal regimes
- On vs. Offshore
- Accessibility
- Existing petroleum or coal resources
- Industry maturity

**Identifying a Prospective Site**
Site details meet all of the reservoir and seal criteria for CO₂ sequestration.

**Detailed Site Characterization**

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**Injectivity**
- quality
- geometry
- connectivity

**Containment**
- geomechanics
- hydromechanics
- seal and trap

**Capacity**
- geological models
- porosity

**Economics**
- Capital and operating costs; compression transport & injection

**Risk**
- Risk assessment
- CO₂ loss
- uncertainty

**Monitoring**
- direct and remote sensing
- near surface & atmosphere

**Decision to Commercialise**
- Proved Capacity
- Monitoring and verification
- Economics
- Injection
- Regulation

(Modified from Gibson-Poole, 2008)
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(Modified from Gibson-Poole, 2008)
Atlantic Canada Sedimentary Basins

- Paleozoic and Mesozoic basins for CO\textsubscript{2} storage near several major sources.

- Carbonate and clastic reservoirs have seal pairs.

- Capped by thick shale deposits or evaporite deposits which can form excellent seals.
SOURCES OF CO$_2$
SOURCES OF CO$_2$

Emissions for Nova Scotia Power Generating Stations

- 2004
- 2005
- 2006
- 2007
- 2008

Megatonnes of CO$_2$

LEGEND
- Power generation plant
- Cement plant
- Pipe line
- 150 km radius around CO$_2$ source

(Modified from NS Power Group Inc.)
MARITIMES BASIN

- Magdalen, Sydney, & Cumberland Basins

(Modified from Hu and Dietrich, 2008)
**Horton Group:** lacustrine clastic sediments
**Windsor Group:** marine incursions including evaporites and limestones mixed with red muds

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(Modified from Hu and Dietrich, 2008)
- **Cumberland (Morien) Group**: lacustrine and fluviodeltaic shale, widespread coal
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MARITIMES BASIN

- **Pictou Group**: red mudstones & sandstones
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MAGDALEN BASIN

- Up to 12 kilometers of continental and shallow marine strata
- Two major tectono-stratigraphic units:
  - Clastics and volcanic rocks in fault-bounded sub-basins
  - Carbonates, evaporites and clastics
- Abundant coal beds (Pictou Group)
- Structures associated with rift faulting and salt tectonics
MAGDALEN BASIN

Reservoir: widespread reservoir strata of continental and shallow marine sediments.

(quality in deeper parts of the basin (below 2000 m) is a risk as the sandstones may be of low porosity and tight )

Seal: Carboniferous volcanics and middle Carboniferous carbonates and evaporites.
SYDNEY BASIN

- Same stratigraphy as Magdalen Basin, with less salt
- Contains abundant coal
  - mining has provided useful information about seal geometry

**Reservoir:** coarse clastics

**Seal:** evaporites and salt of the Windsor Group
SALMON RIVER SUBBASIN

- Analog for the Sydney basin
- ‘Walk in’ reservoir

(Modified from Scott, 1990)
SALMON RIVER SUBBASIN

Polished thin sections in reflected light – 275x

Sandstone with galena emphasizing layers

Thin sections in PPL - 45x
Polished thin section in reflected light – 275x

Sandstone with galena emphasizing layers

Thin sections in PPL - 45x

SALMON RIVER SUBBASIN
SALMON RIVER SUBBASIN

PARTIAL LOBE

Ore zone in thin repeating cyclical units (1-3 m thick). Up to 4 cycles, limited continuity of rock units - partic. shale. Sandstone massive and coarse-grained, abundant coal lag. Footwall locally comprising green siltstone assemblage.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Shale (0-1.5m)</td>
<td>Dark grey claystone &amp; siltstone, commonly slump folded.</td>
</tr>
<tr>
<td>Sandstone (1-2.5m)</td>
<td>Coarse-grained, massive sandstone with coal partings, occasional cross-bedding.</td>
</tr>
<tr>
<td>Conglomerate (0-10m)</td>
<td>Shale flake congl., limestone pebble congl. &amp; coal lag. All with sand matrix.</td>
</tr>
<tr>
<td>Green Siltstone Assemblage</td>
<td>Interbedded green shale (0-1m), siltstone (0-1m) &amp; shale flake congl. (0-3m).</td>
</tr>
<tr>
<td>WINDSOR</td>
<td>Green clay - regolith (0-70cm) Calcrete (0-1.5m) Windsor shales - green &amp; maroon shales and siltstones.</td>
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SOUTH EAST LOBE

Ore zone confined to thick 1st cycle (2-6 m) and base of 2nd cycle. Units traceable throughout lobe area. 1st cycle sandstone medium-grained and commonly cross-bedded.

