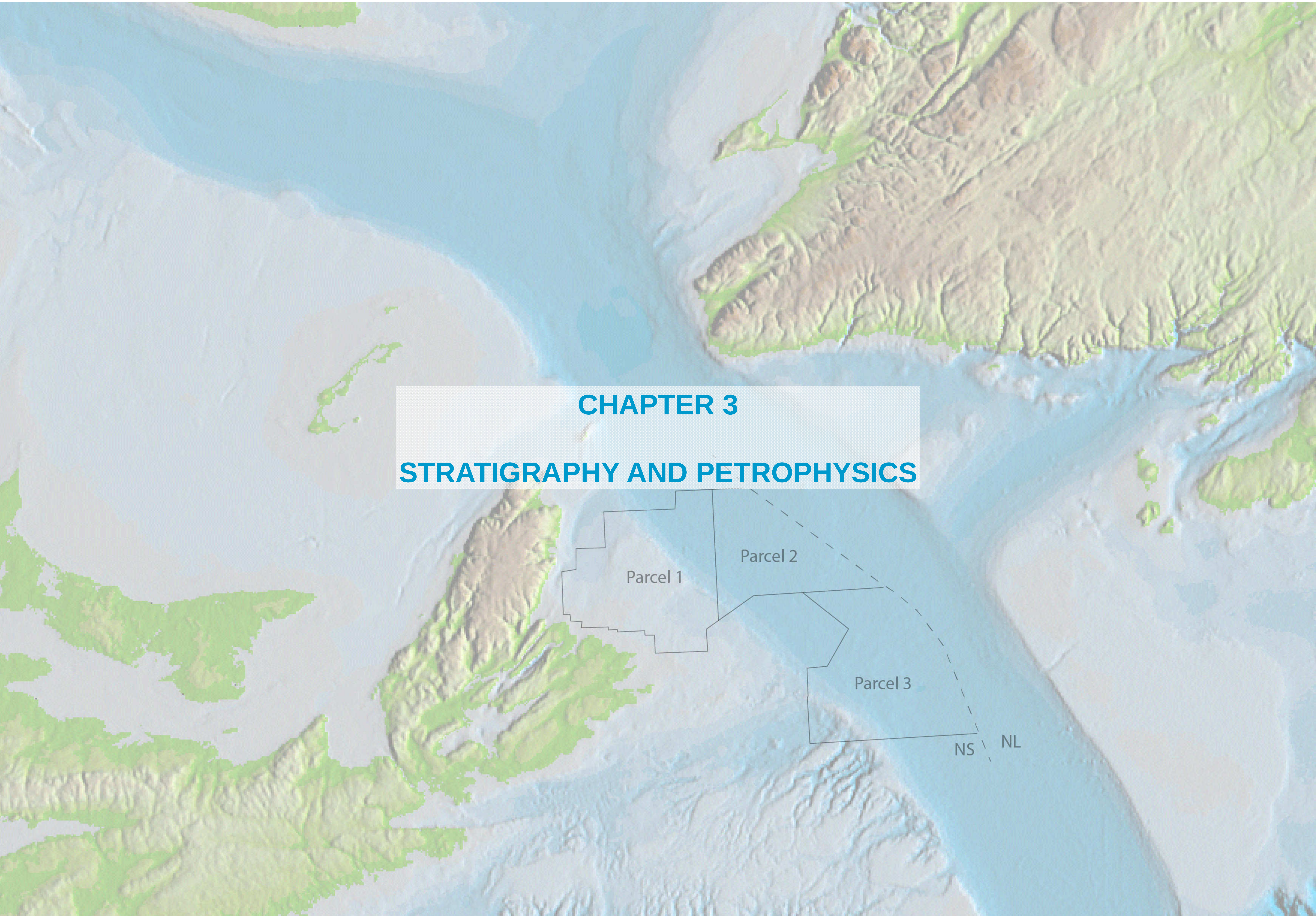
CHAPTER 3

STRATIGRAPHY AND PETROPHYSICS



INTRODUCTION

Objectives

The objective of Chapter 3 is to update the Carboniferous stratigraphic framework of the Sydney Basin in order to refine the current understanding of the petroleum systems in the area.

Results of the study are:

- A lithostratigraphic update of Sydney Basin based on seismic interpretation and lithological interpretation, for three relevant stratigraphic surfaces delimited by eight key seismic horizons;
- An updated stratigraphic and lithostratigraphic chart for the Sydney Basin (Chapter 3.2 – Figure 1) adapted from a merge between onshore and offshore stratigraphic charts;
- A chronostratigraphic and lithostratigraphic interpretation of three key seismic transect (Chapter 6 – PL. 6.1.1 to 6.1.3);
- A set of GDE maps for each key interval (see Chapter 6.3).

Well Database and Methodology

The well database consists of five key wells (Table 1) distributed over the Sydney Basin. Two wells are onshore (Birch Grove P-84 and CCSNS-1 P-140) and the three others are located offshore (North Sydney F-24 and P-05; and Saint Paul P-91). These wells were used for refining the lithostratigraphy and sequence stratigraphy of the area.

The composite geological well logs are presented in Enclosures 9 to13. They display (1) a suite of logs (GR, NPHI curve, RHOB); (2) a lithological column; (3) biostratigraphic surfaces; (4) formation tops; (5) sequence stratigraphic breakdown and (6) depositional environments.

- *Well lithology and petrophysics*

Lithological and petrophysical interpretations were obtained from CSNOPB and used as such. Such information includes qualitative log interpretations, existing composite well logs, and master logs. An alternative porosity interpretation is provided by Beicip-Franlab (Chapter 3.1).

5 wells are available in this study, of which 4 are in the Sydney Basin. From each well, cuttings are available describing a total of 8 lithologies. Lithofacies column available for each well are derived from these cuttings descriptions. Considering the log quality in some of the wells and the heterogeneity of the log suite, the cuttings are the best way to represent with fair confidence the lithologies on the whole section of the wells.

- *Biostratigraphy in wells*

A new complete biostratigraphic analysis was produced by RPS in early 2017 on four of the five key wells: P-140, F-24, P-05 and P-91. The well P-84 does not have any recent biostratigraphic analyses, however, analogy with nearby well P-140 is used to a certain extent.

- *Depositional environment in wells*

The depositional environments were determined using the lithologies from cuttings and the biostratigraphic results; the onshore geology helped with correlation and seismic transects (Chapter 6.3).

- *Well correlations*

Only one well correlation was produced, and includes the five wells. It is oriented roughly in a South North direction (Chapter 3.2 - Figure 1 and 2).

Content

Chapter 3 includes:

- A lithologic and stratigraphic overview of Sydney Basin supported by an updated Stratigraphic Chart of the area (Figure 2). This overview establishes the stratigraphic framework that will be used in the current study;
- One well correlation panel that illustrates the vertical and lateral variation of sedimentary facies and depositional environments through time (PL. 3.2.15);
- One lithostratigraphic section in time that shows the impact of geological events on sequence thickness and the spatial distribution of depositional sequences (PL. 3.2.14).

Stratigraphic framework results will be used in Chapter 6 for:

- Three key seismic transects interpreted in terms of seismic stratigraphy (Chapter PL. 6.1.1 to 6.1.3) showing the 2D geometry of the full sedimentary system and successive depositional sequences in response to geological events;
- A set of GDE maps for each key interval (PL. 6.2.3 to 6.2.10).

Well ID	Company	Year	Latitude	Longitude	KB	TD	Well Classification	Formation at TD	TD Geological Age
Birch Grove P-84	Murphy Oil Company Ltd.	1968	46°08'42.40"N	59°56'05.04"W	49.74 m	1343.6 m	Exploration	Point Edward	Namurian A?
CCSNS-1 P-140	SLB Carbon Services	2014	46°10'35.61"N	59°59'55.45"W	37.64 m	1526.5 m	Carbone Capture	Basement	Pre Carboniferous
North Sydney F-24	Shell Canada Ltd.	1976	46°33'24.00"N	59°48'45.00"W	29.7 m	1707 m	Test well - no gas show	Point Edward	Namurian A – Arnsbergian
North Sydney P-05	Murphy Oil Company Ltd.	1974	46°34'46"N	59°45'01"W	29.9 m	1660.85 m	Exploration	Point Edward	Namurian A – Arnsbergian
Saint Paul P-91	Petro Canada	1984	47°10'57.88"N	60°13'36.83"W	25.2 m	2880.2 m	Exploration	Sydney River	Viséan

Table 1: The five selected wells for the stratigraphic framework study.

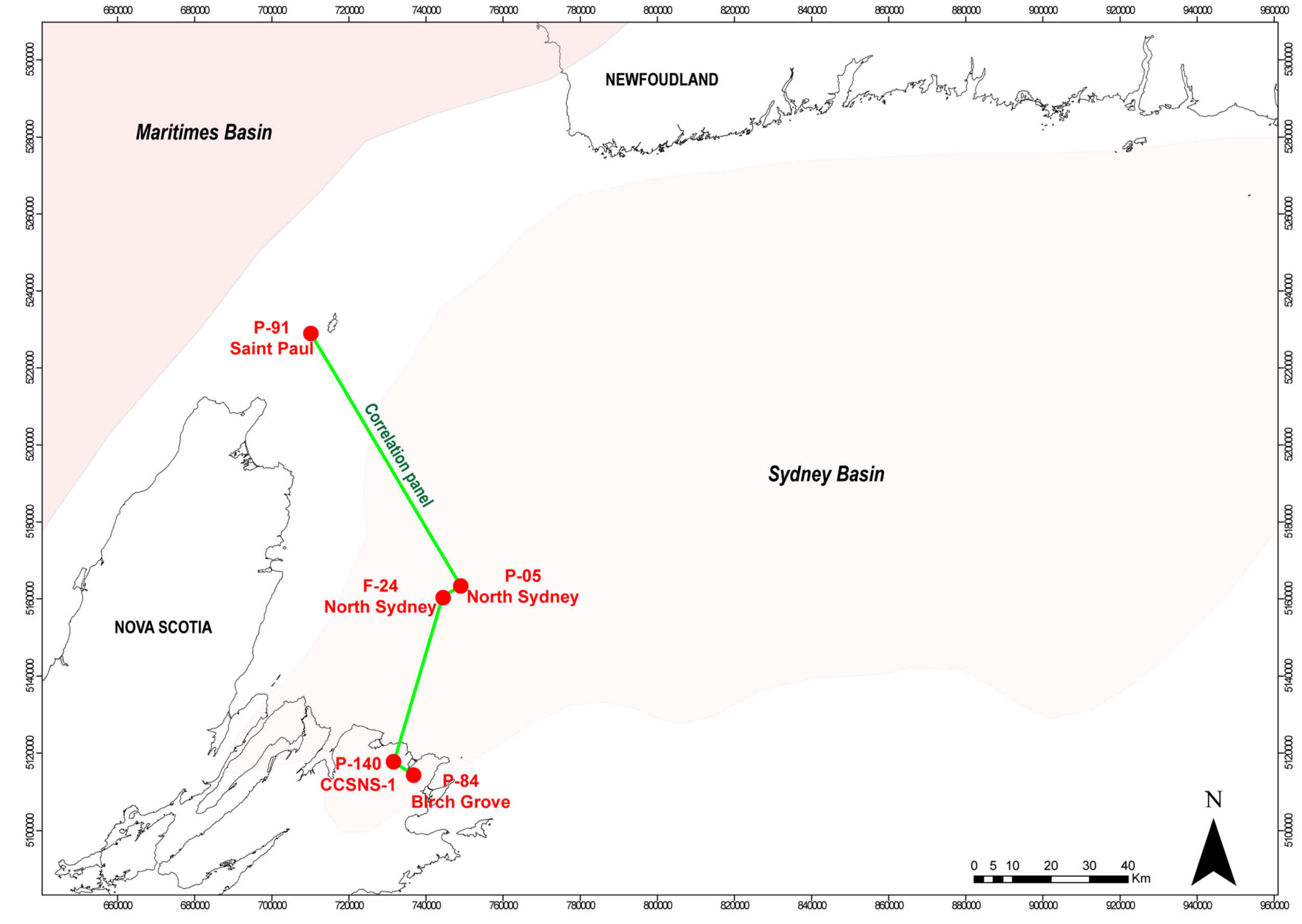
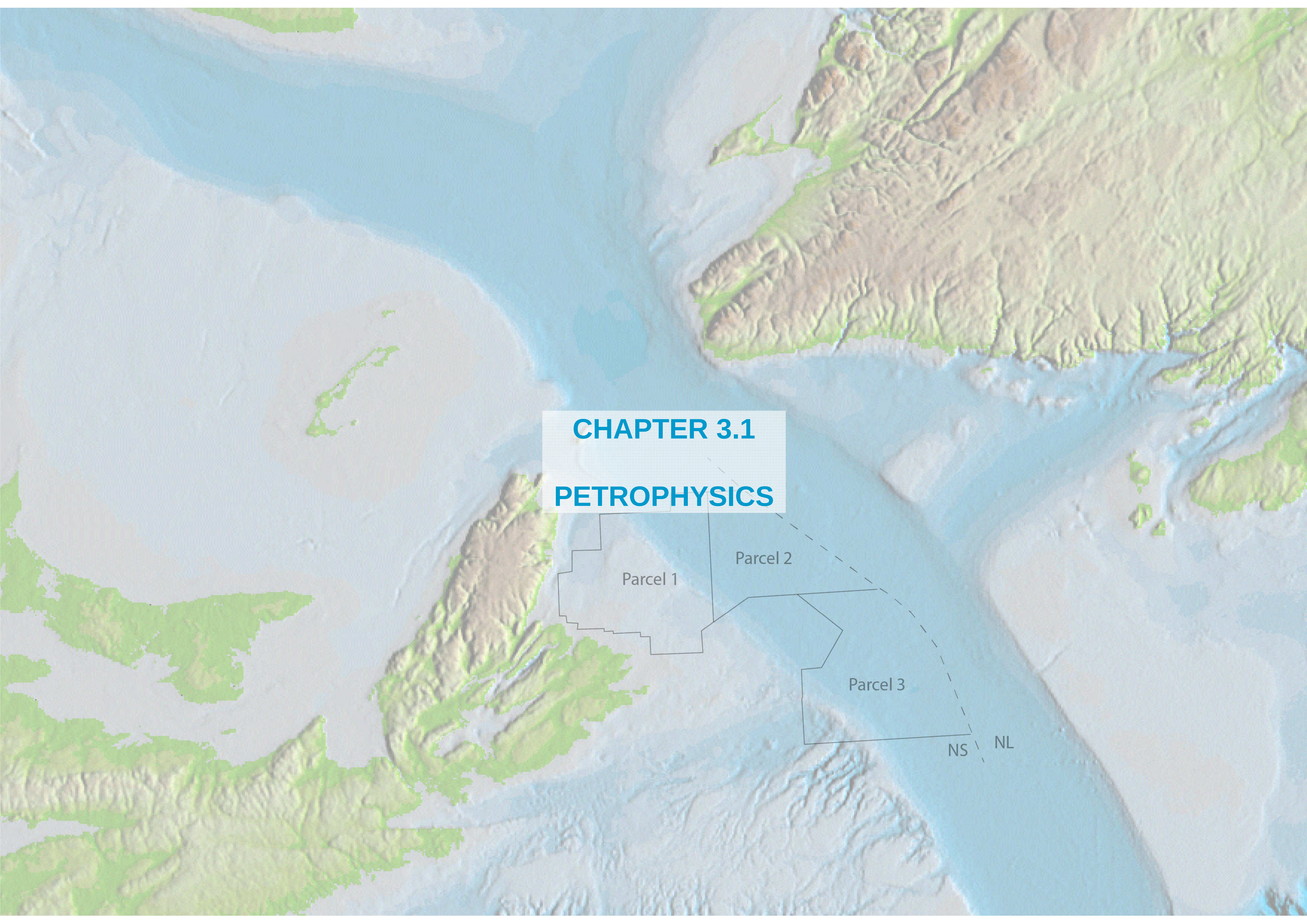


Figure 1: Wells and correlation transect location across the Sydney Basin.

CHAPTER 3.1

PETROPHYSICS



Lithofacies at wells

5 wells are available in this study of which 4 are in the Sydney Basin. For each well, cuttings records are available (Figure 2, Figure 3 and Figure 4) describing a total of 8 lithologies. Lithofacies columns for each well originate from these cuttings descriptions. Considering the log quality in some of the wells and the heterogeneity of the log suite, the cuttings are the best way to represent with fair confidence the lithologies on the whole section of the wells.

Figure 2: Lithofacies at wells

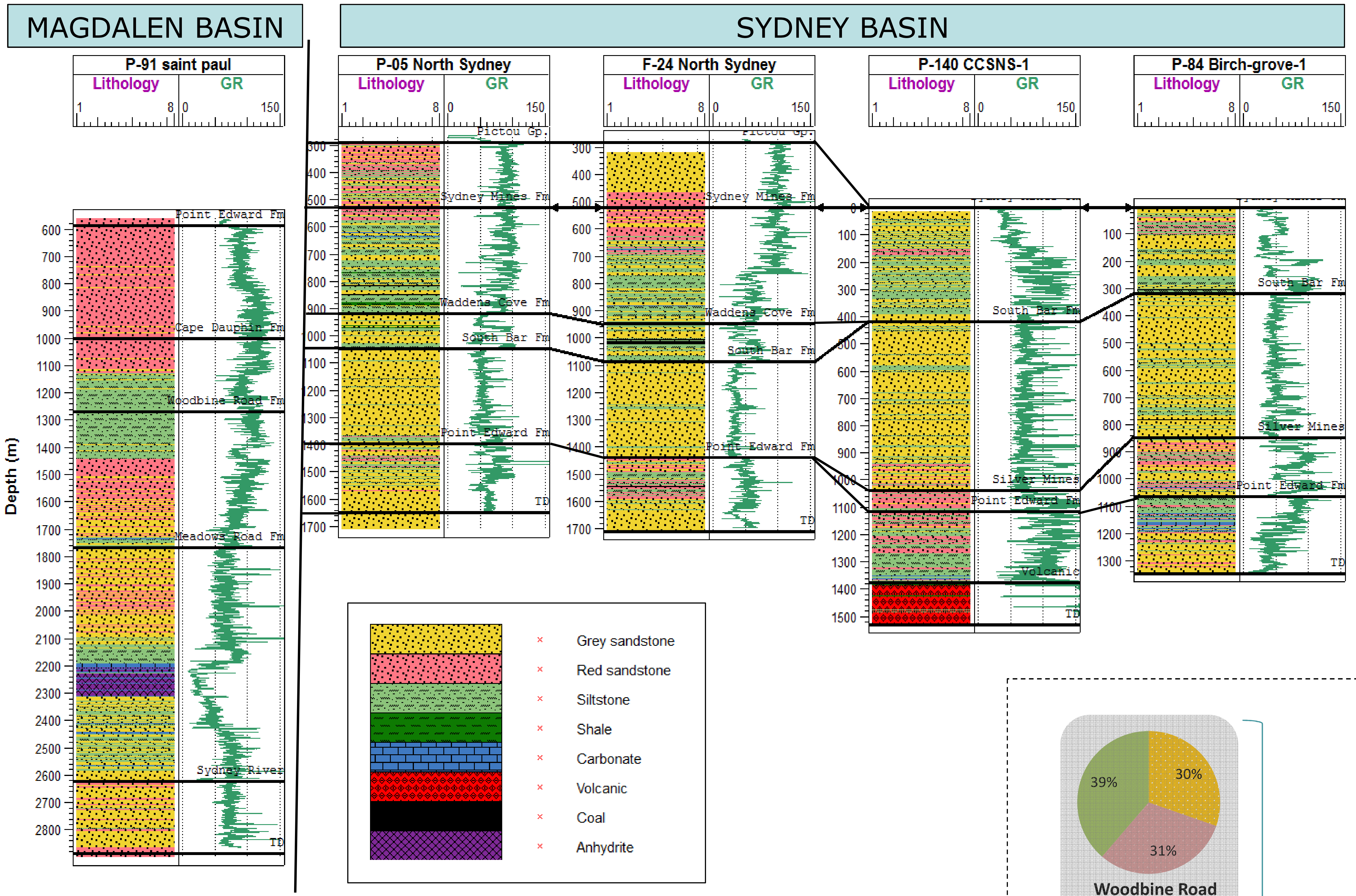


Table 2: Net sand from cuttings per formation

Formation	Net Sand Formation From Cuttings
Pictou	27%
Sydney Mines	38%
Waddens Cove	60%
South Bar	86%
Silver Mines	29%
Point Edward	44%
Cape Dauphin	10%
Woodbine Road	30%
Meadows Road	49%
Sydney River	62%

The table on the left provides an average cumulative thickness of net sand according to the cuttings descriptions available and converted into lithofacies.

