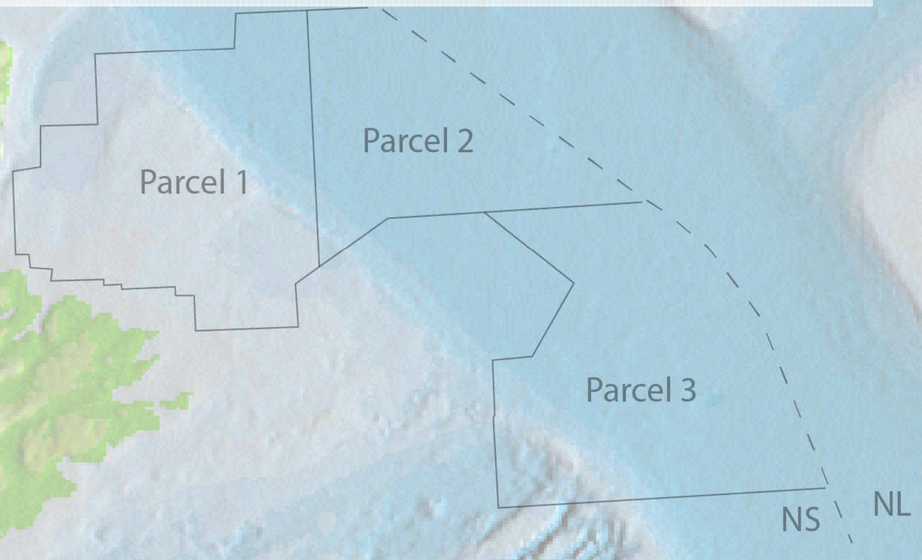
# CHAPTER 6

# SEISMIC STRATIGRAPHY AND GROSS DEPOSITIONAL ENVIRONMENT MAPPING

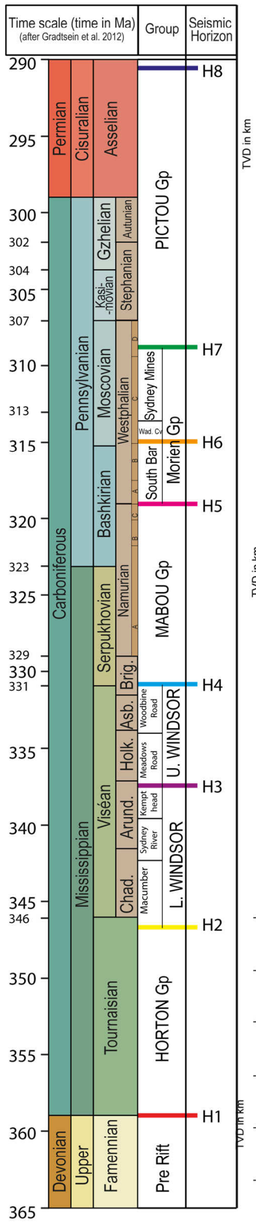


# CHAPTER 6.1

# SEISMIC STRATIGRAPHY

# SEISMIC STRATIGRAPHY



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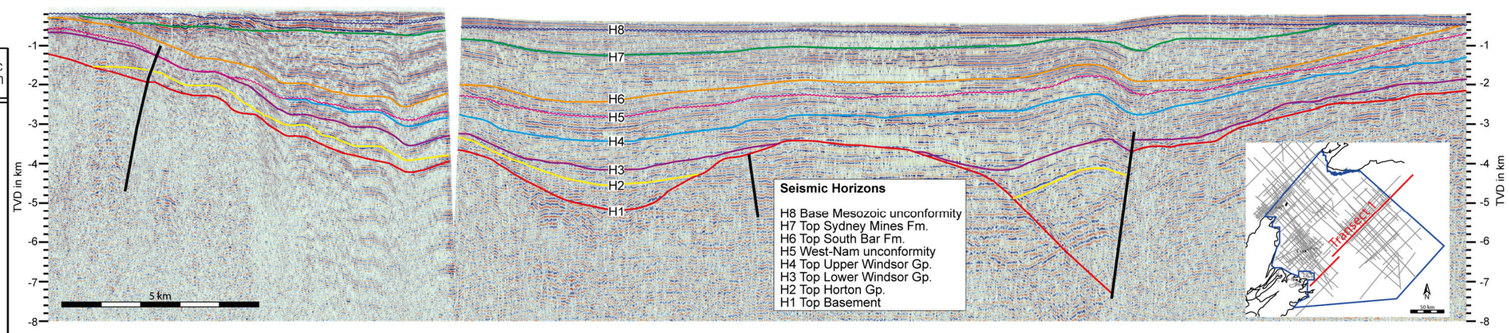


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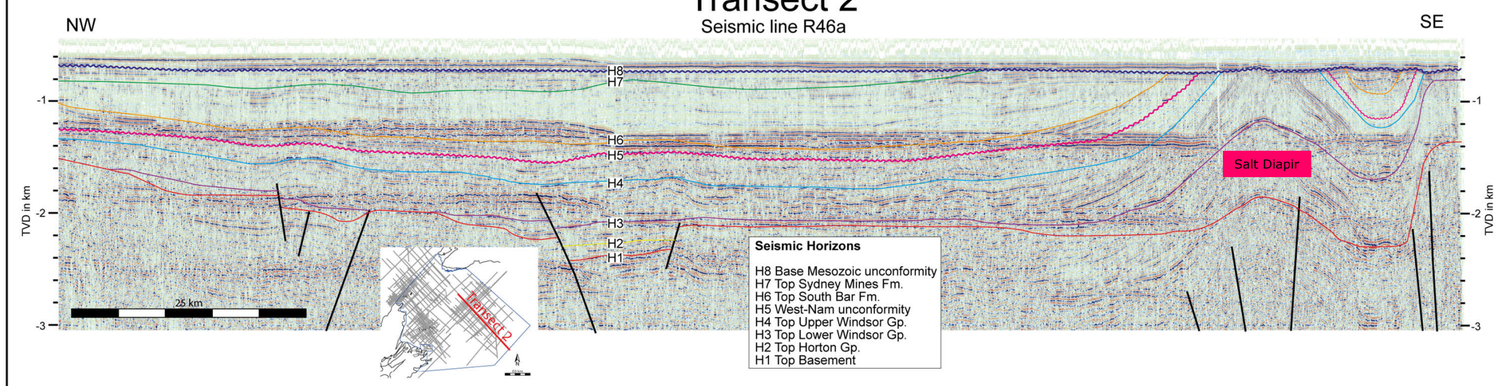


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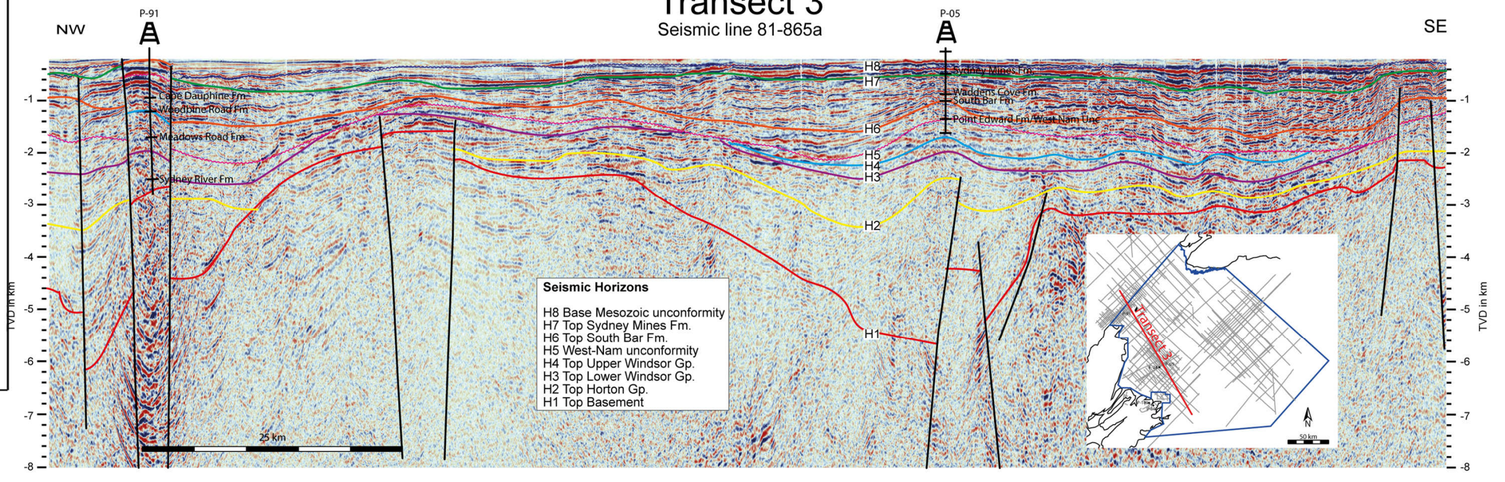
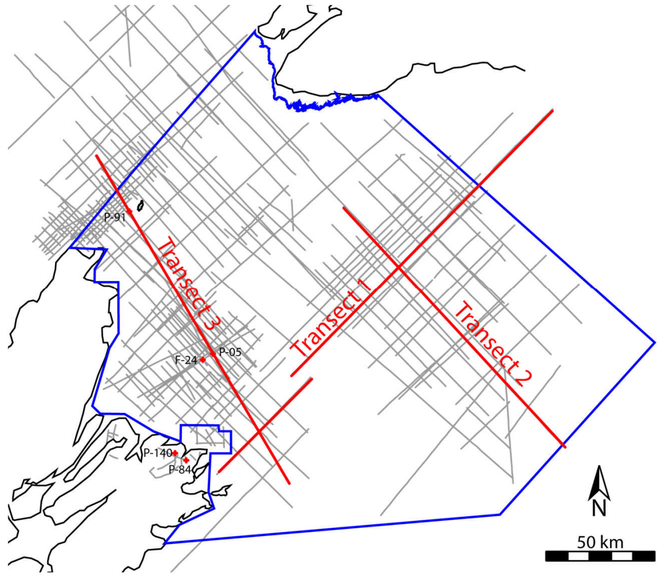


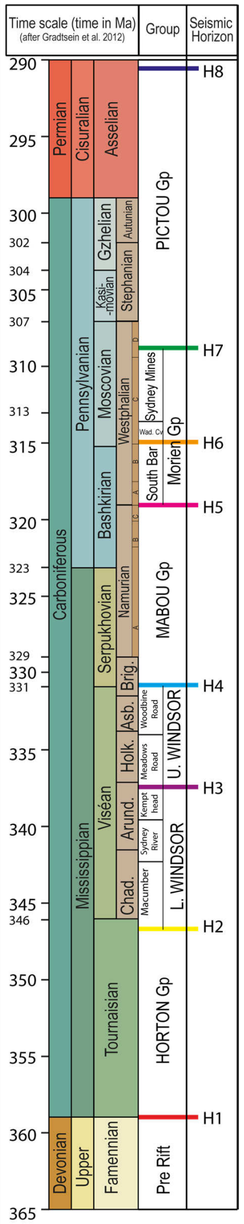

The three sections shown here illustrate deposition of the Carboniferous succession within Sydney Basin. It includes the entire succession between the basement (H1) to the Quaternary sea bed. Eight main horizons have been mapped across the basin, named H1 to H8 (Plate 3.2.1). They correspond to formation tops or major unconformities.

Transect 1 is an oblique dip transect; Transects 2 and 3 are oblique strike sections. The main structures observed are:

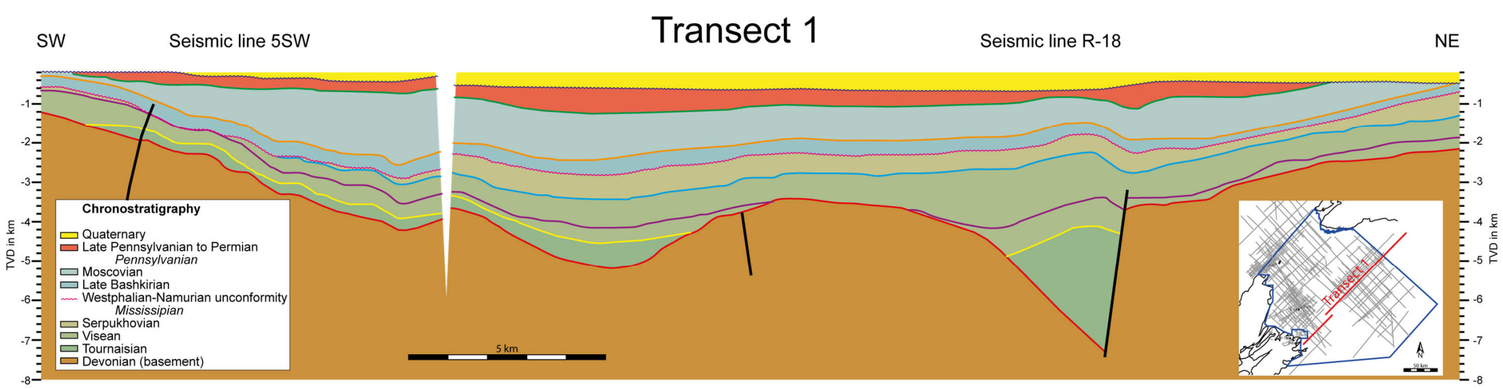
- A growth fault system in the lower part of the succession controlling deposition of the Horton and Windsor Groups
- The Westphalian / Namurian Unconformity (H5) strongly eroding the Mabou and Windsor Groups, especially along the basin edges
- Salt tectonics are not common and only affect deposition in the eastern part (see Transect 2) and along the Cabot Fault system (edge of the Maritimes Basin)

Transect 3, which goes through wells P-91 and P-05, illustrates the limited depth of the wells across the Carboniferous succession. P-05 does not reach the top Upper Windsor, and P-91, located on a basement high, reaches the Lower Windsor but misses the Horton Group.

Finally, note the low to average quality of the seismic data. Horizons are in places challenging to map across the transects.




## Transect 1

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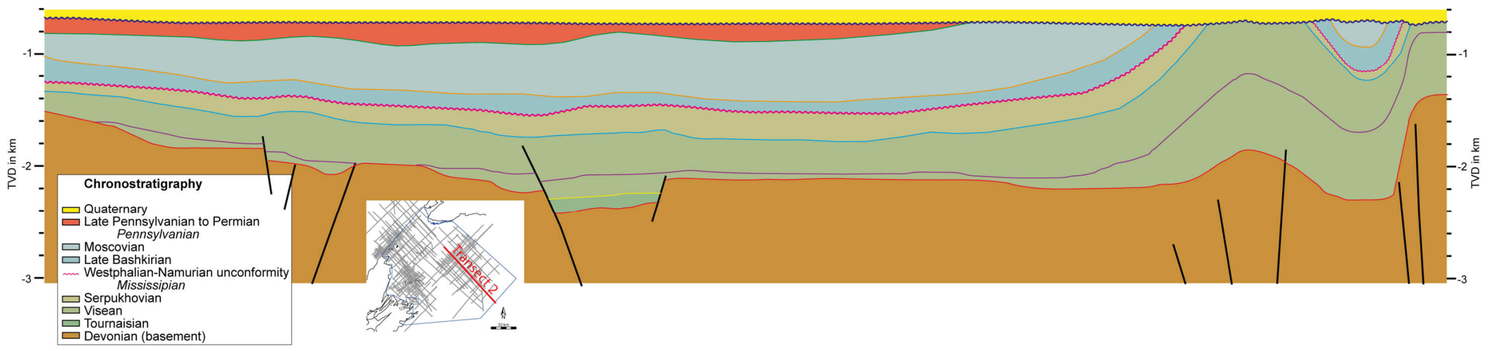


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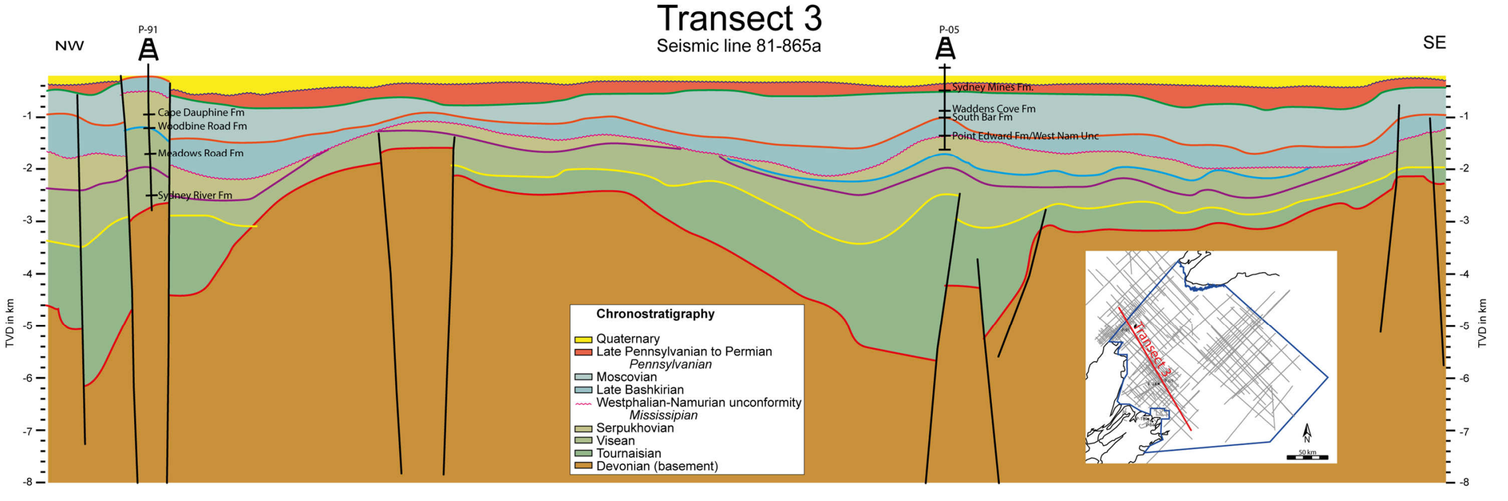
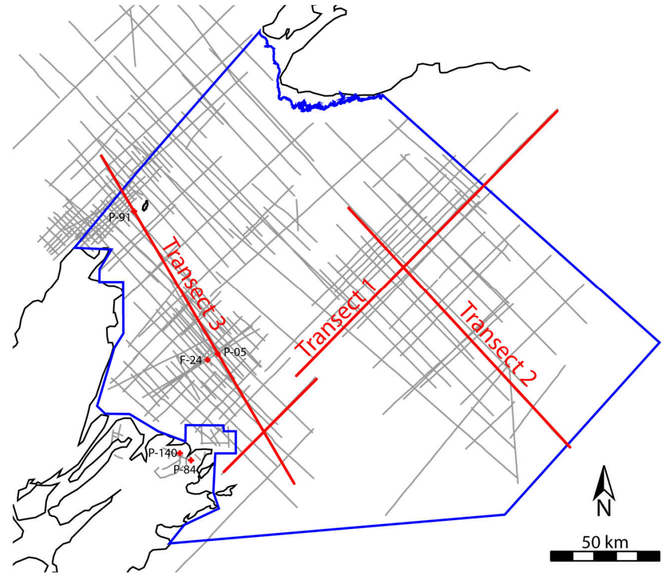



These three sections show the typical chronostratigraphic succession of the Sydney Basin. It includes the entire succession between the basement (brown color) to the Quaternary succession (yellow). Time lines range from Top Devonian (H1) to intra Westphalian (H7 equivalent).

