Reservoir and Seal Pairs:

CARBON SEQUESTRATION IN ATLANTIC CANADA

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Inspiring Minds

Basin & Reservoir Lab

CONTENTS

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 CO_2 sequestration.

Detailed Site Characterization

Structural Model

- geometry of major horizons
- fault juxtaposition
- fault/fracture intensity

Stratigraphic Model

- sedimentology
- depositional environments
- sequence stratigraphy

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
- CO_2 loss
- uncertainty

Monitoring

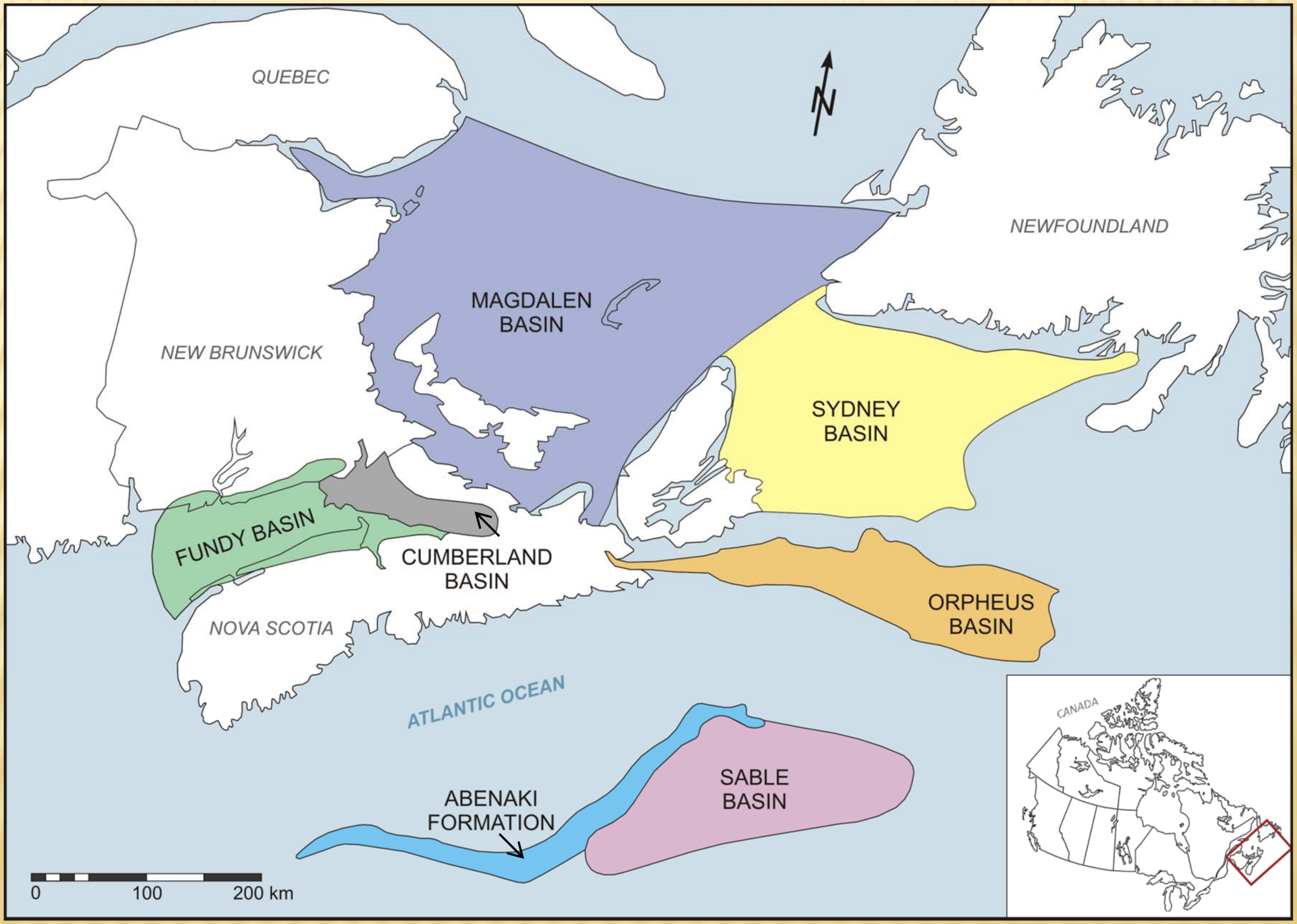
- direct and remote sensing
- near surface & atmosphere

Decision to Commercialise

- Proved Capacity
- Monitoring and verification
- Economics
- Injection
- Regulation

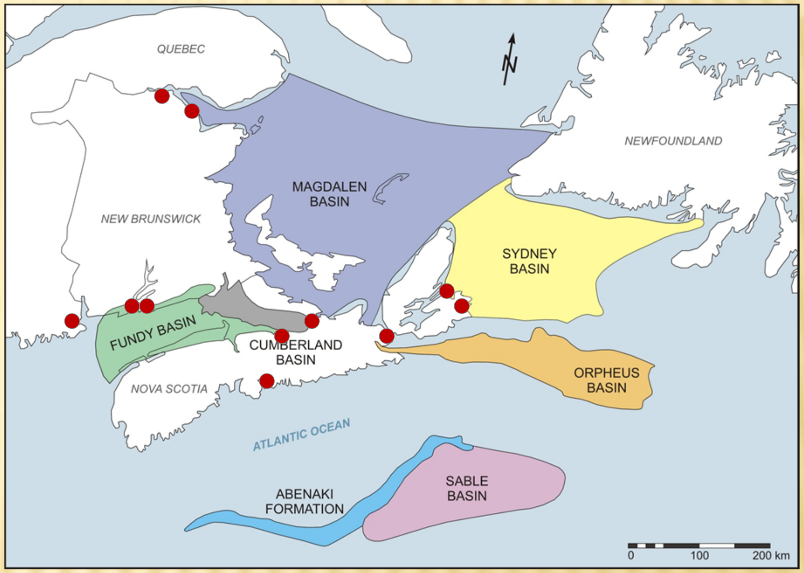
(Modified from Gibson-Poole, 2008)

ATLANTIC CANADA SEDIMENTARY BASINS



ATLANTIC CANADA SEDIMENTARY BASINS

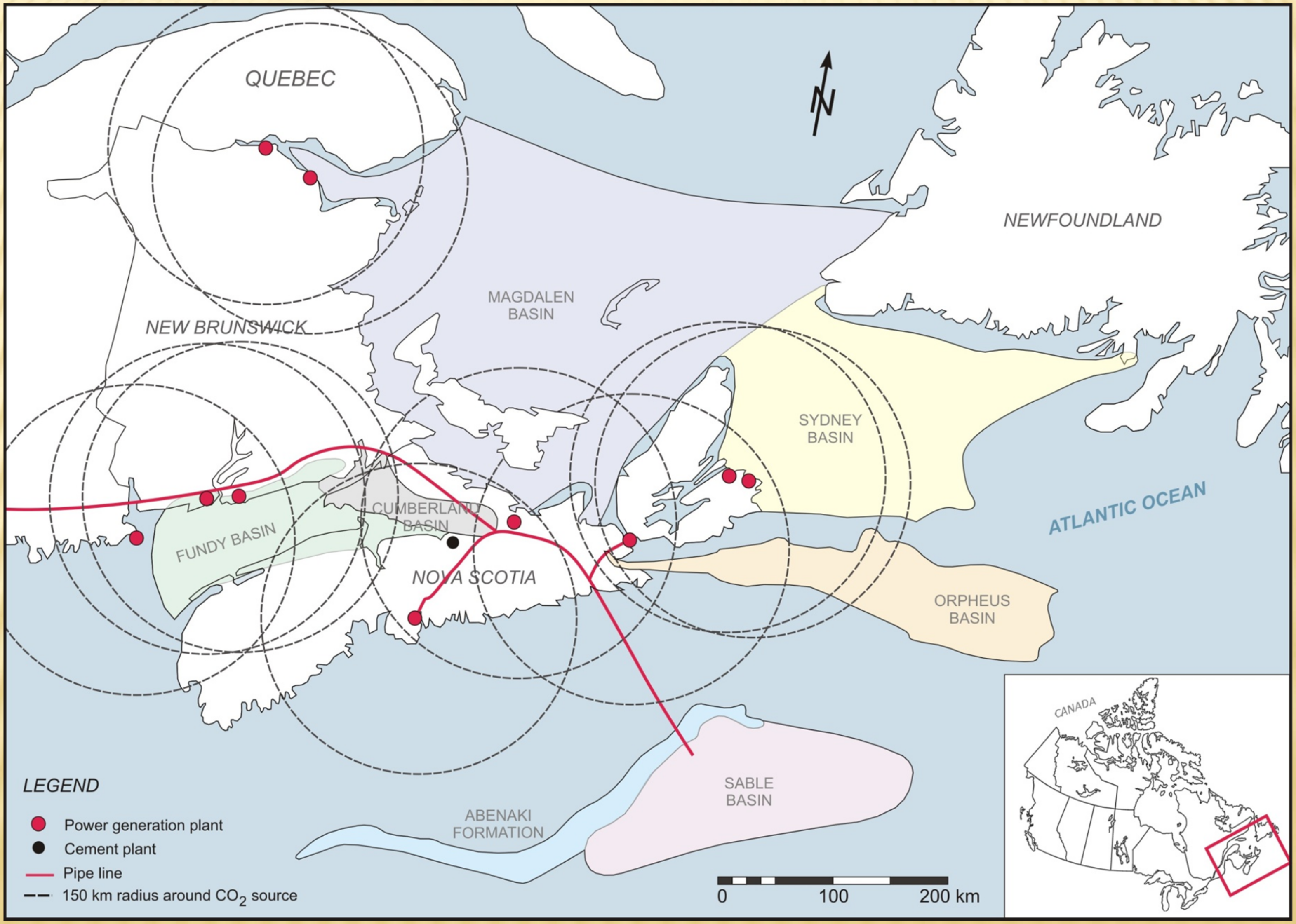
- Paleozoic and Mesozoic basins for CO_2 storage near several major sources.



- Carbonate and clastic reservoirs have seal pairs.

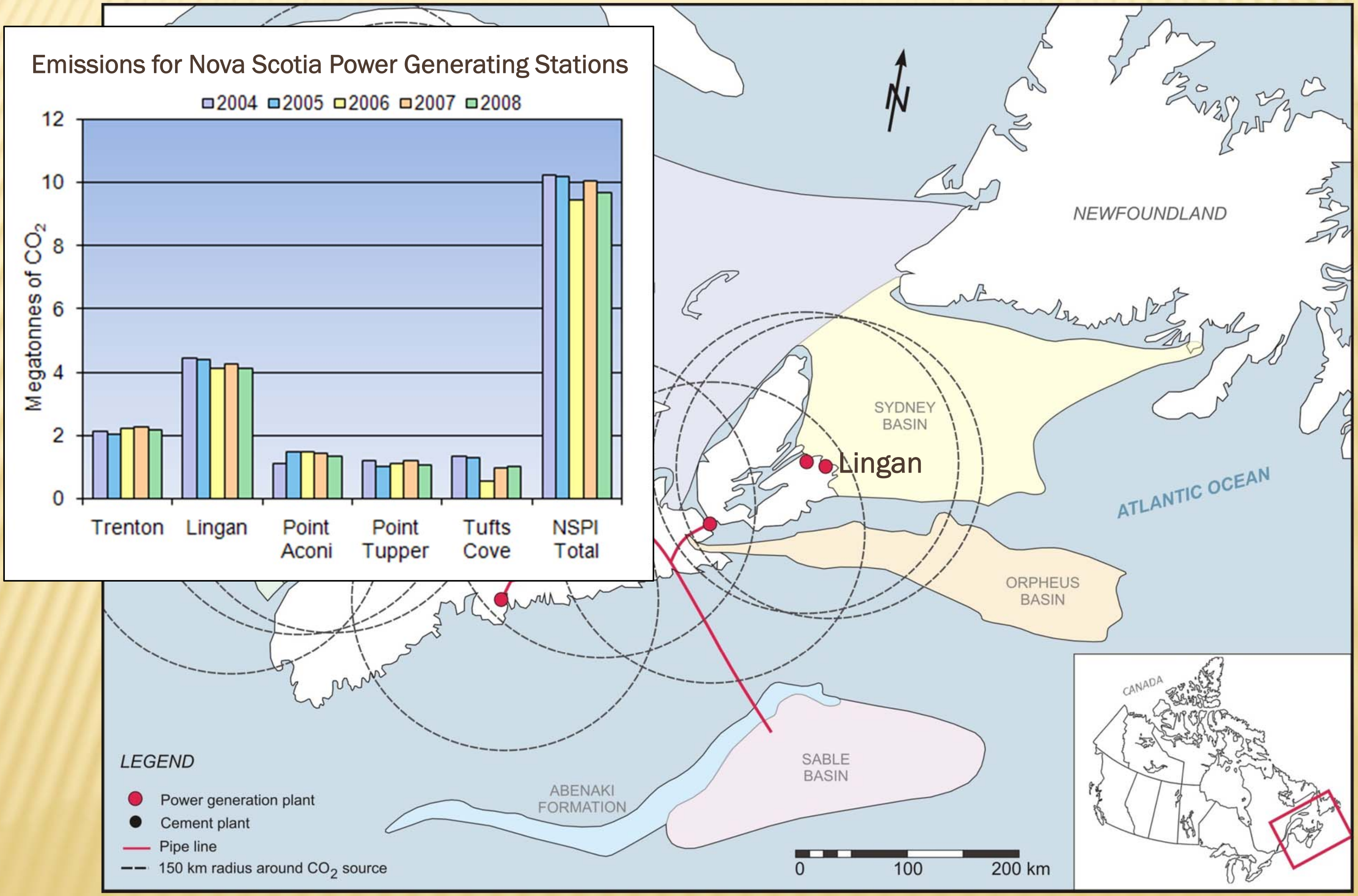
- Capped by thick shale deposits or evaporite deposits which can form excellent seals

SOURCES OF CO_2



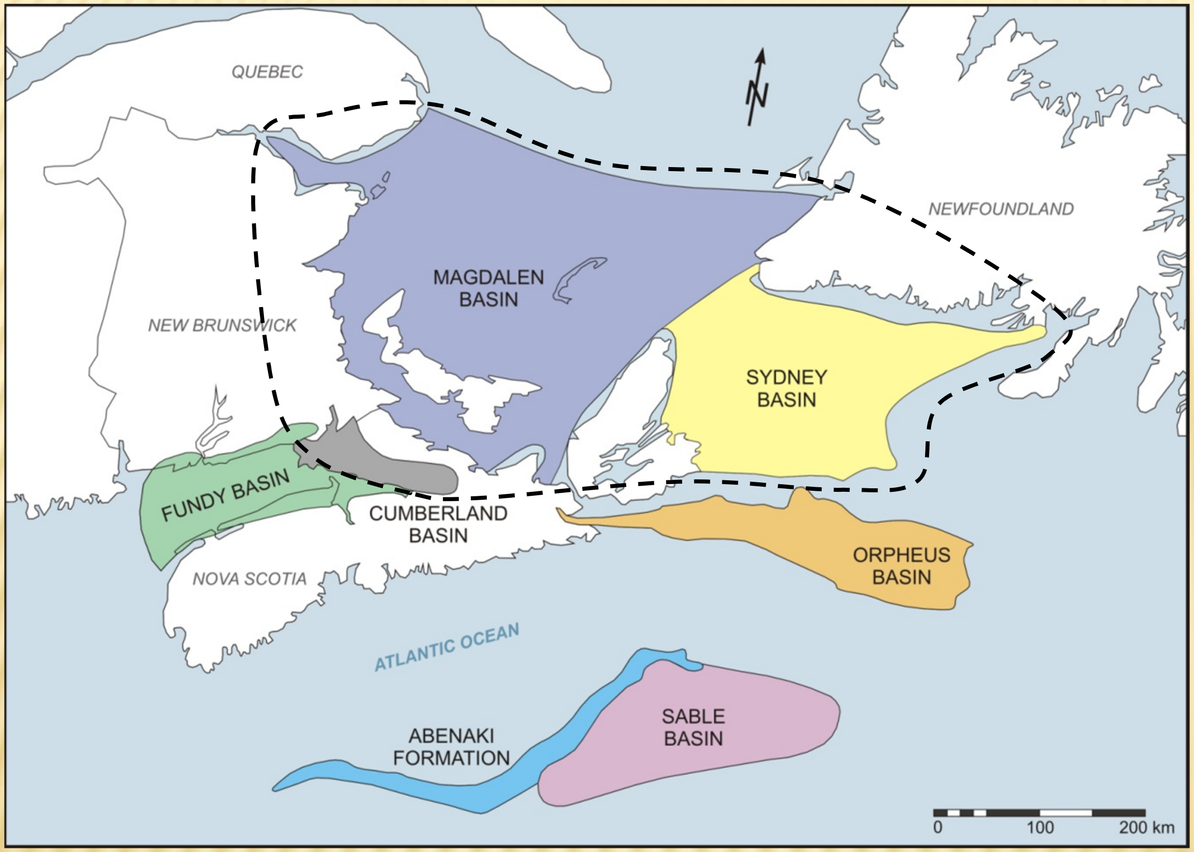
(Modified from)