From Pictou to Point Edward Formation, the percentages include the 4 wells from the Sydney Basin: P-05 North Sydney, F-24 North Sydney, P-140 CCS-NS-1 and P-84 Birch Grove. Note that none of the 4 Sydney Basin wells penetrated the Windsor Group.

From Cape Dauphin to Sydney River, the percentages include only well P-91 Saint-Paul Island.

Figure 3: Vertical lithofacies distribution

Percentage of cumulative thickness of each lithology described, per formation

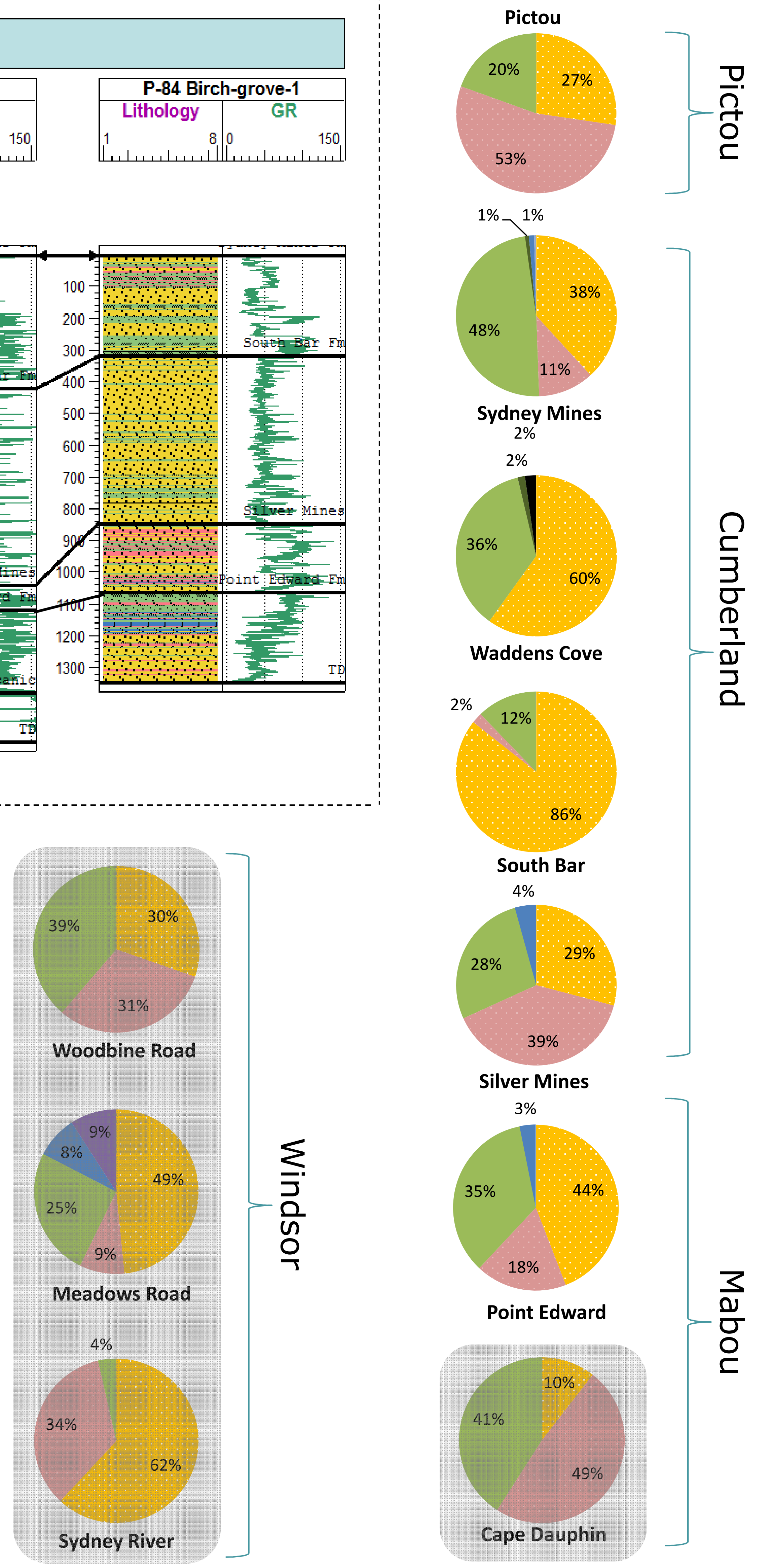
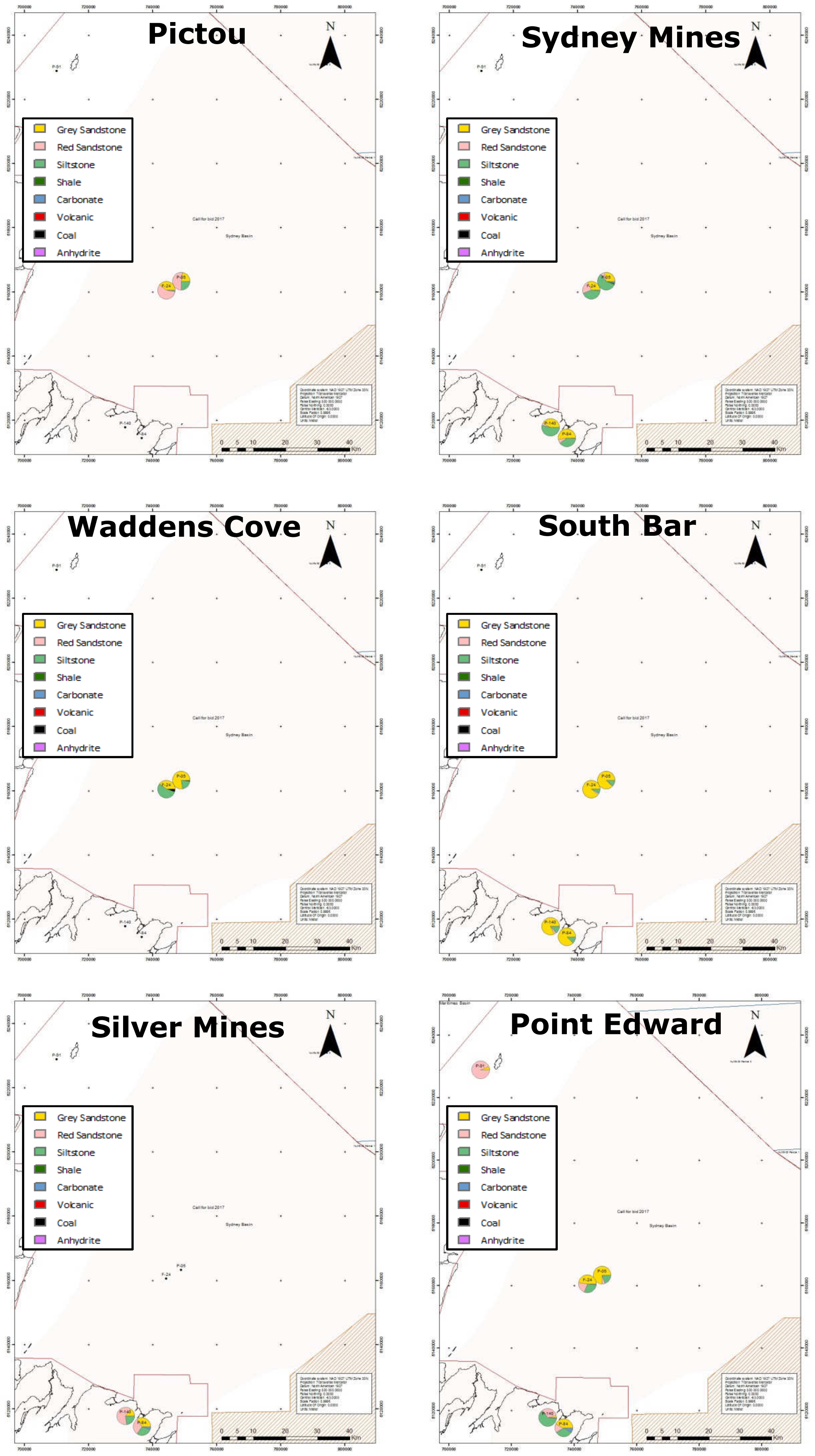


Figure 4: Horizontal lithofacies distribution



Legend:

- Grey Sandstone
- Red Sandstone
- Siltstone
- Shale
- Carbonate
- Volcanic
- Coal
- Anhydrite

Lithofacies calculated from P-91 Saint Paul Island cuttings descriptions (not considered in the Sydney Basin)

Log data

Log data are available for 5 wells of which 4 are drilled in the Sydney Basin (Figure 5). The 4 wells stopped in Point Edward Formation (Mabou group). No well has penetrated the Windsor or Horton Groups in the Sydney Basin. The available log data sets were acquired over a period of 46 years, from 1968 (P-84 Birch Grove) to 2014 (P-140 CCS-NS), and are heterogeneous in quality, numbers and types. Apart from well P-140 CCS-NS, log interpretation of these wells is difficult because the log data are generally of poor to fair quality. The CCS-NS well drilled in 2014 includes a 724 m section with NMR, lithoscanner and FMI, in addition to the standard logs.

NMR logs from P-140 CCS-NS allow a better understanding of the porosity distribution in the Cumberland Group (see Figure 6). The effective porosity from NMR shows little mobile fluid which could be due to siliceous cement in the formation.

Porosity interpretation from CNSOPB (Track 13, Figure 5) in the Sydney Basin is close to 0%. An alternative porosity interpretation is provided by Beicip-Franlab (Track 14, Figure 5). The more optimistic porosity interpretation from Beicip-Franlab was conducted according to observations from NMR logs in well P-140 CCS-NS, while the porosity interpretation from CNSOPB is closer to the moveable fluid porosity. The representative porosity values per well and interval are shown in Table 3.

The basin petroleum system modeling requires a net-sand and a total porosity value per layer as well as an effective porosity value in reservoir layers. The values used in the basin petroleum system modeling will be chosen according to the petrophysical properties observed and gathered.

Figure 5: Raw and interpreted logs available

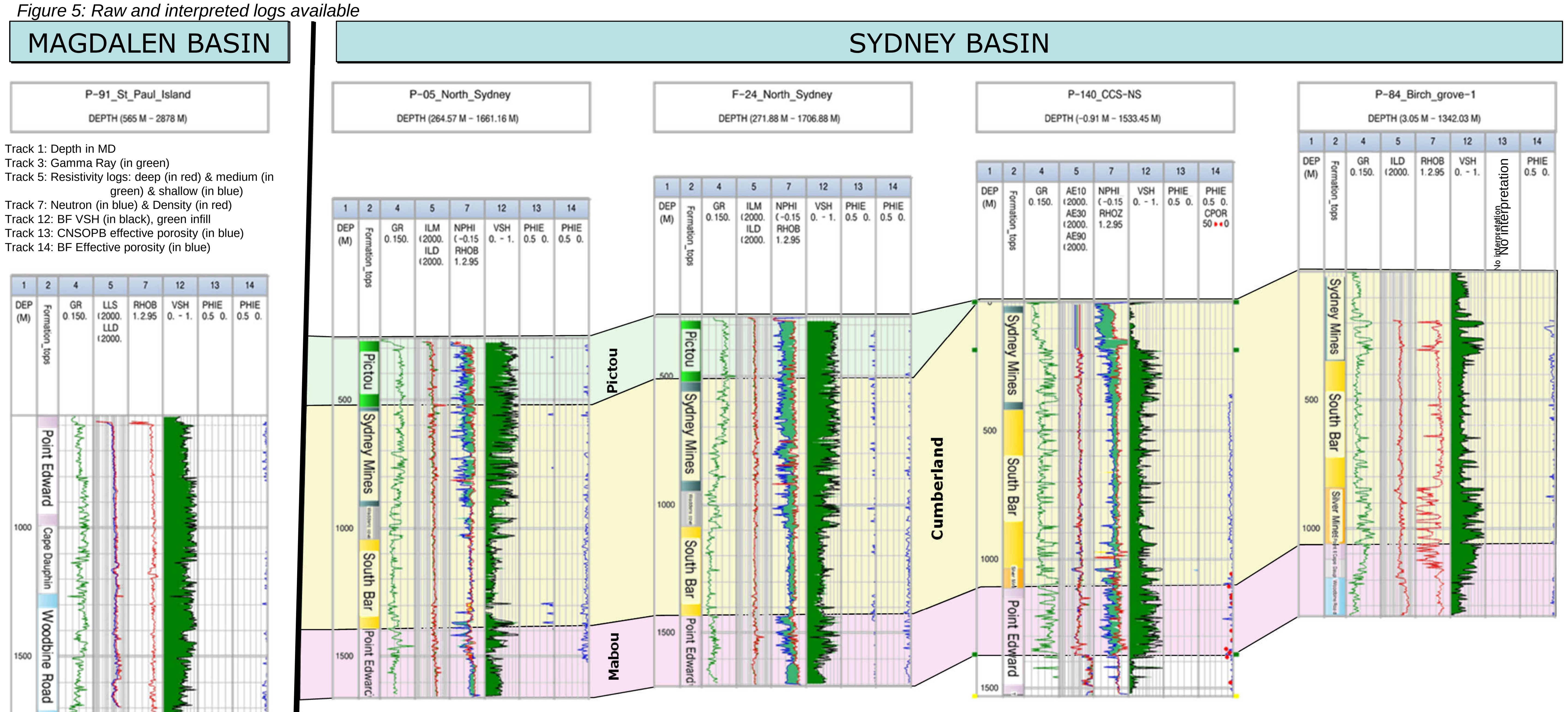
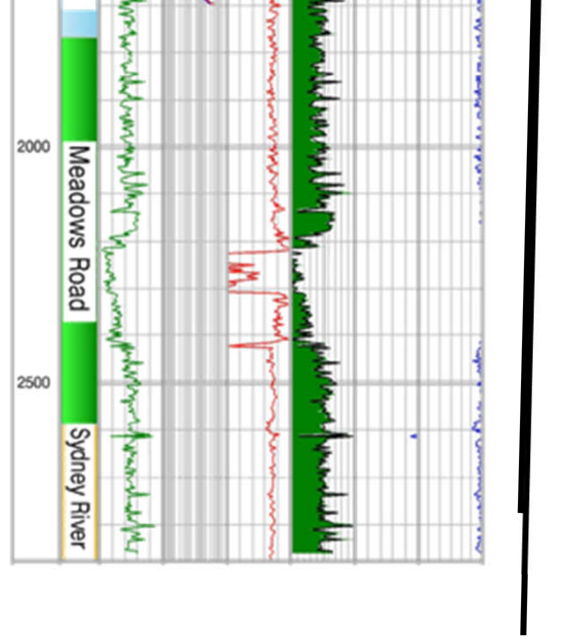
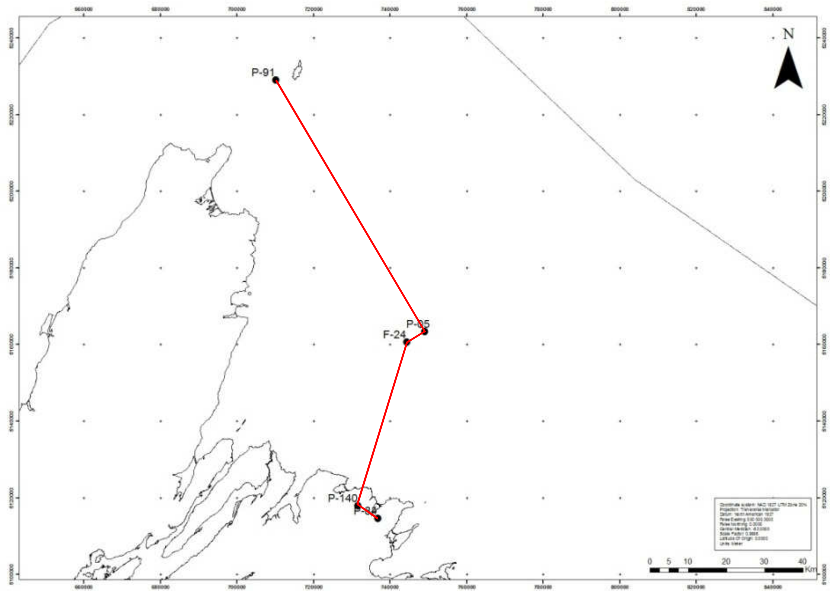



Table 3: Maximum & average porosity values per formation

	PHIE values from CNSOPB petrophysical interpretation		PHIE values from BF petrophysical interpretation		PHIT values from BF petrophysical interpretation		
Formation	Max	Avg	Max	Avg	Min	Max	Avg
Pictou	10%	0,5%	10%	0,8%	5%	21%	6,1%
Sydney Mines	10%	0,3%	10%	1,0%	1%	23%	6,4%
Waddens Cove	10%	0,4%	10%	2,7%	2%	19%	6,4%
South Bar	10%	0,3%	10%	2,7%	1%	19%	5,7%
Silver Mines	10%	0,1%	10%	0,8%	2%	17%	6,5%
Point Edward	10%	0,0%	10%	1,5%	0%	24%	5,7%
Cape Dauphin	0%	0,0%	6%	0,6%	2%	9%	6%
Woodbine Road	0%	0,0%	10%	1,2%	1%	13%	6%
Meadows Road	8%	3,3%	10%	1,4%	0%	14%	4,4%
Sydney River	10%	0,1%	9%	2,6%	0%	12%	6,2%

Note:
- From Pictou to Point Edward Fm, statistics are derived from Sydney Basin wells
- From Cape Dauphin to Sydney River, statistics are derived from well P-91
- Minimum PHIE value is 0% for all formations and both interpretations



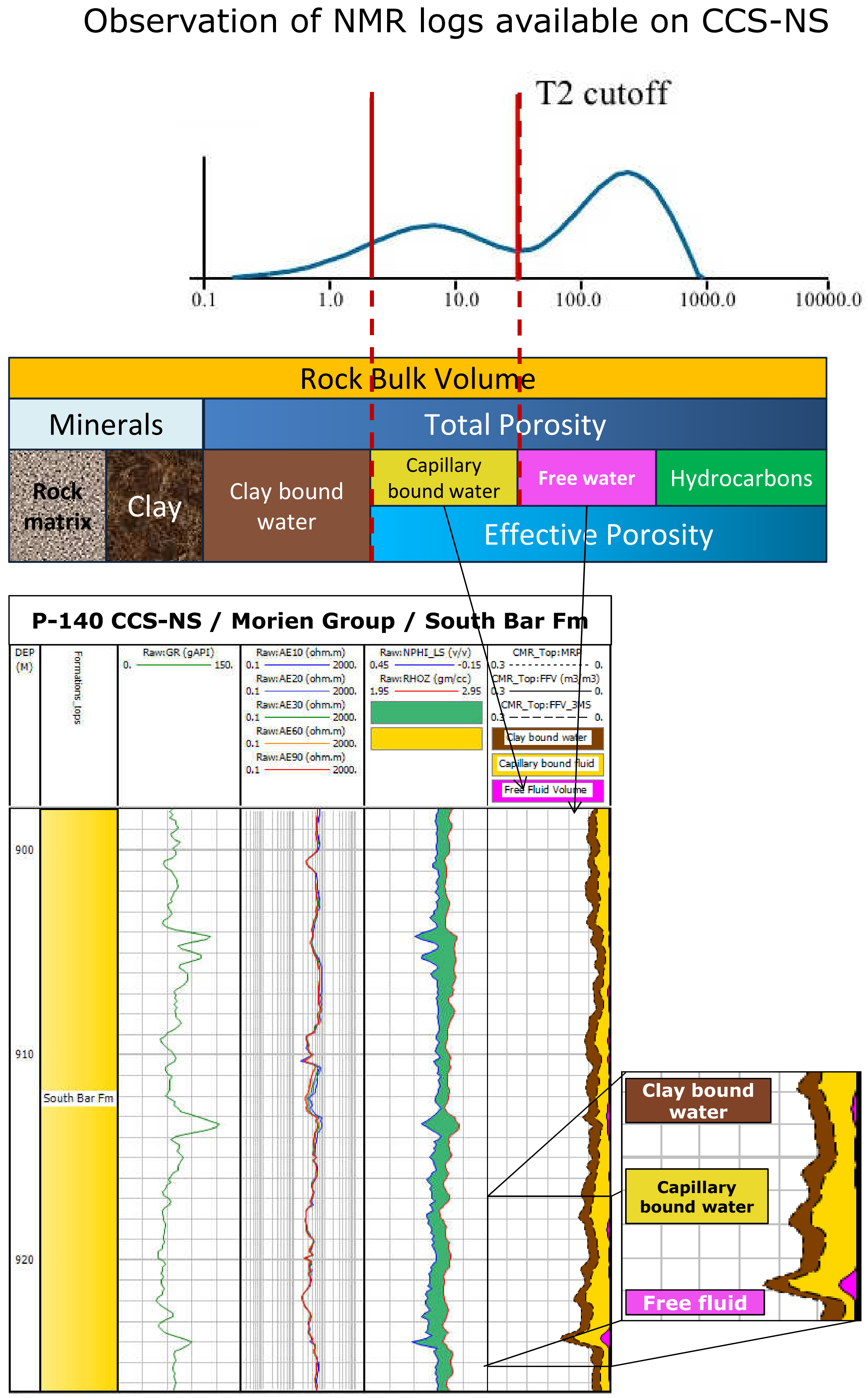


Figure 6: NMR interpretation principle

The NMR logs in well CCS-NS show a free fluid volume close to 0% but an effective porosity (free fluid volume using T2 at 3ms = capillary bound water + free fluid volume) between 1% and 5%.