The deepest parts of the sections show the Devonian basement, highly faulted.

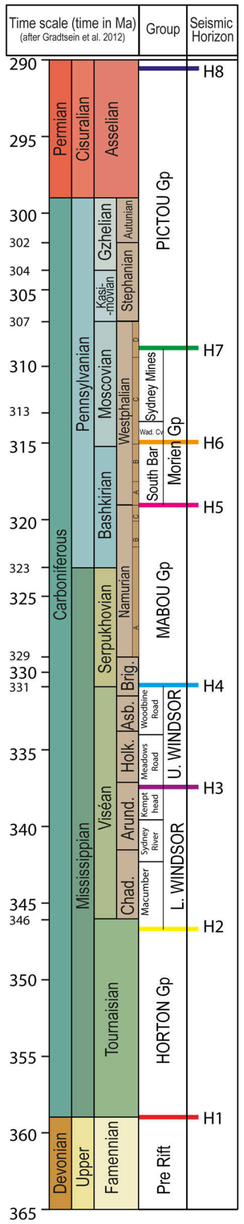
The Tournaisien succession is only observed in the topographical lows, and can be very thick in places (see Transect 1). It is highly faulted and therefore shows significant variations in thickness across short distances.

The Visean and Carboniferous successions were deposited during a period of tectonic quiescence. On the three transects, evidence of the later regional transpression phase can be observed, where existing normal faults are inverted in some places.

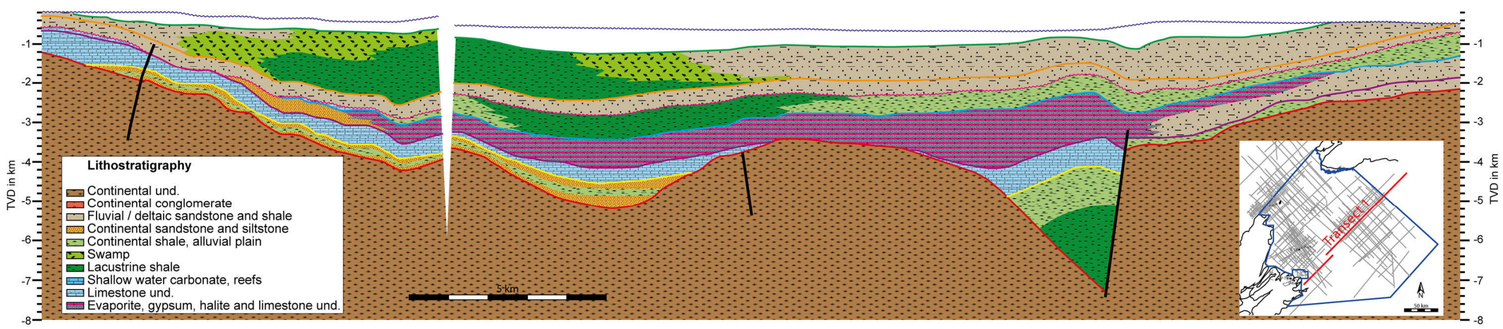
The Visean and Serpukhovian successions are present across the entire basin, and tend to flatten the pre-existing topography. Both of them were later eroded by the Westphalian-Namurian Unconformity.

The Pennsylvanian succession can be very thick in places. The basal surface is erosive (Westphalien-Namurian Unconformity)

The Quaternary succession is tabular and flat lying and is present across the entire basin. It represents an important erosional event that eroded all positive relief down to the Serpukhovian succession (see Transect 2).




## Transect 1

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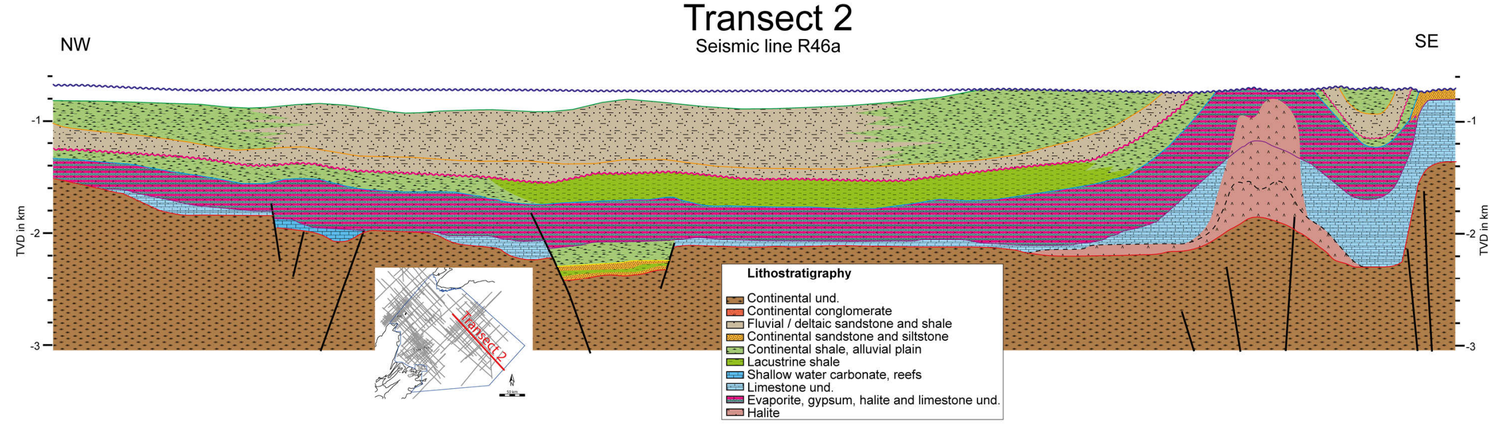


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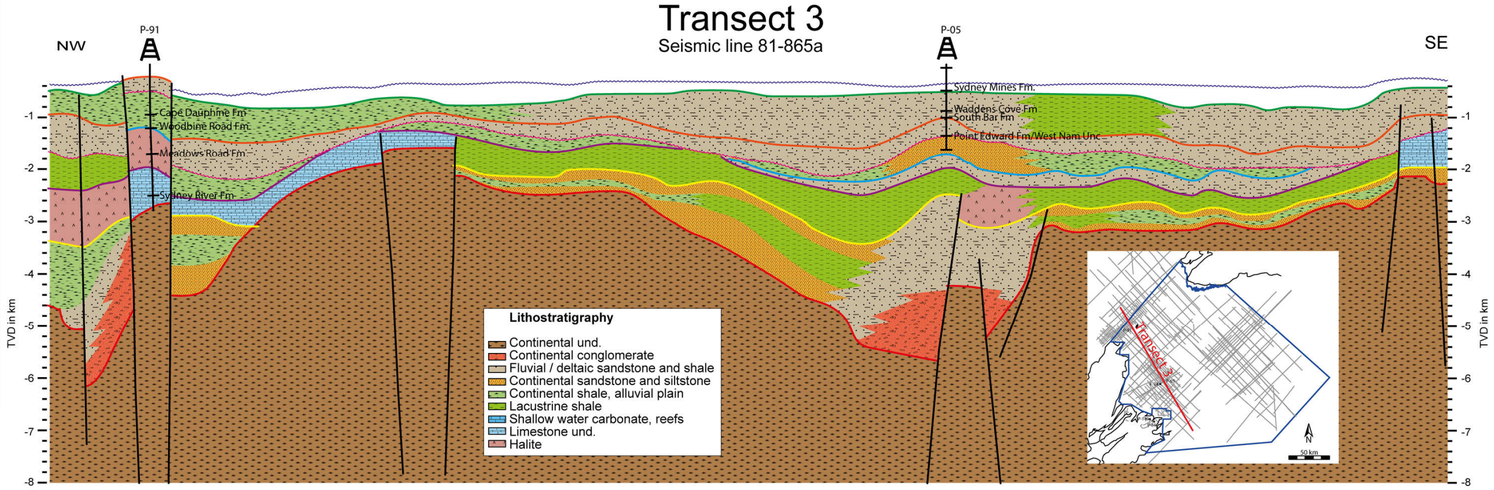
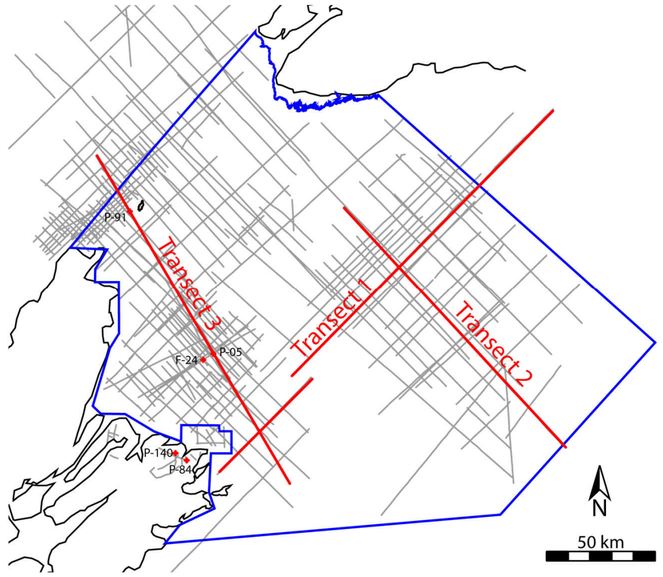



These three sections show the typical lithostratigraphic succession of the Sydney Basin.

The basement is here defined as composed of undifferentiated continental deposits (Devonian and older) since no granitic plutons are observed along these transects. In other places, geophysical data interpretation may suggest the presence of granite plutons (see Chapters 2 and 4).

The Horton Group is highly constrained by the faulted basement, with thick conglomeratic fans developing near the faults margins, and fining away to sandstone and shale. The Middle Horton sees the development of lacustrine shale located in topographical lows.

The Windsor Group consists of carbonate, evaporite and halite deposits resulting from incursions of the Windsor Sea to the east of the basin. Salt diapirs are rare and are only observed in the south of the basin, near Scatarie Ridge, and at the border with the Maritimes Basin across the Cabot Fault.

The Mabou Group, in places eroded away by the Westphalian - Namurian Unconformity, consists predominantly of continental shale, swamps and lacustrine shale.

The Morien – Cumberland Group is sandier, and consists of a thick succession of fluvial channels interbedded with siltstone to shale. Coal beds have been observed along onshore outcrops and are expected to be also present in the offshore Sydney Basin.

# CHAPTER 6.2

# GROSS DEPOSITIONAL ENVIRONMENT MAPPING

## GROSS DEPOSITIONAL ENVIRONMENT (GDE) WORKFLOW

Gross Depositional Environment maps have been drawn for each interval from Top Basement (H1) to Top Morien / Cumberland Group (H9). The objective of the GDE mapping is to provide a rapid overview of the stratigraphic framework in support of the petroleum system assessment. GDE maps allow for a more reliable prediction of reservoir distribution than a correlation between sparsely distributed wells, and a better representation of sediment distribution systems from shelf to deep water.

The methodology used for making the GDE maps is detailed below:

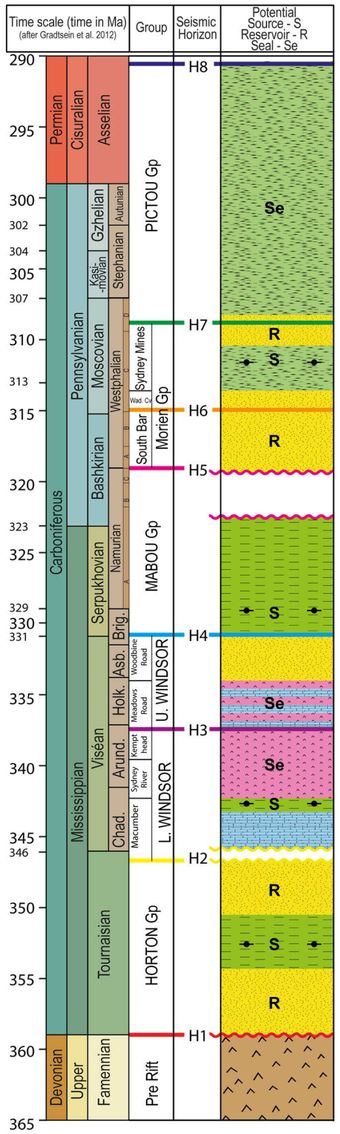



*Figure 1: Stratigraphic column showing the distribution of the main plays*

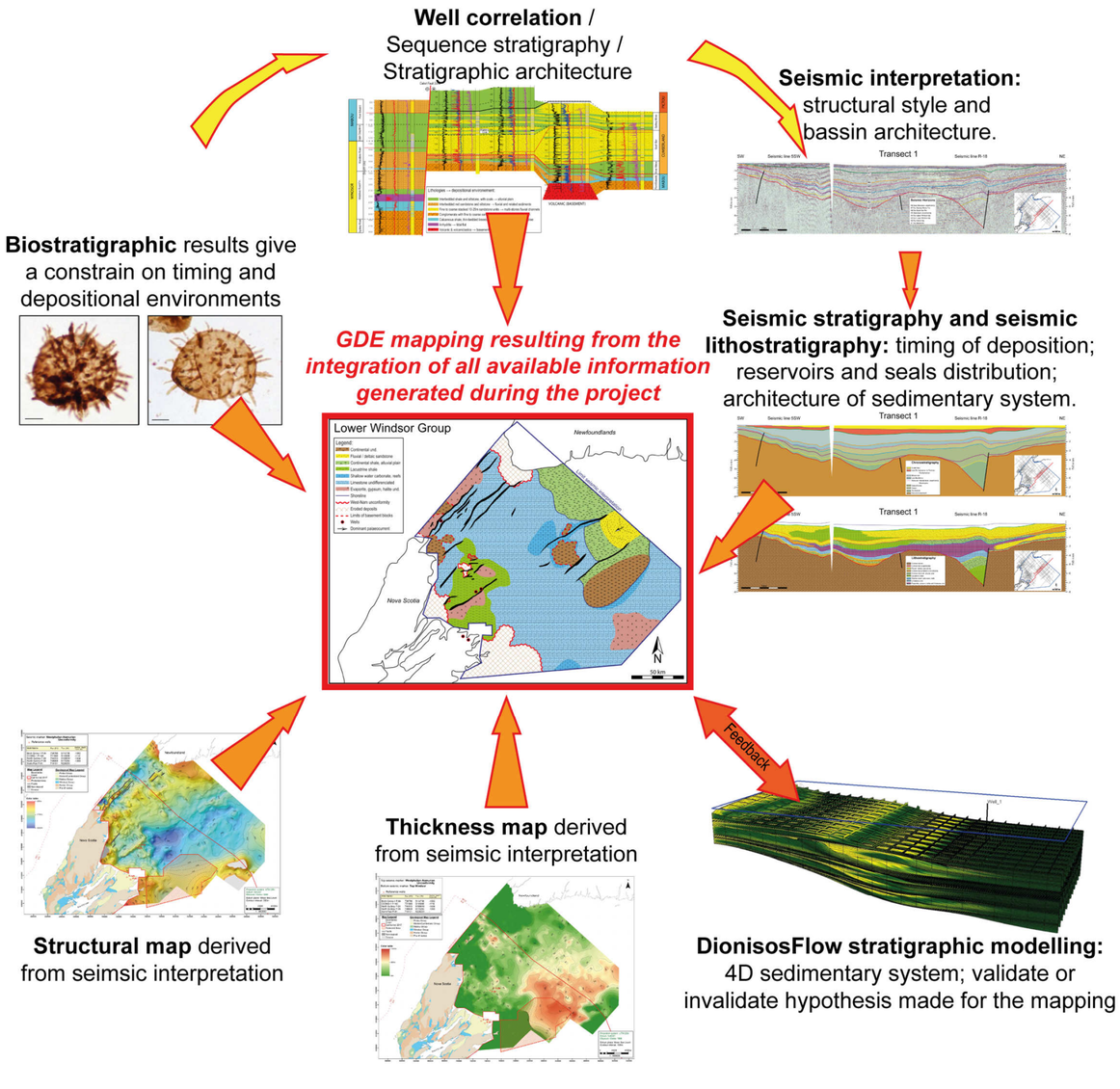



*Figure 2: Workflow used for GDE*

## GROSS DEPOSITIONAL ENVIRONMENTS DURING THE CARBONIFEROUS

The basement is Devonian in age (Famennian) and is in places intrusive (granitic plutons) and in places sedimentary. The top of the basement is an unconformity and is here mapped as horizon H1. Above H1, Carboniferous fill is recorded.