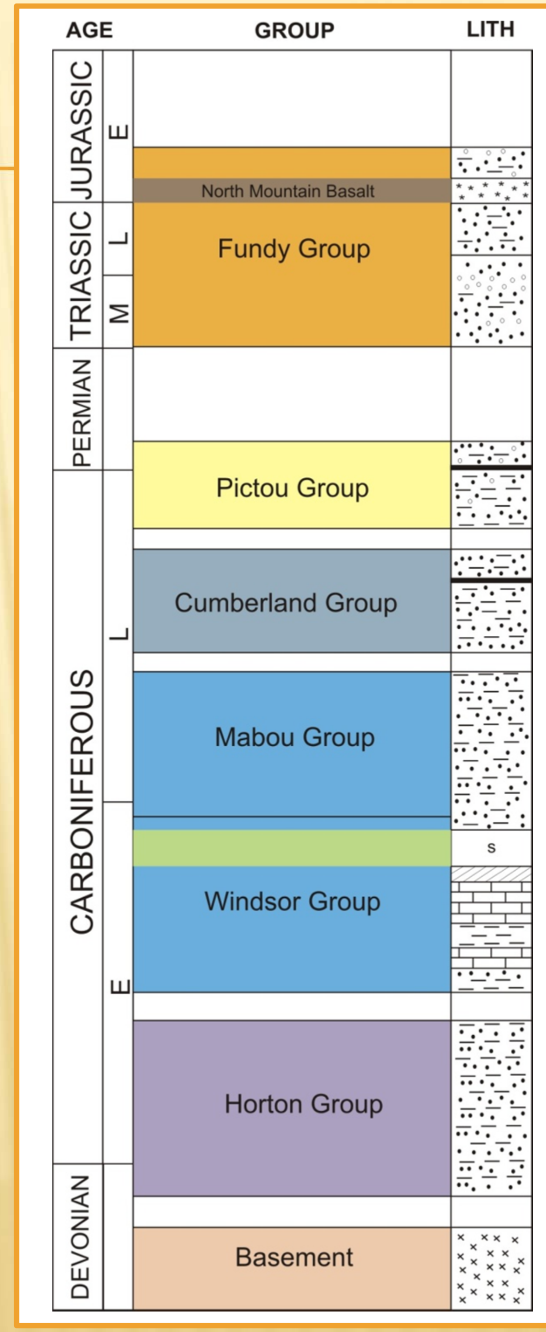
SOURCES OF CO_2



(Modified from NS Power Group Inc.)

MARITIMES BASIN

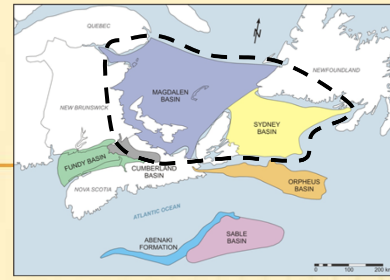


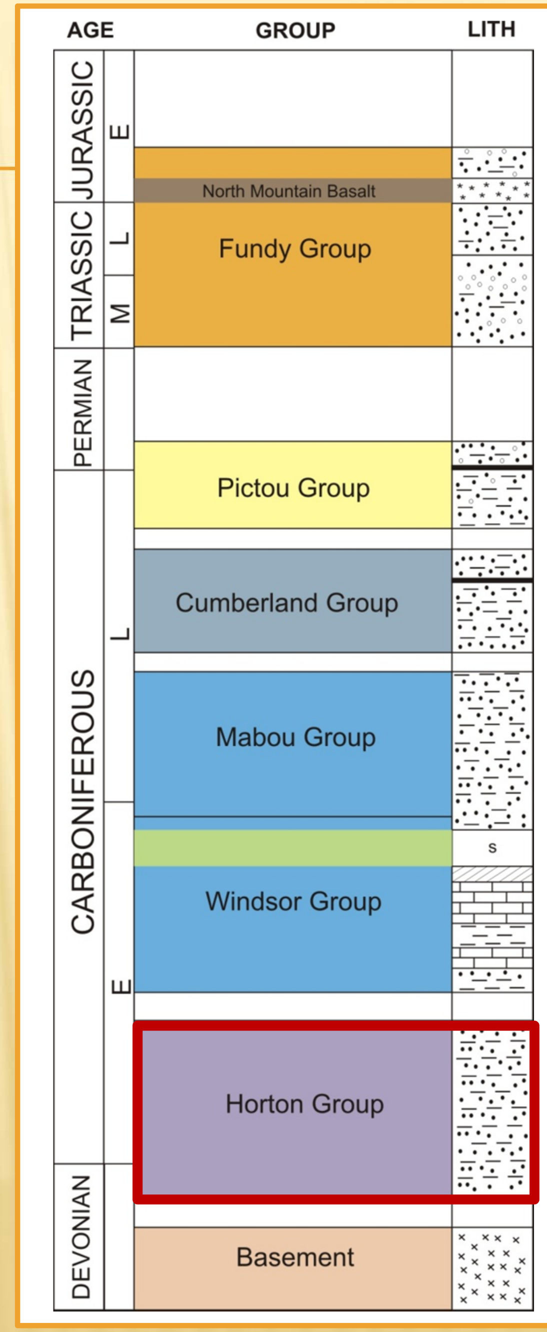


(Modified from Hu and Dietrich, 2008)

- Magdalen, Sydney, & Cumberland Basins

MARITIMES BASIN

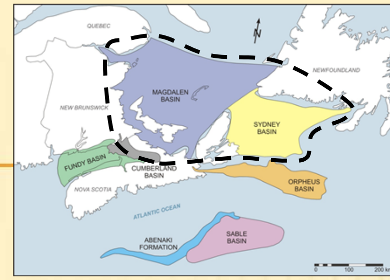




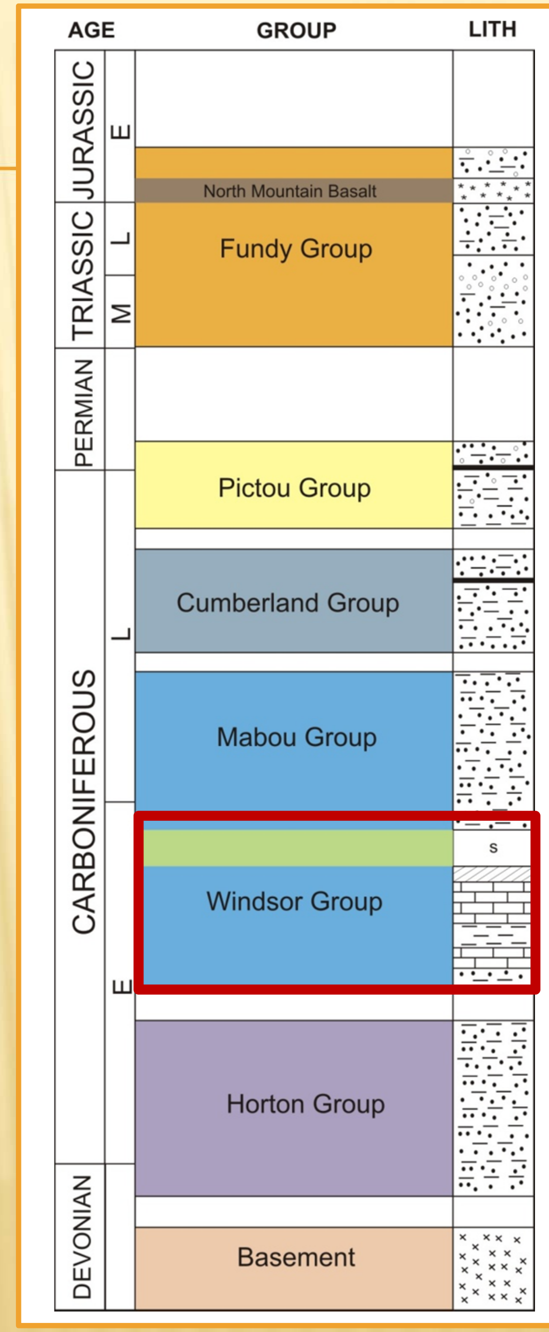
(Modified from Hu and Dietrich, 2008)

- **Horton Group:** lacustrine clastic sediments

MARITIMES BASIN



- **Windsor Group:** marine incursions including evaporites and limestones mixed with red muds
- **Horton Group:** lacustrine clastic sediments



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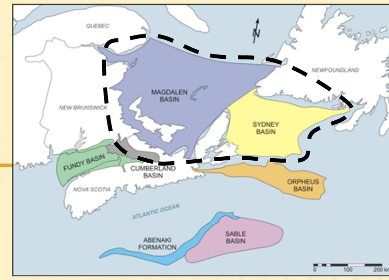
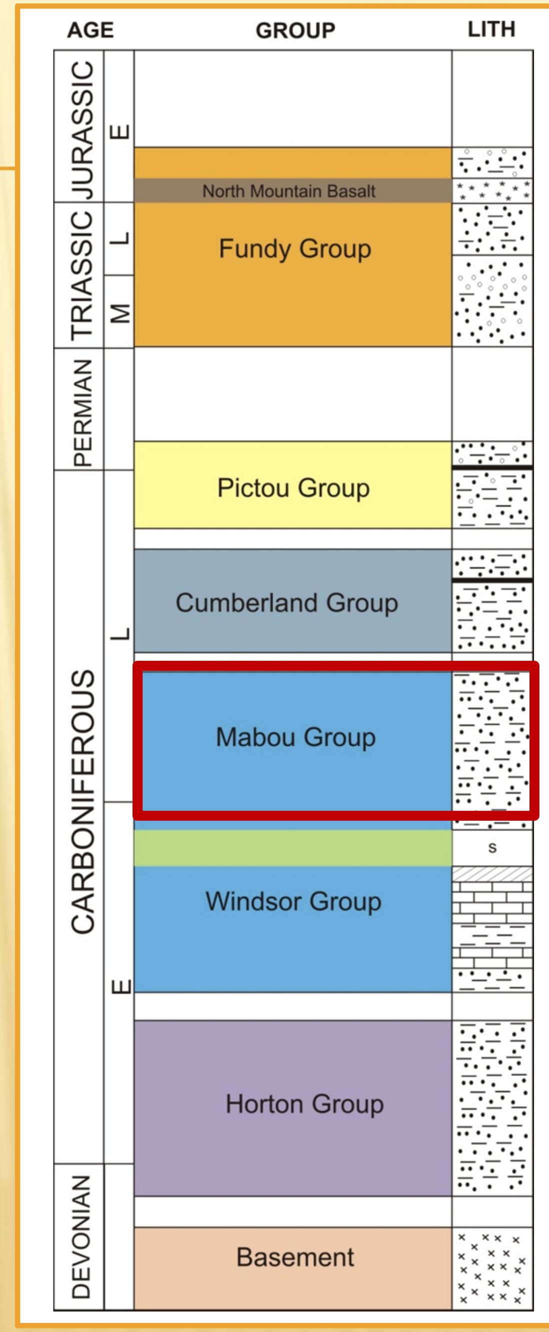


- **Mabou Group:** clastic, non-marine sediments
- **Windsor Group:** marine incursions including evaporites and limestones mixed with red muds
- **Horton Group:** lacustrine clastic sediments



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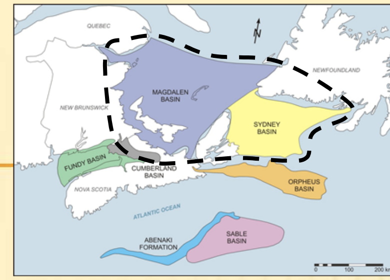

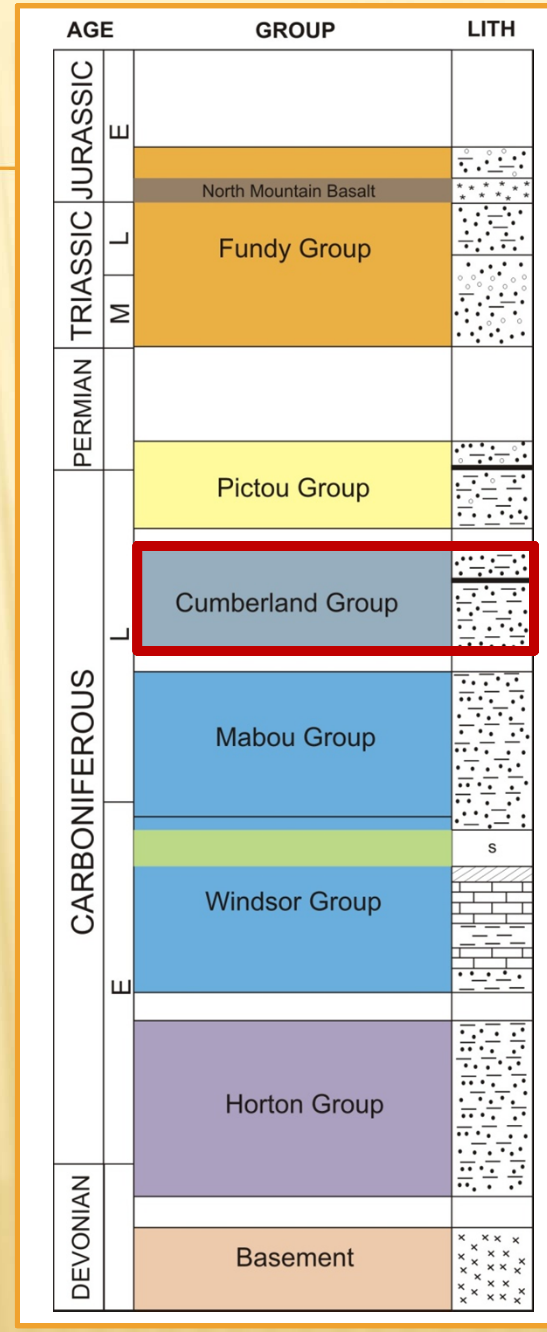

(Modified from Hu and Dietrich, 2008)

- **Cumberland (Morien) Group:** lacustrine and fluviodeltaic shale, widespread coal
- **Mabou Group:** clastic, non-marine sediments
- **Windsor Group:** marine incursions including evaporites and limestones mixed with red muds
- **Horton Group:** lacustrine clastic sediments

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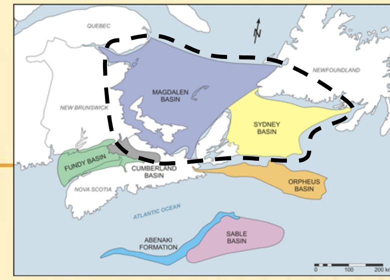