<table>
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<th>Cycle</th>
<th>Description</th>
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<td>2nd Cycle</td>
<td>Shale (1-10m) Sandsone (5cm-2m) Conglomerate (0-1.5m)</td>
</tr>
<tr>
<td>1st Cycle</td>
<td>Shale (0-2m) Laminar bedded silty mudstone commonly slump folded. Sandstone (1-4m) Medium grained sandstone massive &amp; cross-bedded. Limestone Pebble Conglomerate (0-1.5m)</td>
</tr>
<tr>
<td>WINDSOR</td>
<td>Green clay - regolith (0-30cm) Calcrete (0-1m) Windsor shales - green &amp; maroon shales and siltstones.</td>
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YAVA MINE

GENERALIZED STRATIGRAPHY

West Zone Ore Column (average height - 4.5m)

(Modified from Scott, 1990)
SALMON RIVER SUBBASIN

YAVA-WEST ZONE
Distribution of shale horizons in mine workings

(Modified from Scott, 1990)
CUMBERLAND BASIN

- Fault bounded with 8 km of Carboniferous strata
- Accumulated in phases of subsidence and inversion
- Faulting and salt withdrawal increased accommodation space

(Modified from Waldron and Rygel, 2006)
**CUMBERLAND BASIN**

- Fault bounded with 8 km of Carboniferous strata
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(Modified from Waldron and Rygel, 2006)
Joggins Section

- Alternating lacustrine-braided floodplain cycles
- More extensive coal and shale units
- Coal-bearing – beds up to 2 m thick
- Transition into finer grained red beds

(Davies et. al., 2005)
CUMBERLAND BASIN - JOGGINS
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CHANNEL
SCOTIAN BASINS

- Fundy, Orpheus, & Abenaki/Sable Basins

(Modified from Natural Resources Canada, 2008)
SCOTIAN BASINS

- Fundy, Orpheus, & Abenaki/Sable Basins

(Modified from Natural Resources Canada, 2008)
FUNDY BASIN

- Half graben basin
- Wolfville Fm. deposited in continental environments by fluvial and aeolian processes.

Reservoir: Wolfville and Blomidon formations

Seal: North Mountain Basalt

(Modified from Moore, 2000)
FUNDY BASIN – CAMBRIDGE COVE
FUNDY BASIN

EAST

WEST

CAMBRIDGE COVE - WOLFVILLE/ HORTON CONTACT

Channel Bodies
Sandstone and Conglomerate
Siltstone
Shale

Lithological Boundary
Angular Unconformity
Fault
FUNDY BASIN

(Modified from Kettanah et al., 2008)

Well cemented - No porosity

Microfracture Microporosity

Dissolution Microporosity

Primary Porosity

Grain Boundary Microporosity

Mixed Primary and Secondary
FUNDY BASIN

(Modified from Kettanah et al., 2008)

Well cemented - No porosity
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Primary Porosity
Grain Boundary Microporosity
Mixed Primary and Secondary

Ineffective
Effective
ORPHEUS BASIN

- Syn-rift sequences related to the opening of the Atlantic
- Eurydice Fm. total thickness of over 3 km

Reservoir: fine grained to conglomeratic clastics of the Eurydice Formation.

Seal: possibly thick evaporite deposits of the Argo Formation.
ABENAKI FM. AND SABLE BASIN

- Shelf margin deltas deposits
- Up to 16 km thick
- Existing Sable gas fields and new development of Deep Panuke carbonate trend.

(Modified from Kidston et al., 200)
**Reservoir:** Both clastic and carbonate reservoirs. Extensive tidal-fluvial sandstones with thickness of more than 40 m with high porosity and permeability.