**The Horton is here divided into Lower, Middle, and Upper Horton Groups**, based on the work on onshore Newfoundland and Nova Scotia. It uses the three stages commonly defined within the Horton, with names defined within each basin. It also allows us to highlight the more sand-rich Lower and Upper Horton and the shalier Middle Horton. **For more details regarding the internal stratigraphy of the Horton Group, please refer to Chapter 3.**

**GDE 1: Lower Horton Group (Early Tournaisian; PL. 6.2.2)**

The Lower Horton Group (**PL. 6.2.2**) corresponds to initial sediments deposited during rifting of the Sydney Basin. For this interval, the depositional environment was continental to lacustrine and was strongly controlled by faulting, with conglomerate fans deposited in the footwalls of faults and lakes developing in the deepest topographic lows.

**GDE 2: Middle Horton Group (Middle Tournaisian; PL. 6.2.3)**

The Middle Horton Group (**PL. 6.2.3**) was also strongly constrained by the basement topography. Larger lakes developed, allowing the deposition of a thick succession of lacustrine shale. Fewer conglomeratic fans existed, and were restricted to the margin close to the main faults.

**GDE 3: Upper Horton Group (Late Tournaisian; PL. 6.2.4)**

The Upper Horton Group (**PL. 6.2.4**) saw the end of fan activity. Consequently, this interval contains very little to no coarse conglomerate deposits compared to the succession below. Deep lacustrine deposits are constrained to the Magdalen Basin along the northern side of the Cabot Fault.

**GDE 4: Lower Windsor Group (Early Visean; PL. 6.2.6)**

The Lower Windsor Group (**PL. 6.2.6**) is only locally constrained by basement blocks. However, it can be in places eroded by the Namurian-Westphalian Unconformity. A significant sea incursion occurred during deposition of the Windsor Group, allowing the deposition of thick carbonates and evaporites within shallow lakes.

**GDE 5: Upper Windsor Group (Late Visean; PL. 6.2.7)**

The Upper Windsor Group (**PL. 6.2.7**) is more strongly affected by the Namurian-Westphalian Unconformity than the Lower Windsor, and is only preserved in the central part of the Sydney Basin. The retreat of the Windsor Sea allowed the deposition of continental clastics.

**GDE 6: Mabou Group (Serpukhovian; PL. 6.2.8)**

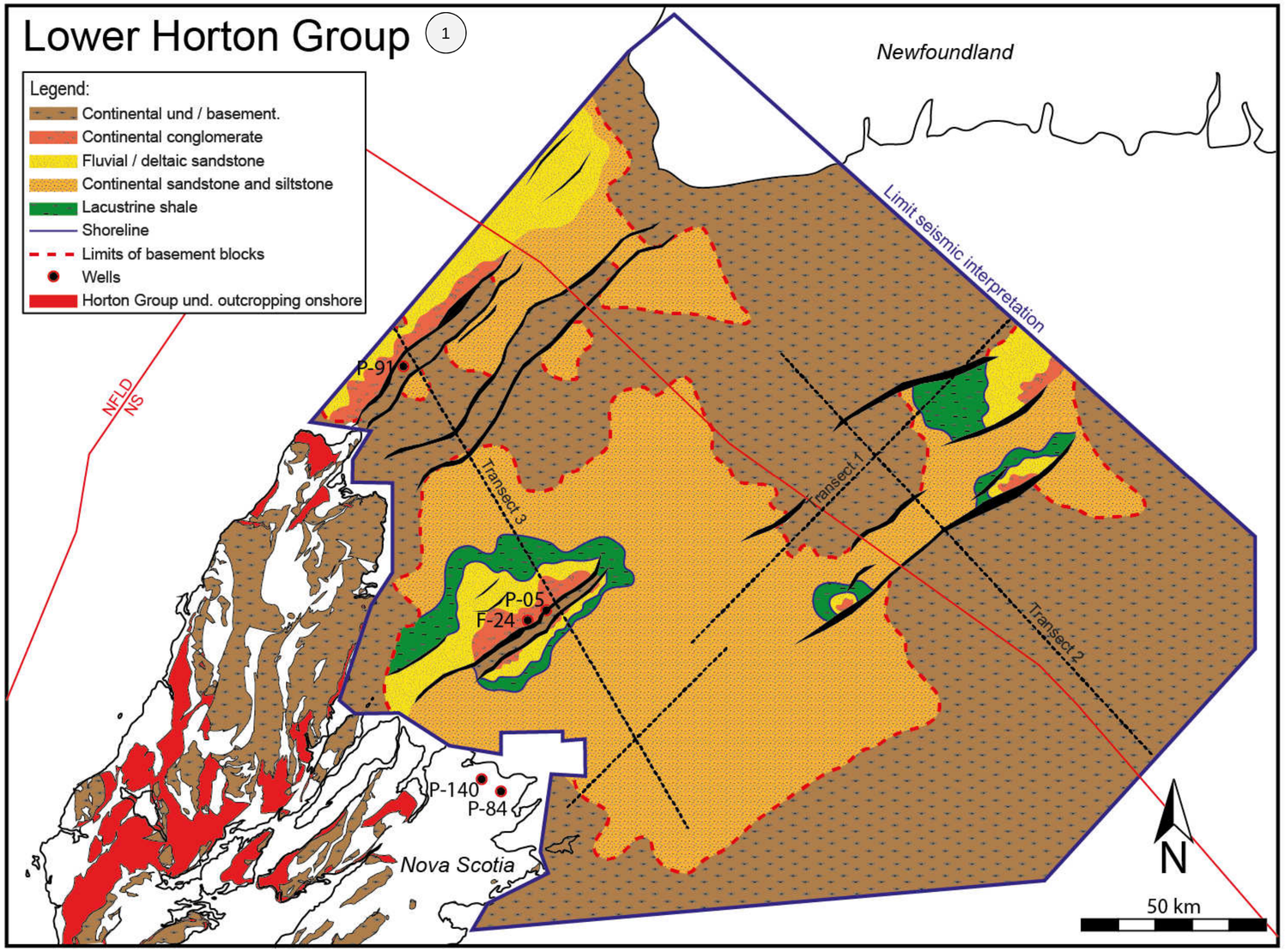
The Mabou Group (**PL. 6.2.8**) is largely dominated by fine-grained clastic deposits. However, a strong influence of rapid marine transgression persists, favoring humid environments and the development of marshes.

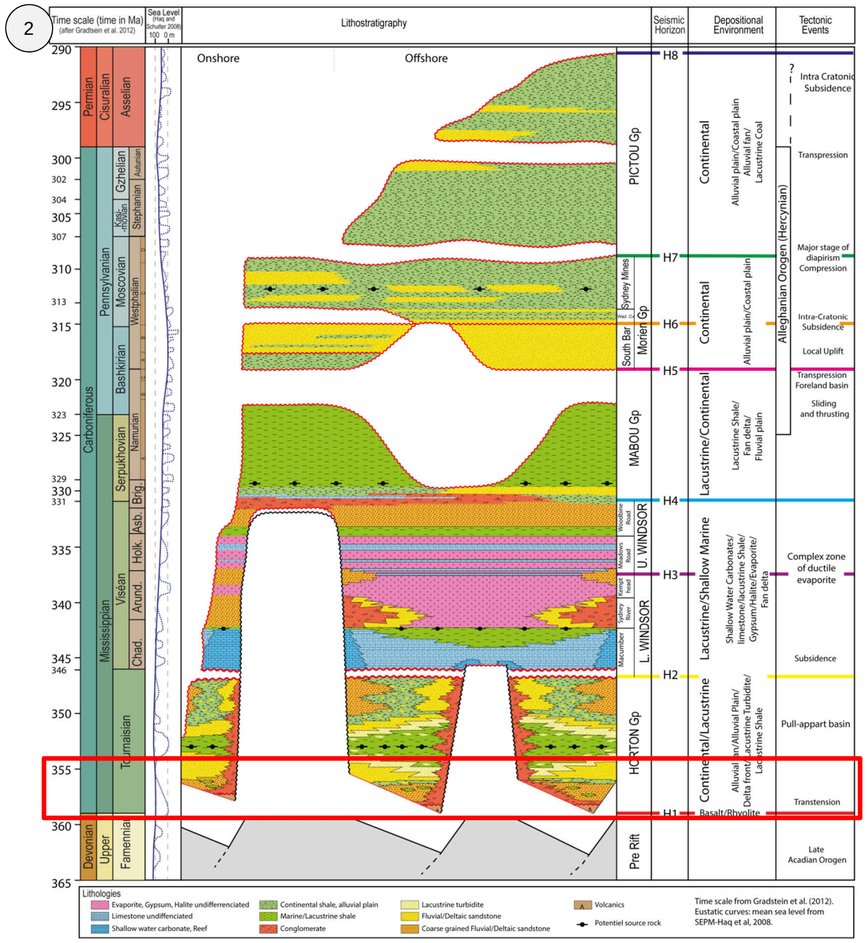
**GDE 7: Morien / Cumberland Group – South Bar Formation (Westphalian A-B; PL. 6.2.9)**

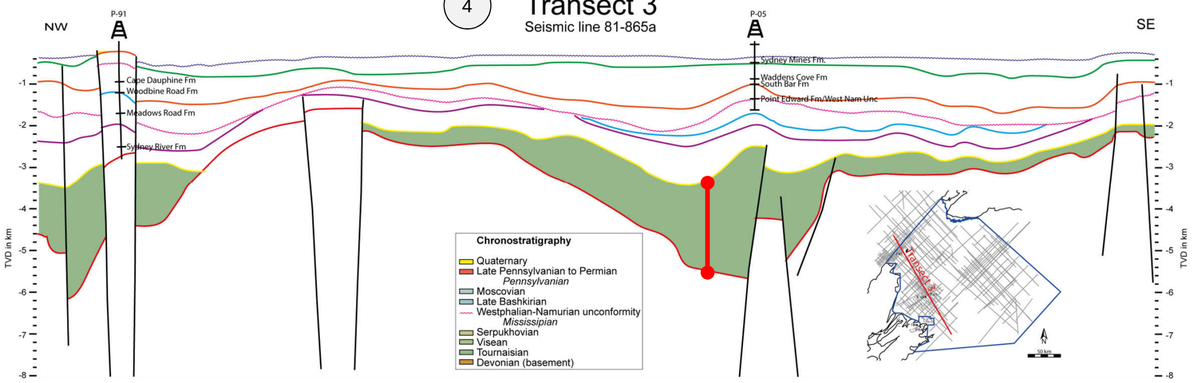
The South Bar Formation of the Morien / Cumberland Group (**PL. 6.2.9**) is characterized by a very homogeneous and constant thickness across the study area. It contains fluvial deposits and represents a blanket of medium-grained sandstone, with a relatively small proportion of fine-grained deposits preserved in between channels.

**GDE7: Morien / Cumberland Group – Sydney Mines Formation (Westphalian C-D; PL. 6.2.10)**

Finally, the Sydney Mines Formation of the Morien / Cumberland group (**PL. 6.2.10**) is dominated by continental deposits rich in coal. This formation is richer in finer-grained material compared to the underlying South Bar Formation.



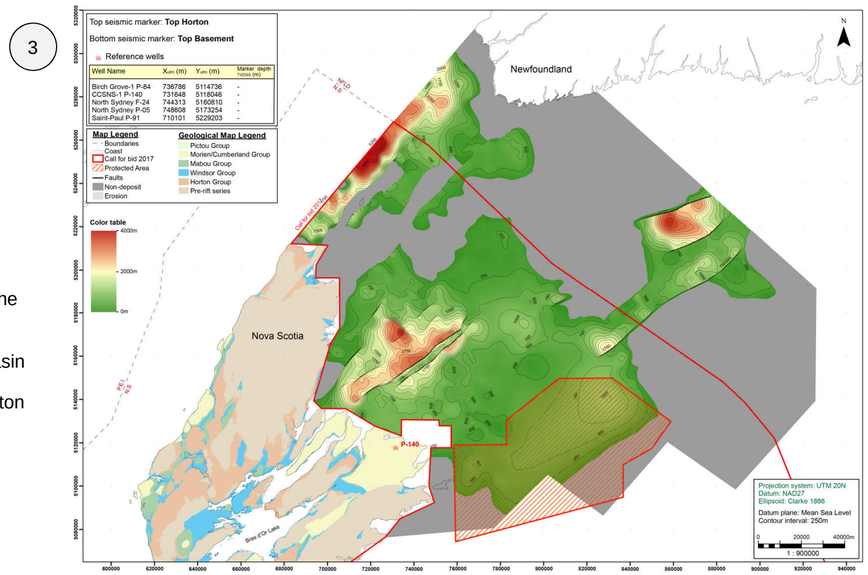




1- Gross Depositional Environment of the Lower Horton Group

2- Stratigraphic Chart of the Sydney Basin

3- Thickness Map Basement – Top Horton

4- Horton Group Interval in Transect 3 Cross-section




**PL. 6.2.2** **Lower Horton Group GDE Map**

# Middle Horton Group

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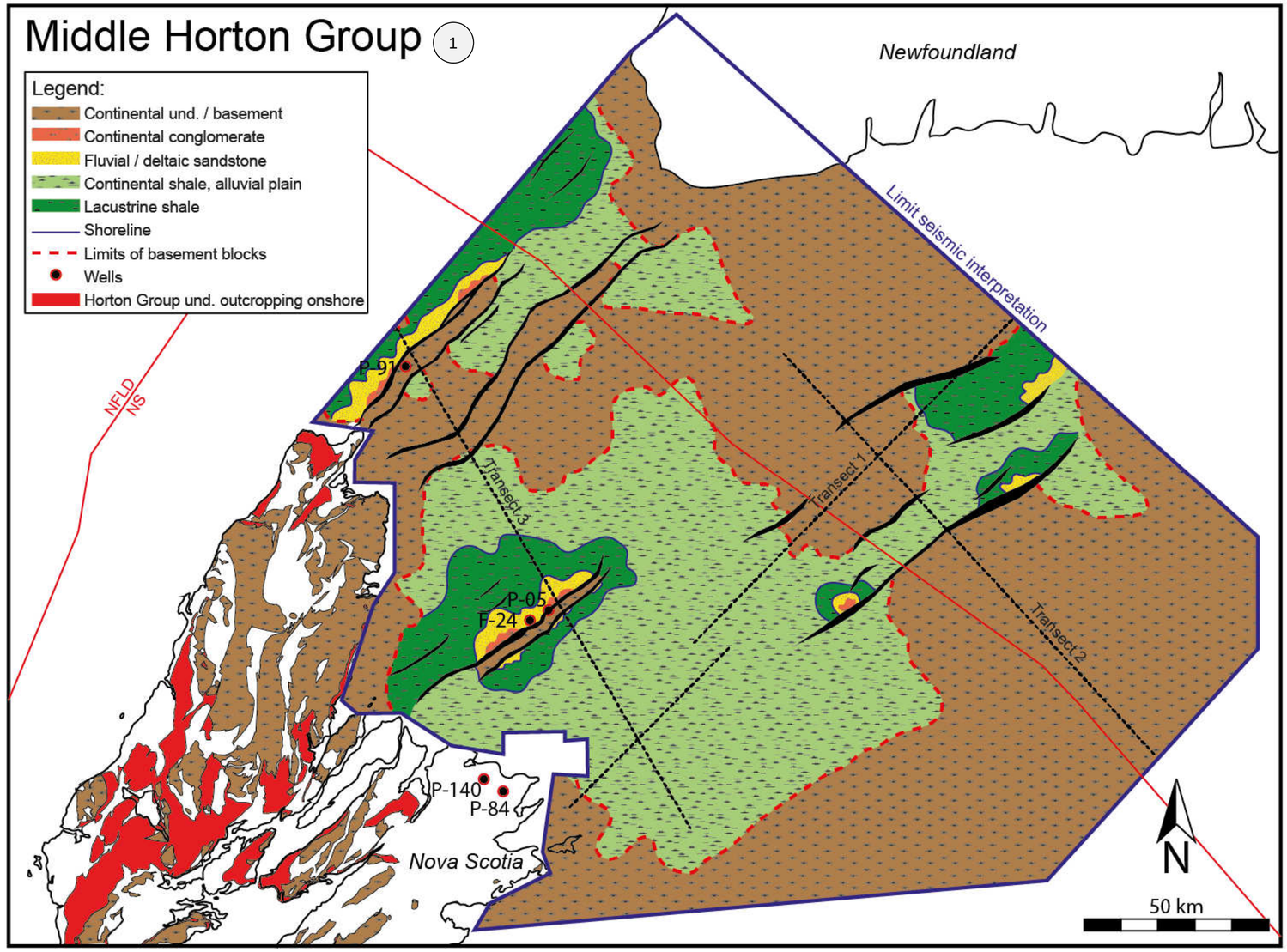