- **Pictou Group:** red mudstones & sandstones
- **Cumberland (Morien) Group:** lacustrine and fluviodeltaic shale, widespread coal
- **Mabou Group:** clastic, non-marine sediments
- **Windsor Group:** marine incursions including evaporites and limestones mixed with red muds
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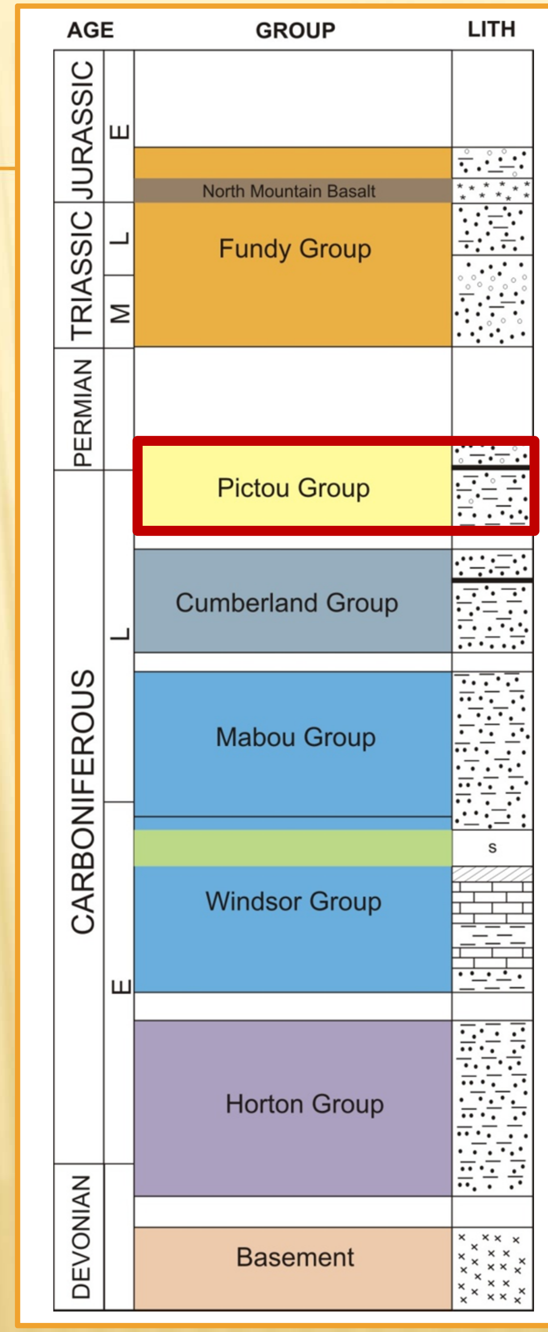
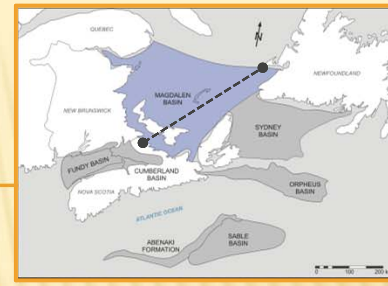
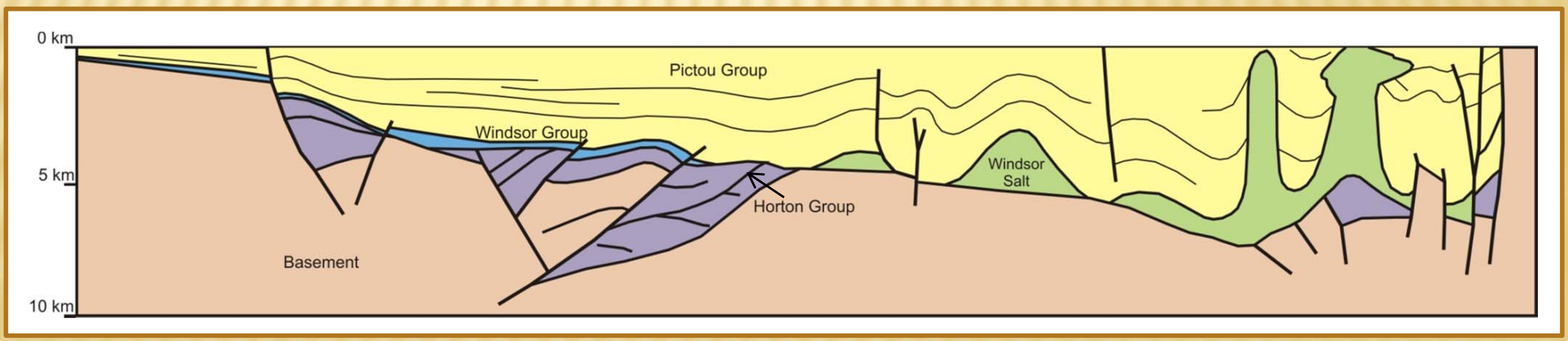


(Modified from Hu and Dietrich, 2008)

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



(Modified from Dietrich, 2009)

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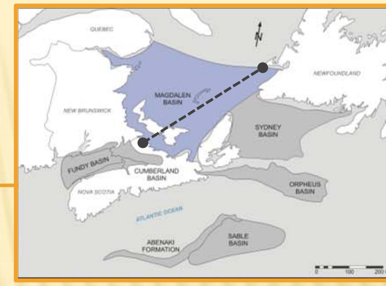
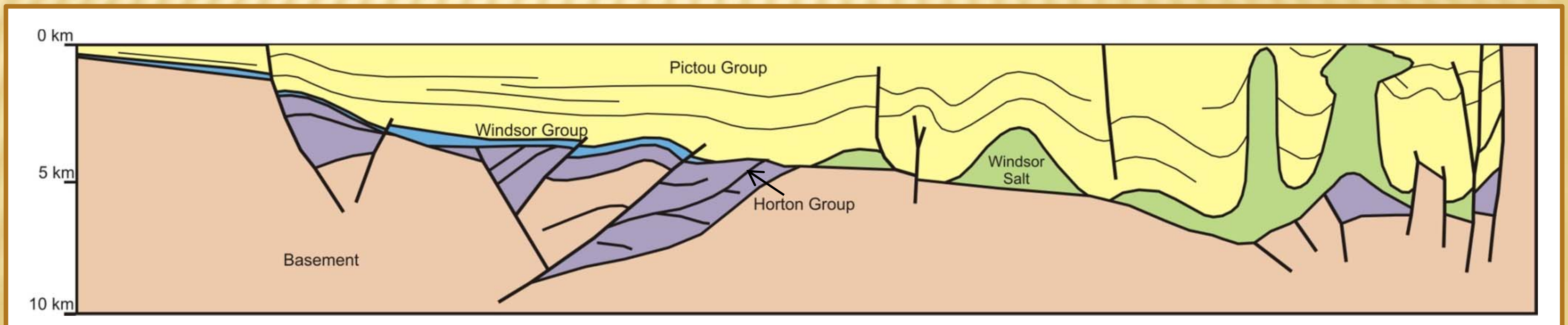


Reservoir: widespread reservoir strata of continental and shallow marine sediments.

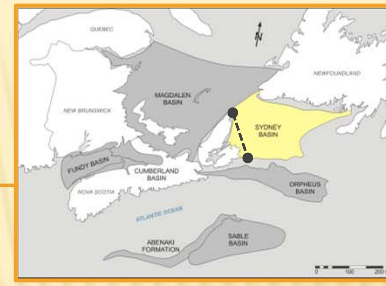
(quality in deeper parts of the basin (below 2000 m) is a risk as the sandstones may be of low porosity and tight)

Seal: Carboniferous volcanics and middle Carboniferous carbonates and evaporites.



(Modified from Dietrich, 2009)

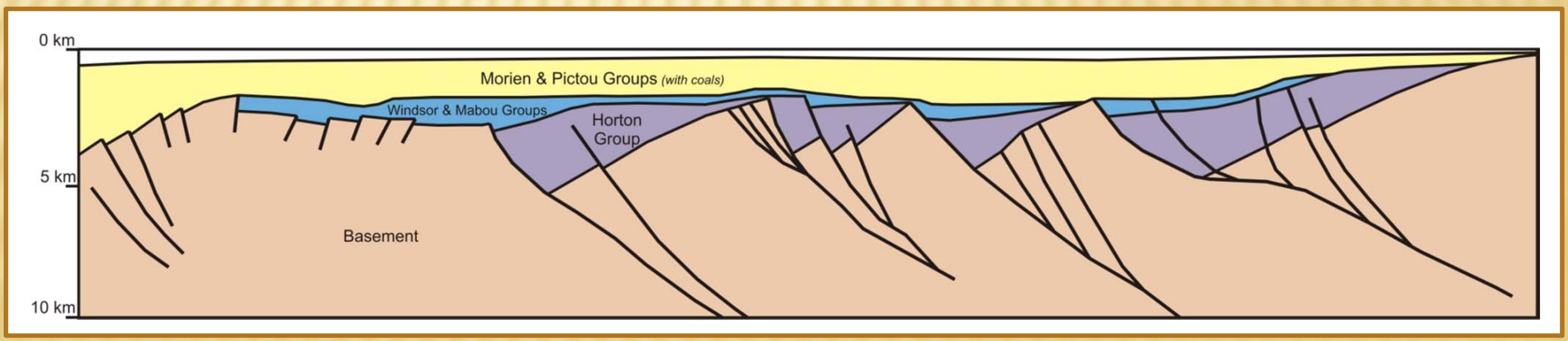
SYDNEY BASIN



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

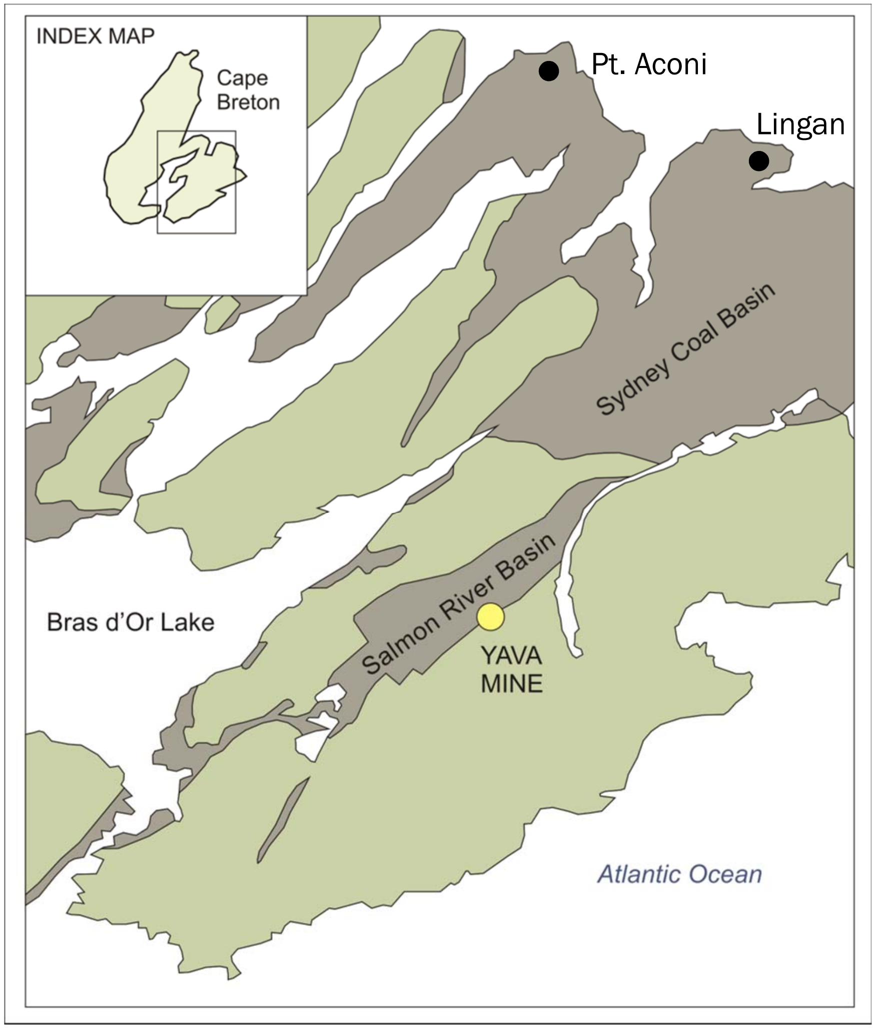
Reservoir: coarse clastics

Seal: evaporites and salt of the Windsor Group



(Modified from Enachescu, 2006)

SALMON RIVER SUBBASIN

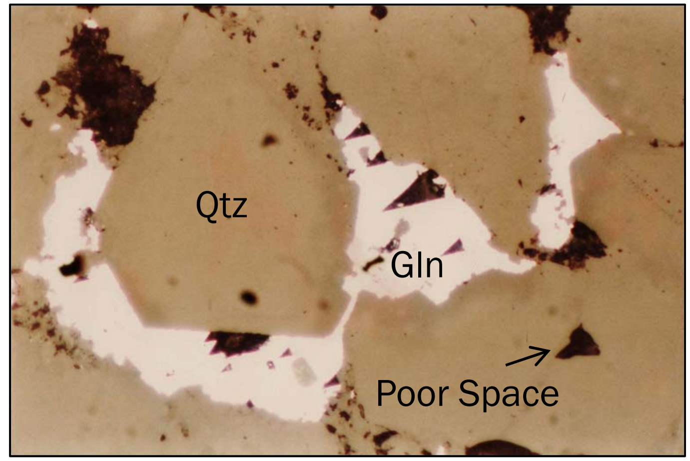


- Analog for the Sydney basin
- *'Walk in'* reservoir

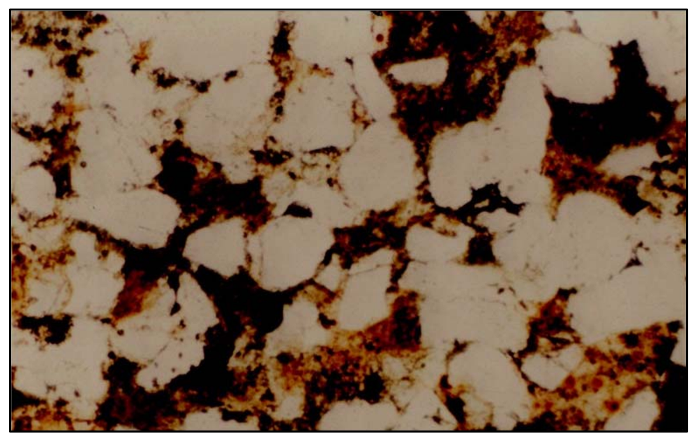
(Modified from Scott, 1990)

SALMON RIVER SUBBASIN

Sandstone with galena emphasizing layers



Polished thin sections in reflected light – 275x



Thin sections in PPL - 45x

SALMON RIVER SUBBASIN

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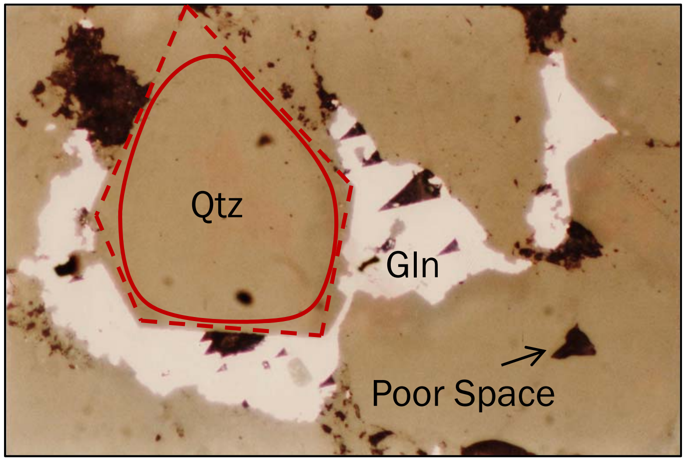

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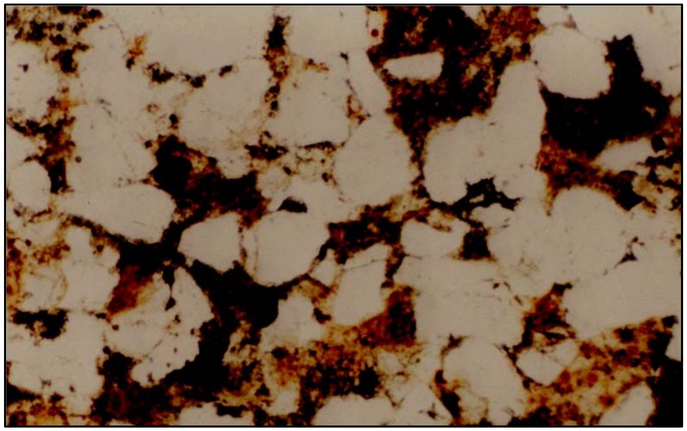