Siliceous cement described from the well summary is most likely responsible for the tight properties of the South Bar Formation.

A sand interval between 4-12% porosity in well F-24 North Sydney was tested but did not flow after fracturing and stimulation with acid (note on Log Analysis, CNSOPB).

Petrophysical Properties of the Pictou, Cumberland and Mabou Groups

The porosity and permeability measurements available have been gathered for the Pictou, Cumberland and Mabou Groups (Table 4) in order to assess the overall consistency of the available porosity values, and to compare to the petrophysical values interpreted from logs. The core porosity measurements generally estimate total porosity. The available core plug measurements are shown in the table below..

Looking at the overall values and measurements (Table 4), outcrop measurements tend to have higher porosity values compared to interpreted log values. The outcrop data (Figure 7) are generally scattered with occasional doubtful values possibly due to de-compaction or alteration of the samples. Nevertheless, the outcrop dataset highlights the variability of the porosity and permeability from one basin to another (best in Antigonish for Cumberland Group). Core plug measurements are more consistent than outcrop measurements and the estimated average porosity values roughly match the interpreted total porosity from logs.

The data considered for the basin petroleum system modeling are the interpreted log values (effective and total porosity) and the permeability from regional core plugs for the Pictou, Cumberland and Mabou Groups.

Table 4: Petrophysical values for Pictou, Cumberland and Mabou Group

In red, the representative petrophysical values to consider for the corresponding Group

Group	Formation	Petrophysical properties from Sydney Basin log data				Petrophysical properties from regional outcrop data						Estimated petrophysical properties from regional plug data			
		Effective porosity (%)		Total porosity (%)		Total porosity (%)			Pemreability (mD)			Total porosity (%)		Pemreability (mD)	
		Max	Avg	Max	Avg	Max	Avg	Mode	Max	Avg	Mode	Max	Avg	Max	Mode
Pictou	Pictou	10%	0,8%	21%	6,1%	23,2%	10,7%	10,2%	98,5	12,97	0,26	20%	10%	100	0,2
Cumberland	Sydney Mines Waddens Cove South Bar Silver Mines	10%	2,0%	23%	6,0%	22,5%	16,5%	17,5%	580	42,58	4,75	20%	6%	30	0,1
Mabou	Point Edward Cape Dauphin	10%	1,5%	24%	5,7%	22,7%	7,5%	5,2%	53	9,98	0,13	13%	8%	0,15	0,1

Two types of porosity and permeability data are presented below: measurements from outcrops and measurements from core plugs:
- outcrop measurements are all outside the Sydney Basin and are distributed within 3 different basins (Minas, Cumberland and Antigonish),
- core plugs measurements are available from several wells but none of them are drilled in the Sydney Basin.

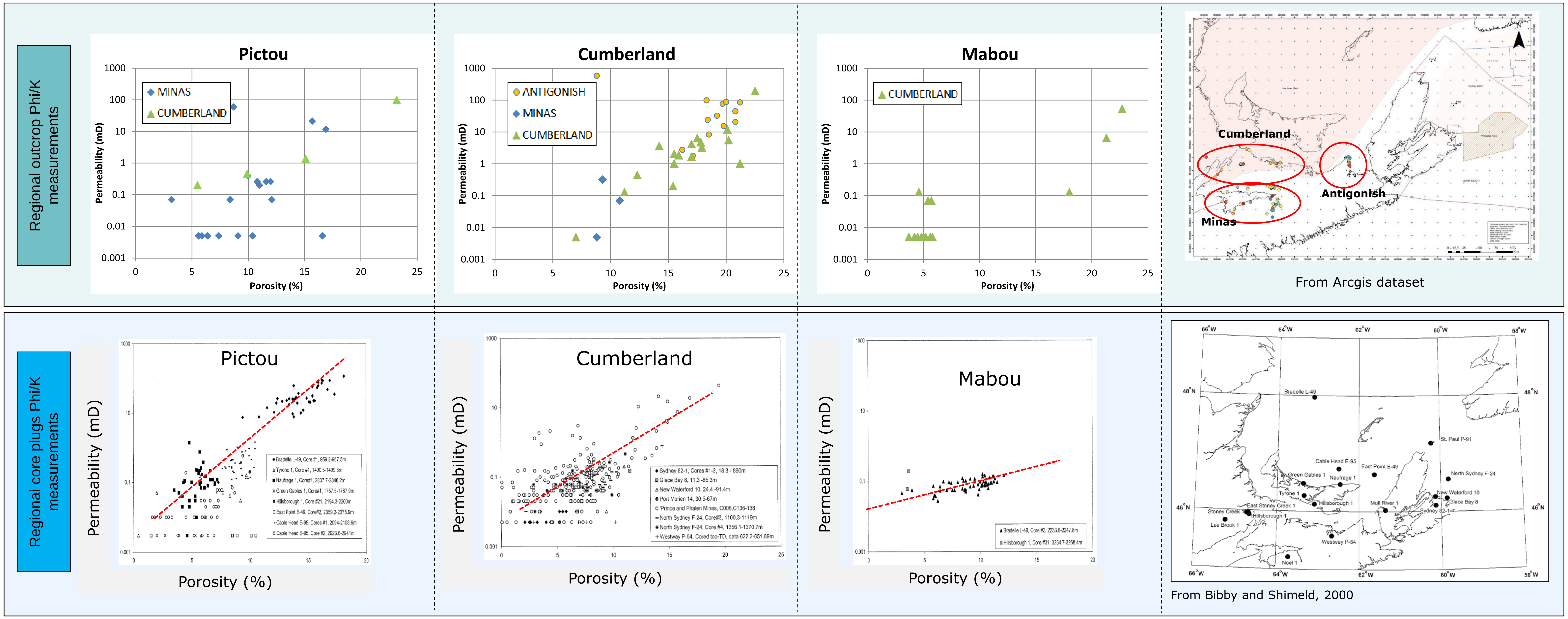


Figure 7: Outcrops and core plug measurements available for Pictou, Cumberland and Mabou Groups

Petrophysical Properties of the Windsor Group

The Windsor Group has not been penetrated in the Sydney Basin. The P-91 Saint Paul Island well penetrated the Windsor down to Sydney River Formation. The petrophysical characteristics computed from the petrophysical interpretation of well P-91 have been gathered and presented for the Windsor Group in Table 5. However, the well is not considered as being within the Sydney Basin. Nevertheless, the values from P-91 have been used as indicative of Windsor properties within the Sydney Basin..

The outcrop data gathered for the Windsor Group (Figure 8) have a wide range of porosity and permeability. They have not been considered to define the petrophysical parameters of the Windsor Group because of the uncertainty in the measurements (possible de-compaction effect of the outcrop sample) and because of the scattering in the data set.

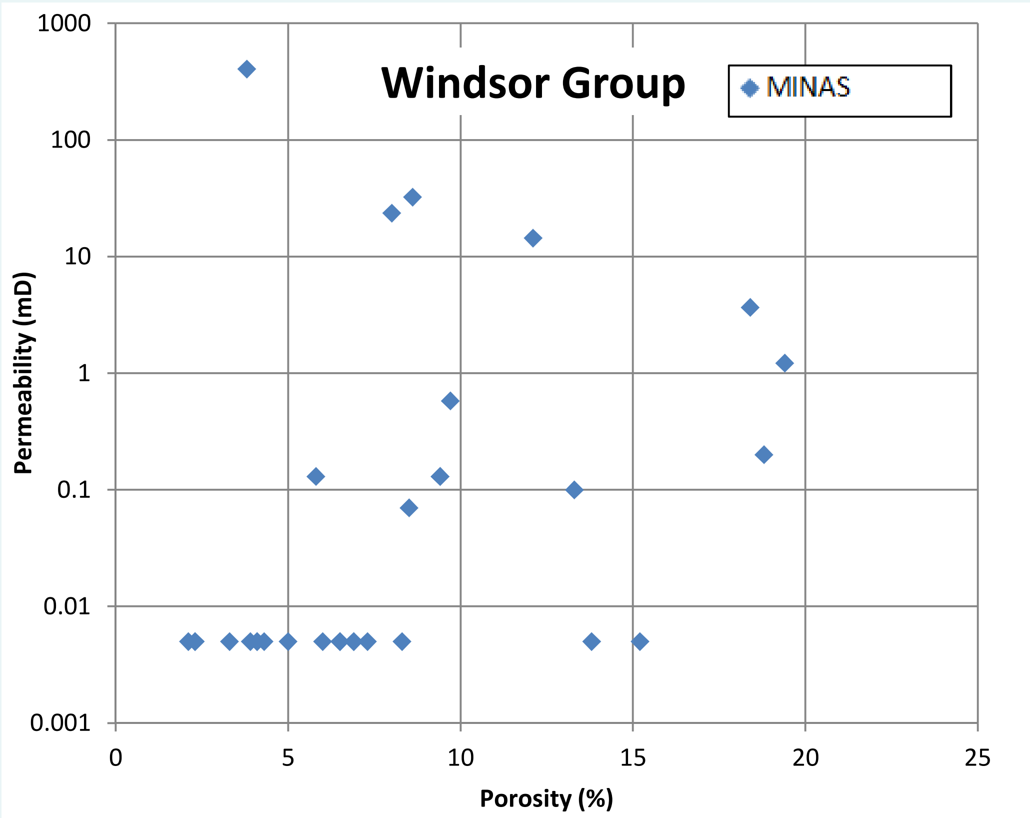
The core plug data appear relatively consistent and have been used to estimate a porosity-permeability relationship. The available measurements belong to the Noel-1 well located in the Minas Basin. Although the well is far from the Sydney Basin, the petrophysical characteristics of the Windsor have been defined according to this data set. The core porosity measurements generally estimate the total porosity; therefore the core plug measurements shown in Table 5 have been considered as such.

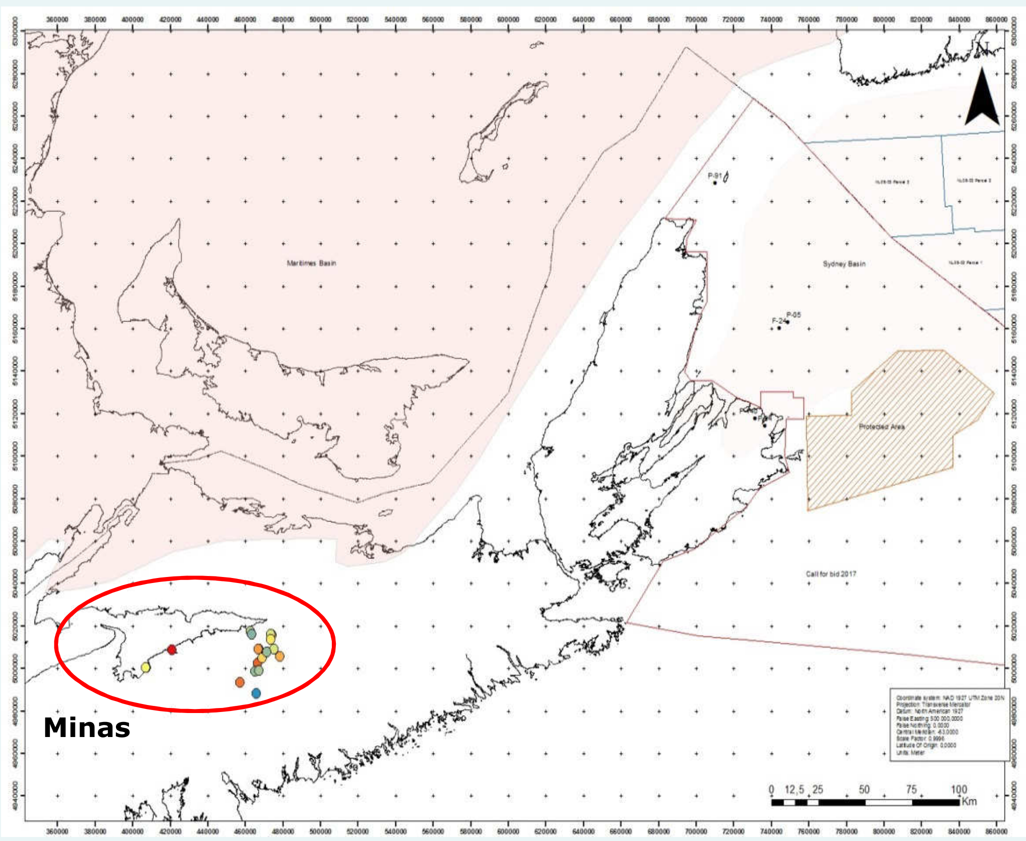
Two types of porosity and permeability data are presented below: measurements from outcrops and measurements from core plugs:

- outcrop measurements are all outside the Sydney Basin: the outcrops were sampled in the Minas Basin,
- core plug measurements are available from well Noel-1 located in Minas Basin.

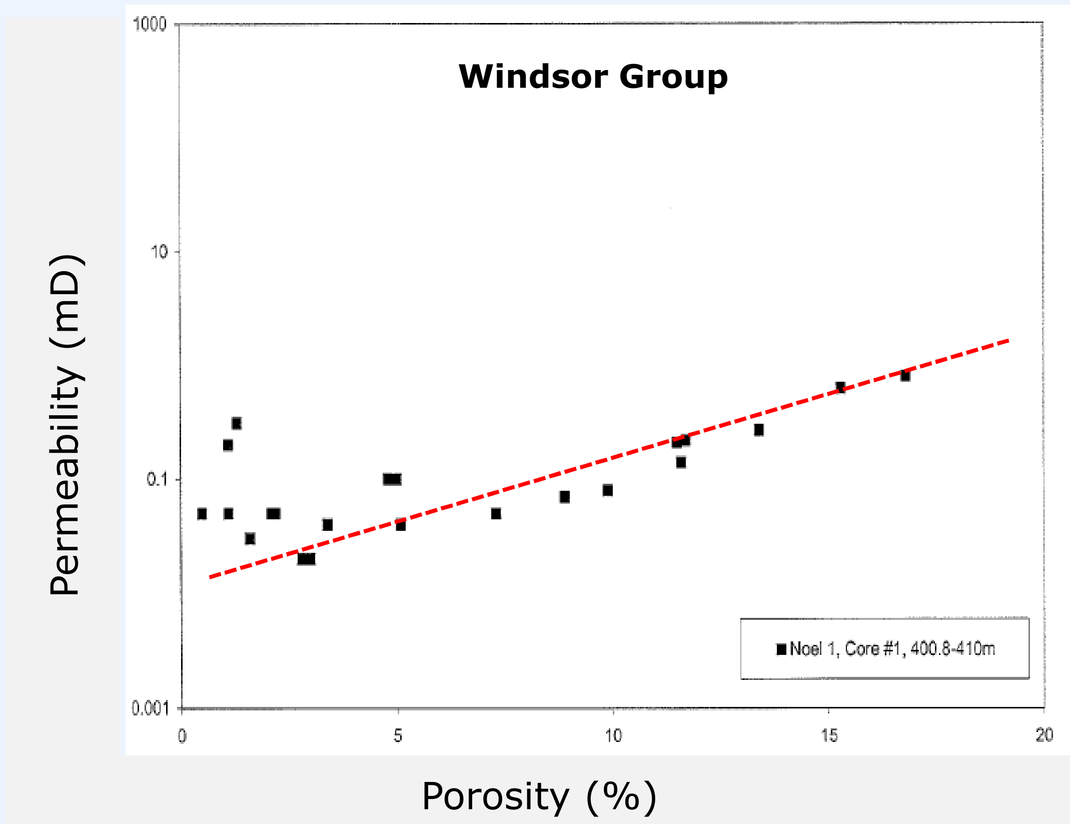
Regional outcrop Phi/K measurements

From Arcgis dataset





Regional core plugs Phi/K measurements



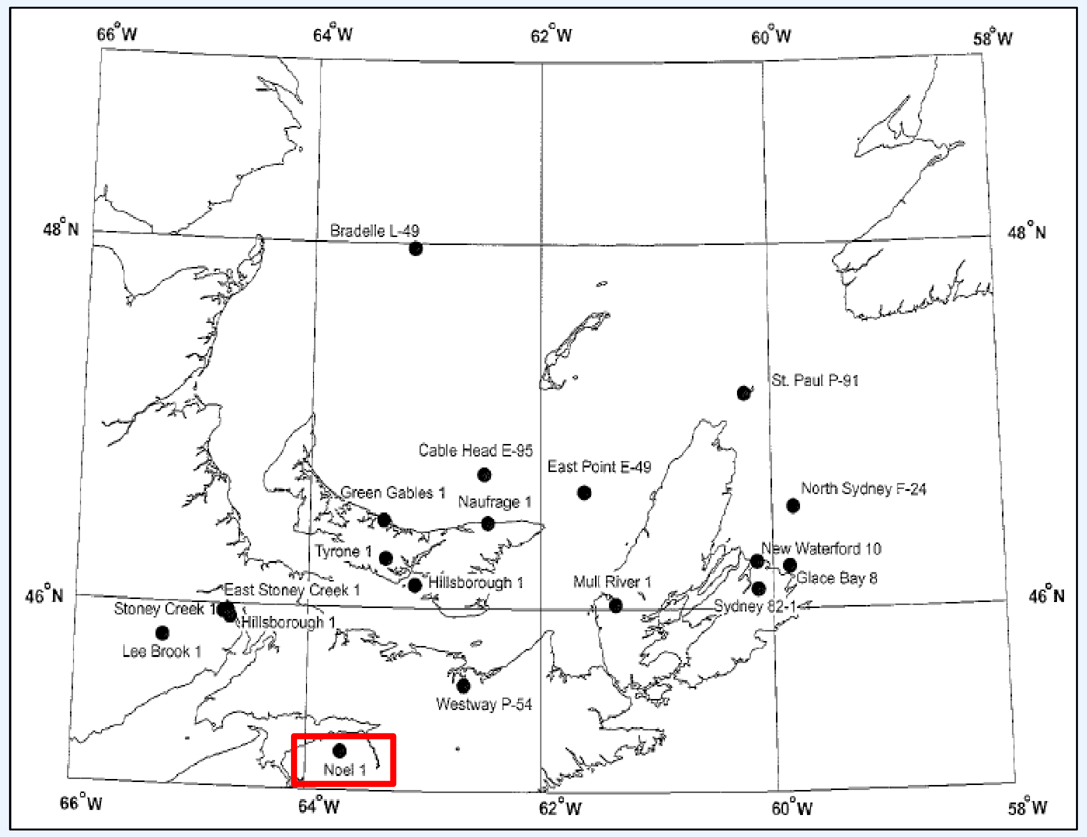


Figure 8: Outcrop and core plug measurements available for the Windsor Group

Figure 9: Overview of the porosity range, type of data and geographical location for Windsor Group