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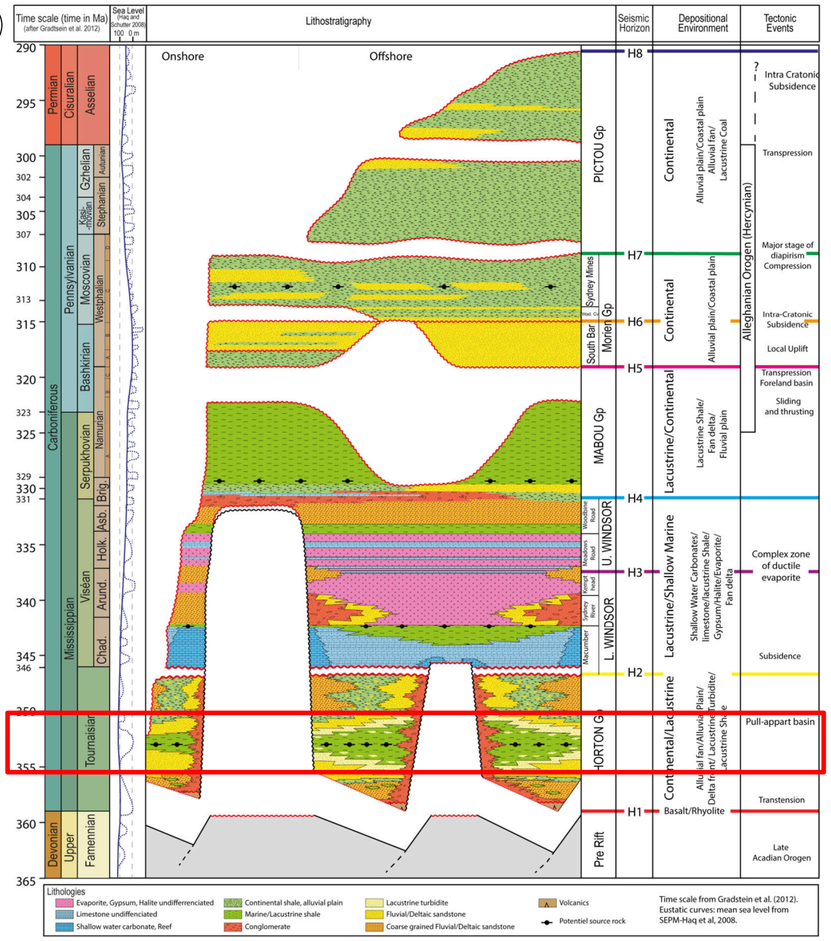


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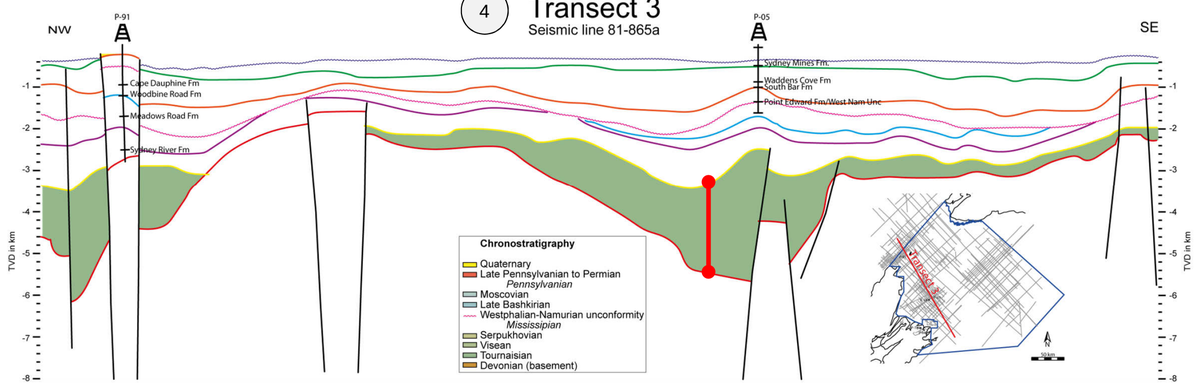
## Transect 3

Seismic line 81-865a



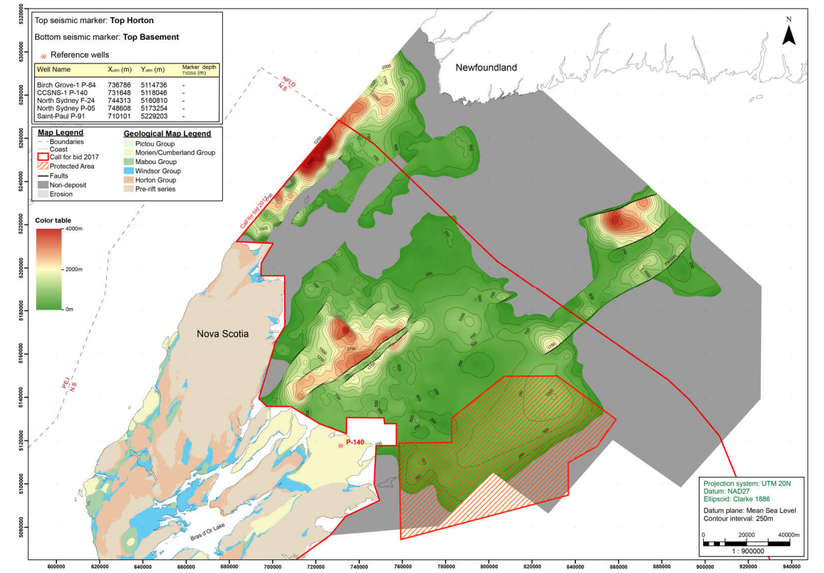

1- Gross Depositional Environment of the Middle Horton Group

2- Stratigraphic Chart of the Sydney Basin

3- Thickness Map Basement – Top Horton

4- Horton Group Interval in Transect 3 Cross-section

3

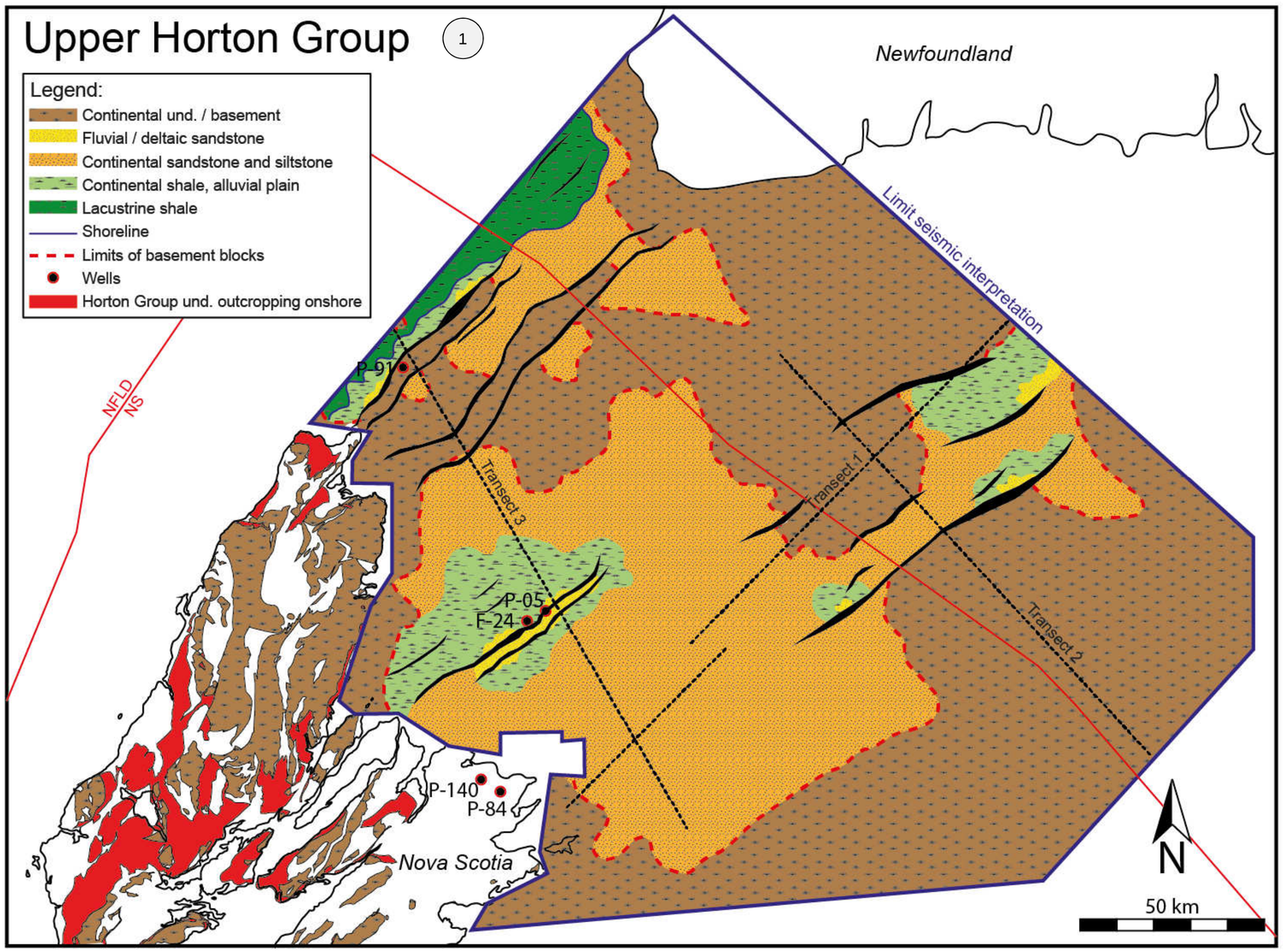



# Middle Horton Group GDE Map

**PL. 6.2.3**

# Upper Horton Group

1

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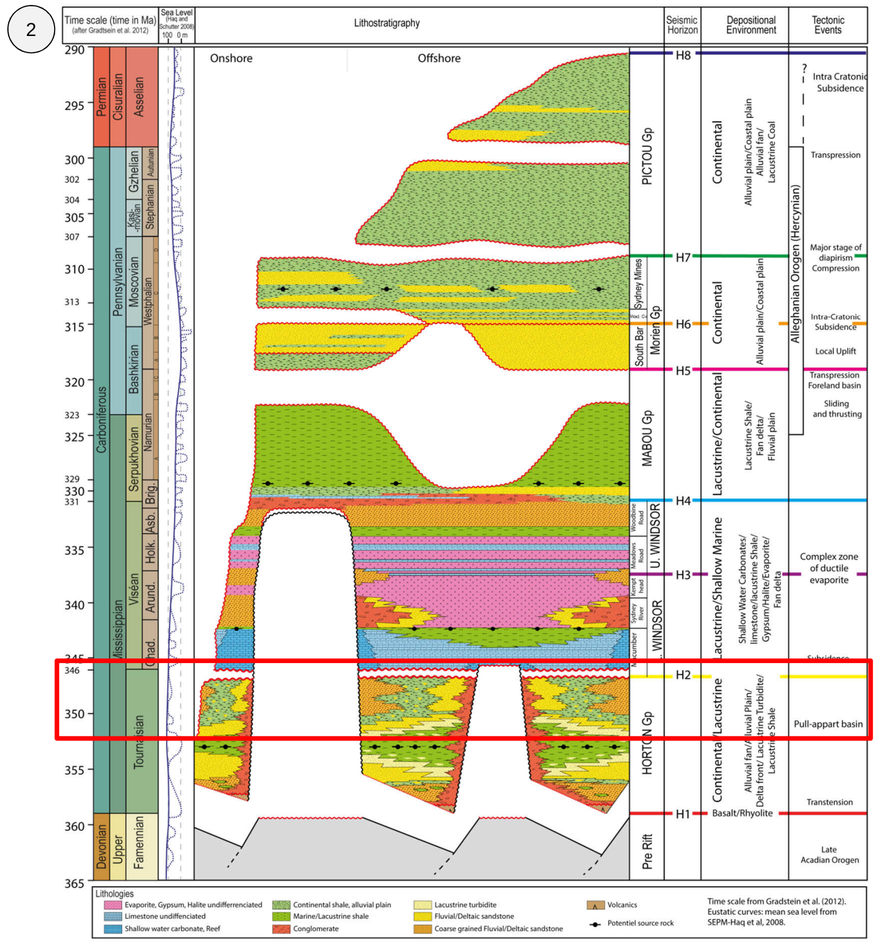


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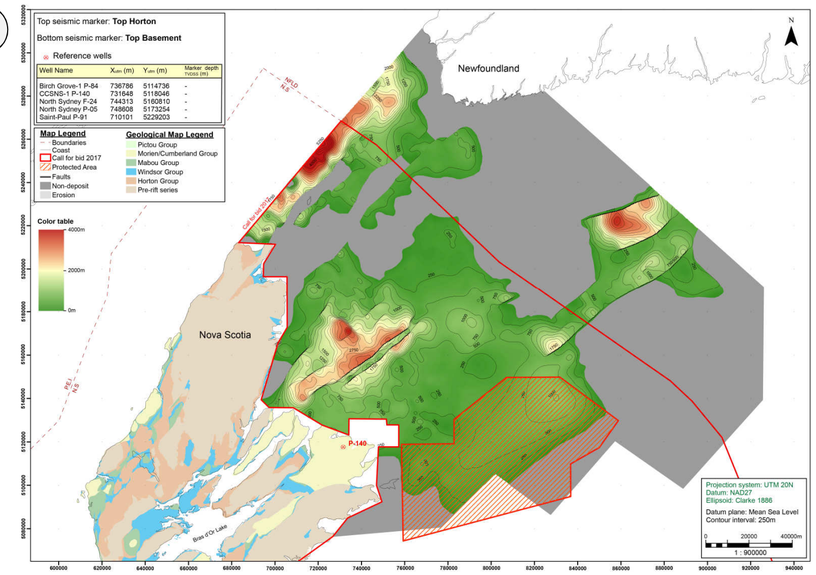


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## Transect 3

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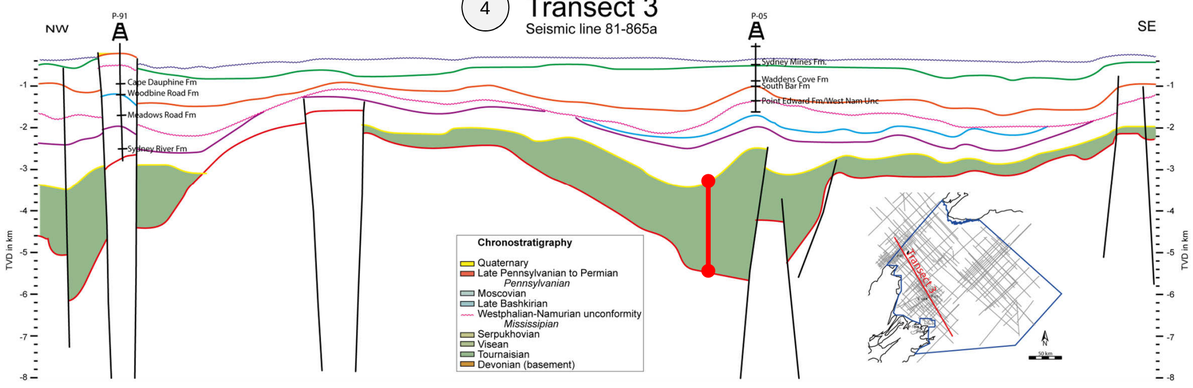


1- Gross Depositional Environment of the Upper Horton Group

2- Stratigraphic Chart of the Sydney Basin

3- Thickness Map Basement – Top Horton

4- Horton Group Interval in Transect 3 Cross-section

**PL. 6.2.4** **Upper Horton Group GDE Map**

# WINDSOR PALEOGEOGRAPHY

SYDNEY BASIN PLAY FAIRWAY ANALYSIS – CANADA – July 2017

## THE VISEAN PALEOGEOGRAPHY

There is a continuous distribution of Carboniferous basins along the Caledonian and Appalachian mountains, and some have shown a potential connection with the Mid Euramerican Sea (Figure 1). Indeed, the data show a restricted marine environment, implying a punctual connection to the ocean.

A sabkha environment is observed within the Windsor deposits, characterised by deposition in a semi-arid to arid climate. The water is stratified (i.e. meromictic environment) implying that the salinity is controlled by evaporation and weak marine incursions.

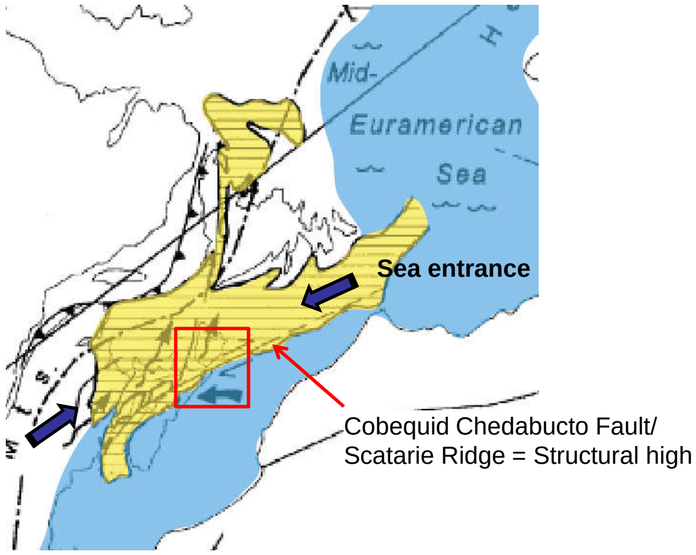


*Figure 3: Nova Scotia in the context of equatorial Euramerica during the Carboniferous. (source: Calder, 1998)*

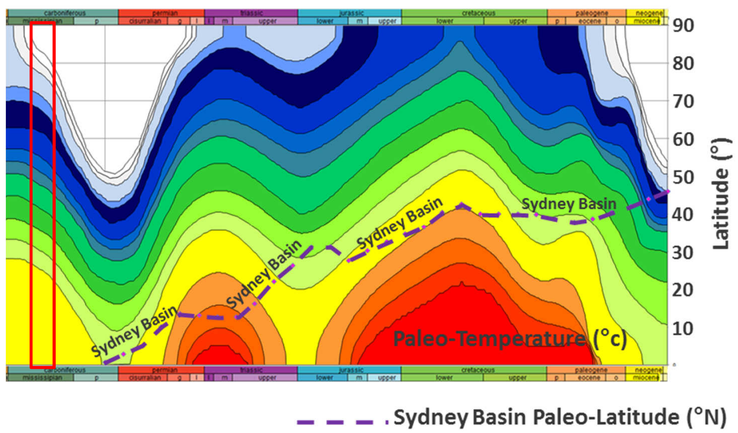


*Figure 4: The Sydney Basin paleo-latitude is here shown on the cross-plot of the paleo-temperature (in°C) trough time versus the latitude (in °). The red box highlights the period of interest. Paleo-surface temperature was defined from paleo-climate combined with paleo-latitude evolution of Sydney Basin (www.paleolatitude.org). Paleo-climate graph (Wygrala, 1989) gives mean surface temperature function of ages and latitude.*

## WINDSOR LITHOLOGY AND PALEOGEOGRAPHY

The lower part of the Macumber Formation (Windsor Group) represents a mix of continental clastic and shallow marine carbonate rocks.