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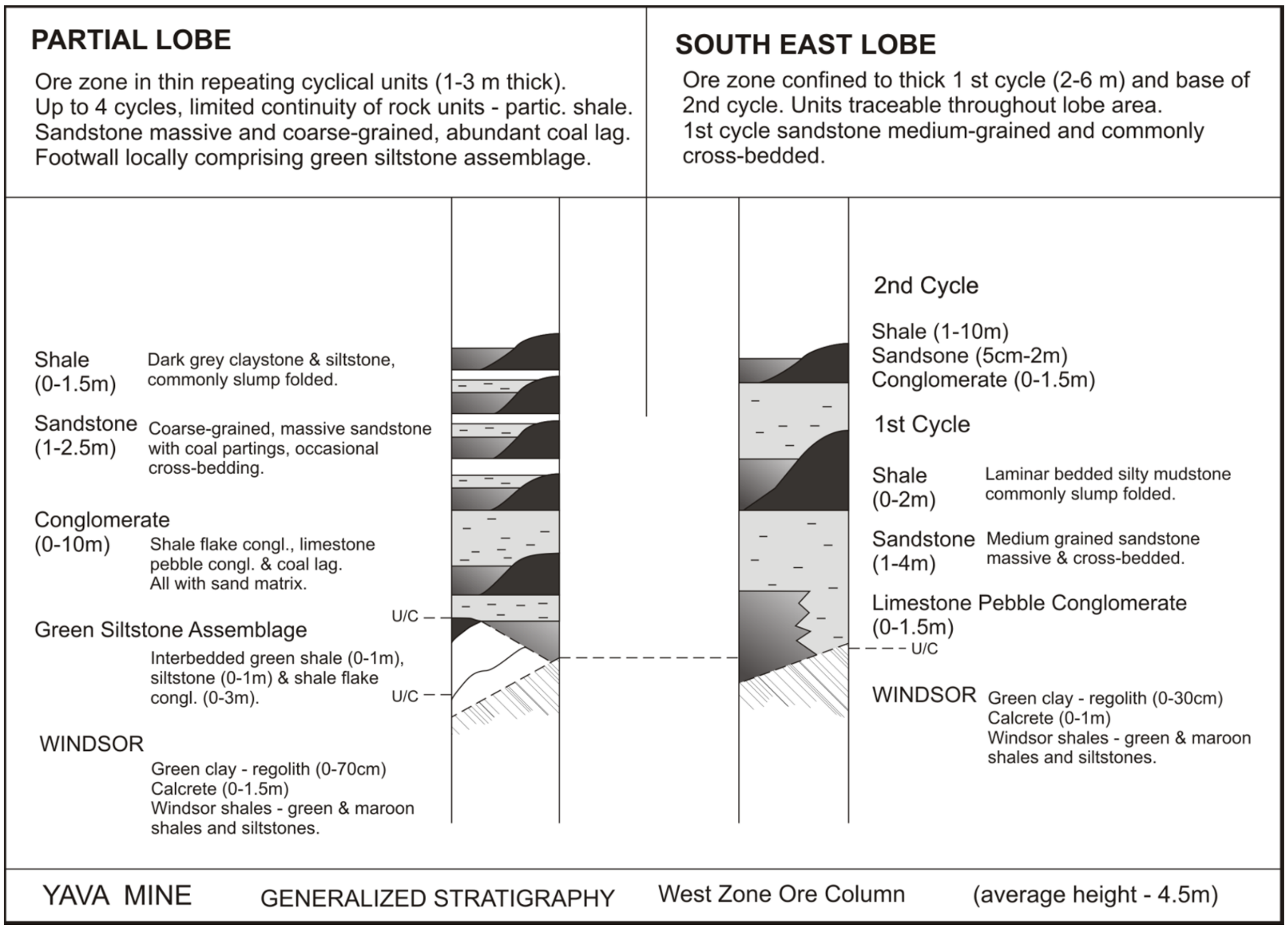

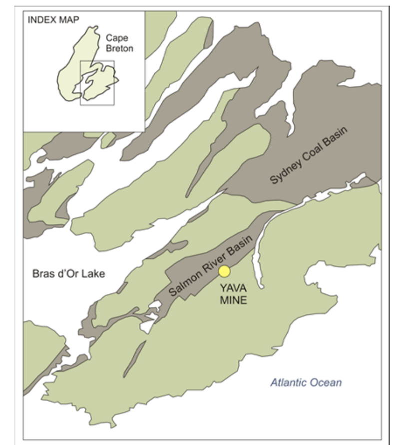

(Modified from Scott, 1990)

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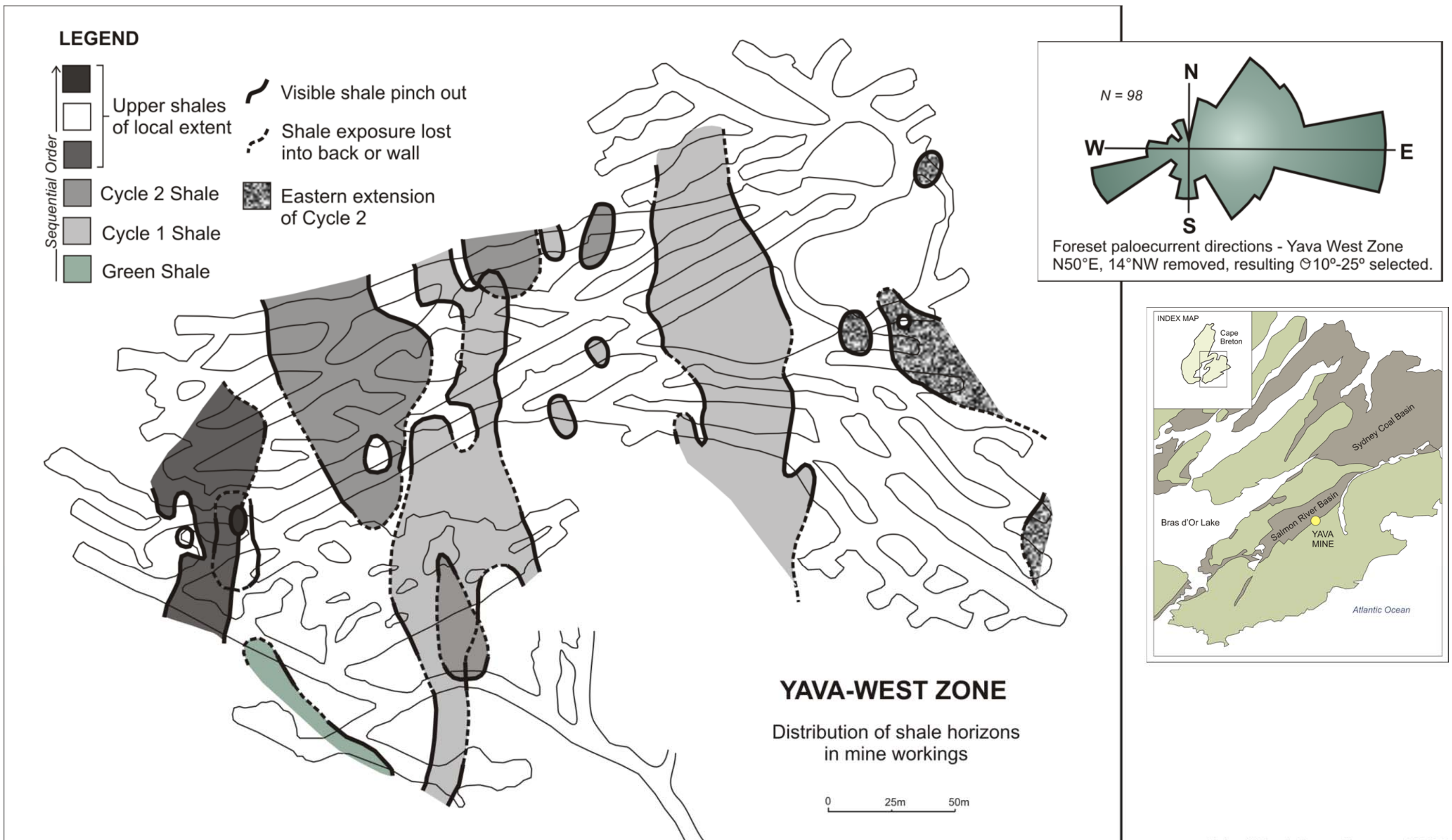
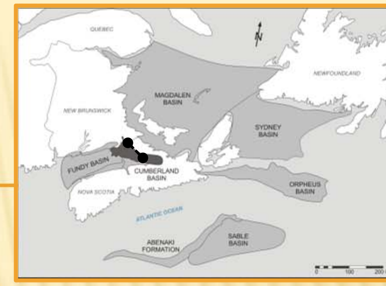
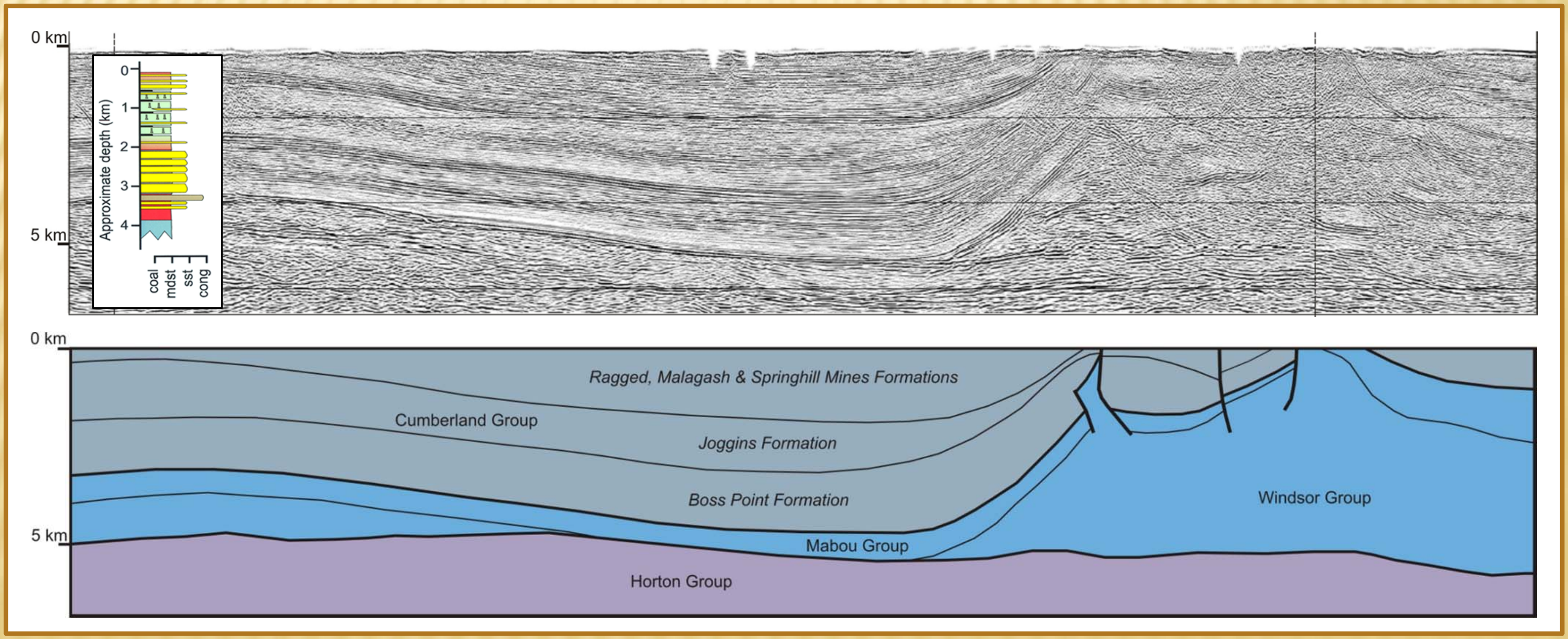


(Modified from Scott, 1990)

CUMBERLAND BASIN

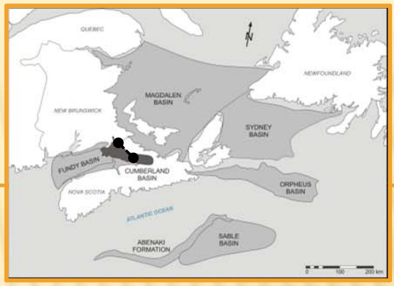


- Fault bounded with 8 km of Carboniferous strata
- Accumulated in phases of subsidence and inversion
- Faulting and salt withdrawal increased accommodation space



(Modified from Waldron and Rygel, 2006)