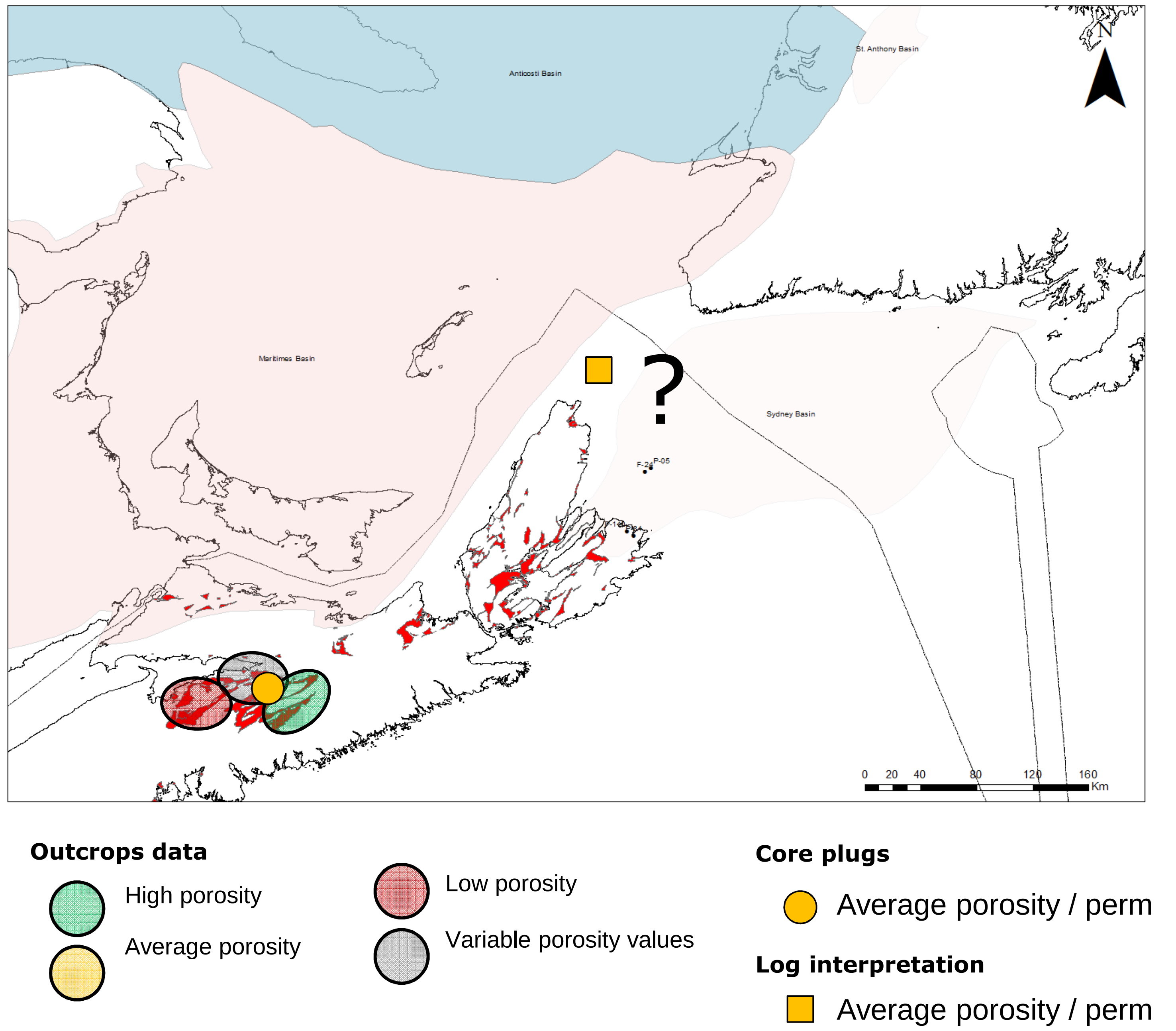


Table 5: Petrophysical values for Windsor Group

Group	Formation	Petrophysical properties from Sydney Basin log data				Petrophysical properties from regional outcrop data						Estimated petrophysical properties from regional plug data			
		Effective porosity (%)		Total porosity (%)		Total porosity (%)			Pemreability (mD)			Total porosity (%)		Pemreability (mD)	
		Max	Avg	Max	Avg	Max	Avg	Mode	Max	Avg	Mode	Max	Avg	Max	Mode
Windsor	Woodbine Road	10%	1,2%	13%	6%	29,6%	8,8%	7,1%	405	34,4	0,39	17%	8%	1	0,1
	Meadows Road	10%	1,4%	14%	4,4%										
	Sydney River	9%	2,6%	12%	6,2%										
	Macumber	-	-	-	-										

In red, the representative petrophysical values to consider for the corresponding Group

According to the core plug data available, the maximum porosity reaches 17% while the average porosity is around 8%. The porosity permeability relationship established gives a maximum permeability at 1mD and a mode of 0.1 mD.

Petrophysical Properties of the Horton Group

The porosity and permeability measurements available for the Horton Group have been gathered in order to estimate the petrophysical properties (Figure 10). None of the available wells penetrated the Horton Group in Sydney Basin, hence the petrophysical properties can only be estimated from surrounding outcrops and core plug measurements. The core porosity generally estimates the total porosity, therefore the available core plug measurements presented below have been considered as such.

Porosity and permeability from outcrops and core plugs show a wide range of values but show some consistency:
- Porosity range: 0 to 20% (few measurements above 20% at Inverness and Antogonish outcrops)
- Permeability range: 0,05 to 100 mD

The outcrop measurements suggest a variability in the reservoir quality depending on the basin, the best porosities and permeabilities being in the Inverness BAsin (with a few measurements between 10 and 25%). A variability of porosity and permeability is also noticeable in the core plug data set as only wells from Brunswick Basin (Lee Brook 1, Hillsborough 1, East Stoney Creek 1 and Stoney Creek 1) show porosity values above 8%. Since all the high Phi/K measurements from core were acquired at shallow depth in the Brunswick wells, the variability in the core plug data set could be related to compaction effects.

Two types of porosity and permeability data are presented below: measurements from outcrops and measurements from core plugs:
- outcrop measurements are all outside the Sydney Basin, spread between 3 different basins (Minas, Antigonish and Inverness),
- core plug measurements are available from several different wells but none of them is drilled in the Sydney Basin.

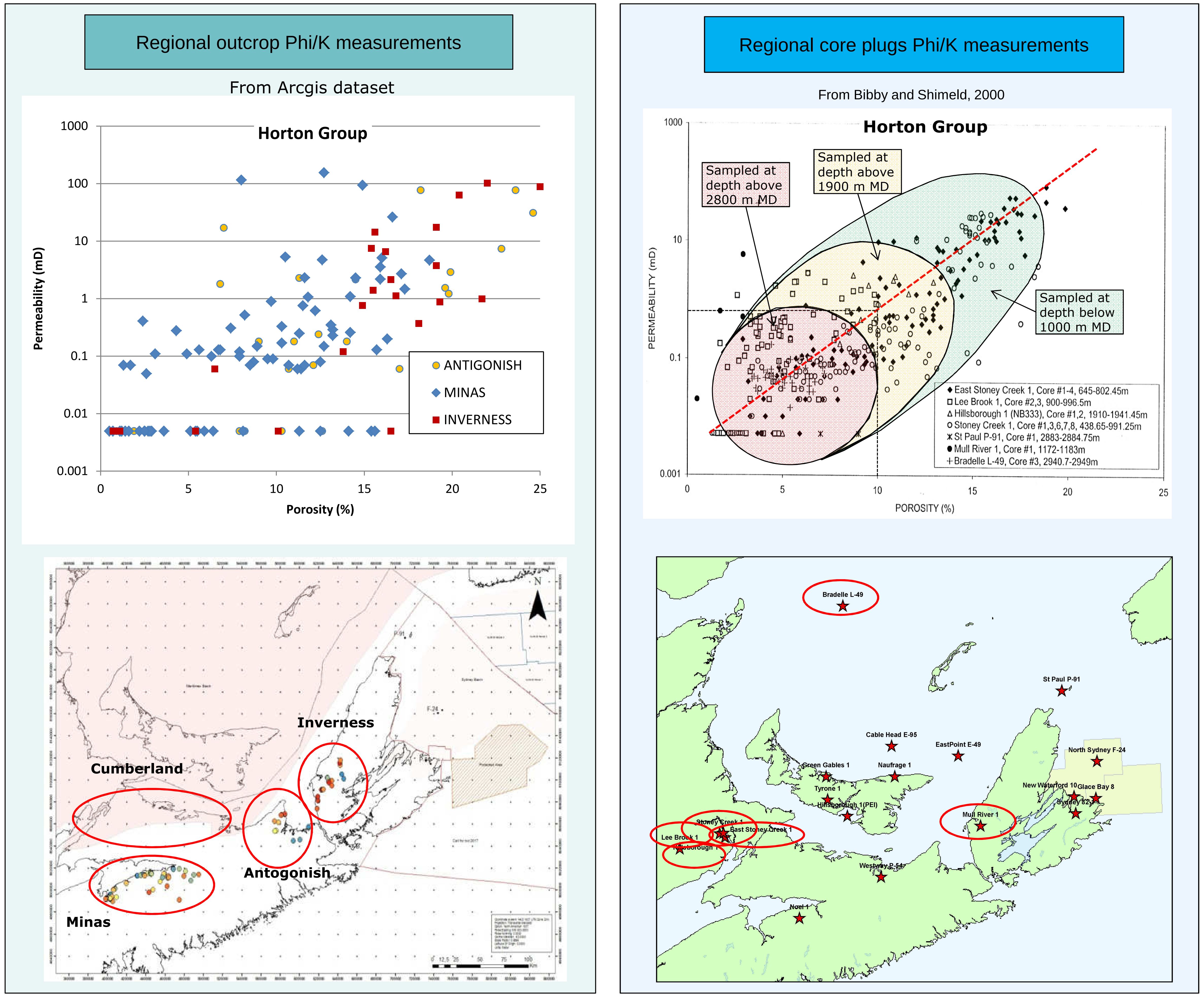
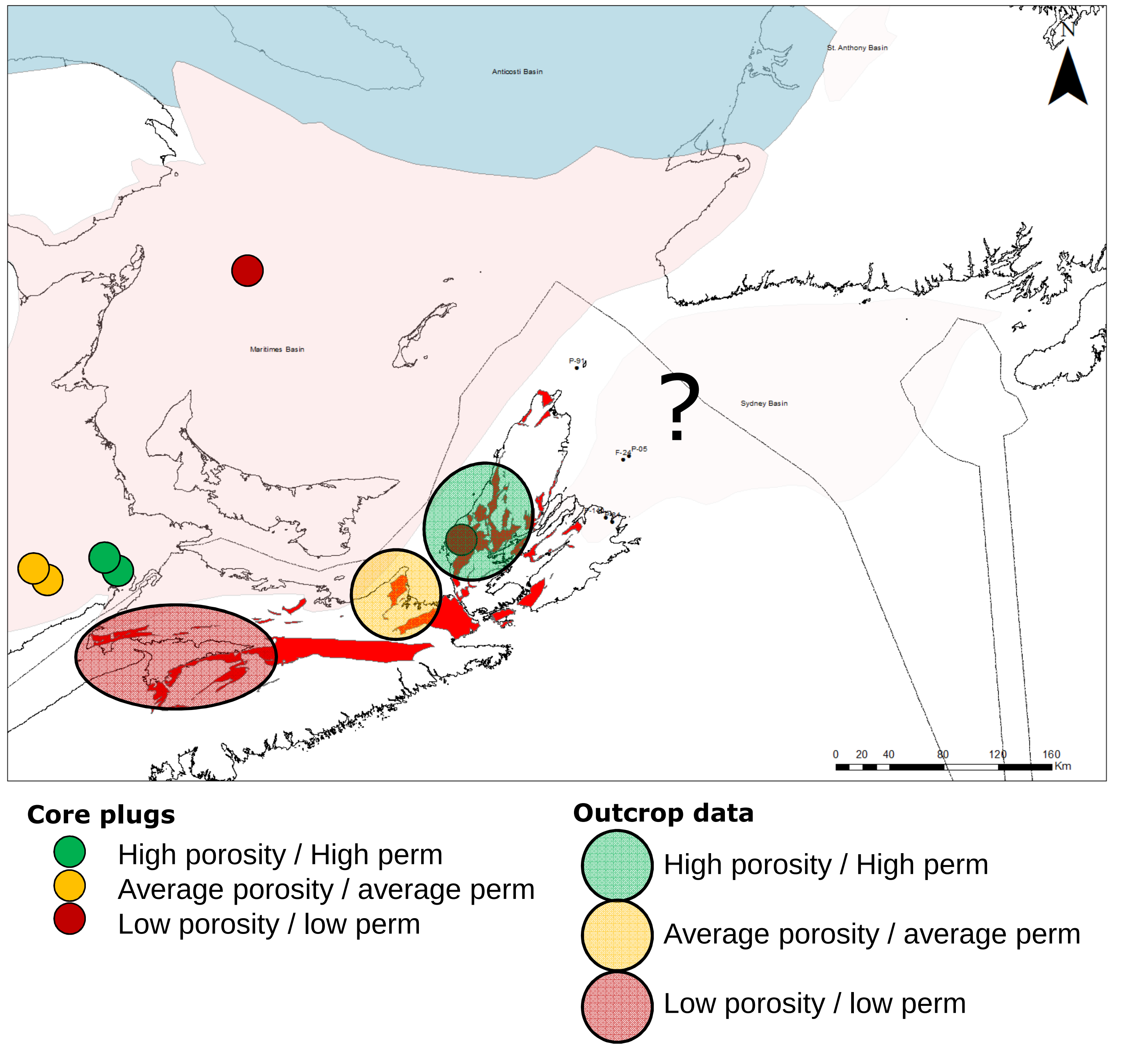


Figure 10: Outcrop and core plug measurements available for the Horton Group

Figure 11: Overview of the porosity range, type of data and geographical location of the Horton Group



The petrophysical properties of the Horton Group in Sydney Basin are uncertain due to the absence of wells reaching the interval and the variability in reservoir quality observed from the core plug and outcrop measurements (see Figure 11 above).

Table 6 shows the estimated representative petrophysical values for the Horton Group according to outcrop and core plug measurements.

Table 6: Petrophysical values for the Horton Group

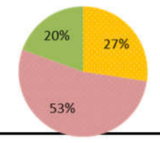
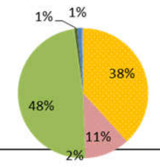
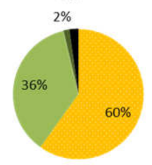
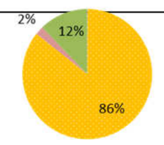
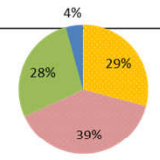
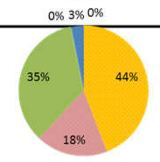
Group	Formation	Petrophysical properties from regional outcrop data						Estimated petrophysical properties from regional plug data			
		Total porosity (%)			Pemreability (mD)			Total porosity (%)		Pemreability (mD)	
		Max	Avg	Mode	Max	Avg	Mode	Max	Avg	Max	Mode
Horton	Upper Horton							20%	10%	100	4
	Middle Horton	25,0%	10,7%	11,1%	156	10,8	0,47				
	Lower Horton							10%	5%	1	0,05

The core plug measurements are preferred to define the representative petrophysical values of the Horton Group in Sydney Basin. However, considering that almost all the high core porosity measurements belong to mainly shallow Horton Formation (possibly undercompacted) in New Brunswick wells, the porosity value to consider for the petroleum basin modeling is suggested not to exceed 10% which is the maximum value for core plugs measurements without the New Brunswick wells (only Bradelle L-49 and Mull River 1).

According to the porosity-permeability trend which appears on the core plug measurements cross-plot, the corresponding maximum permeability for 10% porosity is between 0,5 and 1 mD. The indicated permeabilities are matrix permeabilities that can be possibly enhanced using fracturing techniques as has been done since the early 1900's in New Brunswick field, Stoney Creek reservoir (St. Peter, 2000).

Petrophysical Summary

Table 7: All the petrophysical data gathered and previously presented are summarized below per Group.