The clastic deposits are dominated by conglomerates and alluvial fan sediments while the carbonate deposits are dominated by lime mudstone, calcite nodules, stromatolites and oncolitic limestone (Figures 5 to 7).

*Figure 5: Laminated algal stromatolite of the Windsor Group. Jonhson, 2009*

*Figure 6: Oncolitic limestone of the Windsor Group. Jonhson, 2009*

In the onshore sections of the Windsor Group, up to 1400 m of evaporites are recorded. We speculate that this onshore section is similar to what we would find in the deepest part of Sydney Basin. Depending on the location within the basin, the Windsor Group may start directly with anhydrite or with sandstone (Figure 7).

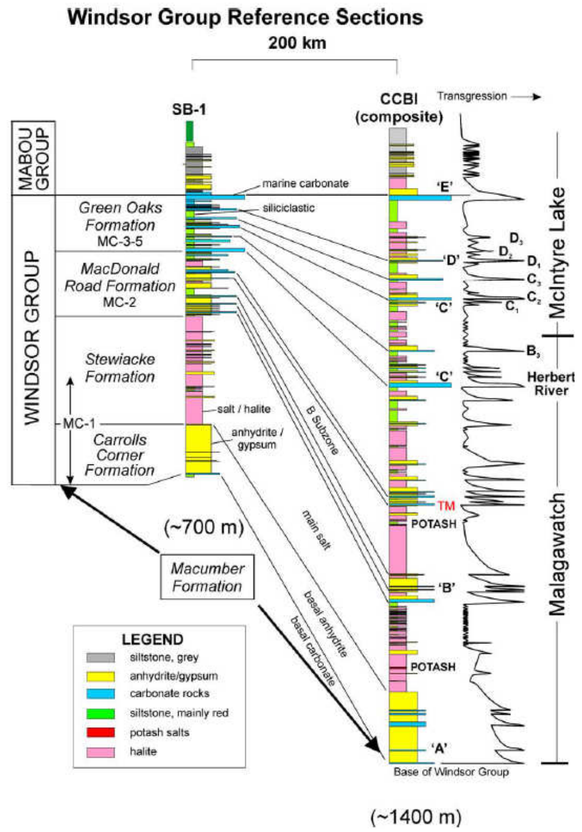


*Figure 7: Windsor Group reference section correlations, Shubenacadie Basin (SB-1) and central Cape Breton Island composite section (CCBI Malagawatch and McIntyre Lake). Giles and Boehner, 2003*

## IMPLICATIONS FOR THE DEPOSITIONAL ENVIRONMENT AND GEOLOGICAL MODEL

The type of evaporites is a function of evaporation versus water volume. This means that an increase in halite or potash thickness implies high evaporation, the presence of sea water, and available accommodation (Figure 8)

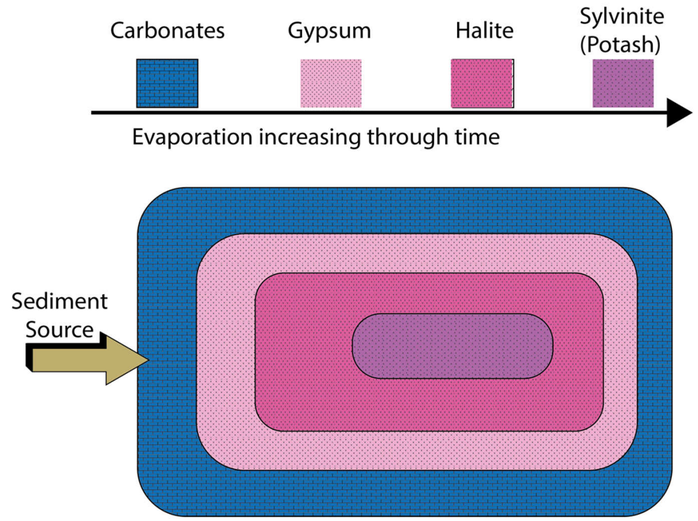


*Figure 8: Schematic concentric distribution in evaporitic basins. Seranne, 2011*

## IMPLICATIONS FOR THE DEPOSITIONAL ENVIRONMENTAL AND GEOLOGICAL MODEL

The presence of stromatolites, fish and certain invertebrates suggests a shallow marine environment and implies connection with the ocean. The rapid evolution from gypsum to halite and potash suggests a sudden isolation from the ocean, with evaporation exceeding seawater inflow. Only seasonal freshwater input allowed salt concentration to decrease. It is important to note that the sporadic connection with the ocean permitted an influx of marine water corresponding to high stands resulting in a thickening of evaporites. In this particular case, sea level was controlled by tectonics or glacio-eustasy.

## REFERENCES


Calder, J.H. 1998. The Carboniferous evolution of Nova Scotia. In: Blundell, D. J. & Scott, A. C. (eds) Lyell: the past is the key to the present. *Geological Society, London, Special Publications*, v. 143, p. 261-302.

Giles, P.S. and Boehner, R.C. 2003. Windsor Group Stratigraphy and Structure, Drill Core Orientation Field Trip 2001. Open File Report ME 2003-2. 51p.

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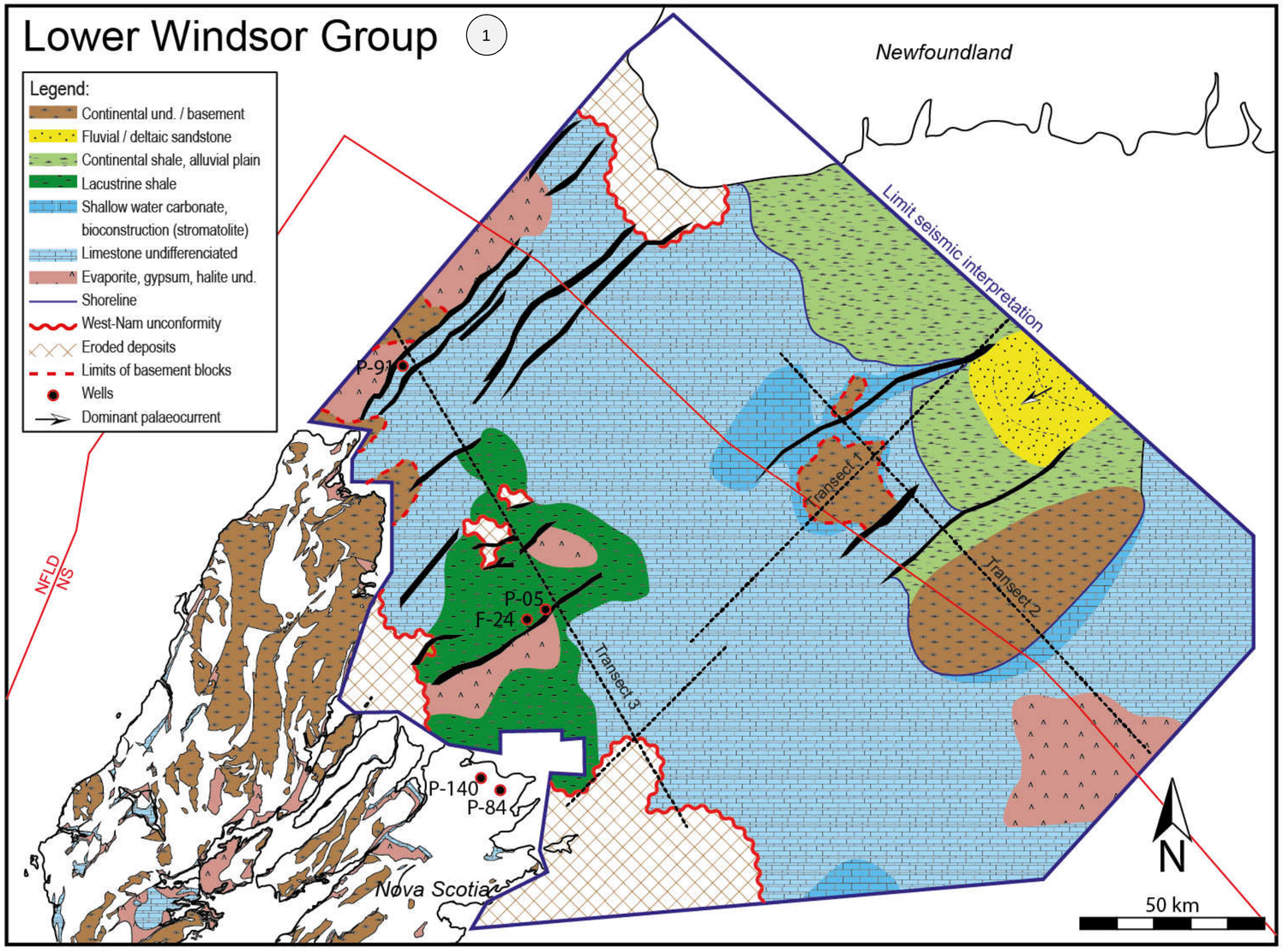
Wygrala, B.P., 1989, Integrated Study of an Oil Field in the Southern Po Basin, Northern Italy: Ph.D. dissertation, University of Cologne, 217p.

# Lower Windsor Group

1

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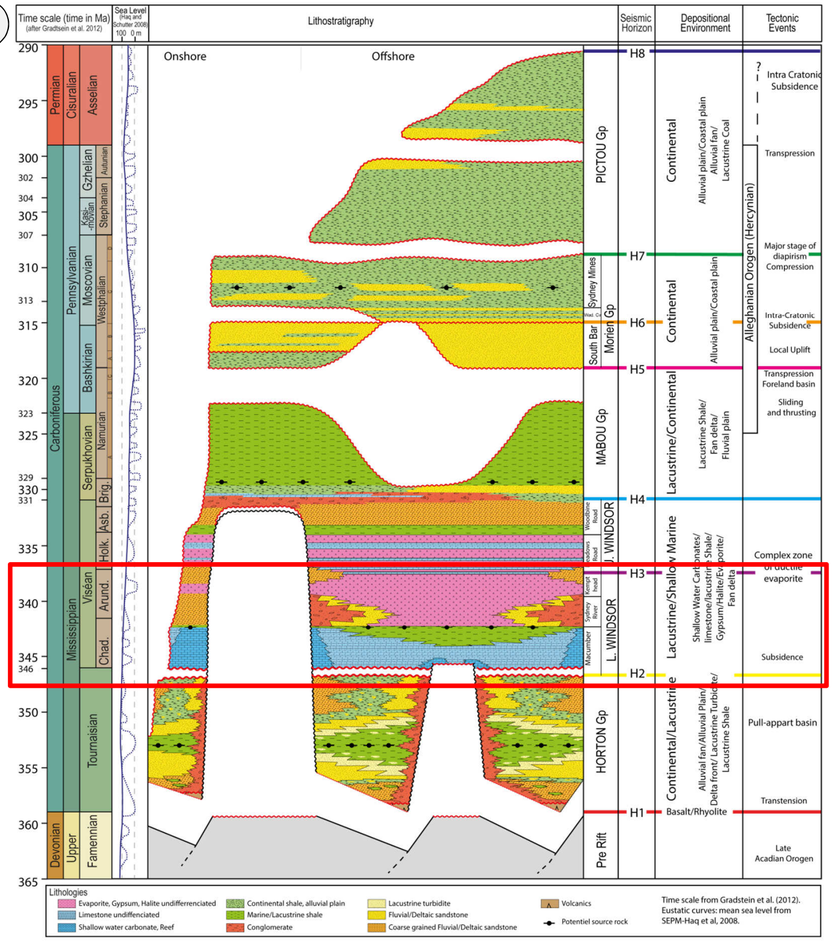


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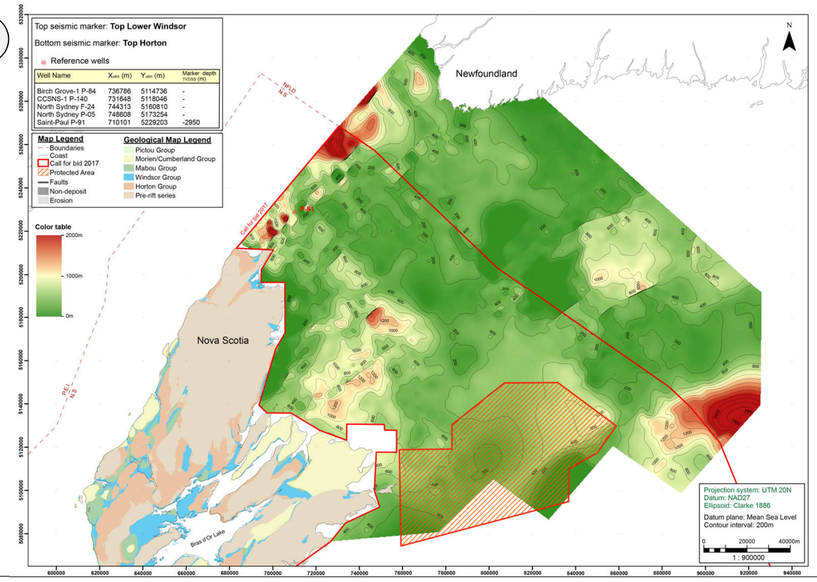


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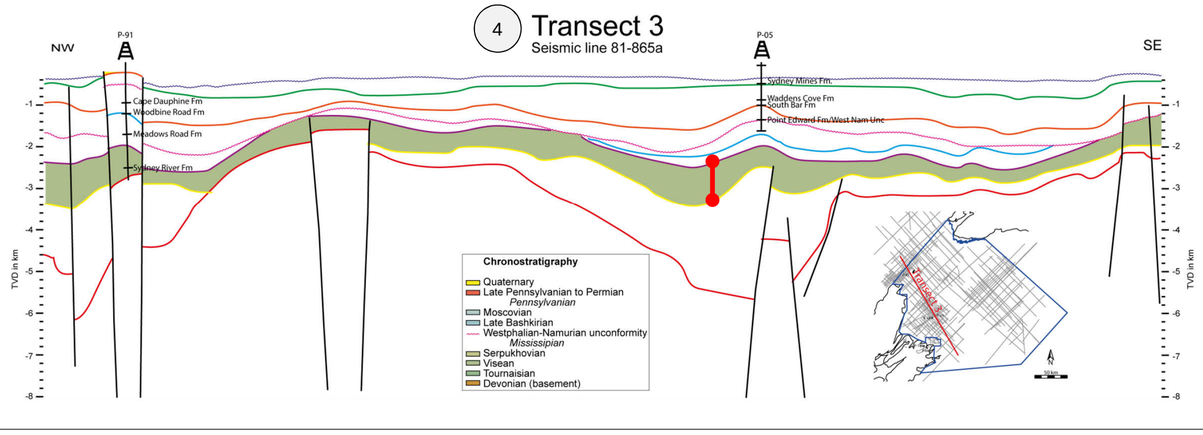



1- Gross Depositional Environment of the Lower Windsor Group

2- Stratigraphic Chart of the Sydney Basin

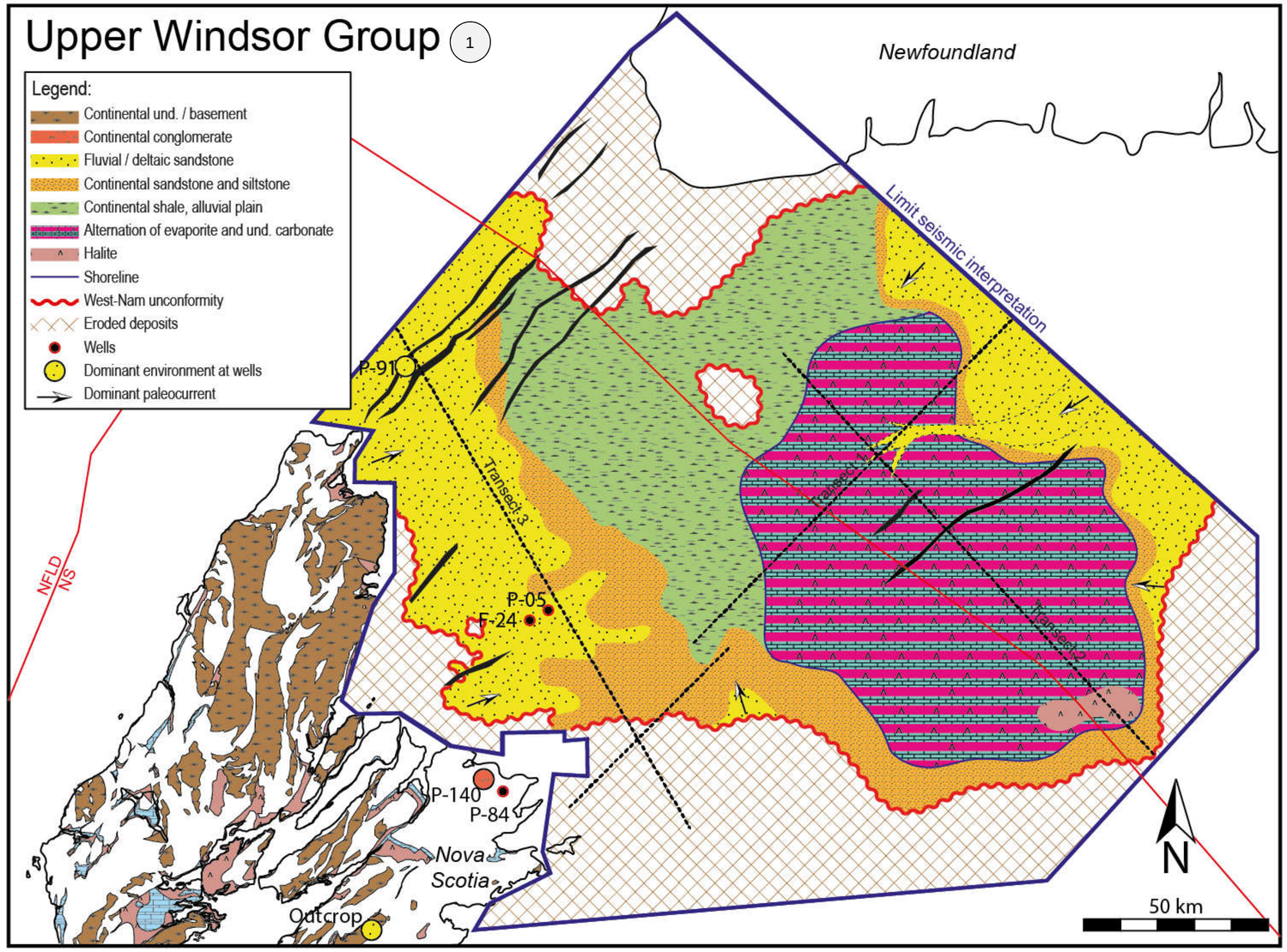
3- Thickness Map Top Horton - Top Lower Windsor