CUMBERLAND BASIN



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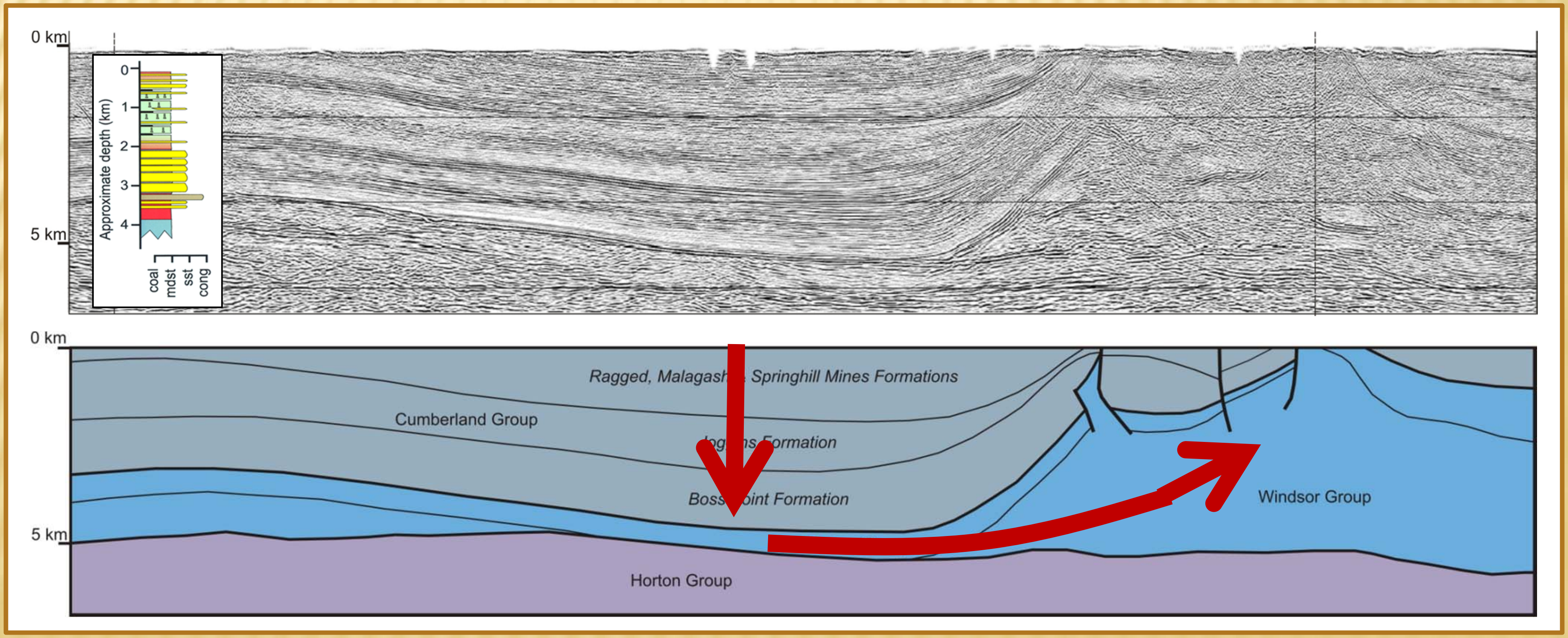
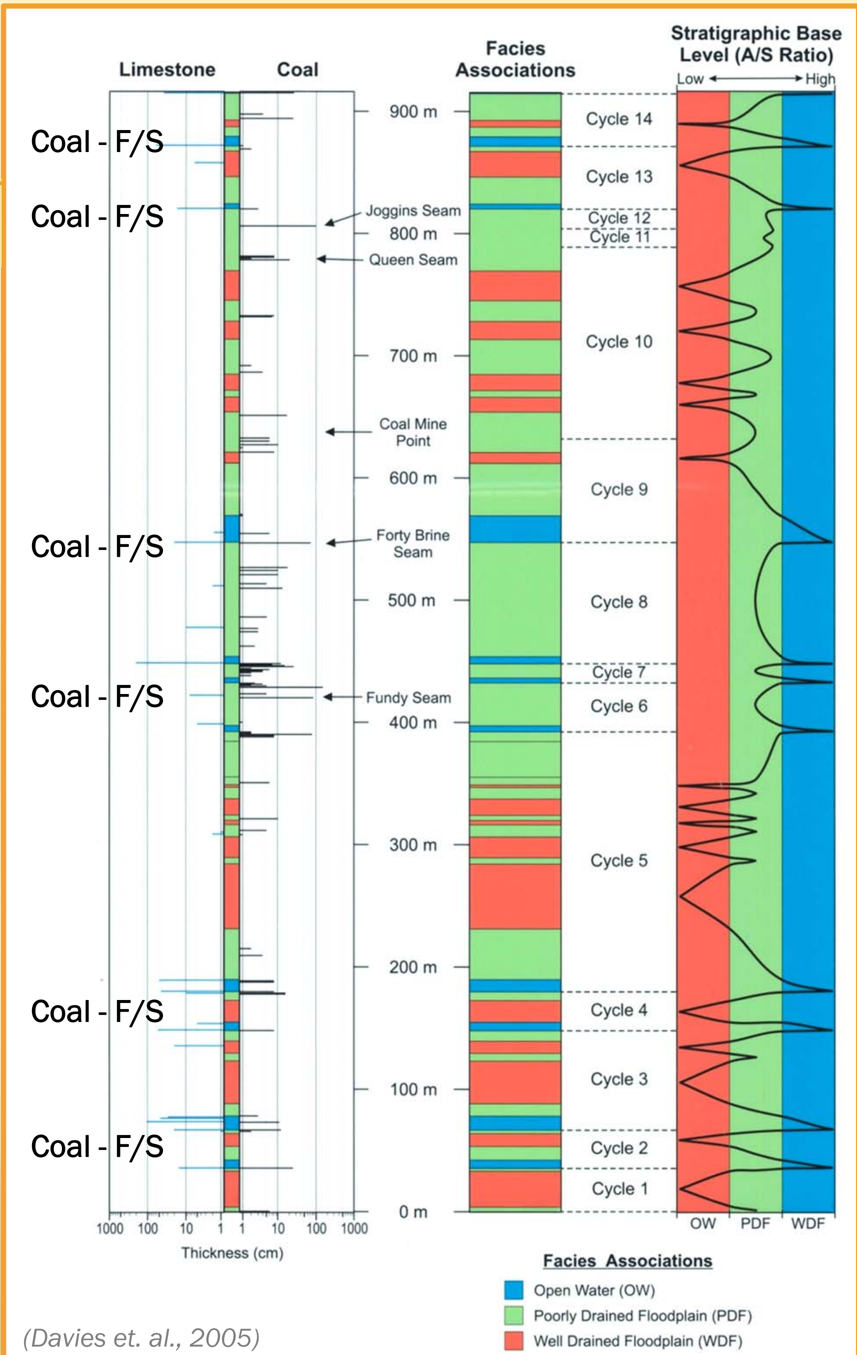


(Modified from Waldron and Rygel, 2006)

CUMBERLAND BASIN

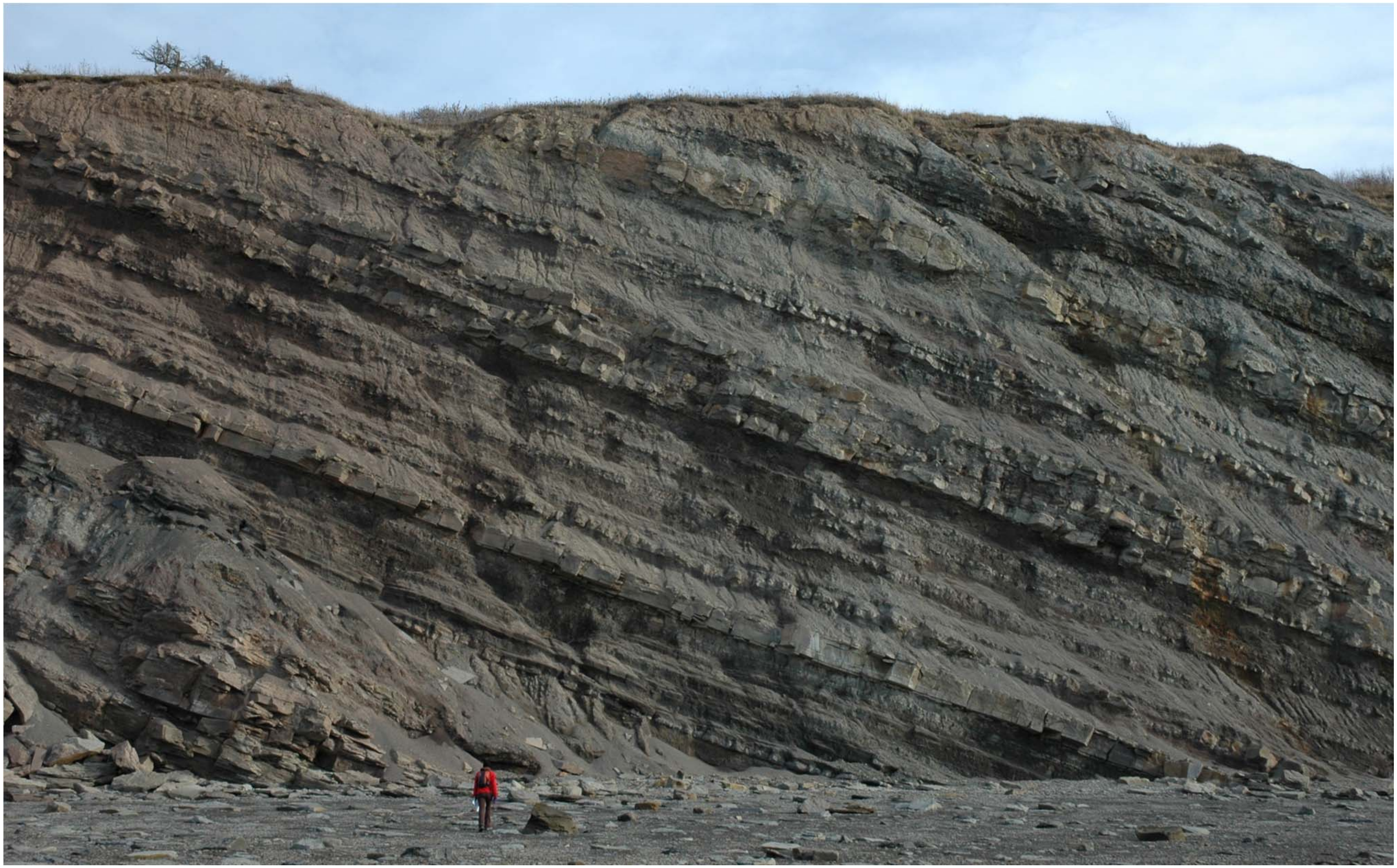
Joggins Section

- 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



CUMBERLAND BASIN - JOGGINS

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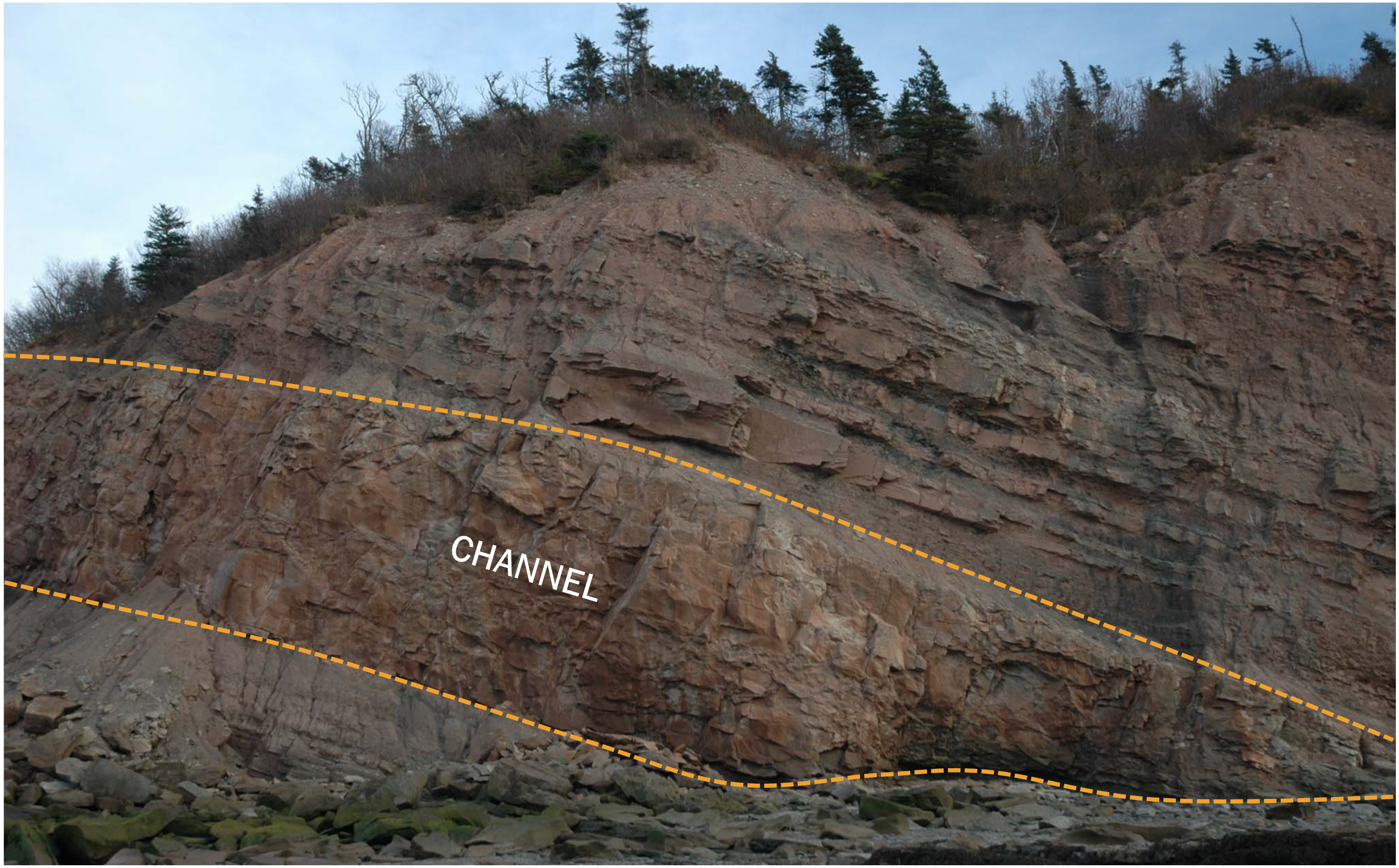
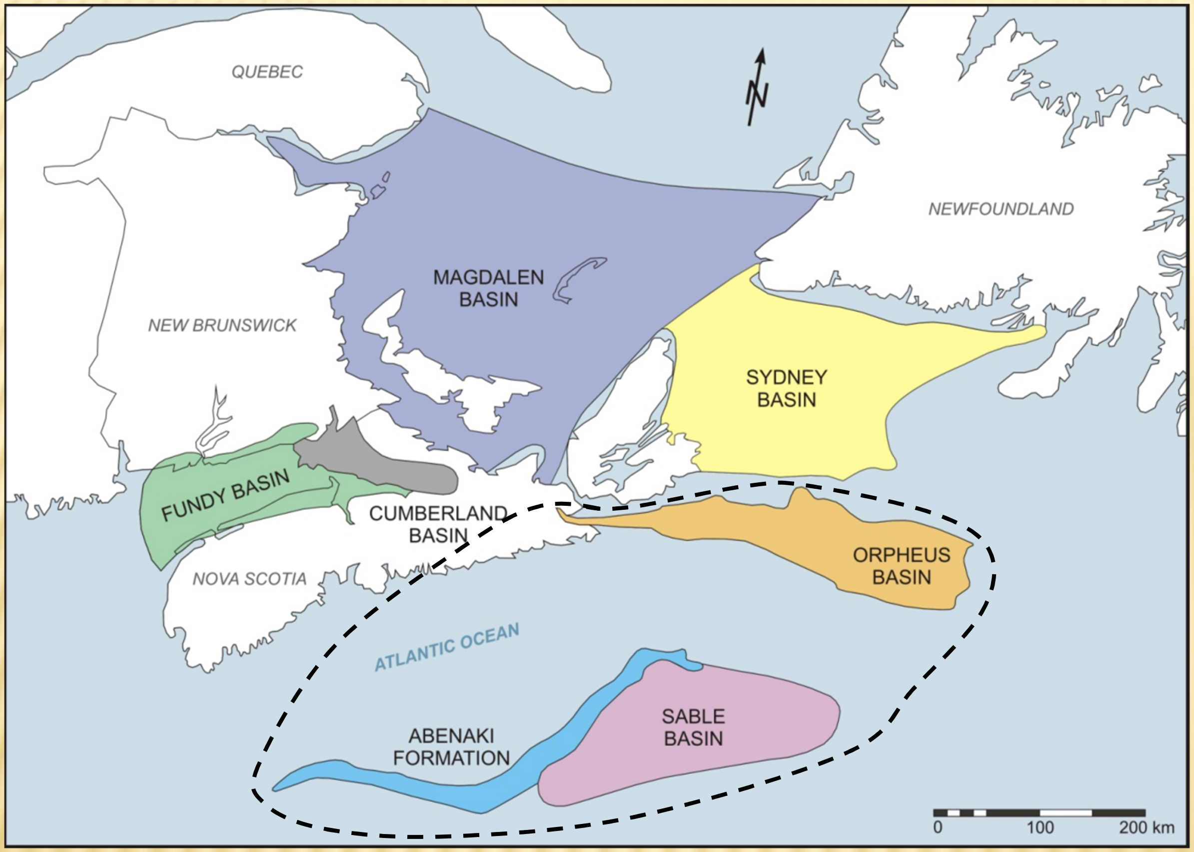
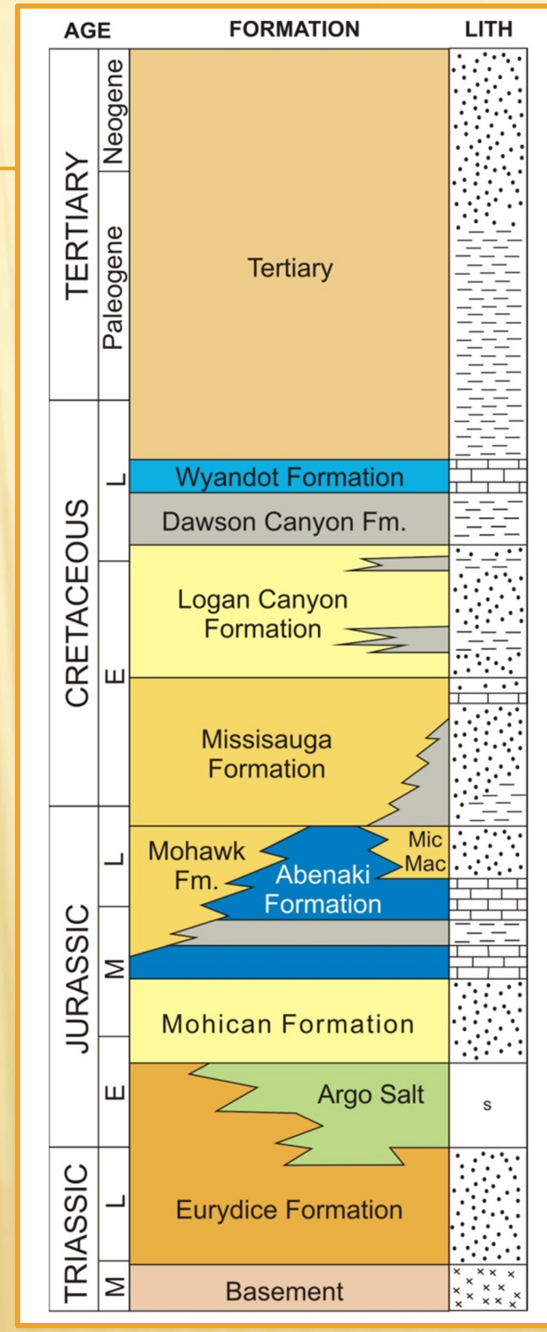