Group	Formation	Petroleum system element	Detail lithology from cuttings	Average net reservoir from cuttings	Petrophysical properties from Sydney Basin log data: Effective porosity (%) Max	Effective porosity (%) Avg	Total porosity (%) Max	Total porosity (%) Avg	Petrophysical properties from regional outcrop data: Total porosity (%) Max	Total porosity (%) Avg	Total porosity (%) Mode	Permeability (mD) Max	Permeability (mD) Avg	Permeability (mD) Mode	Estimated petrophysical properties from regional plug data: Total porosity (%) Max	Total porosity (%) Avg	Permeability (mD) Max	Permeability (mD) Mode	Oil shows Sydney basins offshore and nearshore wells	Oil shows Outside Sydney Basin
Pictou	Pictou	Seal		**27%**	**10%**	**0,8%**	**21%**	**6,1%**	**23,2%**	**10,7%**	**10,2%**	**98,5**	**12,97**	**0,26**	**20%**	**10%**	**100**	**0,2**	**No shows**	No data
Cumberland	Sydney Mines	Source Rock		**38%**	**10%**	**1,0%**	**23%**	**6,4%**	**22,5%**	**16,5%**	**17,5%**	**580**	**42,58**	**4,75**	**20%**	**6%**	**30**	**0,1**	**Shows on core (F-24)**	No data
	Waddens Cove	Reservoir/Carrier		**60%**	**10%**	**2,7%**	**19%**	**6,4%**											**Good straw cut fluorescence (F-24)**	No data
	South Bar	Reservoir/Carrier		**86%**	**10%**	**2,7%**	**19%**	**5,7%**											**Drill break & strong gas show (P-05)**	No data
	Silver Mines	Seal		**29%**	**10%**	**0,8%**	**17%**	**6,5%**											**Drill break & strong gas show (P-05)**	No data
Mabou	Point Edward	Seal		**44%**	**10%**	**1,5%**	**24%**	**5,7%**	**22,7%**	**7,5%**	**5,2%**	**53**	**9,98**	**0,13**	**13%**	**8%**	**0,15**	**0,1**	**No shows**	No data
	Cape Dauphin	Source Rock	-	-	6%	0,6%	9%	6,1%												
Windsor	Woodbine Road	Reservoir/Carrier	**Data from P-91 Saint Paul Island (not in the Sydney Basin)**	-	10%	1,2%	13%	6%	**29,6%**	**8,8%**	**7,1%**	**405**	**34,4**	**0,39**	**17%**	**8%**	**1**	**0,1**	**No shows**	**Onshore seeps coincident with Windsor Group outcrops**
	Meadows Road	Seal	-	-	10%	1,4%	14%	4,4%												
	Sydney River	Seal	-	-	9%	2,6%	12%	6,2%												
	Macumber	Source Rock			-	-	-	-												
Horton	Upper Horton	Reservoir/Carrier			-	-	-	-	**25,0%**	**10,7%**	**11,1%**	**156**	**10,8**	**0,47**	**20%** / **10%**	**10%** / **5%**	**100** / **1***	**4** / **0,05***	Horton not reached	**Strong gas show in Robinsons-1X and Redbrook-2** **Oil and gas production in Stoney Creek field**
	Middle Horton	Source Rock			-	-	-	-					Only core plugs sampled below 2000 m MD							
	Lower Horton	Reservoir/Carrier			-	-	-	-												

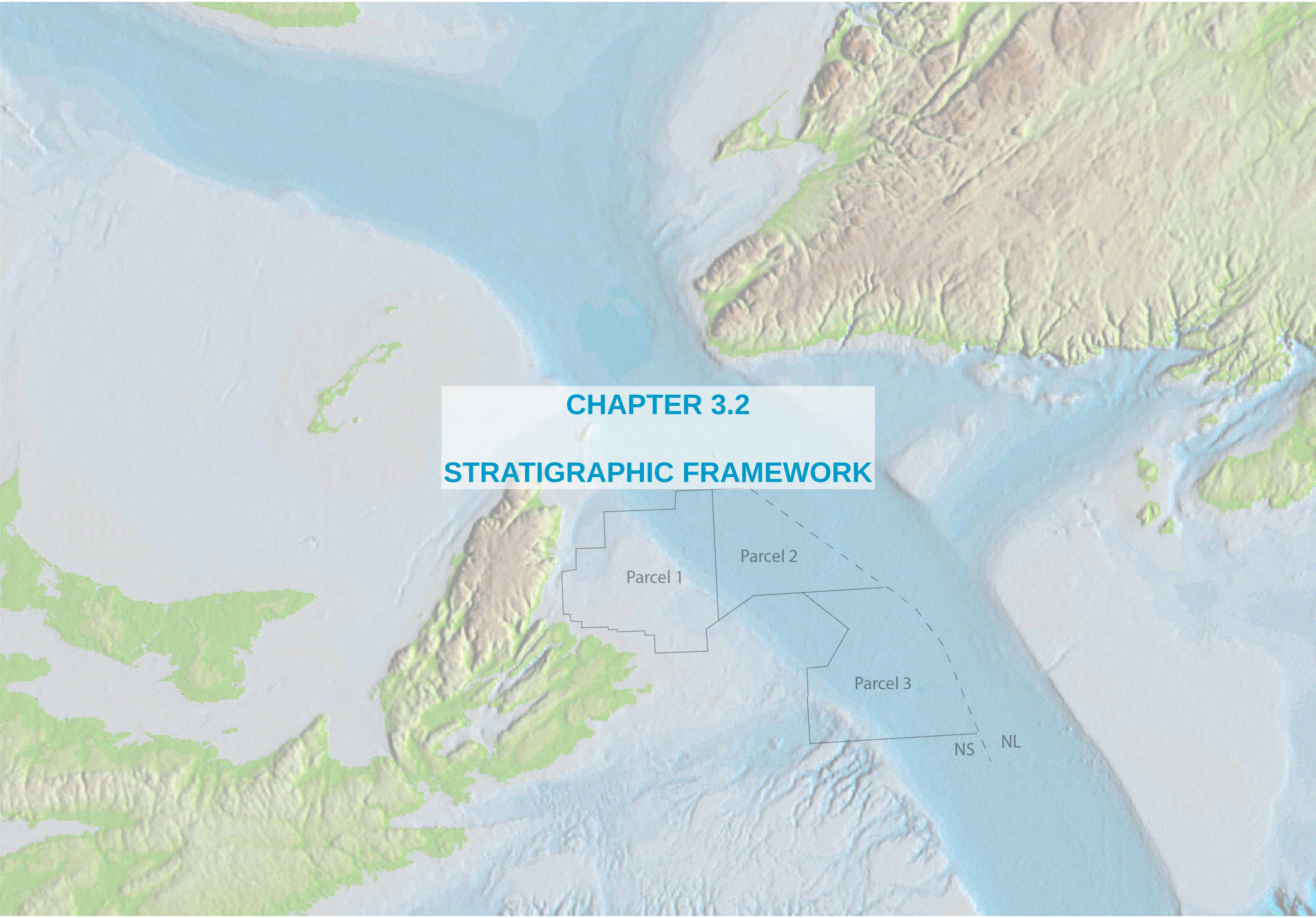
Legend (lithology): Grey Sandstone; Red Sandstone; Siltstone; Shale; Carbonate; Volcanic; Coal; Anhydrite

In red, the representative petrophysical values to consider for the corresponding Group

*** Possible enhancement of the permeability though induced fracturing technics**

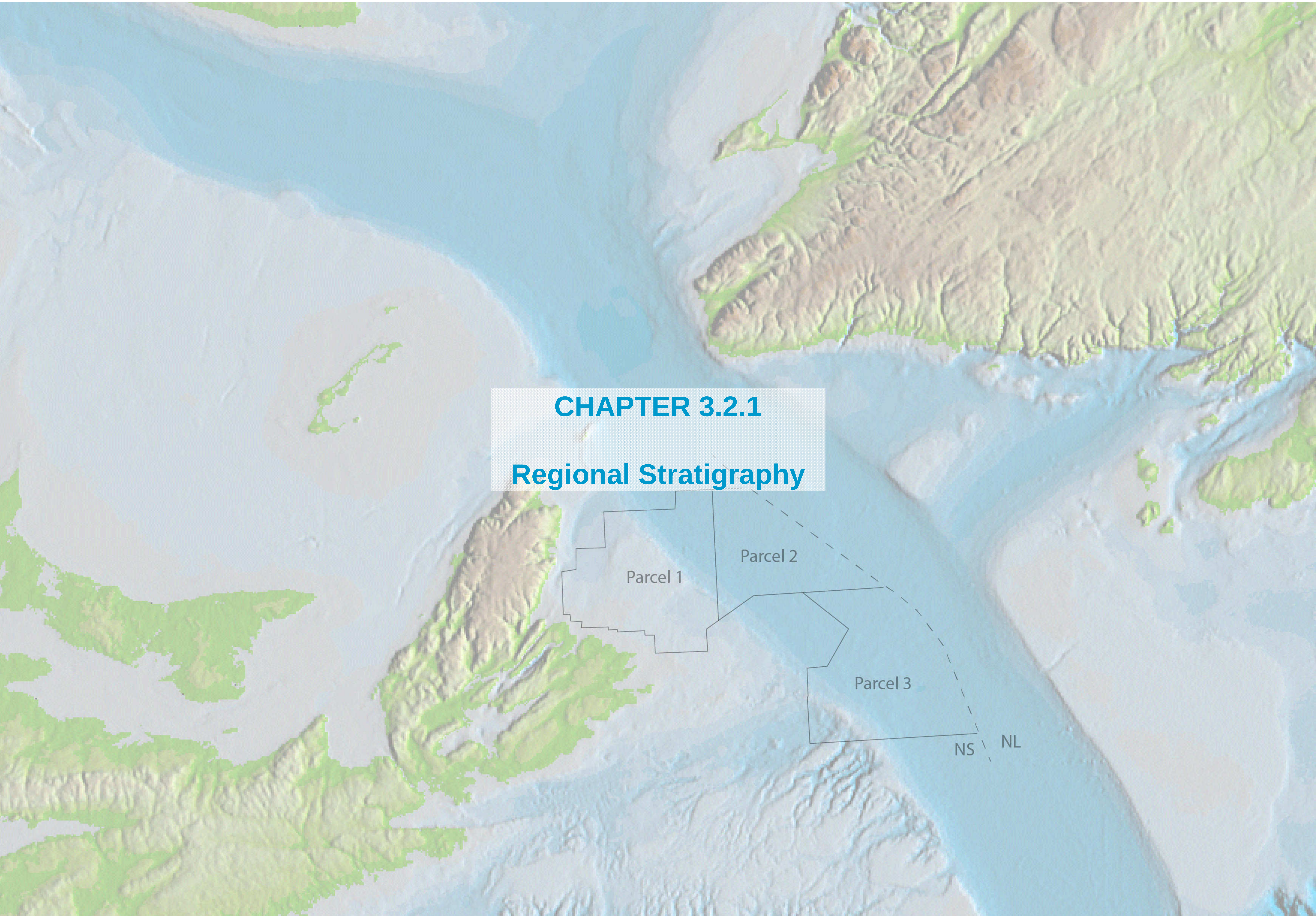
CHAPTER 3.2

STRATIGRAPHIC FRAMEWORK



CHAPTER 3.2.1

Regional Stratigraphy



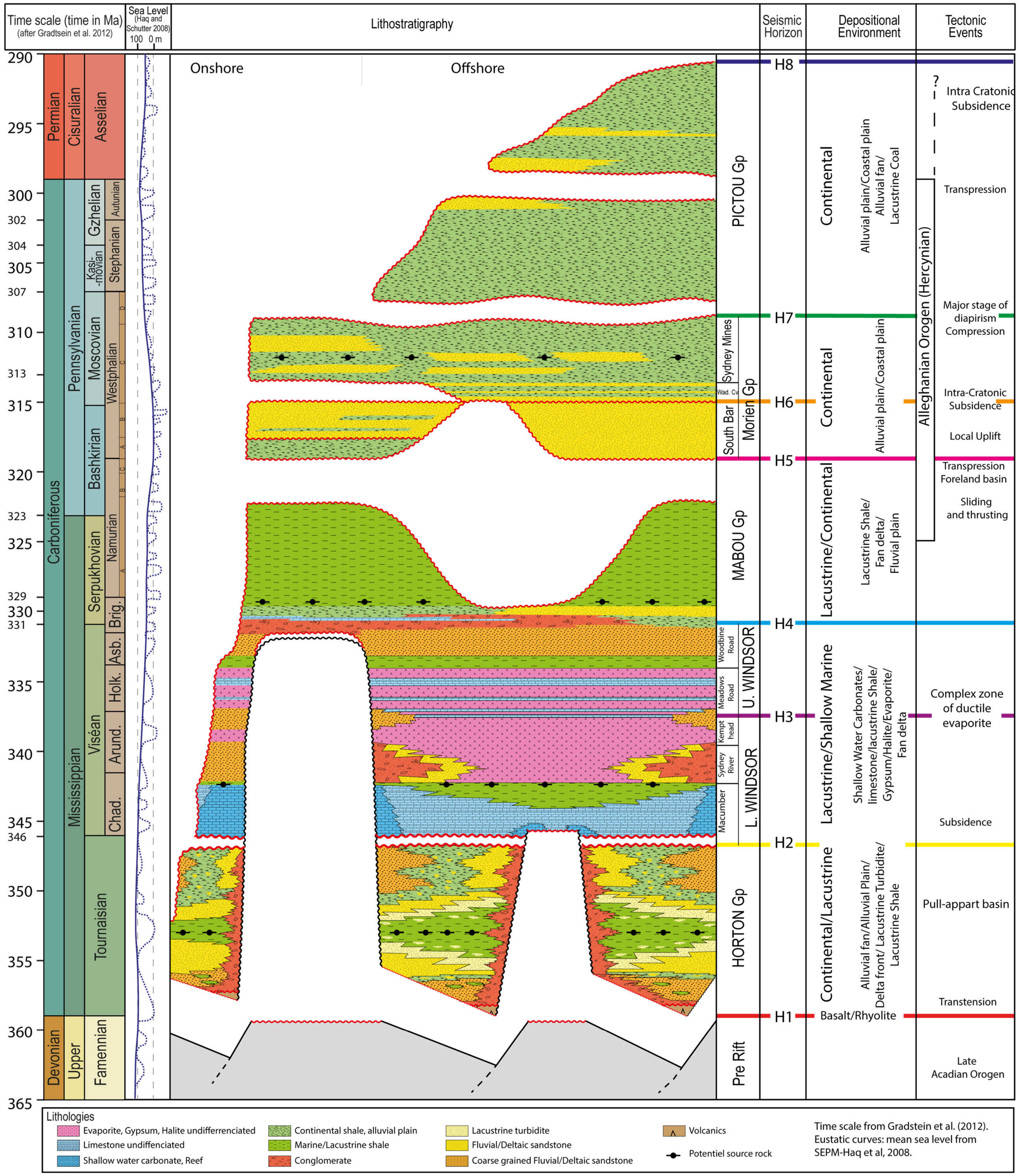


Figure 1: Detailed stratigraphic chart incorporating all sedimentary and geological events as well as major tectonic events.

Regional Geology and Stratigraphic Framework Overview

The Sydney Basin is not well bounded on all sides: the western limit is considered as the Cabot Fault and the Maritimes Basin. To the east, the basin is gradually overlapped by the Mesozoic sediments of the Laurentian Basin and the basin border is therefore not well defined. Northward, the basin terminates onshore near the Newfoundland coastline and southward extends onshore into Cape Breton, while seaward it is bordered by the Proterozoic rocks of the Scatarie Ridge (Pascuscci et al. 2000).

There is a growing interest in Sydney Basin by the oil & gas industry with the opening of a new call for bids for this area in 2017. However, to date there is no production or significant shows in the Sydney Basin. Only 2 wells have been drilled (F-24 and P-05), only reaching the upper part of the Mabou Group. They offer the only source of data in the offshore basin.

The Sydney Basin records an early Devonian to early Permian succession, dominantly clastic and rarely carbonate (Figure 1). Quaternary deposits are present but there is a lack of Triassic, Jurassic and Cretaceous deposits. The basin registers 6 main tectonic phases, detailed below. The Carboniferous succession reaches 6000 m in thickness in places (see Seismic Transects in Chapter 6) and records several distinctive tectonic events.

1. PRE-RIFT

The pre-rift succession is, at its youngest, late Devonian in age (Fammenian). It is interpreted as the basement, and is in places volcanic (such as seen in well P-140), and elsewhere comprises highly metamorphosed sediments. It is difficult to map with great accuracy the different rock types, mainly because of the quality of the seismic data, but also because little data exist on the nature of the basement in wells and in outcrops. As such, it is challenging to compare and contrast the existing data with the seismic data offshore. The pre-rift succession has experienced a complex tectonic history, which is briefly summarised in Chapter 2.

2. EXTENSIONAL PHASE

An extensional phase (probably transtensional) during the late Devonian / early Carboniferous controlled the deposition of the Horton Group. Growth strata have been identified on seismic, typical of syn-kinematic deposition. Therefore, the Horton Group, Tournaisian in age, is strongly controlled by the basement topography, and is only present in basement lows. The rifting or extension of the basin likely occurs in transtension and creates pull-apart basins. Faults are oriented in a NE-SW direction, and the Horton Group is thickest in the footwall of those faults.

Deposits of the Horton Group are exclusively clastic, with conglomeratic fans in the footwall of faults fining up to sandstone and continental shale. In the Middle Horton, fault activity decreases allowing the development of deep lakes. Lacustrine shales were deposited which today represent a potential source rock. In the Upper Horton Group, the topography created by the faulting is less pronounced than previously and therefore no conglomeratic fans develop.

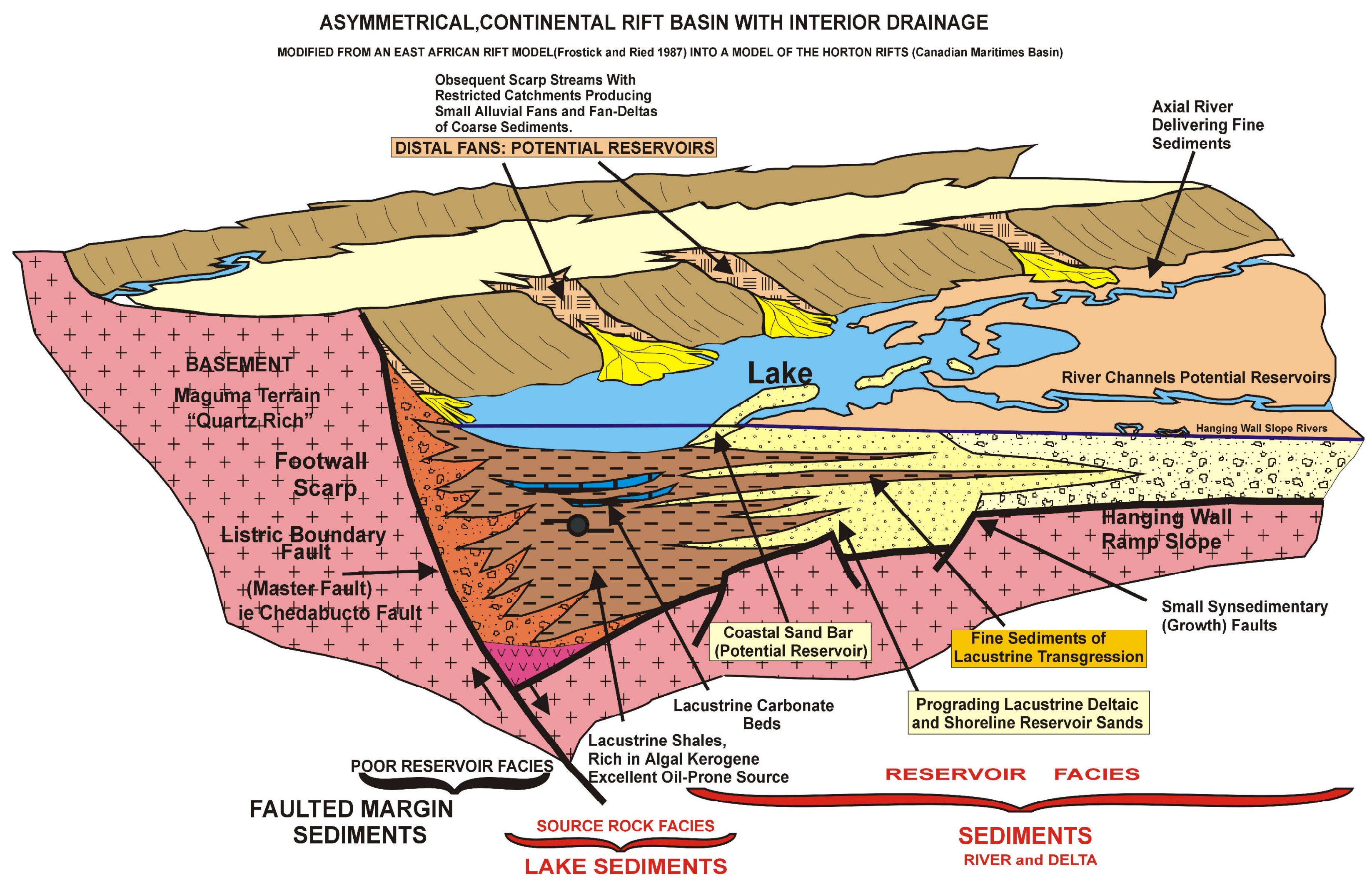


Figure 2: Horton Group rift basins – source and reservoir depositional model.

3. SUBSIDENCE

The extensional phase is followed by a period of subsidence with local and minor extensional activity that controlled the deposition of the Windsor Group (Visean - Carboniferous). Therefore, deposition of the Windsor Group is still strongly controlled by the basement topography, especially for the Lower Windsor Group (Figures 3-4-5).

The **Lower Windsor Group** is dominated by carbonate (Macumber Fm.) and salt deposition (Sydney River and Kempt Head Fm.) (Figure 1).

The **Upper Windsor Group** is dominated by an alternation of salt and carbonate (Meadows Road Fm) overlain by continental sandstone, rare conglomerate and local lacustrine shale (Woodbine Road Fm.) (Figure 1).