4- Lower Windsor Interval in Transect 3 Cross-section

**PL. 6.2.6** **Lower Windsor Group GDE Map**

# Upper Windsor Group

1

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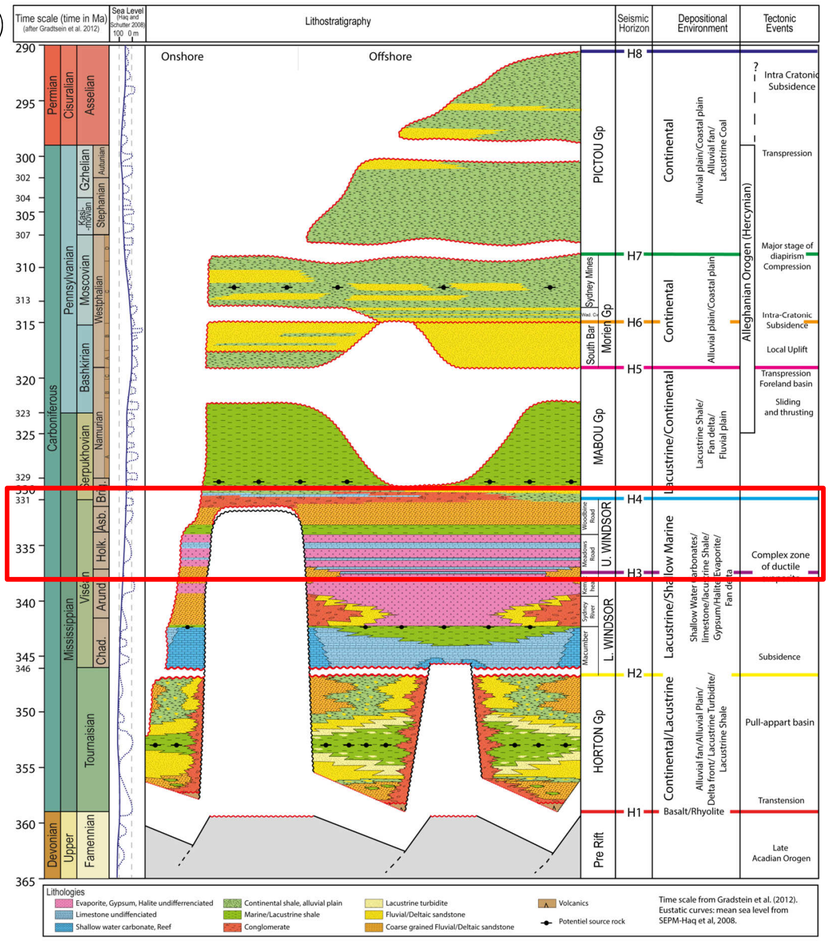
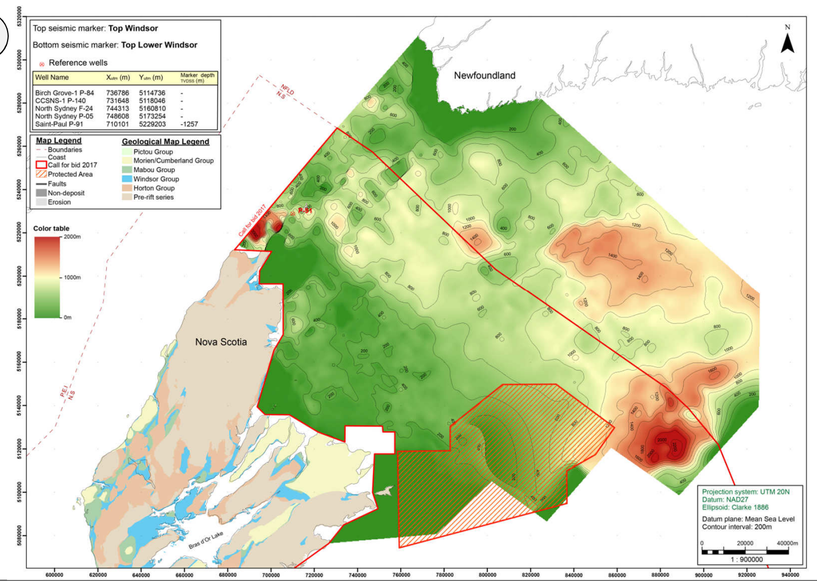


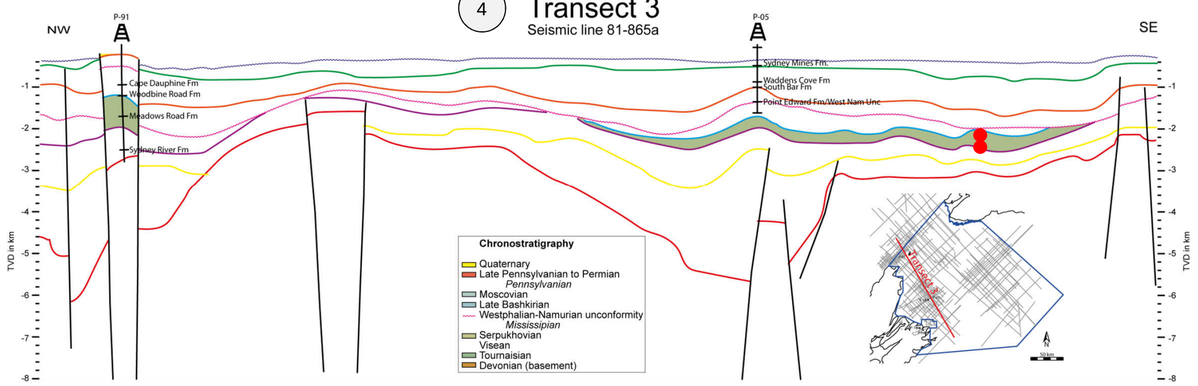

3




4

## Transect 3

Seismic line 81-865a




1- Gross Depositional Environment of the Upper Windsor Group

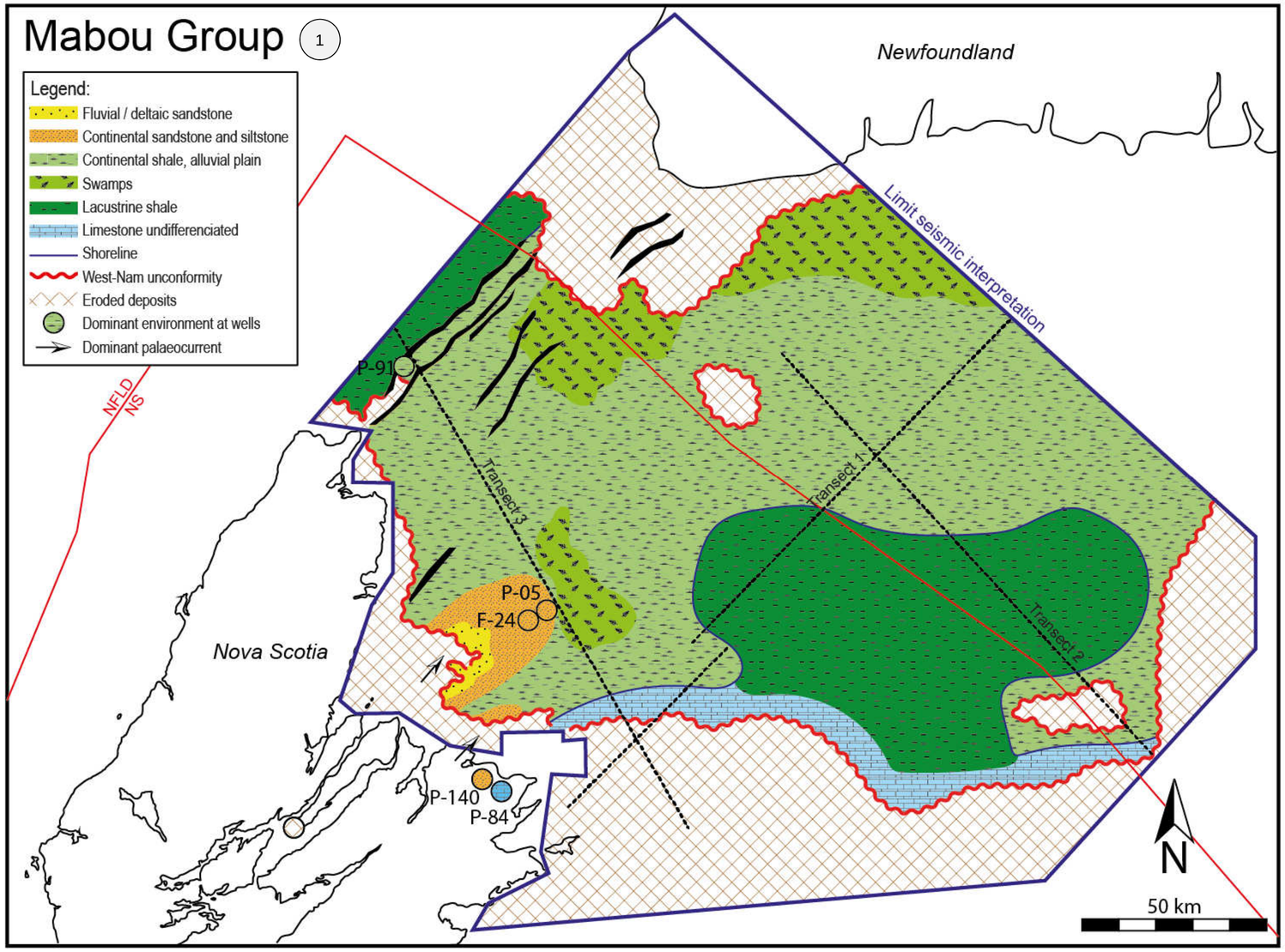
2- Stratigraphic Chart of the Sydney Basin

3- Thickness Map Top Lower Windsor – Top Windsor

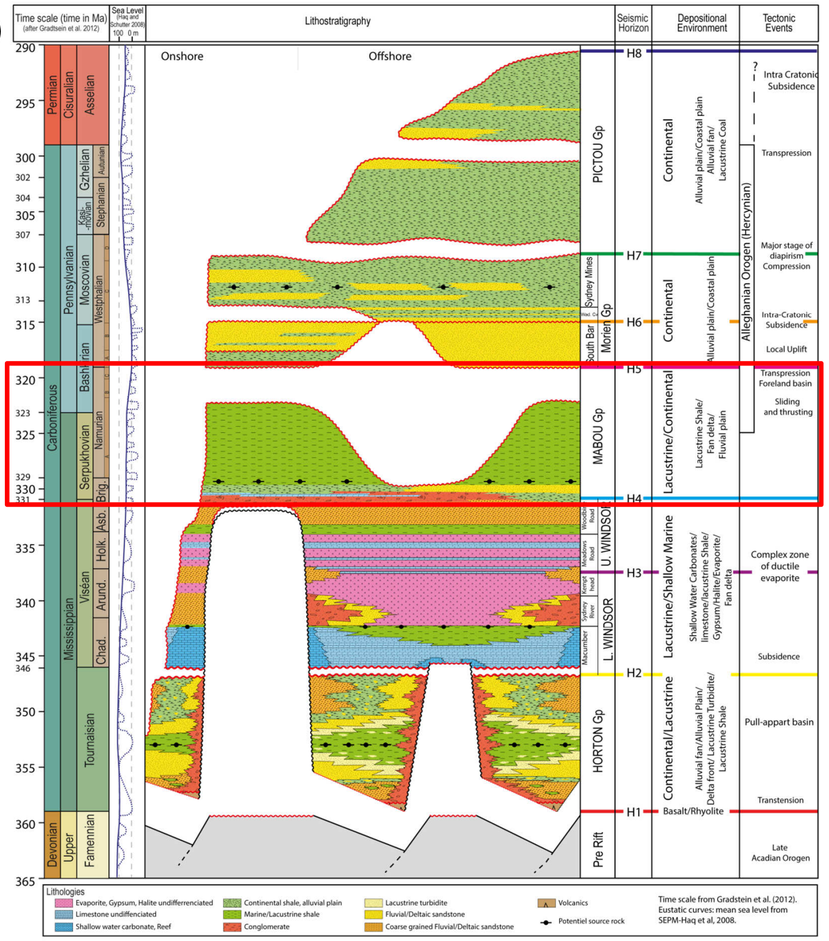
4- Upper Windsor Interval in Transect 3 Cross-section

# Mabou Group

1




2

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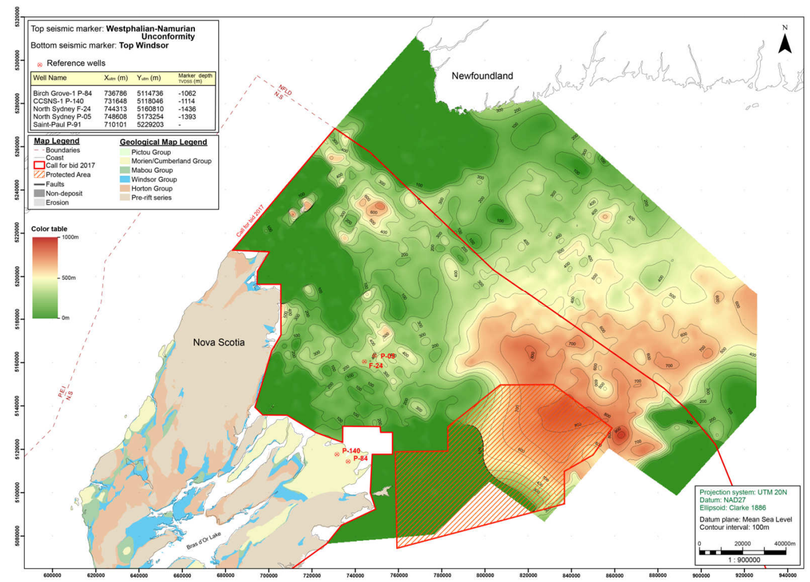


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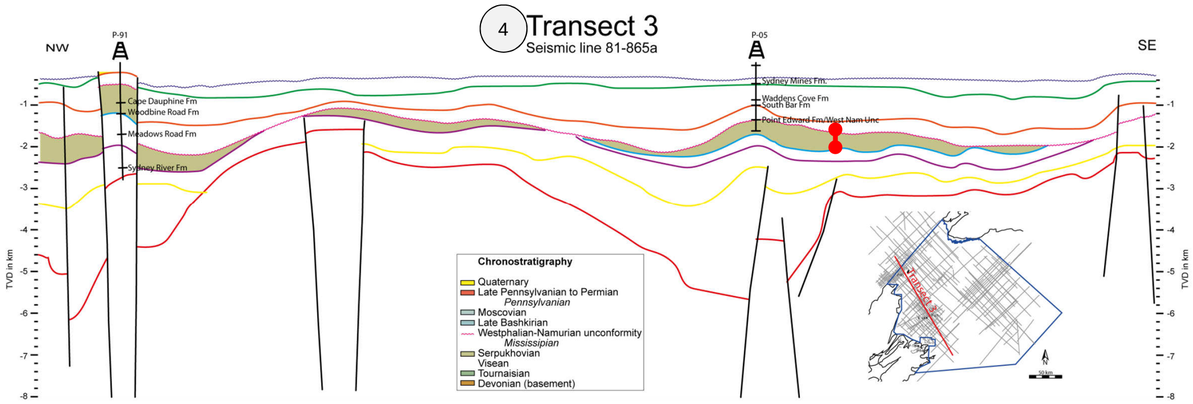