SCOTIAN BASINS

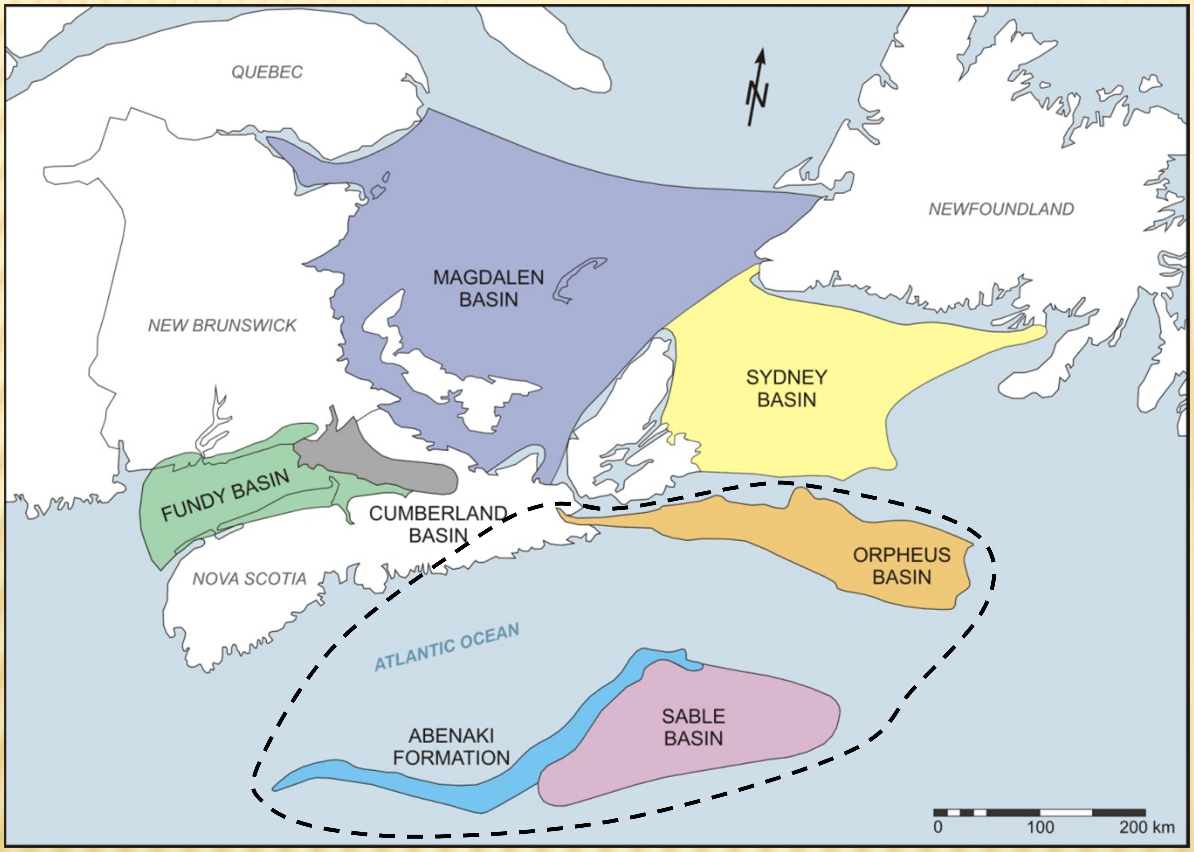


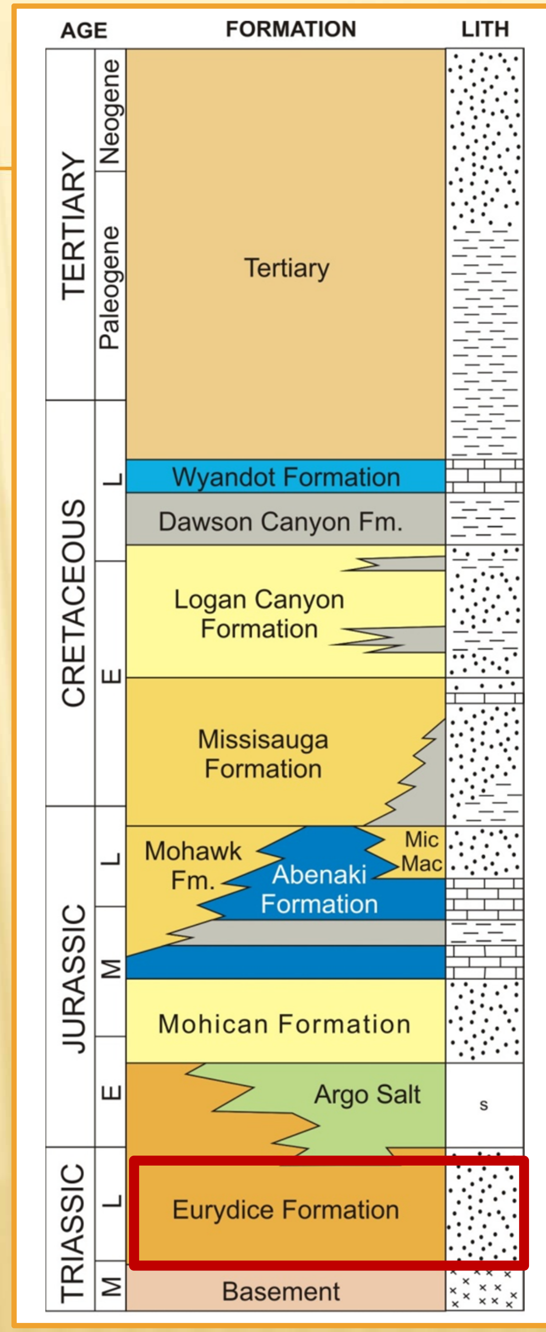


(Modified from Natural Resources Canada, 2008)

- Fundy, Orpheus, & Abenaki/Sable Basins

SCOTIAN BASINS





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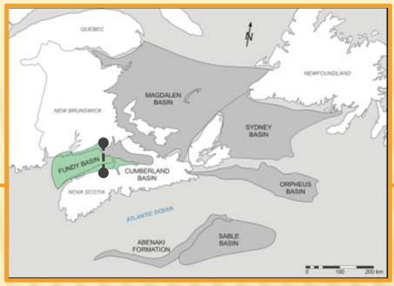
- Fundy, Orpheus, & Abenaki/Sable Basins

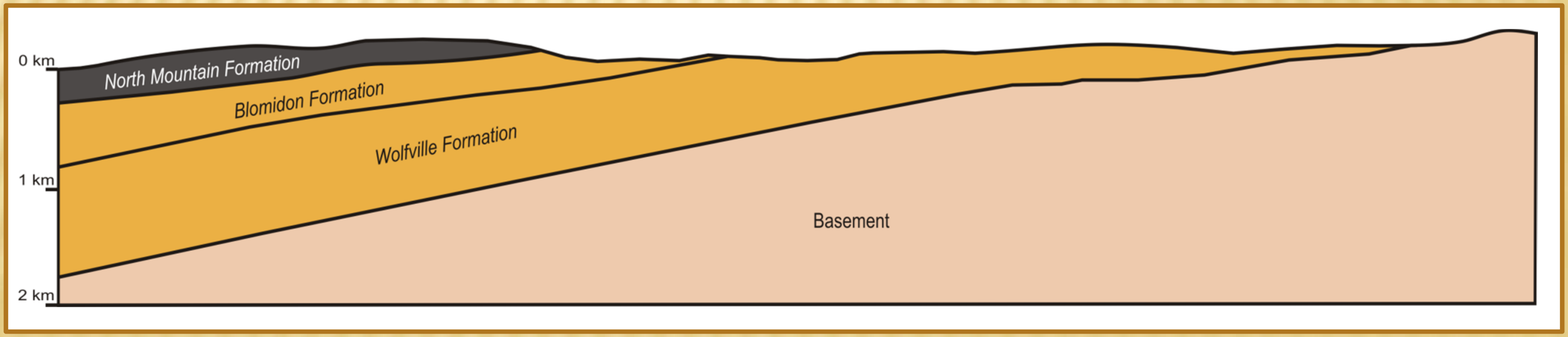
FUNDY BASIN



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

Reservoir: Wolfville and Blomidon formations

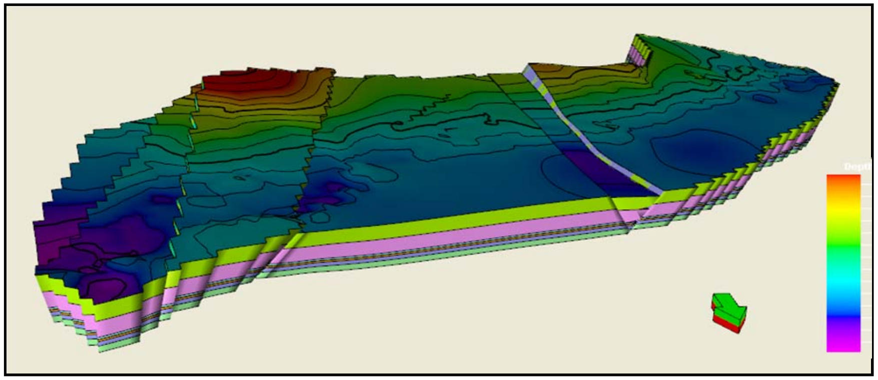
Seal: North Mountain Basalt

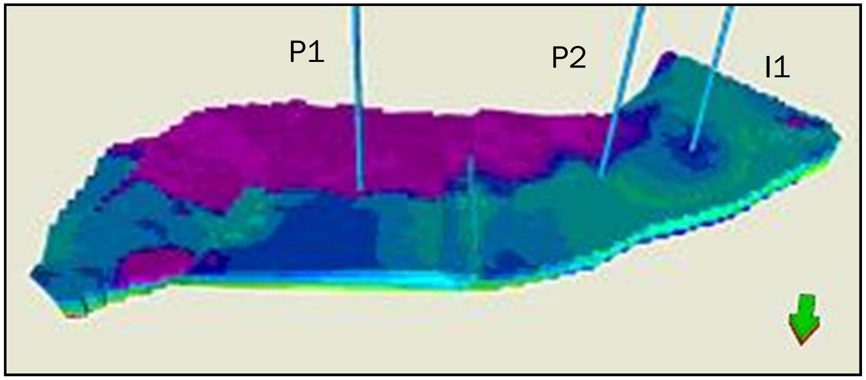


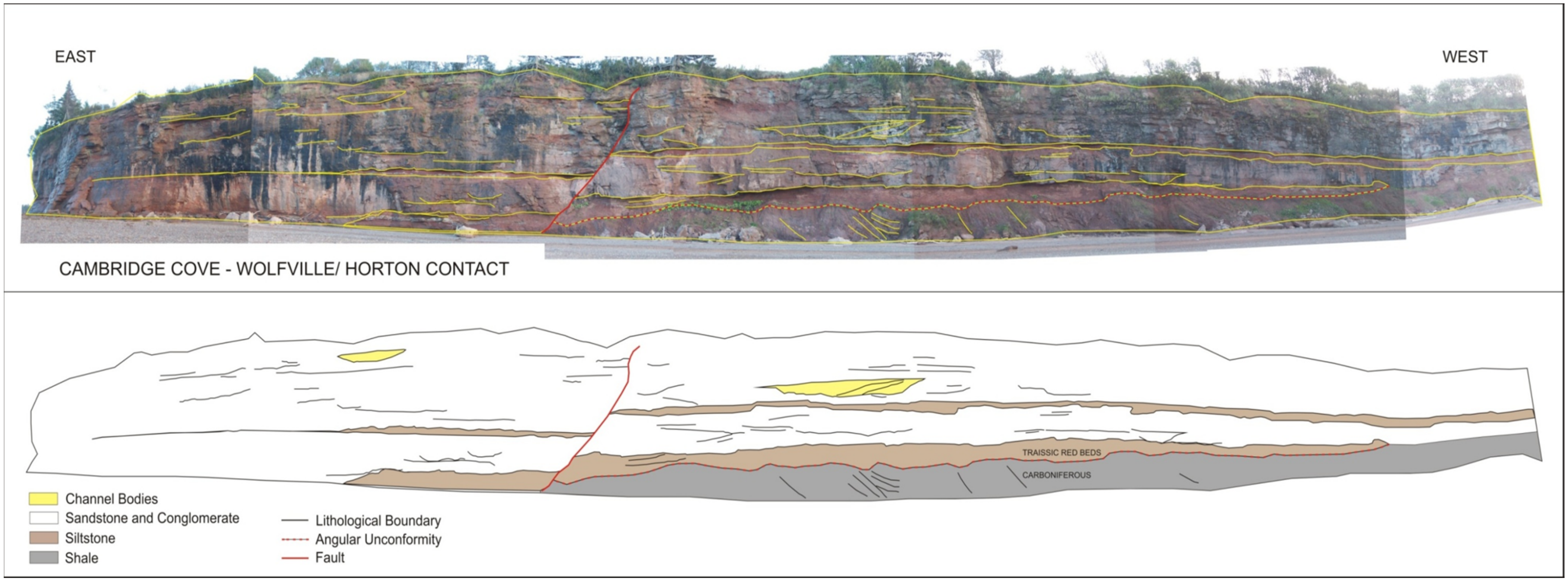
(Modified from Moore, 2000)

FUNDY BASIN – CAMBRIDGE COVE

FUNDY BASIN

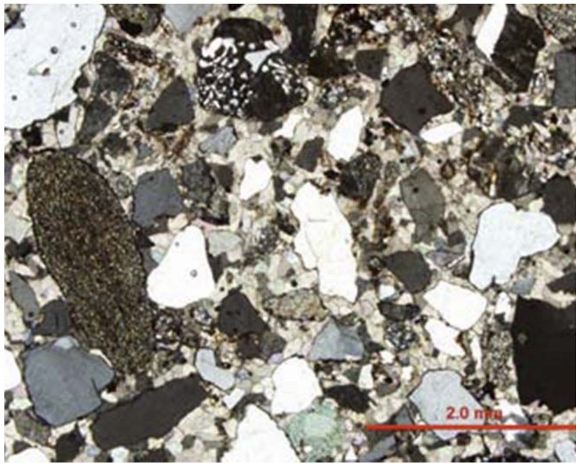



P1
P2
I1

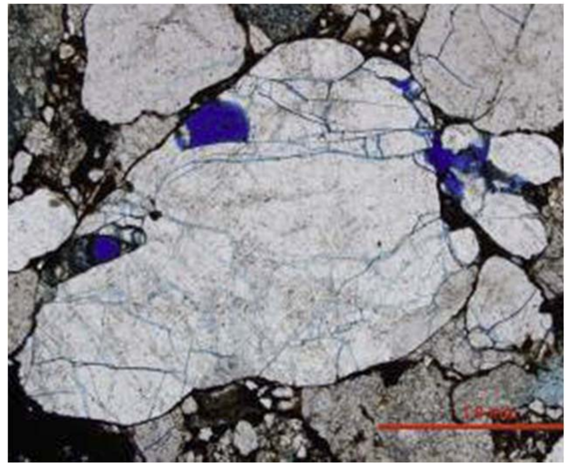

EAST
WEST
CAMBRIDGE COVE - WOLFVILLE/ HORTON CONTACT
TRAISSIC RED BEDS
CARBONIFEROUS
Channel Bodies
Sandstone and Conglomerate
Siltstone
Shale
Lithological Boundary
Angular Unconformity
Fault