4. TECTONIC QUIESCENCE

The late Carboniferous and Permian deposition (Mabou, Morien / Cumberland, and Pictou Gp.) was mainly affected by large subsidence (Figures 3 and 5). Several erosional surfaces are identified in this unit, typical of a continental depositional environment. The most relevant unconformity is the Westphalian / Namurian, identified both on well and seismic data.

The **Mabou Group**, comprising the Cape Dauphin and the Point Edwards Formations, is a succession dominated by fluvial and lacustrine deposits with grey mudrocks and red sandstone (Figure 1). Locally, carbonates do develop, and are seen as thin intervals in onshore wells P-140 and P-84.

The **Morien / Cumberland Group** comprises the South Bar, Waddens Cove and Sydney Mines Formations. This succession is characterized by alluvial plain and coastal plain deposits (Figure 1), consisting of sandstone, shale and coal.

Finally, the Pictou Group red beds occur as incomplete sections in the upper parts of several offshore petroleum and coal exploration wells including North Sydney P-05 and North Sydney F-24. There are no outcrop sections of these strata in the onshore part of the basin, but they are inferred to subcrop beneath the waters of the Cabot fault (Boehner and Gilles 2008).

5. TRANSPRESSION

The entire Carboniferous and Permian sequence was affected by a regional transpressional phase. The pre-existing normal faults were locally inverted. Positive structures are formed during this phase with a fault propagation fold mechanism. A representative example is the North Sydney fault. Seismic evidence allows the definition of the lower age limit of this tectonic event as the end of the deposition of the Pictou Group (Late Asselian, 294 Ma). Lack of data does not permit the definition of the upper age limit, but it is reasonable to assume that it is related to the Hercynian orogeny, which was active until the Late Permian.

6. MESOZOIC EROSION

An erosional event occurred subsequent to the creation of the positive structures due to the lower Permian inversion. 1D Basin Modeling performed by Beicip-Franlab would suggest up to ~1500/2000 m of eroded sediments.

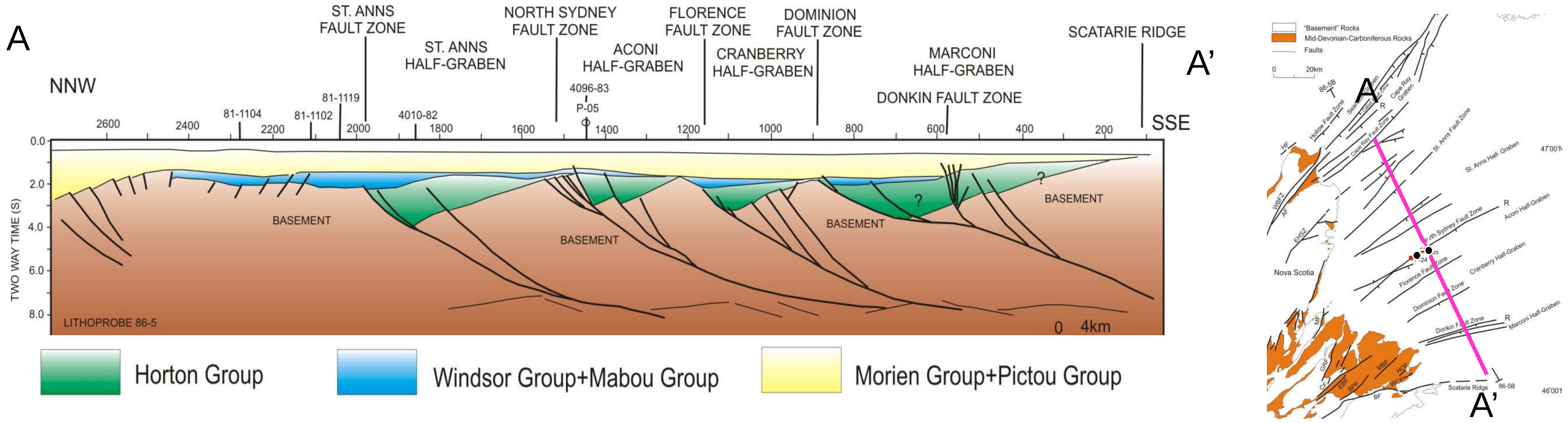


Figure 3: Lithoprobe deep-crustal seismic line 86-5 showing the basement and Horton to Pictou Groups distribution. From Pascucci et al. 2000

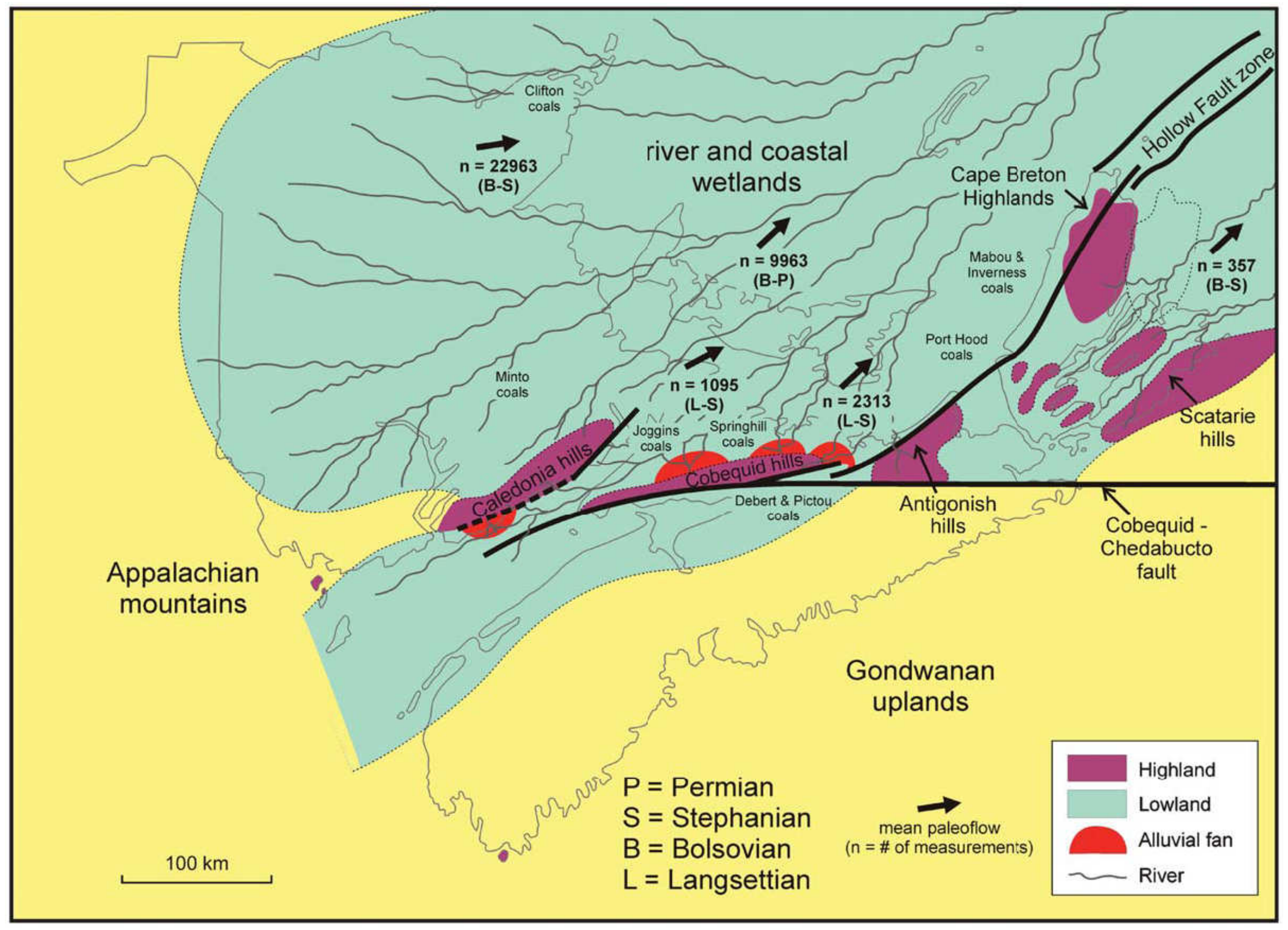


Figure 4: Paleogeographic map of part of eastern Canada during the Pennsylvanian. Flow directions based on paleoflow data summarized in Gibling et al. (1992); Ages for paleoflow data: L, Langsettian; B, Bolsovian; S, Stephanian; P, Permian. Areas of some major coal beds are shown, ranging in age from Langsettian to Asturian. modifed from Atlantic Geoscience Society (2001).

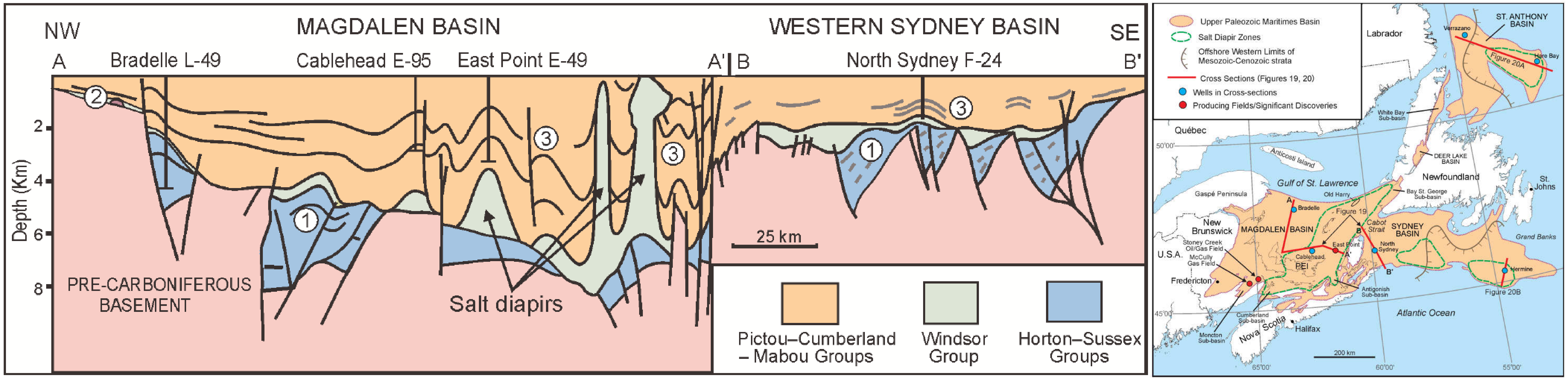


Figure 5: Geological cross-sections showing stratigraphic relationships between New Brunswick and Nova Scotia (modified from Wade and MacLean, 1990).

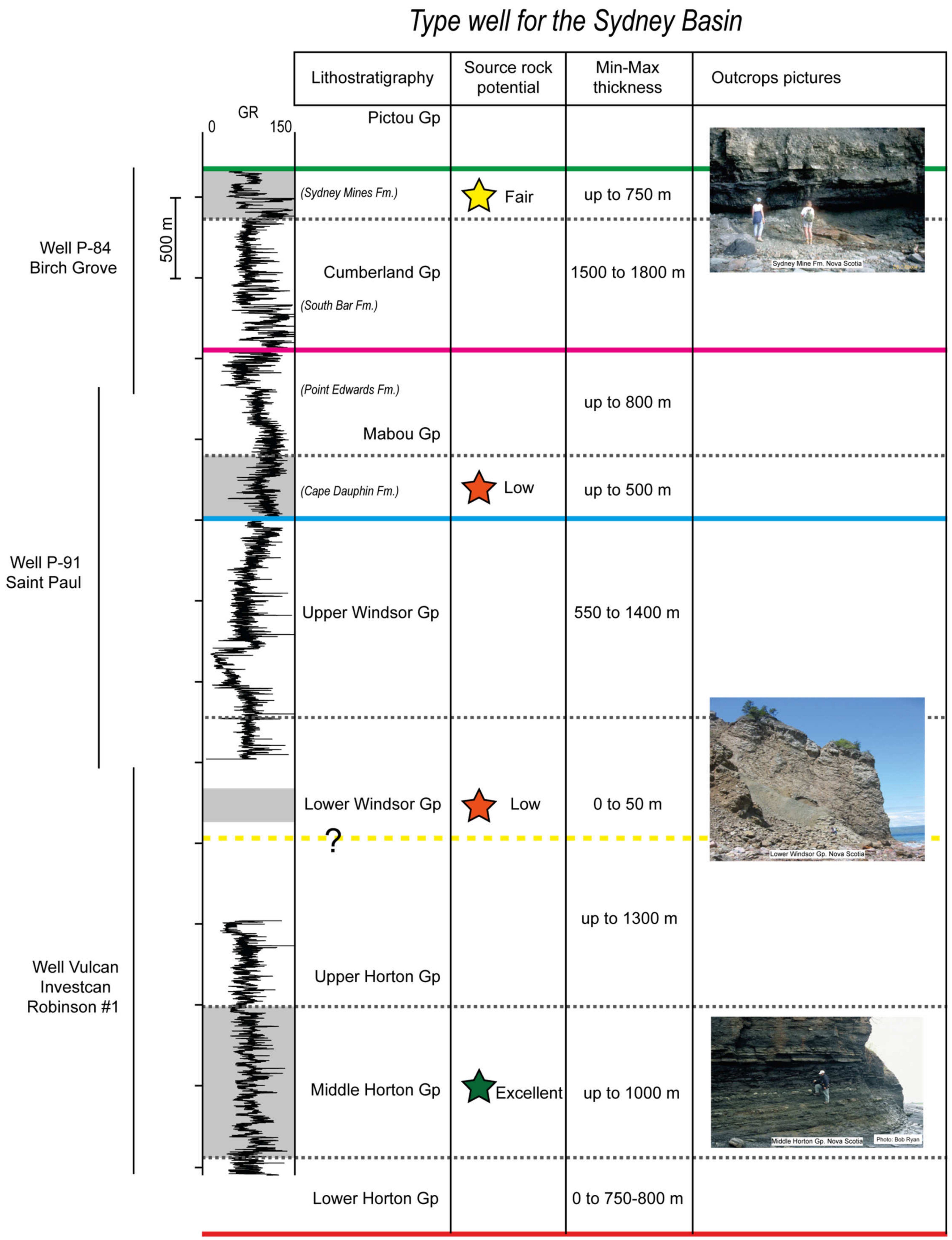


Figure 6: Type well for the Sydney Basin showing the lithostratigraphy, the source rock potential for key units, the minimum and maximum thickness, and outcrop photographs.

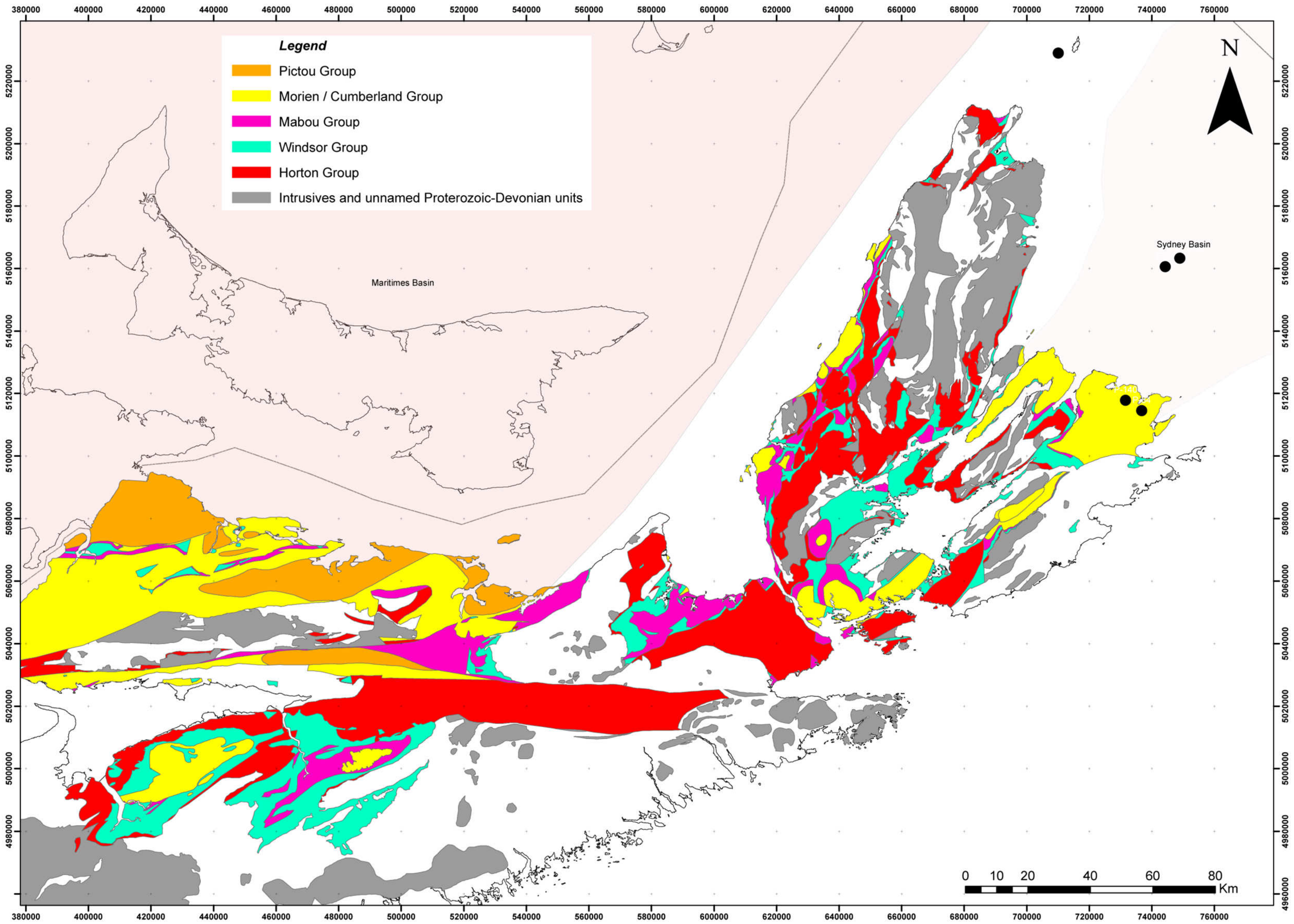
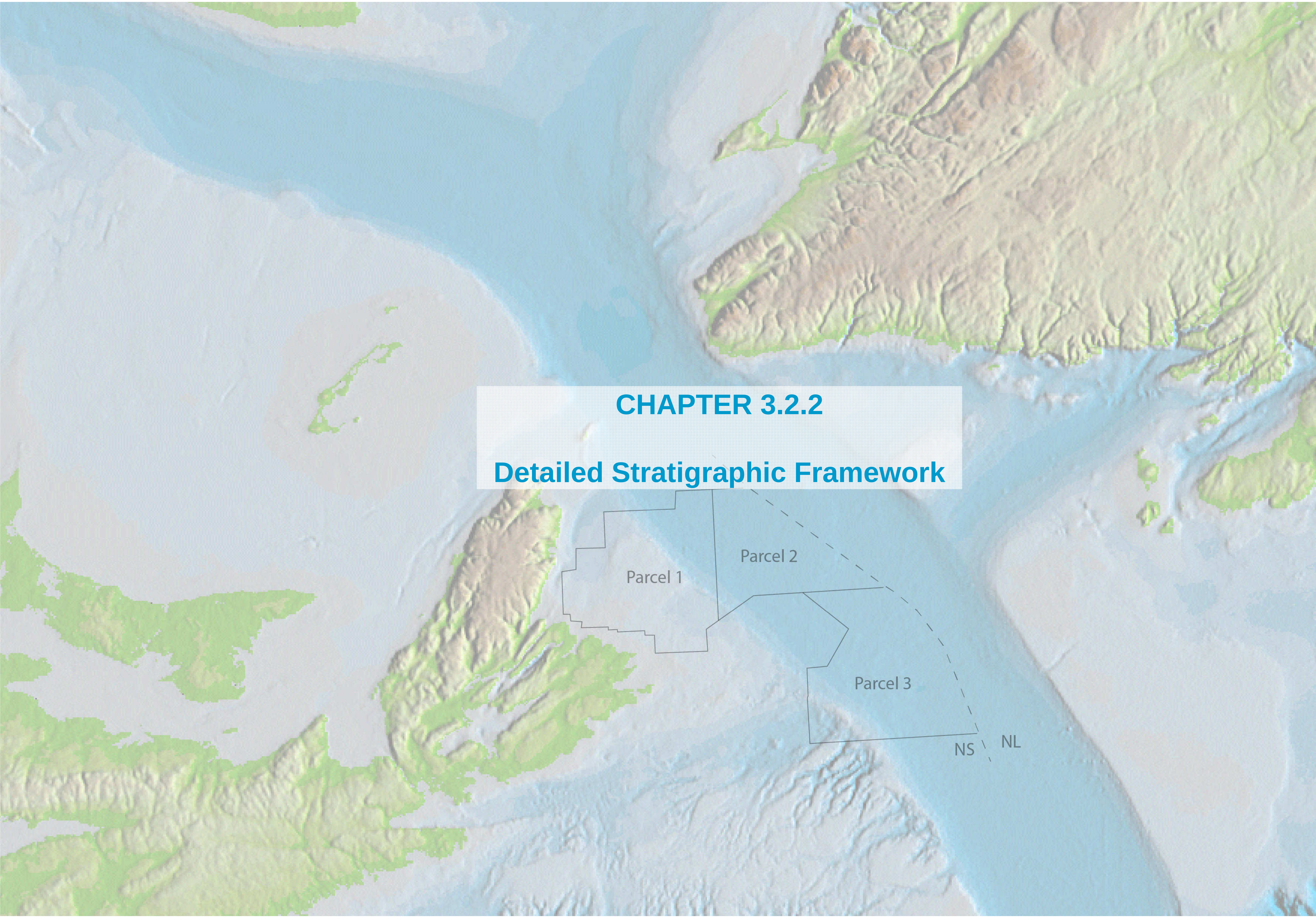


Figure 7: Geological map of the onshore, Cape Breton Island and central Nova Scotia. The only groups colored here are the ones with equivalents in the offshore Sydney Basin.