1- Gross Depositional Environment of the Mabou Group

2- Stratigraphic Chart of the Sydney Basin

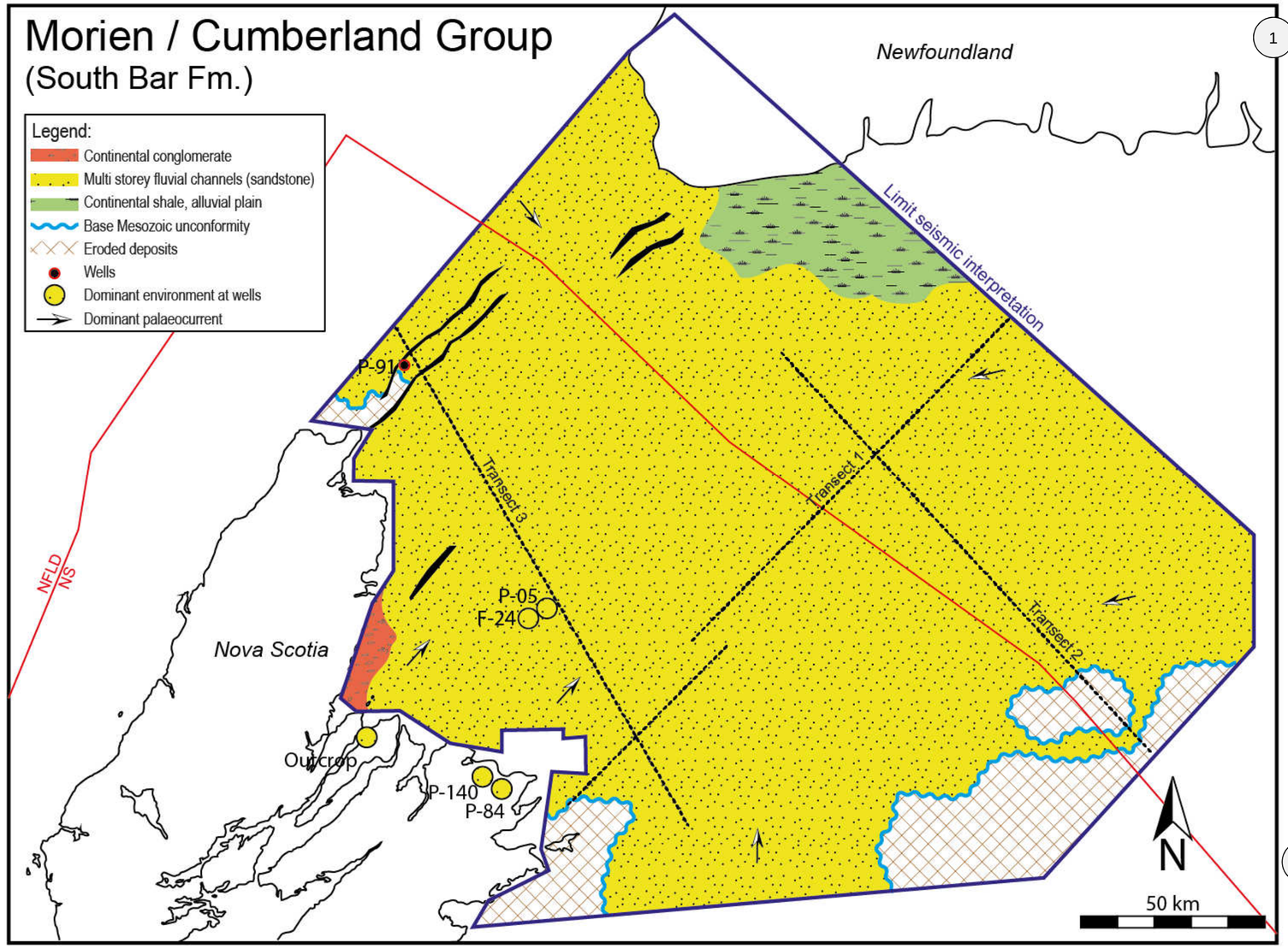
3- Thickness Map Top Windsor – Westphalian Namurian Unconformity

4- Mabou Group Interval in Transect 3 Cross-section

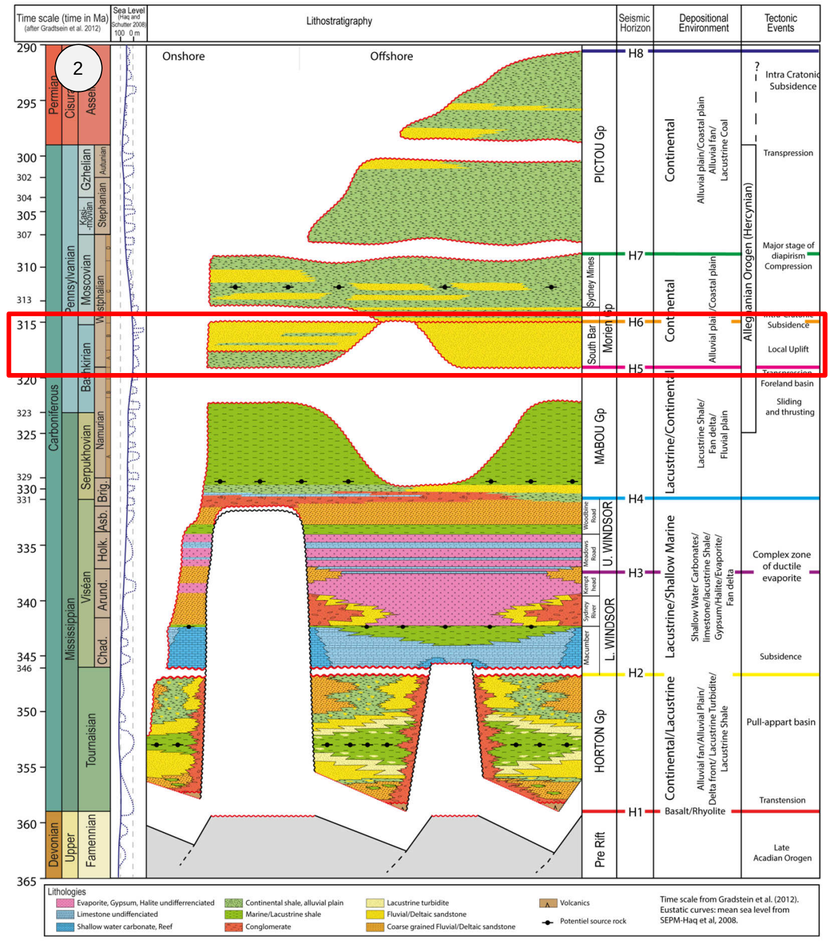
**PL. 6.2.8** **Mabou Group GDE Map**

# Morien / Cumberland Group
## (South Bar Fm.)

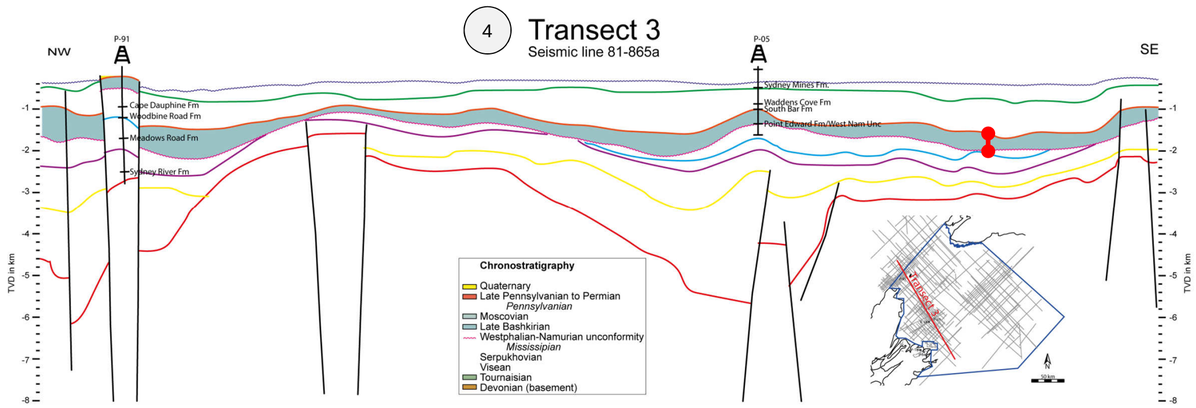
1




2




4



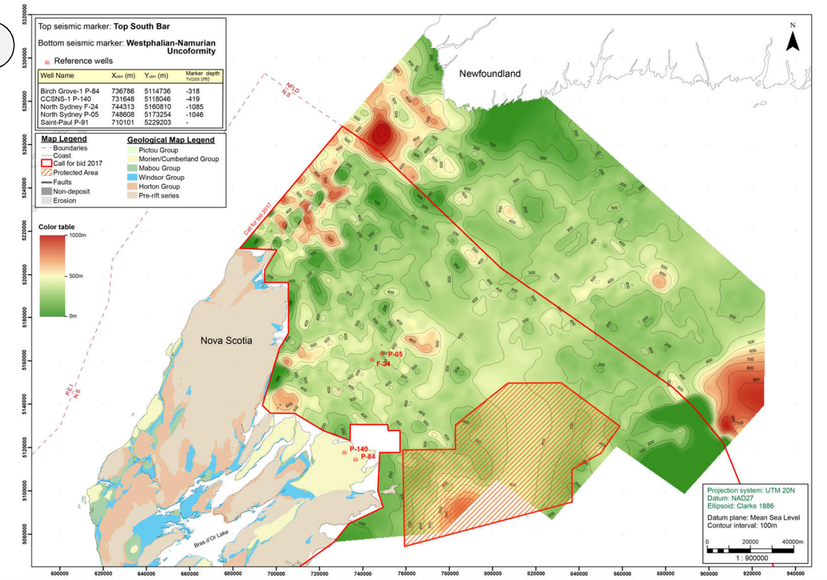

1- Gross Depositional Environment of the South Bar Fm (Morien Group)

2- Stratigraphic Chart of the Sydney Basin

3- Thickness Map Westphalian Namurian Unconformity – Top South Bar Fm.

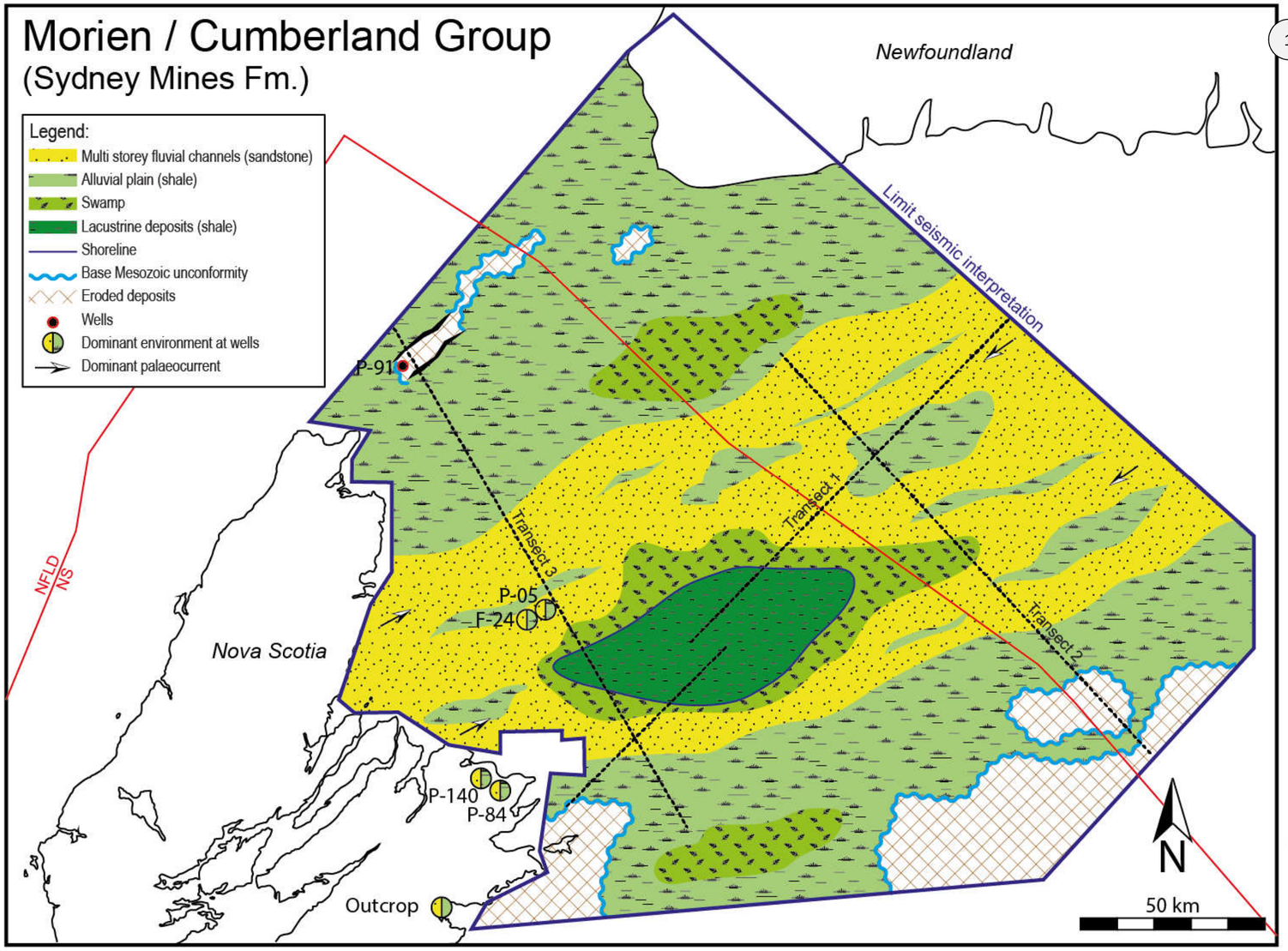
4- South Bar Fm Interval in Transect 3 Cross-section

3

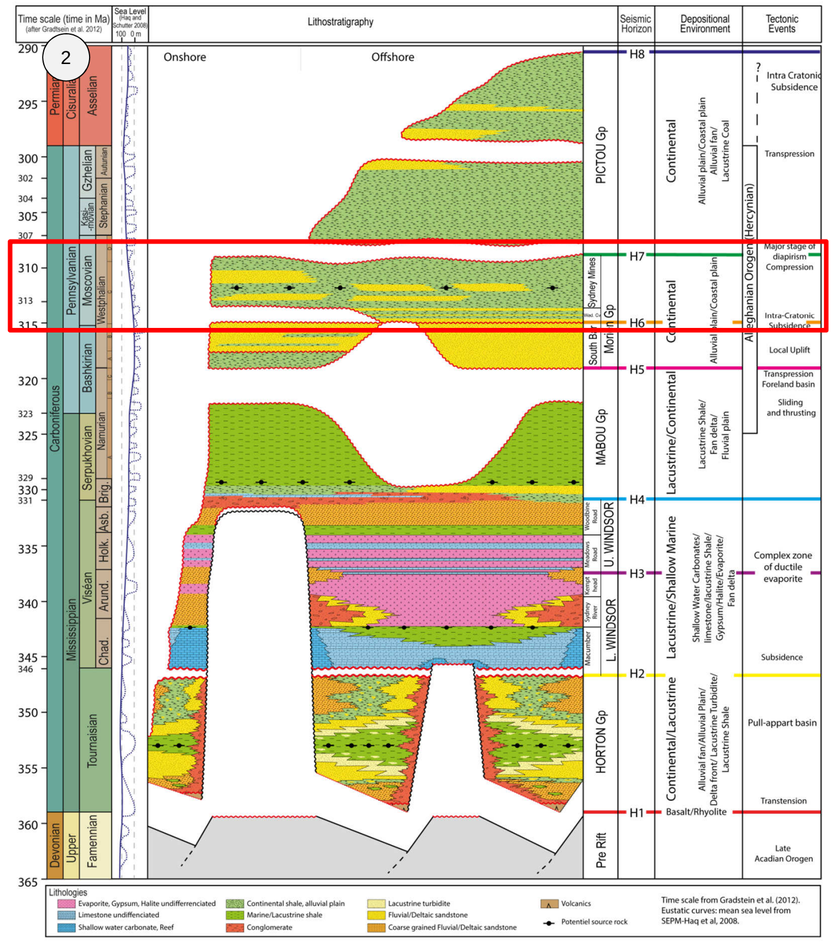


1

# Morien / Cumberland Group
## (Sydney Mines Fm.)




2

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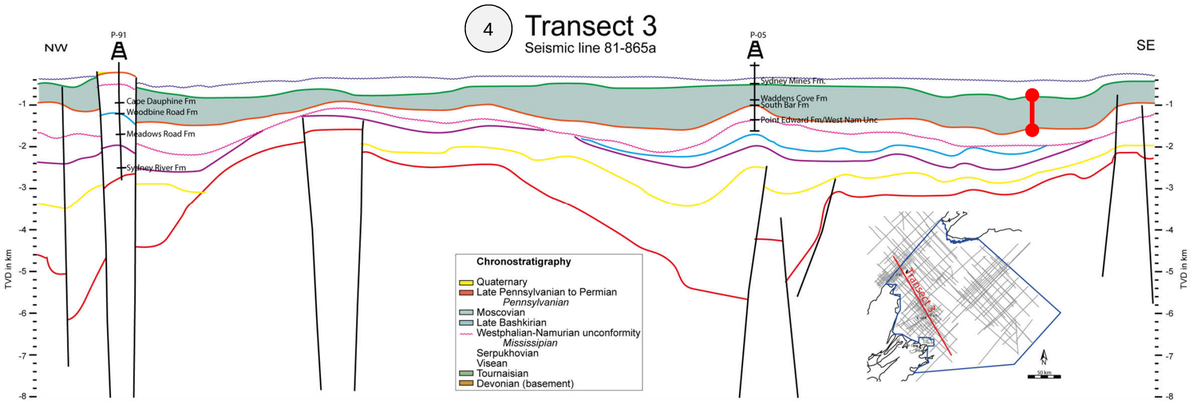


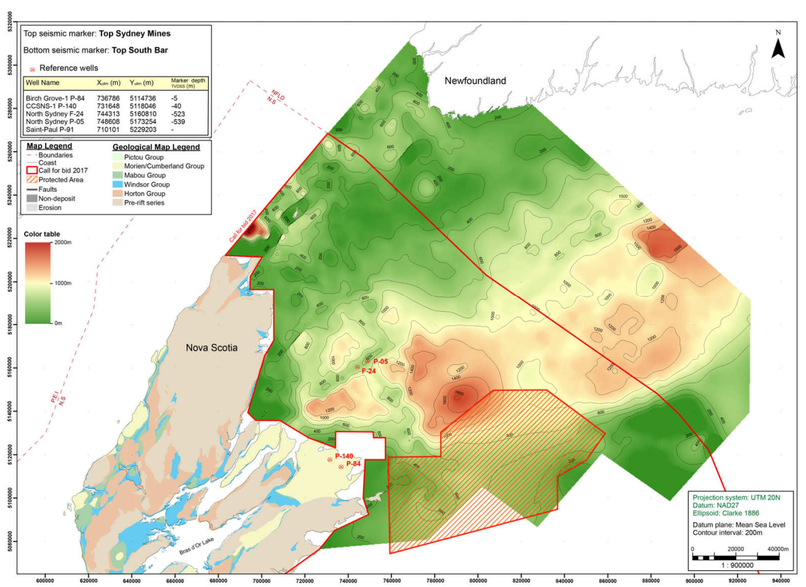

1- Gross Depositional Environment of the Sydney Mines Fm (Morien Group)

2- Stratigraphic Chart of the Sydney Basin

3- Thickness Map Top South Bar - Top Sydney Mines

4- Sydney Mines Fm. Interval in Transect 3 Cross-section

3



| STRATIGRAPHY | | | | | PETROLEUM SYSTEM ELEMENT | | |
|---|---|---|---|---|---|---|---|
| AGE | | | | GROUP | | | |
| Period | Epoch | Stage-ICS | Stage-EUR | Formation | Source Rock | Reservoir / Carrier | Seal |
| Permian | Cisuralian | Asselian | Asselian | **Pictou** | | | |
| | | | | Pictou | | | |
| | | Kasimovian | | **Cumberland** | | | |
| | | | Westphalian | Sydney Mines | | | |
| | | | | Waddens Cove | | | |
| | | | | South Bar | | | |
| | Mississippian | Serpuhkovian | | **Mabou** | | | |
| | | | | Point Edward | | | |
| | | | | Cape Dauphin | | | |
| | | Visean | Visean | **Windsor** | | | |
| | | | | Woodbine Road | | | |
| | | | | Meadows Road | | | |
| | | | | Sydney River | | | |
| | | | | Macumber | | | |
| | | Tournasian | Tournasian | **Horton** | | | |
| | | | | Upper Horton | | | |
| | | | | Middle Horton | | | |
| | | | | Lower Horton | | | |
| Hadrynian to Devonian | | | | **Basement** | | | |

**PETROLEUM SYSTEM ELEMENTS**

The table above summarises the main elements present within the succession, from the Horton Group to the Pictou Group.