**Seal:** Thick transgressive shales. Also non-porous limestone in the mixed-carbonate-siliciclastic settings.
ABENAKI FM. AND SABLE BASIN

Potential Storage Reservoirs

- Wyandot (chalk)
- Logan Canyon
- Missisauga
- Abenaki (carbonate)

(Kidston et al., 2005)
ABENAKI FM. AND SABLE BASIN

Potential Seals

- Banquereau Shale
- Naskapi Shale
- Misaine Shale

(Kidston et al., 2005)
FUTURE WORK

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(Modified from Gibson-Poole, 2008)

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SUMMARY

- Eastern Canada has several major CO$_2$ emission sites
- Atlantic sedimentary basin have potential candidates for CO$_2$ storage
  - Reservoir – extensive sandstone units
  - Seal – thick marine transgressive shales and evaporites
## MARITIMES BASIN

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<th>Pros</th>
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<td><strong>Cumberland</strong></td>
<td>Pennsylvanian coarse clastics (Joggins and Polly Brook Fms.)</td>
<td>evaporites</td>
<td>Close proximity to emission site</td>
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<tr>
<td><strong>Magdalen</strong></td>
<td>Devono-Carboniferous to Permian age coarse clastics</td>
<td>Mississippian evaporites and salt</td>
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<td><strong>Sydney</strong></td>
<td>Devono-Carboniferous to Permian age coarse clastics</td>
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# BASIN EVALUATION

## SCOTIAN BASIN

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<td><strong>Orpheus</strong></td>
<td>fine grained to conglomeratic clastics (Eurydice Fm.)</td>
<td>thick evaporites (Argo Fm.)</td>
<td>Close proximity to emission site; potential for salt seal</td>
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<tr>
<td><strong>Sable</strong></td>
<td>thick deltaic sands (Missisauga Fm.)</td>
<td>thick transgressive prodelta shales</td>
<td>Pipeline in place and good porosity</td>
</tr>
<tr>
<td><strong>Abenaki</strong></td>
<td>carbonates with fracture and dolomitic porosity (Abenaki Fm.)</td>
<td>thick transgressive prodelta shales</td>
<td>Pipeline in 2010; planned H₂S injection site so some infrastructure</td>
</tr>
<tr>
<td><strong>Fundy</strong></td>
<td>fine grained to conglomeratic clastics (Blomidon and Wolfville Fms.)</td>
<td>Basalt</td>
<td>Good Porosity</td>
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ACKNOWLEDGMENTS

- Yawooz Kettanah
- Muhammed Kettanah
- Hasley Vincent
- Peter Mulcahy
- Jordan Nickerson
- Beth Cowan
- Martin Gibling
ABENAKI STRATIGRAPHY

Detailed sequence stratigraphic chart for the Abenaki Formation (Encana)

(Kidston et al., 2005)
BU = Break-up Unconformity (~mid-late Sinemurian)

**SOURCES**
1. Early Synrift (Triassic: Carnian - Norian)
2. Late Synrift (Jurassic: Hettangian - Sinemurian)
3. Mohican (Toarcian – Aalenian)
4. Jurassic Verrill Canyon (Oxfordian – Kimmeridgian)
5. Cretaceous Verrill Canyon (Berriasian - Valanginian)

**RESERVOIRS**
1. Scatarie / Abenaki 1 (Bajocian – Callovian)
2. Baccaro / Abenaki 4, 5 & 6 (Callovian – Kimmeridgian)

**SEALS**
1. Misaine / Abenaki 2 for Scatarie / Abenaki 1
2. Top Abenaki 6 for Baccaro / Abenaki 4, 5 & 6
3. Lower Cretaceous Shales for Baccaro / Abenaki 4, 5 & 6

**OVERBURDEN**
Several periods of variable erosion:
1. Early Cretaceous (Aptian?)
2. Early Eocene
3. Late Eocene (Montagnais Impact Event)
4. Late Paleocene
5. Middle Oligocene
6. Middle Miocene

**TRAP FORMATION**
1. Diagenetic & Subsidence (L. Jur. – E. Cret.)
2. Tectonic & Structural (L. Cret.)

**TIMING**
Expulsion periods based on previously modelled deepwater succession (Kidston et al., 2002 – Sites 3-5).

Figure 25. Events Timing Chart – regional Abenaki Formation. This chart does not reflect the differences for each of the three defined segments. Individual charts for the Panuke and Acadia Segments are shown in Figures 92 and 109 respectively.
**BASIN EVALUATION CRITERIA**

**Depth** – Greater than 800 m, less than 2,500 m

**Thickness** – A minimum thickness of 20 m has been suggested

**Area** - Although this is not part of the indicators, a polygon of 15 km x 15km is suggested for the purpose of this proposal

**Porosity** – A minimum of 10%

**Permeability** – A minimum of 10 mD

**Salinity** – a minimum of 30,000 mg/l

**Caprock Thickness** – Minimum of 20 m

**Caprock Lateral Continuity** – Low to moderate faulting

**Capillary Entry Pressure** – Similar to buoyancy force of maximum predicted height of CO₂ column