CHAPTER 3.2.2

Detailed Stratigraphic Framework



Generalized Stratigraphy of the Sydney Basin

The Sydney Basin is a Carboniferous structural basin situated in eastern Cape Breton, Nova Scotia. It extends both onshore in eastern Cape Breton and offshore towards Newfoundland. A vast amount of literature exists on the onshore geology (Duff et al., 1982; Boehner and Giles, 2008; Fielding et al., 2009; Gibling et al., 1992; and Hamblin, 2001), however, few studies have been conducted on the sedimentology of the offshore area (Pascucci et al. 2000).

Onshore, the Sydney Basin contains both continental and marine sediments. A similar succession is expected in the offshore Sydney Basin. The Carboniferous sedimentary succession reaches 3500 m in stratigraphic thickness. A total of 10 seismic horizons (named H1 to H10, see Table 2) have been mapped (see Chapter 5). Each horizon is either mapped across the whole basin, or locally to help define the stratigraphy.

PRE CARBONIFEROUS BASEMENT

All basement rocks are here included as a single unit, but they can be separated into two groups: (1) the stratified sedimentary, metasedimentary and volcanic rocks, and (2) the plutonic rocks (Boehner and Giles, 2008). The basement outcrops in Cape Breton (Figure 8) allowing these two groups to be characterized.

- Stratified rocks

The stratified rocks included in the basement block comprise the Fourchu, George River, Kelvin Glen and Bourinot Groups as well as the weakly deformed formations of the Cambrian sedimentary sequence and the Middle Devonian MacAdam Lake Formation (Boehner and Giles, 2008). These stratified rocks comprise a thick suite of interstratified metasedimentary, volcanic and volcanoclastic rocks and form a prominent component of detritus in the coarse grained Carboniferous basin fill. The succession is variably deformed with locally weak deformation. A greenschist or higher grade metamorphism is commonly observed in the older rocks of the succession, while the younger units may have undergone less complicated deformation.

- Plutonic rocks

The metasedimentary and volcanic rocks have been intruded by small granitoid plutons and porphyry (Figure 9). The plutonic basement rocks are also a prominent source of immature detritus in alluvial fan conglomerates of the Carboniferous basin fill.

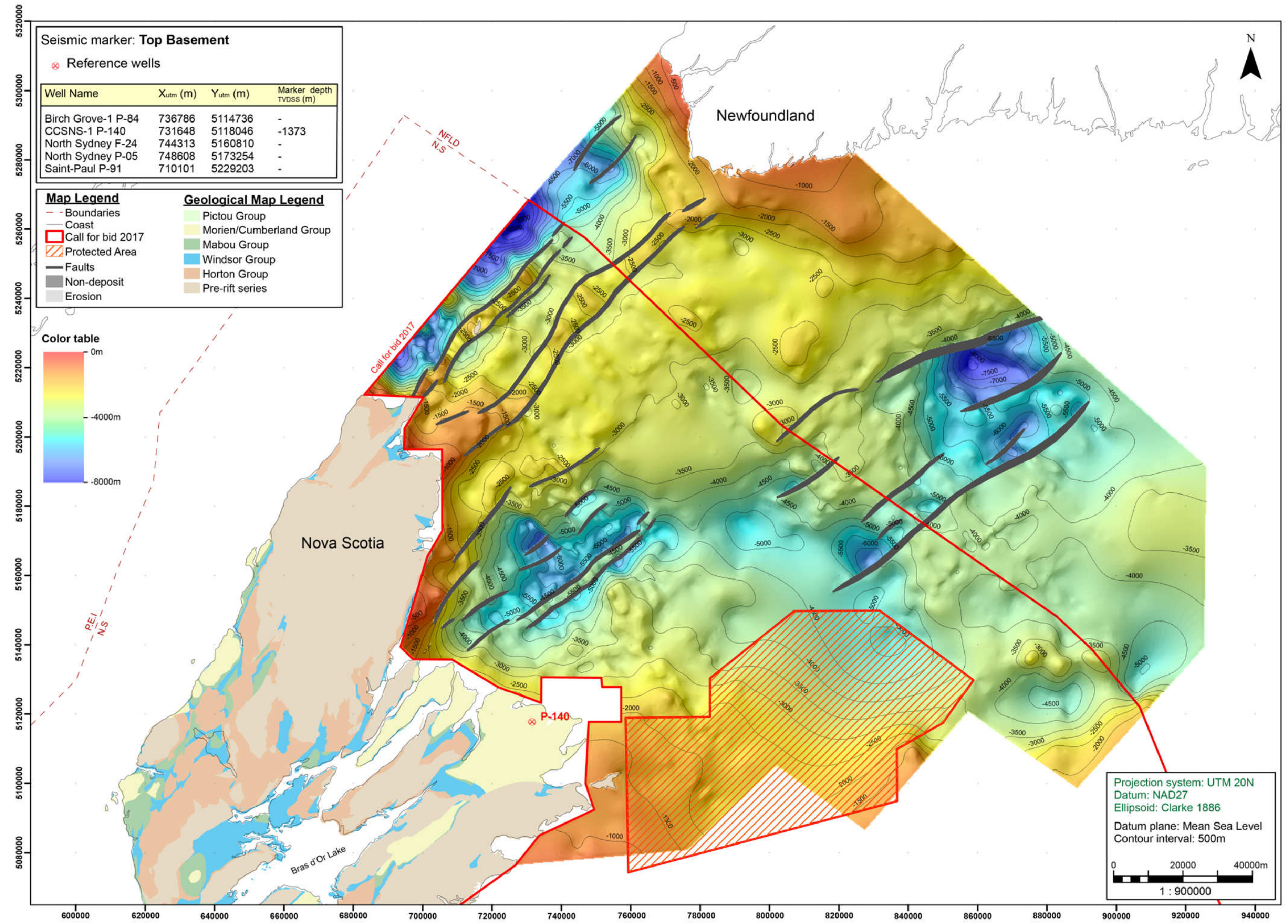


Figure 8: In grey, onshore extent of basement rocks and structural offshore map of Top basement.

Stratigraphic Marker	Stratigraphic Surface	Stage	Equivalent Formation or Group	P-140	P-84	F-24	P-05	P-91
H10	Unconformity	Permian Asselian						
H9	Unconformity	Westphalian C-D	Pictou		4	522	529	
H8	Unconformity	Westphalian B-C	Sydney Mines	395	318	1085	1046	
H7	Unconformity	Westphalian / Namurian	South Bar	1114	1062	1436	1393	
H6	Conformity	Visean / Serpukhovian	Mabou Gp.					1257
H5	Conformity	Visean	Upper Windsor Gp					
H4	Unconformity	Tournaisian / Visean	Lower Windsor Gp.					
H3	Conformity	Tournaisian	Horton Gp.					
H3	Conformity	Tournaisian						
H2	Conformity	Tournaisian						
H1	Unconformity	Devonian/Carboniferous	Basement	1373				

Table 2: Well markers and biostratigraphic surfaces in meters MD.

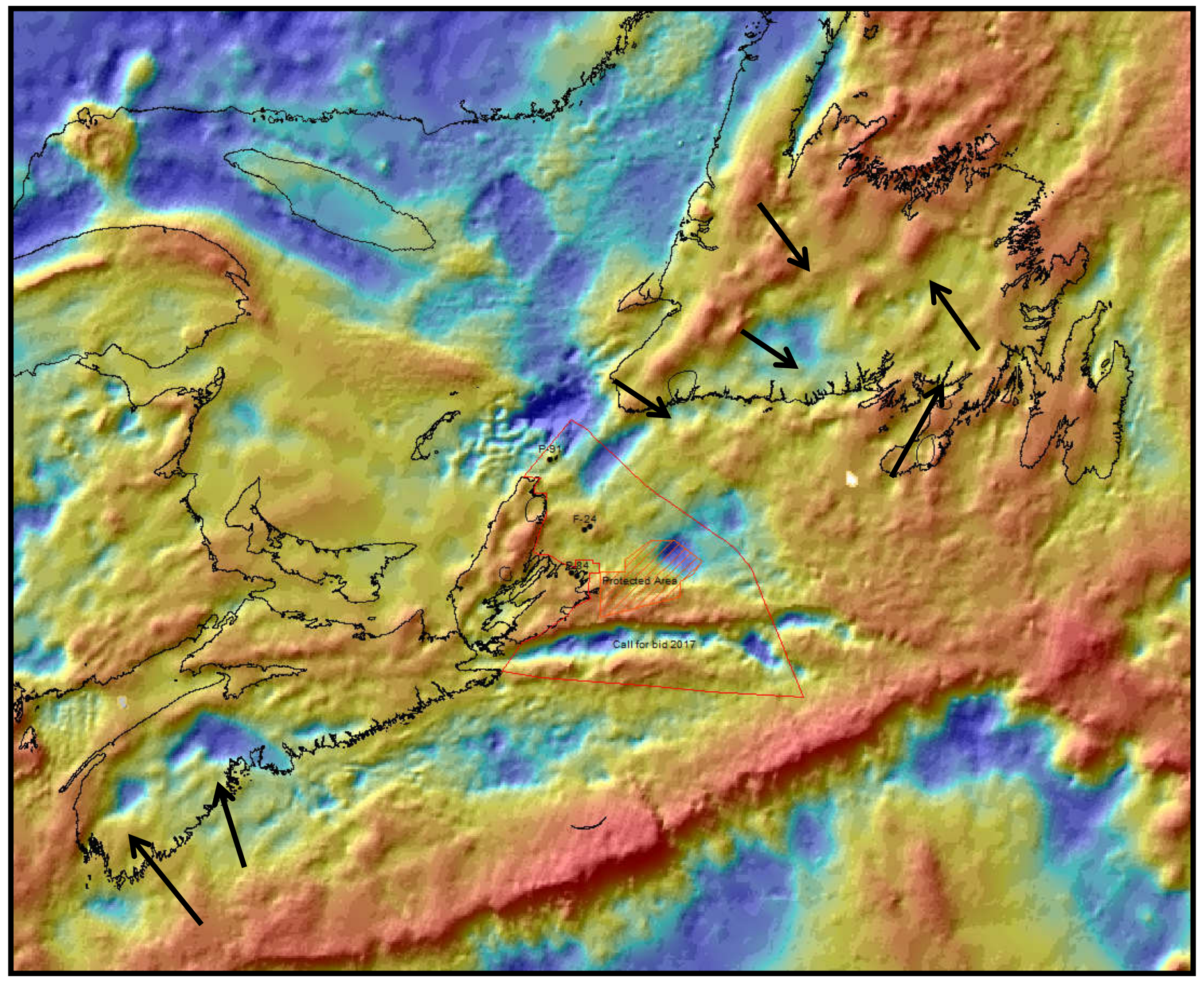


Figure 9: Gravity map illustrating the possible location of plutons (black arrows). It is to be noted that pluton bodies can appear as either gravity highs (red) and lows (blue) overshadowing depocenter signatures (see also chapters 2 and 4).

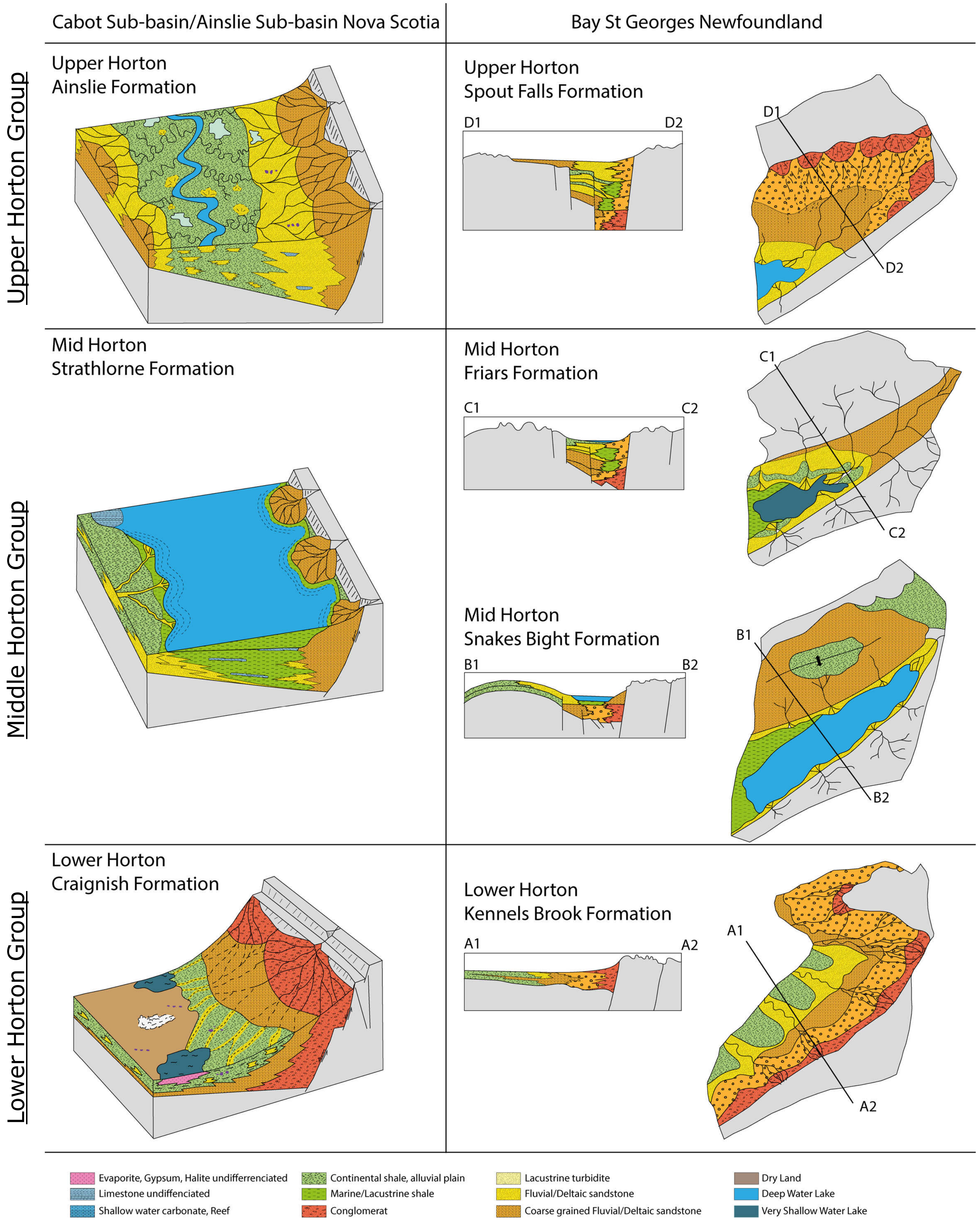


Figure 10: Conceptual paleoenvironments for the Horton Group. Redrawn from Hamblin and Rust (1989)

HORTON GROUP

The Horton Group is well developed across the entire Maritimes Basin, and can be observed both onshore and offshore. Onshore, the Horton Group outcrops well in Cape Breton where it unconformably overlies basement. Offshore, it is present throughout much of the Sydney Basin. The Horton Group is characterized by terrestrial and lacustrine clastic deposits, ranging from coarse conglomerate to fine shale. The distribution, thickness and inferred palaeocurrent data indicate deposition in large fault-bounded sub-basins (Hamblin, 1992).

- **Lower Horton Group**

In the nearby Maritimes Basin, the Lower Horton Group corresponds to the Craignish Formation (Hamblin and Rust, 1989; Hamblin, 1992) (Figure 10). This formation unconformably overlies the basement rocks. At its base, the Craignish Formation is dominated by 1) well-stratified, fine to coarse-grained pebbly sandstone in units 1-2 m thick which fine-upward from scoured bases; 2) sandy conglomerate in coarsening-upward sequences up to 50 m thick, and 3) green siltstone to very fine rippled sandstone in thin lenses between coarser beds, or as thick units up to 75 m thick in basin centres (Hamblin and Rust, 1989). In its upper part, the Craignish Formation gradationally fines upwards into brick red, massive siltstone in units up to 50 m thick, with abundant calcrete zones and root casts.

The Craignish Formation corresponds to deposition in proximal wedges (conglomerate) to distal braidplain (sandstone). The presence of thick green siltstone units near the basin center suggests that this braidplain was low-lying, with a high water-table and standing bodies of water (Hamblin and Rust, 1989). The climate was warm and semi-arid.

- **Middle Horton Group**

In the nearby Maritimes Basin, the Middle Horton Group corresponds to the Strathlorne Formation (Hamblin and Rust, 1989) (Figure 10). This formation is conformable with deposits below and above. The Strathlorne Formation is overall much finer than formations above and below, and consists dominantly of grey fined-grained sediments. However, near faulted basin margins, grey pebbly medium to coarse sandstone or matrix-supported pebble to boulder conglomerate occur in sharp scour-based units up to 5 m thick. Away from fault margins, shale and fine-grained sediment are preserved.

The Strathlorne Formation corresponds to lacustrine complexes deposited within fault-bounded sub-basins. Near faulted sub-basin margins, alluvial fan and fandelta deposits prograded into normally low-energy environments after short-lived phases of fault motion. The more distal mudflats show evidence for subaerial exposure in a warm arid climate in the form of red coloration, calcrete nodules, root traces and desiccation cracks. Away from shoreline influence, quiet water lacustrine sedimentation of silt and clay dominated (Hamblin and Rust, 1989).