The Sydney Basin includes four main potential sources rocks: the lacustrine shale deposited within the Middle Horton Group; the thin organic-rich marine shales deposited in the Lower Windsor Group; the organic-lean shales deposited in the Mabou Group; and the coaly intervals contained within the Morien / Cumberland Group.

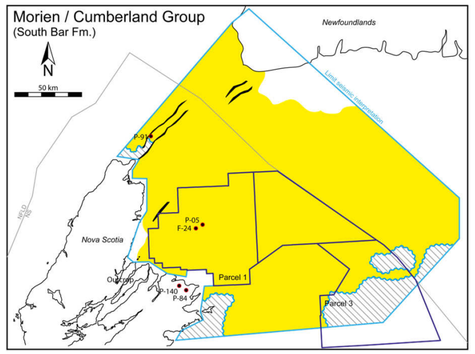
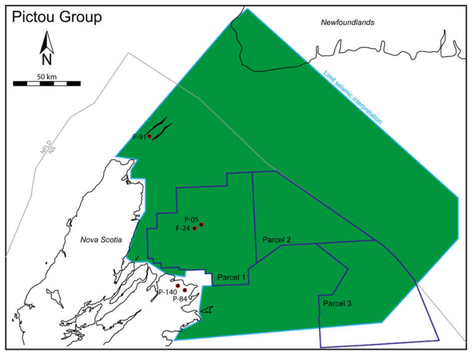
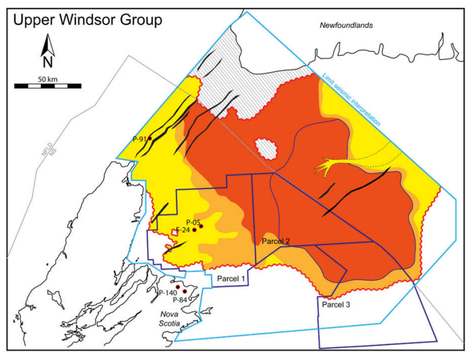
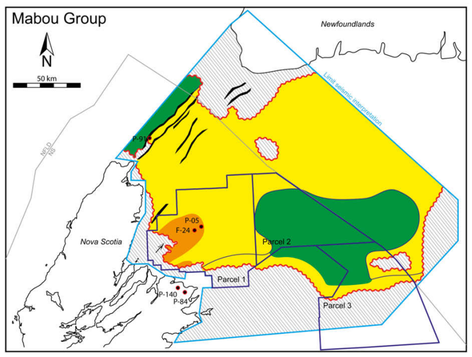
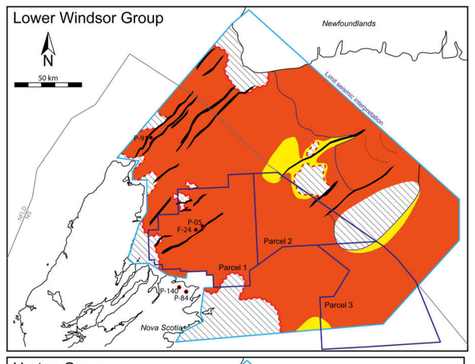
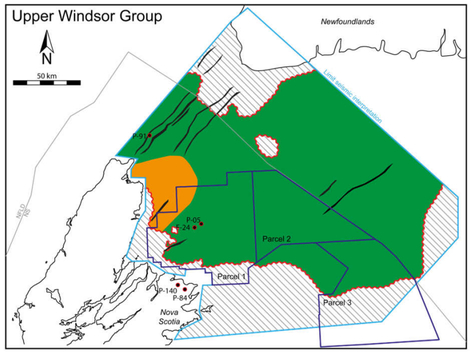
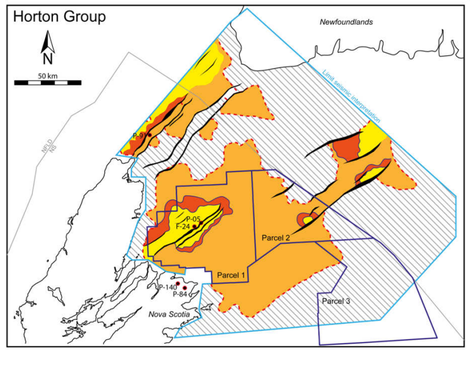
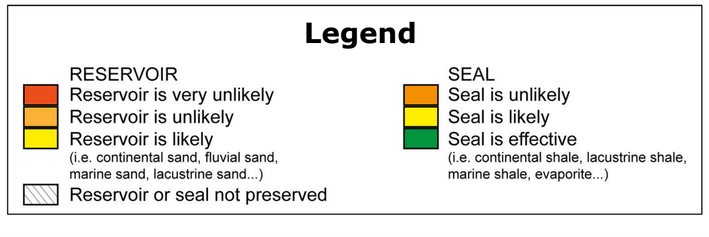
The Sydney Basin includes several units that are potential reservoirs: the fluvial / deltaic sandstone of the Lower and Upper Horton Group; the shallow water carbonate and bioconstruction (stromatolite) of the Lower Windsor Group; the deltaic sandstones of the Upper Windsor Group, and the fluvial sandstone of the Morien / Cumberland Group.

Finally, several potential seals have been interpreted: the halite and evaporite units of the Lower Windsor; and the fine grained sediment of the Pictou Groups.

The following slides present five potential plays of the Sydney Basin: the Horton clastic play (PL. 6-3-2), the Horton / Windsor carbonate play (PL. 6-3-3); the Windsor clastic play (PL. 6-3-4), the South Bar Formation clastic play (PL. 6-3-5); and the Sydney Mines Formation clastic play (PL. 6-3-5).

# PLAYS

SYDNEY BASIN PLAY FAIRWAY ANALYSIS – CANADA – July 2017

| | POTENTIAL RESERVOIRS | POTENTIAL SEALS | KEY PLAY RISKS |
|---|---|---|---|
| ***Cumberland clastic play*** |  |  | • Poor seismic coverage and quality<br>• Reservoir diagenesis |
| | ***Morien / Cumberland Group***<br>Formation: South Bar<br>Age: Westphalian A-B<br>Dominant lithology: fluvial sandstone | ***Pictou Group***<br>Age: Permian<br>Dominant lithology: alluvial plain shale | |
| ***Windsor clastic play*** |  |  | • Poor seismic coverage and quality<br>• Reservoir presence<br>• Reservoir diagenesis<br>• SR extent, thickness and quality |
| | ***Upper Windsor Group***<br>Formation: Sydney River and Kempt Head<br>Age: Visean (Arundian)<br>Dominant lithology: fluvial / deltaic sandstone | ***Mabou Group***<br>Seal Formation: Cape Dauphin<br>Age: Westphalian<br>Dominant lithology: anhydrite and evaporite | |
| ***Windsor carbonate play*** |  |  | • Poor seismic coverage and quality<br>• Reservoir presence<br>• Reservoir diagenesis<br>• SR extent, thickness and quality |
| | ***Lower Windsor Group***<br>Age: Visean (Chadian)<br>Formation: Macumber<br>Dominant lithology: shallow water carbonate, bioconstruction (stromatolite) | ***Windsor Group***<br>Seal Formations: Kempthead & Meadows Road<br>Age: Visean<br>Dominant lithology: anhydrite and evaporite | |
| ***Horton clastic play*** |  |  | • Poor seismic coverage and quality<br>• Reservoir presence<br>• Reservoir diagenesis<br>• SR extent, thickness and quality |
| | ***Horton Group***<br>Age: Tournaisian<br>Dominant lithology: fluvial / deltaic sandstone | | |

**Sydney Basin, Nova Scotia**

Sydney Basin is the least explored of all eastern Canadian Paleozoic basins. The only offshore wells to date have been in the Scotian part of the basin and none of them reached their initial targets, i.e. Horton series. Compared to western Newfoundland or New Brunswick Carboniferous basins, the Sydney Basin appears to be structurally less complex with typical half grabens up to 6 km deep (Figure 1). The main inversion phase that occurred during the late Carboniferous/Lower Permian has not significantly impacted the basin much in comparison with the other Paleozoic basins of eastern Canada (See Chapters 2 to 5). Most of the faults are inactive since the Visean period except in the Cabot Fault complex which is active throughout the stratigraphic record. Sydney Basin shows various types of structural traps, stratigraphic traps and combination traps (Figures 1 to 5). Salt diapirism is less developed than in Magdalen Basin but enough so they locally creates significant anticlines (Figure 4). None of those structures have been tested.

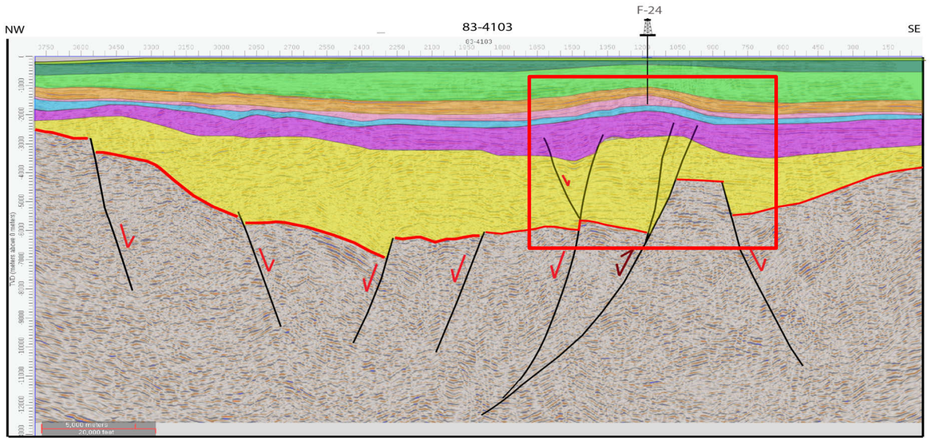



*Figure 1: Gentle transpressional anticline (four-way closure). North Sydney P-05 and F-24 wells targeted the structure but missed the stratigraphic target, i.e. Horton. This structure is the largest in the basin, and new estimates give 690 MM bbl of oil and 1.9 Tcf of gas in place (see also chapter 8).*

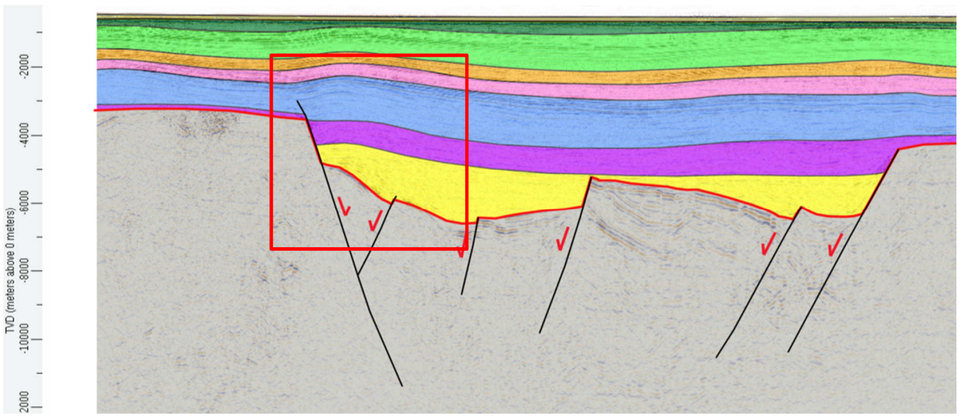



*Figure 2: Gentle transpressional anticline against basement related fault (three-way closure)*

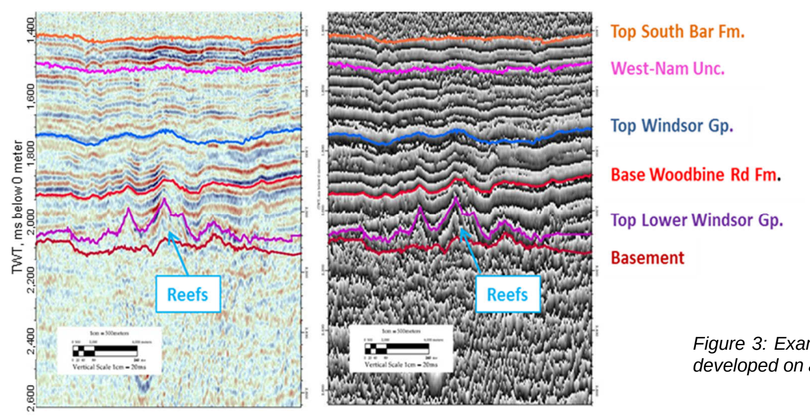



*Figure 3: Example of reefal structures of the Windsor Gp developed on a basement top (four-way closure).*

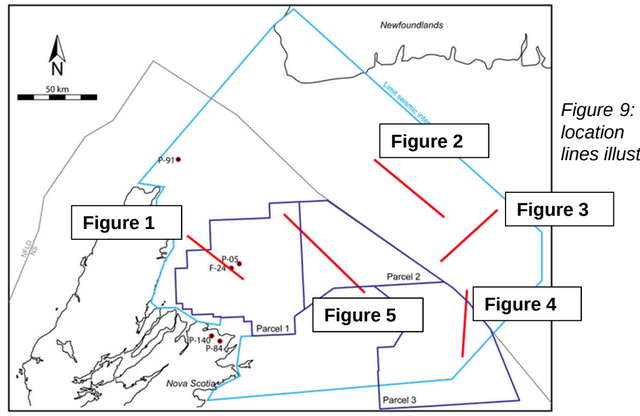



*Figure 9: Map showing the location of the seismic lines illustrated below.*

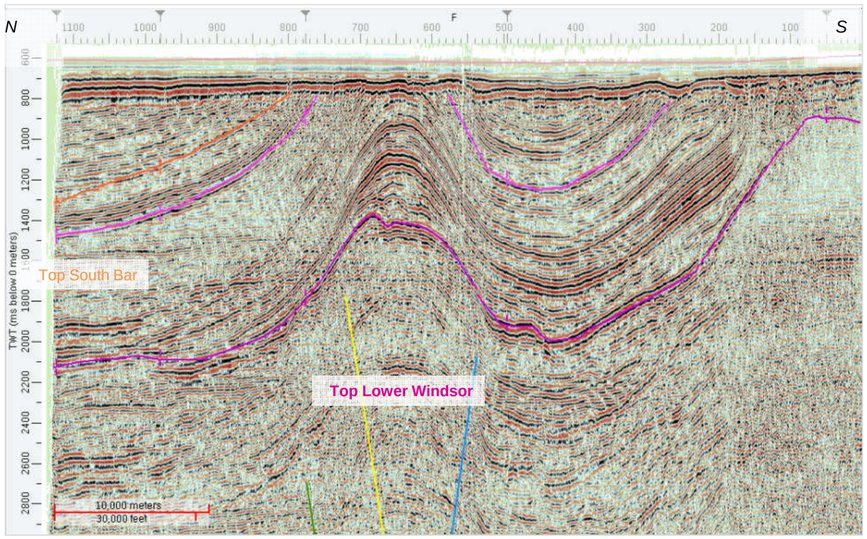



*Figure 4: Salt diapir related anticline and subsalt structure (four-way closure)*

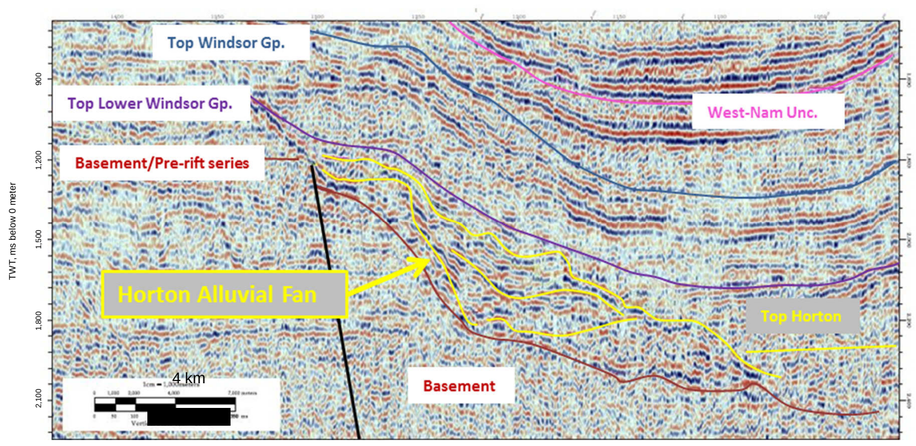



*Figure 5: Example of an Horton alluvial fan against a basement related fault (three-way closure).*