FUNDY BASIN

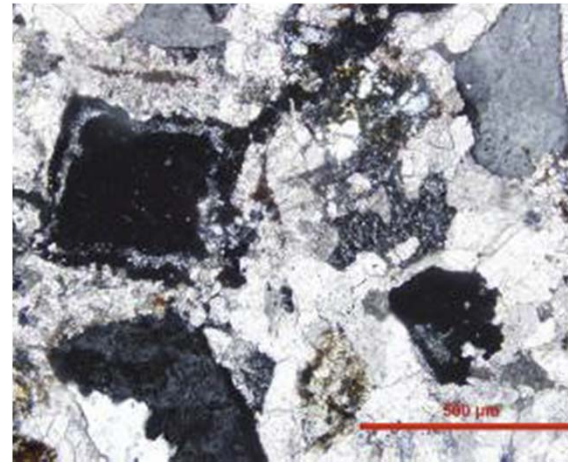
(Modified from Kettanah et al., 2008)



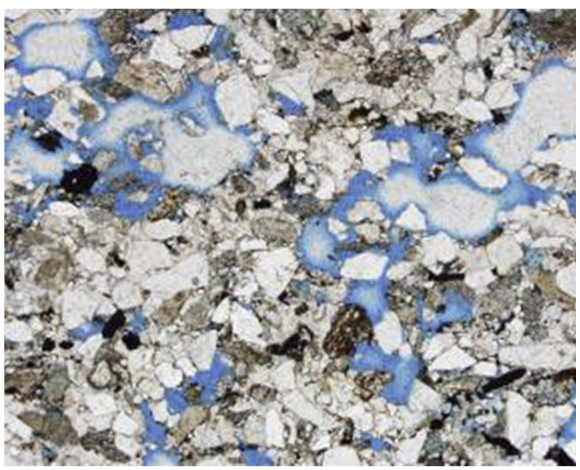
Well cemented - No porosity



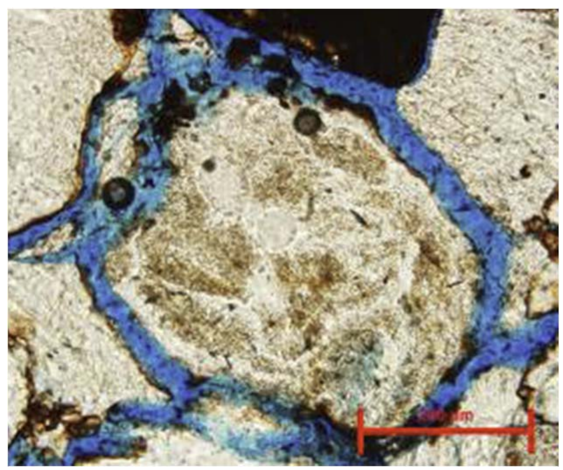
Microfracture Microporosity



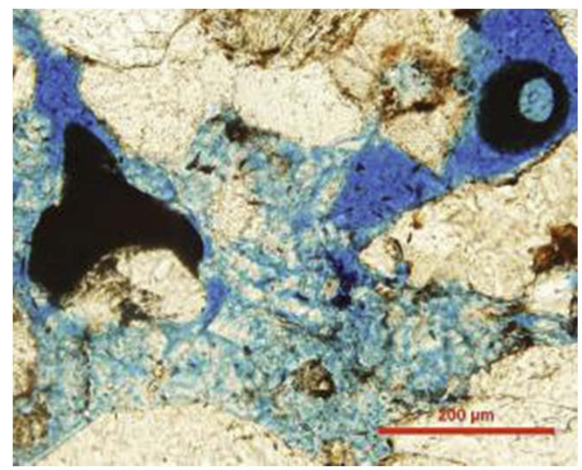
Dissolution Microporosity



Primary Porosity



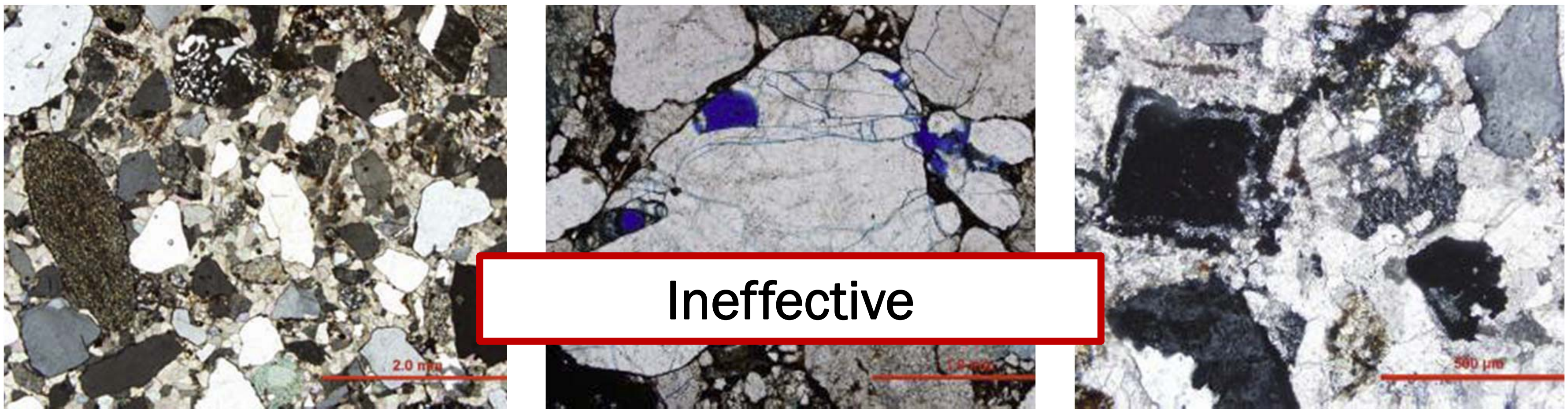
Grain Boundary Microporosity



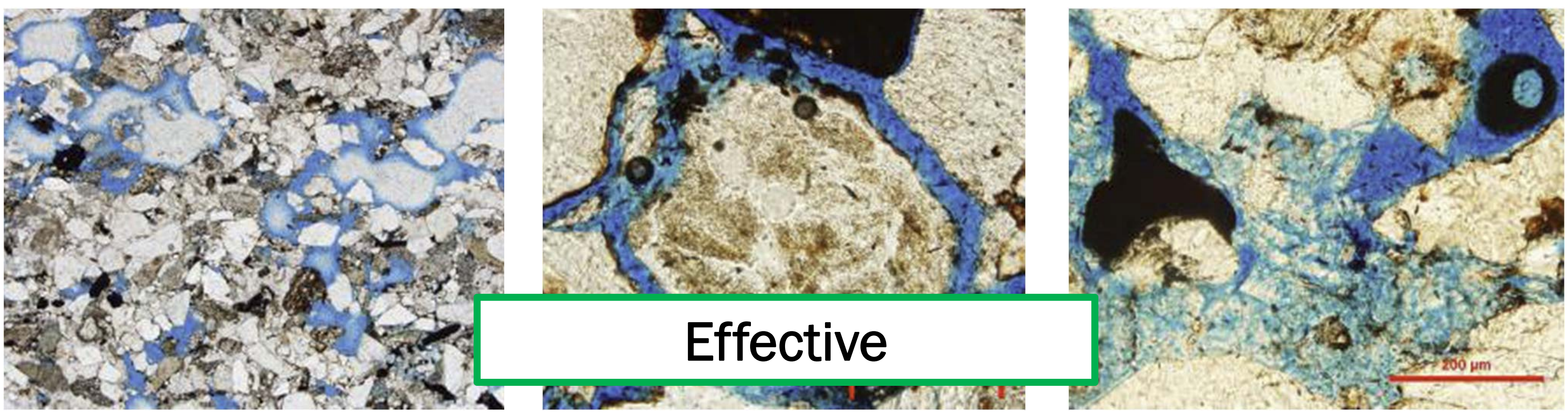
Mixed Primary and Secondary

FUNDY BASIN

(Modified from Kettanah et al., 2008)

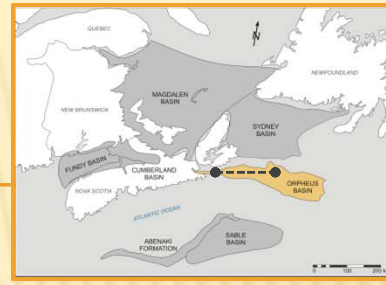


Well cemented - No porosity | Microfracture Microporosity | Dissolution Microporosity



Primary Porosity | Grain Boundary Microporosity | Mixed Primary and Secondary

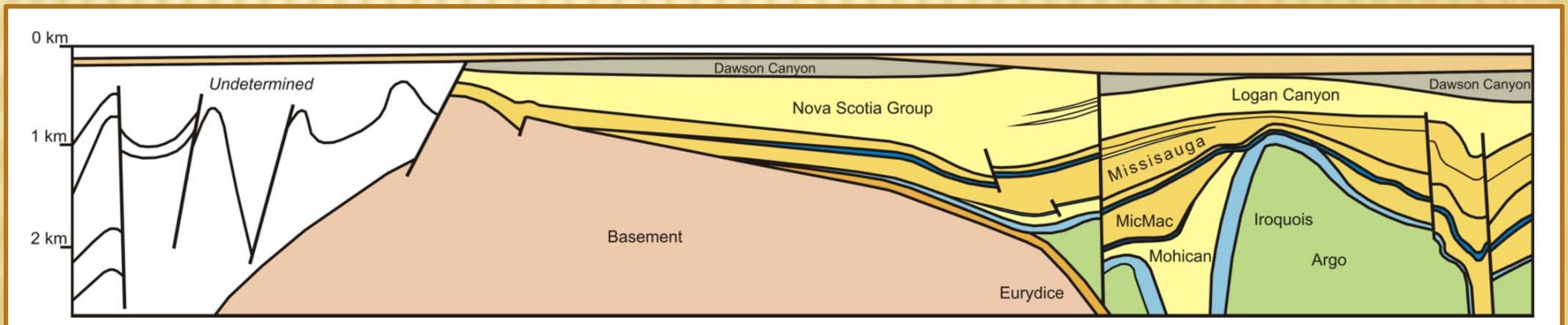
ORPHEUS BASIN



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

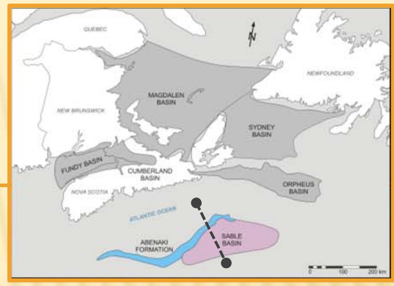
Reservoir: fine grained to conglomeratic clastics of the Eurydice Formation.

Seal: possibly thick evaporite deposits of the Argo Formation.

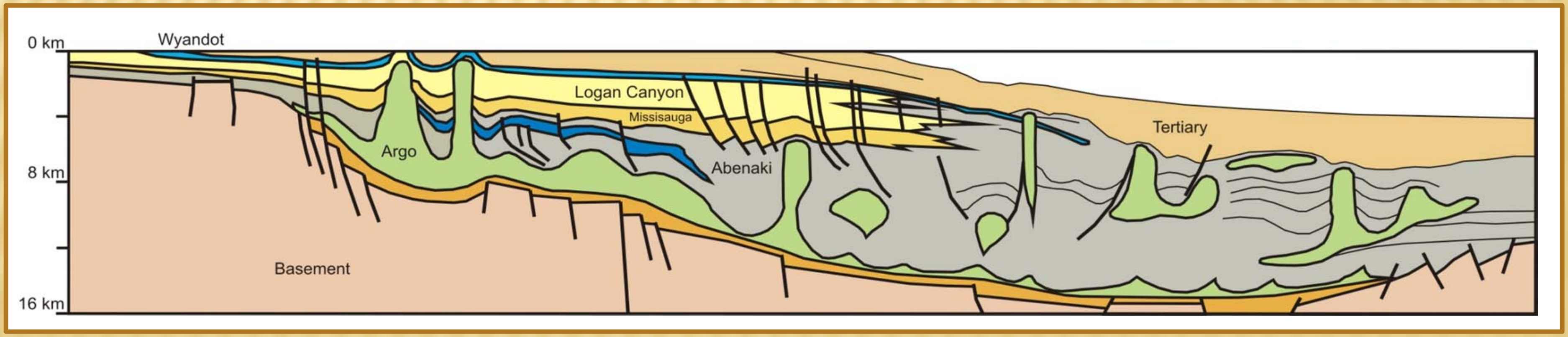


(Modified from Lyngberg, 1984)

ABENAKI FM. AND SABLE BASIN

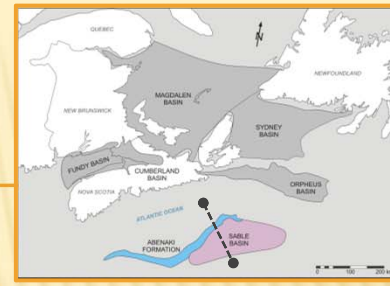


- Shelf margin deltas deposits
- Up to 16 km thick
- Existing Sable gas fields and new development of Deep Panuke carbonate trend.



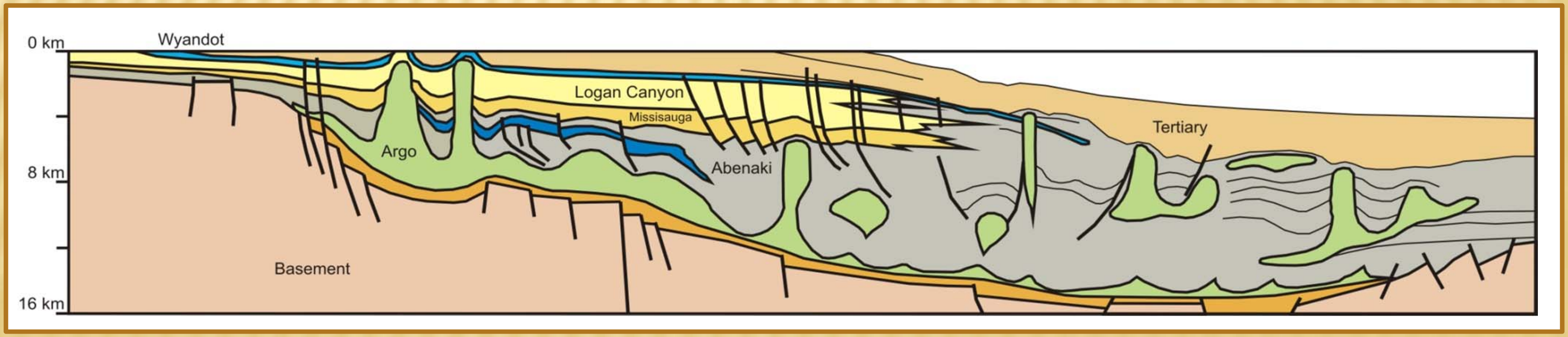
(Modified from Kidston et al., 200)

ABENAKI FM. AND SABLE BASIN



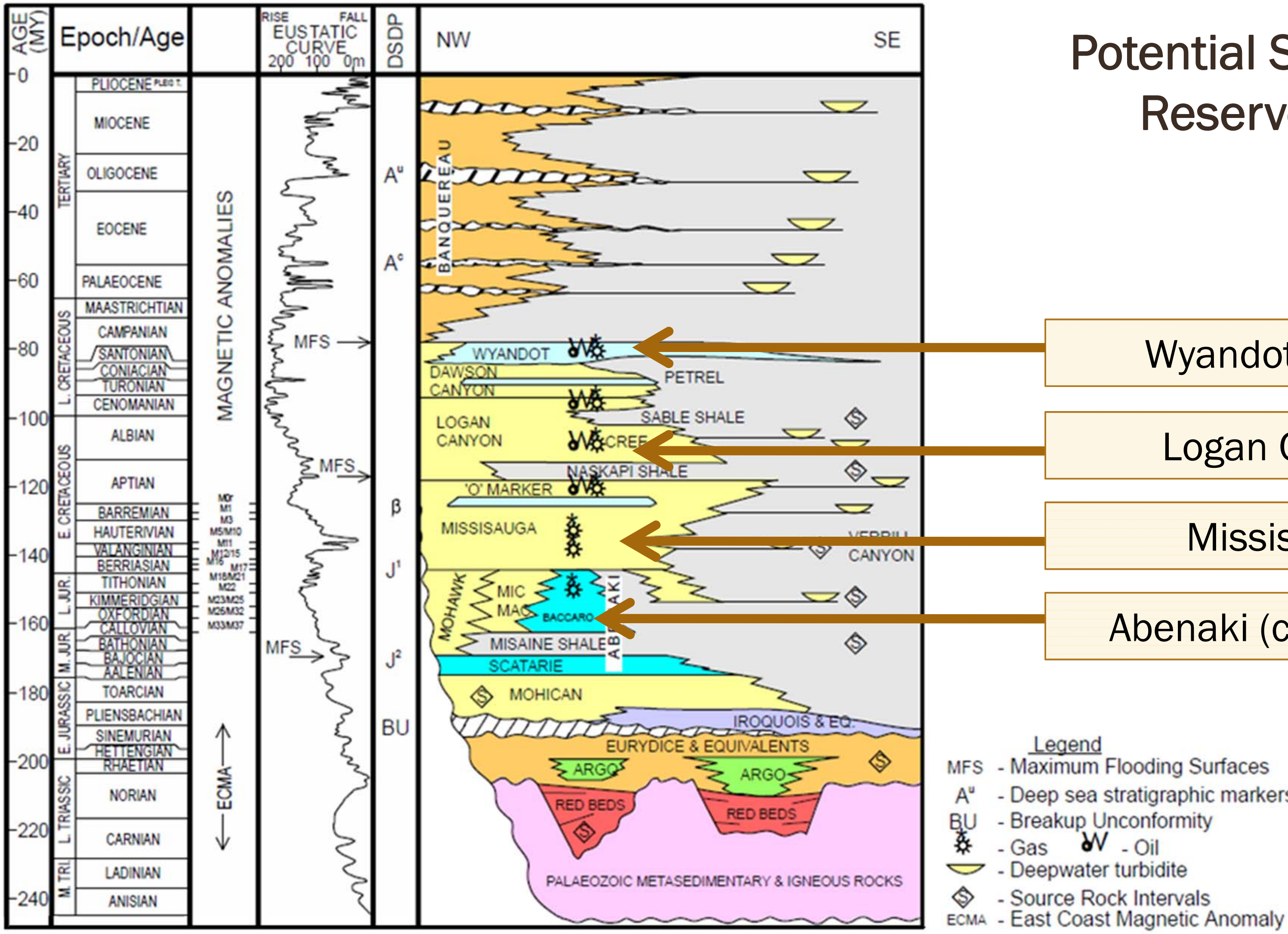
Reservoir: Both clastic and carbonate reservoirs. Extensive tidal-fluvial sandstones with thickness of more than 40 m with high porosity and permeability.

Seal: Thick transgressive shales. Also non-porous limestone in the mixed-carbonate-siliciclastic settings.



(Modified from Kidston et al., 200)

ABENAKI FM. AND SABLE BASIN



Potential Storage Reservoirs

Wyandot (chalk)

Logan Canyon

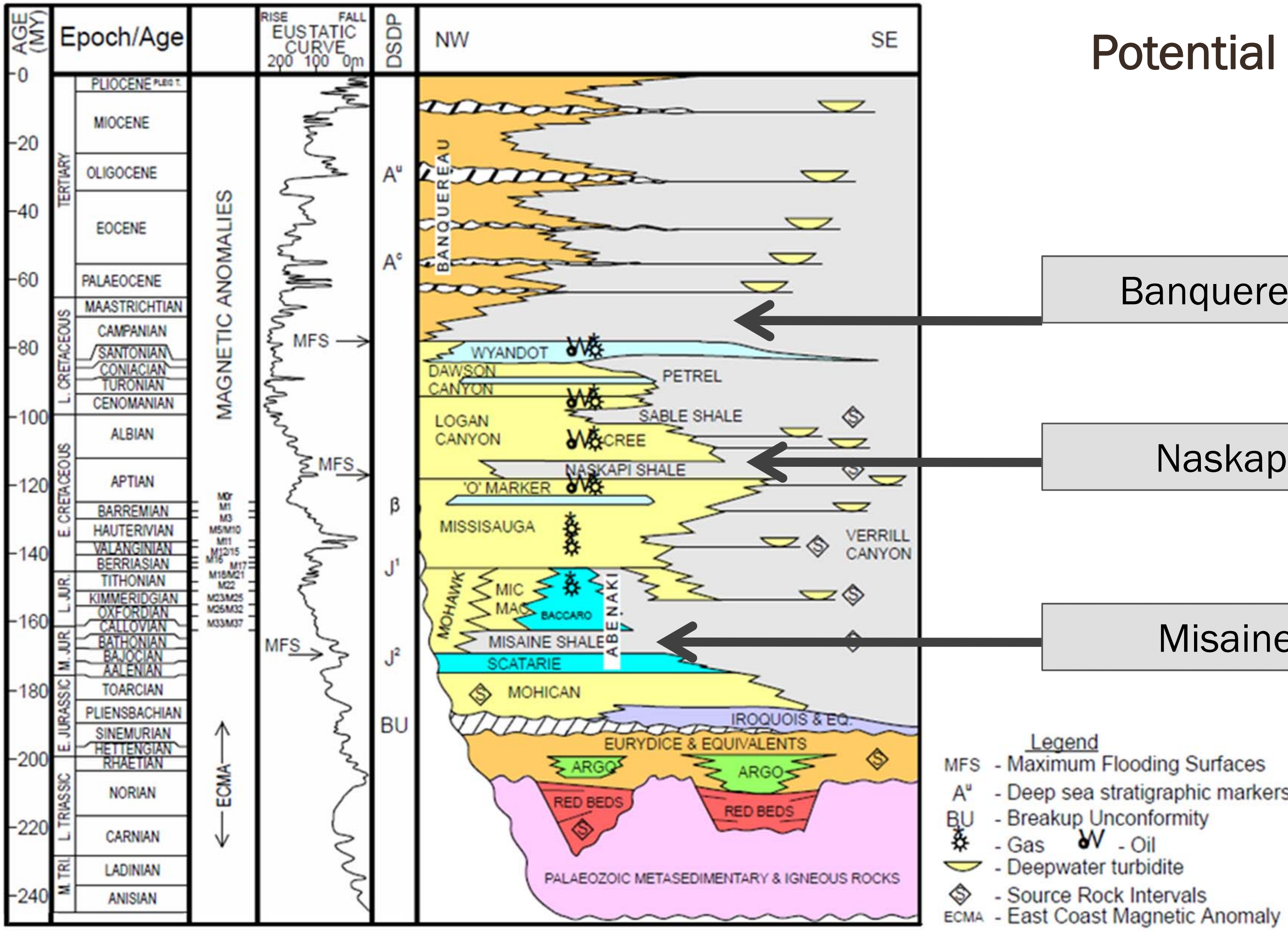
Missisauga

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

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 CO_2 sequestration.

Detailed Site Characterization

Structural Model

- geometry of major horizons
- fault juxtaposition
- fault/fracture intensity

Stratigraphic Model

- sedimentology
- depositional environments
- sequence stratigraphy

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
- CO_2 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)

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

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BASIN EVALUATION

MARITIMES BASIN	
Cumberland	**Reservoir** - Pennsylvanian coarse clastics (Joggins and Polly Brook Fms.) **Seal** - evaporites
	Pros - Close proximity to emission site **Cons** - Low Porosity and Permeability
Magdalen	**Reservoir** - Devono-Carboniferous to Permian age coarse clastics **Seal** - Mississippian evaporites and salt
	Pros - Close proximity to emission site **Cons** - Low Porosity and Permeability
Sydney	**Reservoir** - Devono-Carboniferous to Permian age coarse clastics **Seal** - Mississippian evaporites and salt
	Pros - Close proximity to emission site **Cons** - Low Porosity and Permeability

BASIN EVALUATION

SCOTIAN BASIN	
Orpheus	**Reservoir** - fine grained to conglomeratic clastics (Eurydice Fm.) **Seal** - thick evaporites (Argo Fm.)
	Pros - Close proximity to emission site; potential for salt seal **Cons** - Offshore pipeline and monitoring survey needed
Sable	**Reservoir** - thick deltaic sands (Missisauga Fm.) **Seal** - thick transgressive prodelta shales
	Pros - Pipeline in place and good porosity **Cons** - Far from emission sites
Abenaki	**Reservoir** - carbonates with fracture and dolomitic porosity (Abenaki Fm.) **Seal** - thick transgressive prodelta shales
	Pros - Pipeline in 2010; planned H_2S injection site so some infrastructure **Cons** - Far from emission sites
Fundy	**Reservoir** - fine grained to conglomeratic clastics (Blomidon and Wolfville Fms.) **Seal** - Basalt
	Pros - Good Porosity **Cons** - Farther from emission sites

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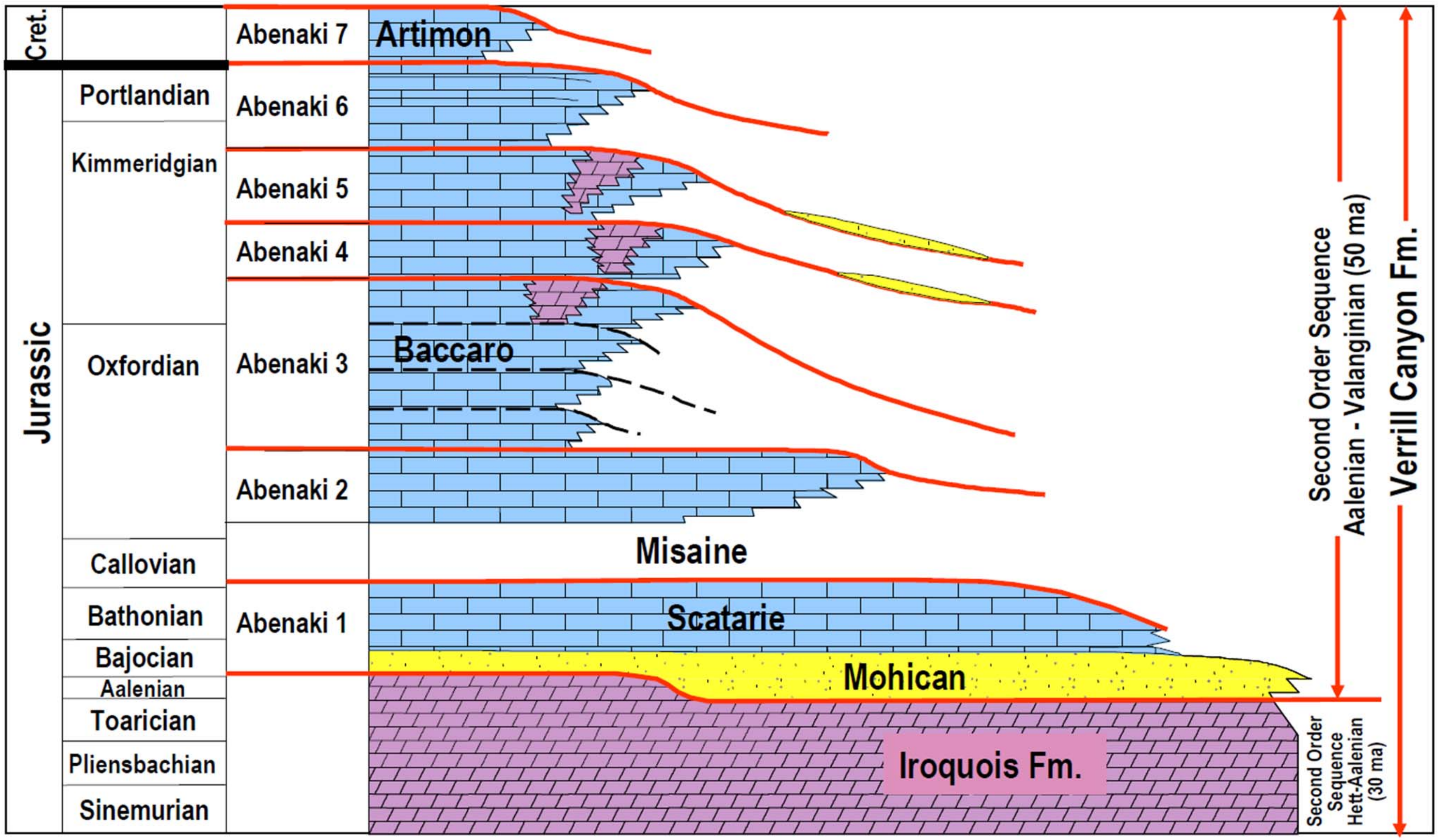
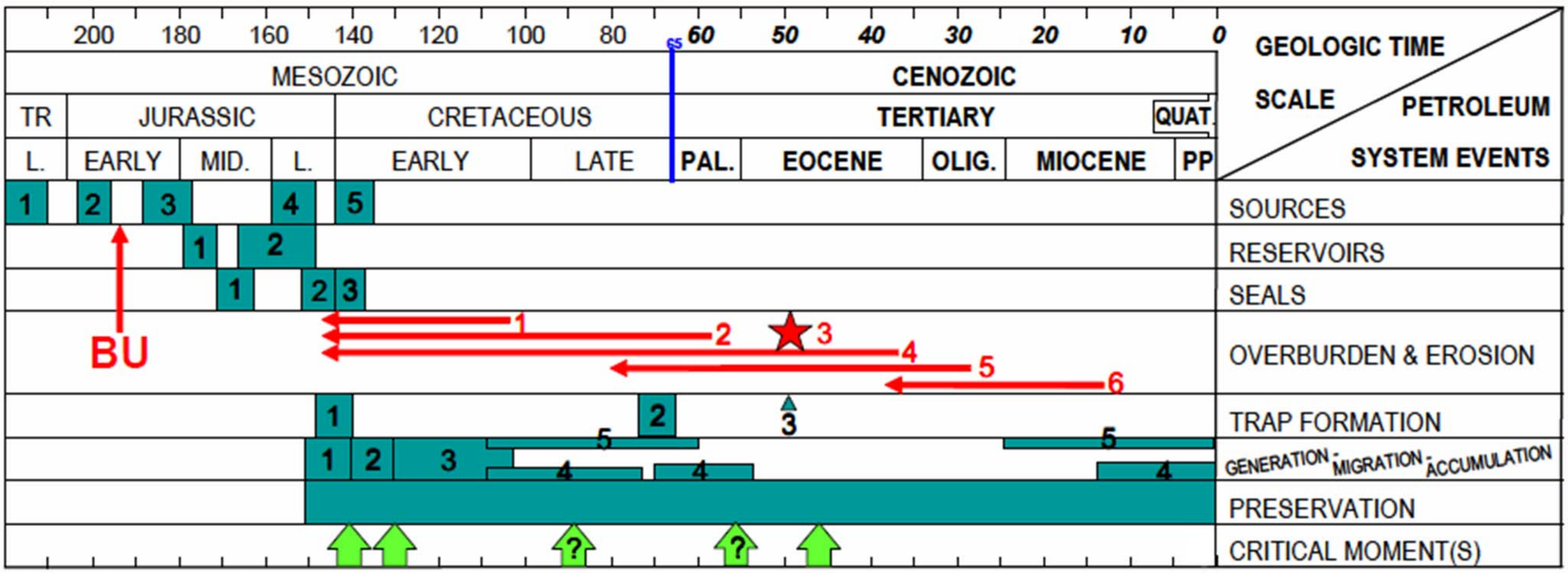
CUMBERLAND BASIN - JOGGINS

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 – Kimmeridigian)

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 CO_2 column

Figure caption