- **Upper Horton Group**

In the nearby Maritimes Basin, the Upper Horton Group corresponds to the Ainslie Formation (Hamblin and Rust, 1989) (Figure 10). It generally consists of red to grey, coarse to fine grained clastics, commonly with an overall coarsening-upward trend. In most areas of the Maritimes Basin, it contrasts markedly with the sediments above and below. However, like for the Lower and Middle Horton Group, the deposition of the Ainslie Formation is controlled by faulting. Near the main faulted basin margins, sediments are coarse, such as red conglomerate and pebbly coarse sandstone. Away from main faulted basin margins, the Ainslie Formation consists of red micaceous fine to coarse-grained sandstone in sharp-based fining-upward units up to 10 m thick. Finally, in the most distal, or basin-central positions, the Ainslie Formation is composed of grey to greenish grey well sorted very fine to fine-grained sandstone in fining-upward units up to 15 m thick, separated by thick grey to reddish grey siltstone (Hamblin and Rust, 1989).

The Ainslie Formation corresponds to alluvial fans and proximal braid plains near the faulted basin margins. Medial zones are dominated by transitional low/high sinuosity fluvial channels. The climate was warm and semi-arid and vegetation was sparse (Hamblin and Rust, 1989).

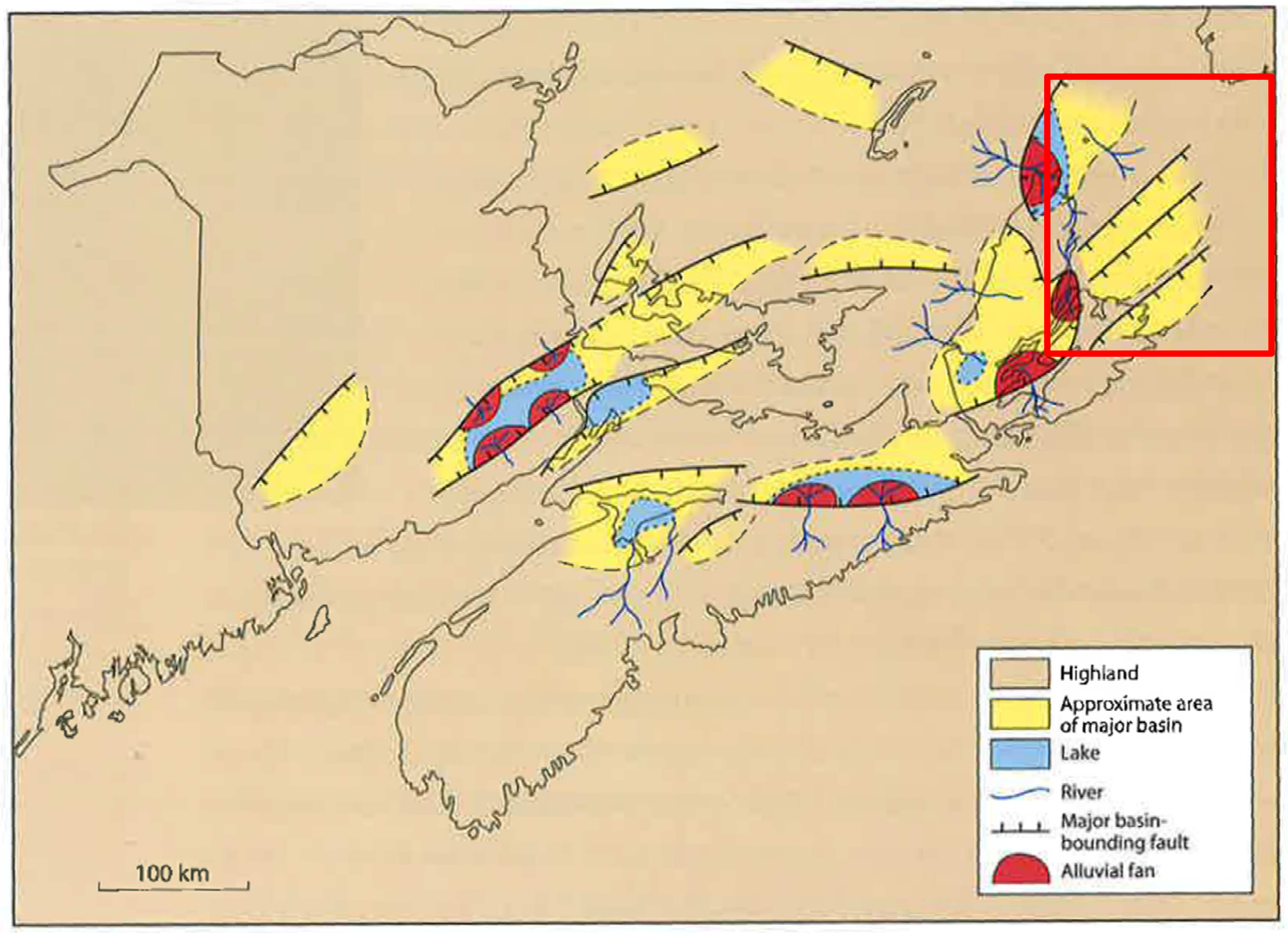
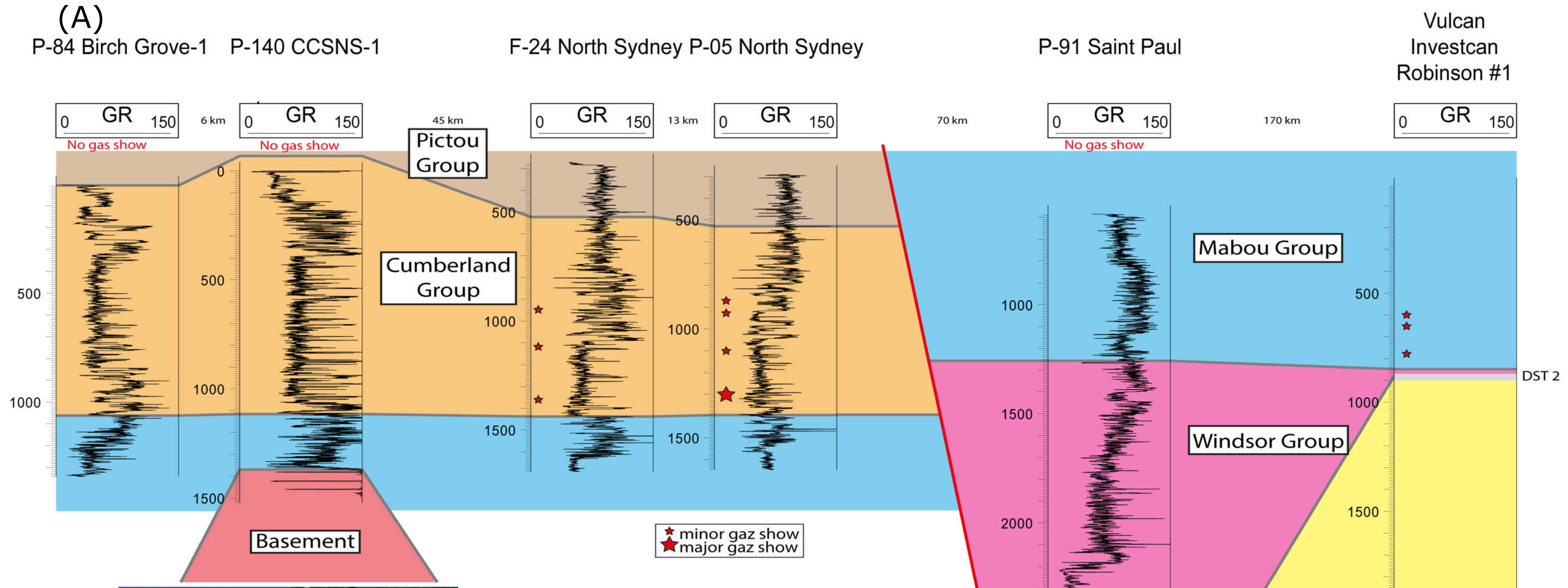
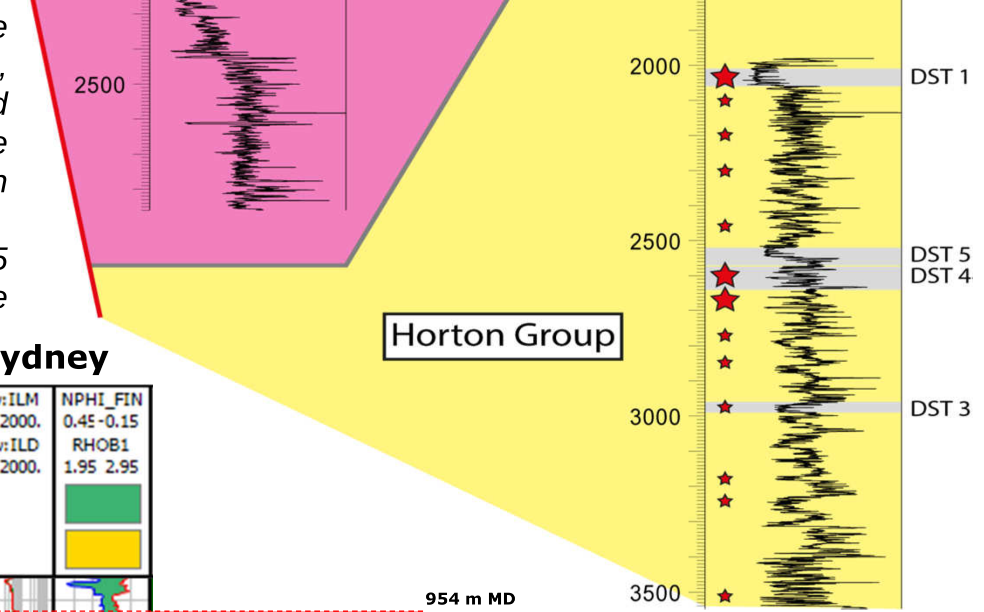


Figure 11: Regional paleogeography in the early Carboniferous, about 355 million years ago. Gibling et al. 2008

Figure 12: Horton Group organic-shale and sandstone: Type section, Horton Bluff, Windsor subbasin. Photo credit: Rob Ryan

(A)





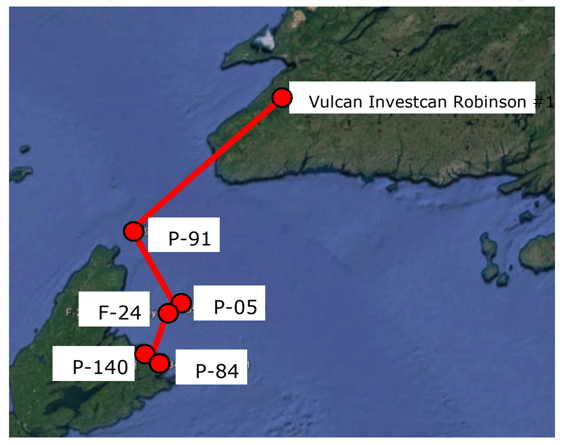
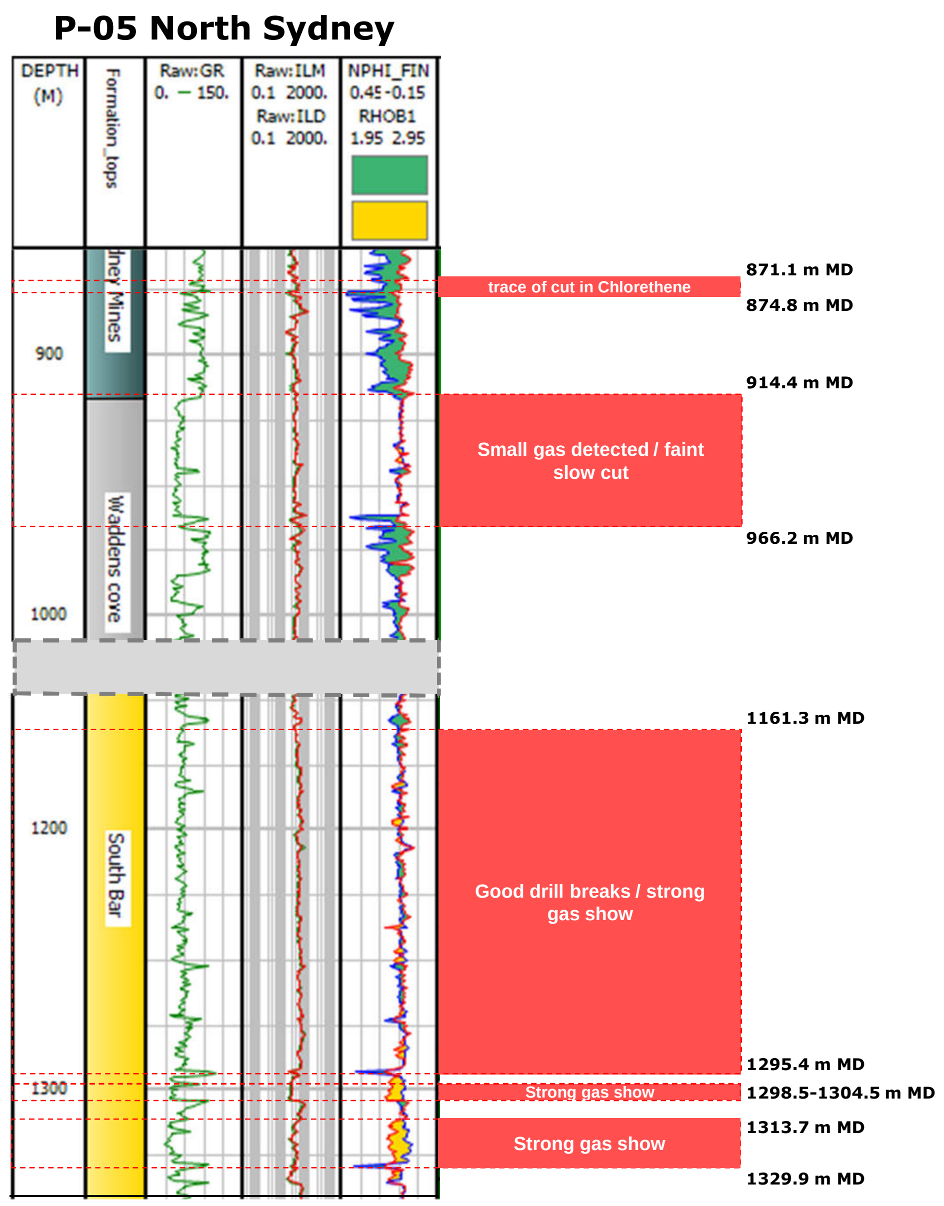
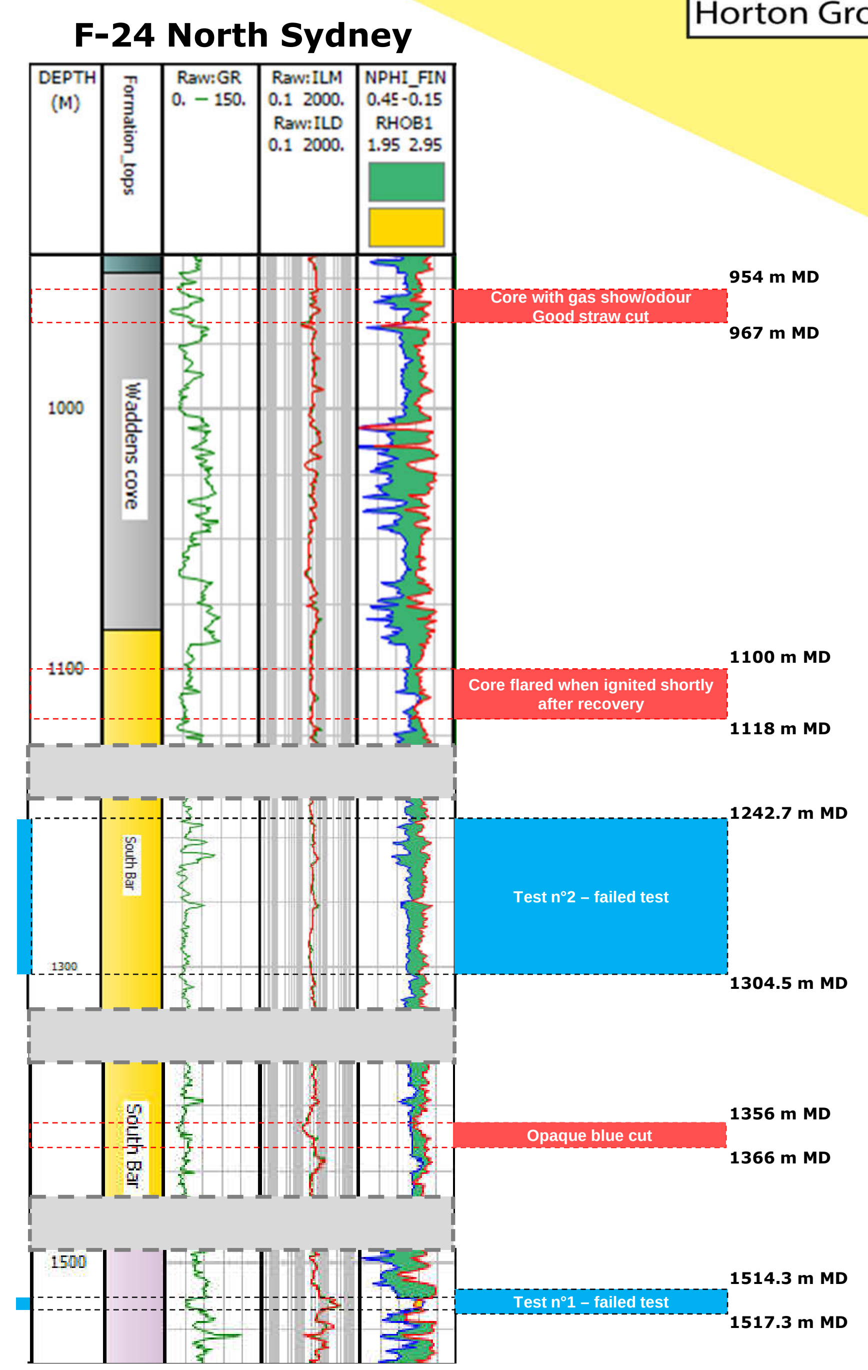


Figure 13: A. Correlation panel showing the relationship between the Sydney Basin (P-84, P-140, F-24 and P-05) and the Maritimes Basin (P-91 and Vulcan Investcan Robinson #1). Note the considerable thickness of the Horton Gp in Vulcan Investcan Robinson #1.
B. Raw logs on specific intervals of F-24 and P-05 wells, where gas shows from cuttings or core have been recorded.

(B)





The Horton Group is not penetrated in the five wells studied here. However, it outcrops well in the onshore Cape Breton, where all the sedimentary characteristics are extracted from. Several wells, such as the Vulcan Investcan Robinson #1 (west Newfoundland), do penetrate the Horton Group, but are located away from our study area (Figure 13).

PETROLEUM POTENTIEL OF THE HORTON GROUP

The Horton Group represents an excellent potential source rock within onshore mainland Nova Scotia and Cape Breton Island (Figure 14-15), and also in nearby basins, such as Newfoundland and the Grands Banks regions. The Horton Group also hosts potential reservoir successions, with variable quality, ranging from poor to good (Mukhopadhyay, 2004; Figure 16). Finally, within onshore Cape Breton Island and mainland Nova Scotia, the thermal maturity of Horton rocks ranges from low to high (Utting and Hamblin, 1991).

Source rock potential
The Middle Horton Group, with thick accumulations of lacustrine black shales, is interpreted as a potential source rock. Lacustrine shales contain Type I and II organic matter capable of significant oil and gas generation. Total organic content (TOC) is commonly above 2% and up to 20% in organic-rich shale intervals (Dietrich et al., 2011; Fowler, 2017).

Reservoir potential
The Lower and Upper Horton Group represent thick successions of arkosic pebble conglomerate and coarse grained sandstone; these units are essentially ‘Granite Wash’ and have excellent reservoir rock potential (20% porosity, 221-437 mD permeability). However, the reservoir degradation can occur due to deep burial (Dietrich et al., 2011).

Seal capacity potential
The Horton Group lacks significant sealing facies.

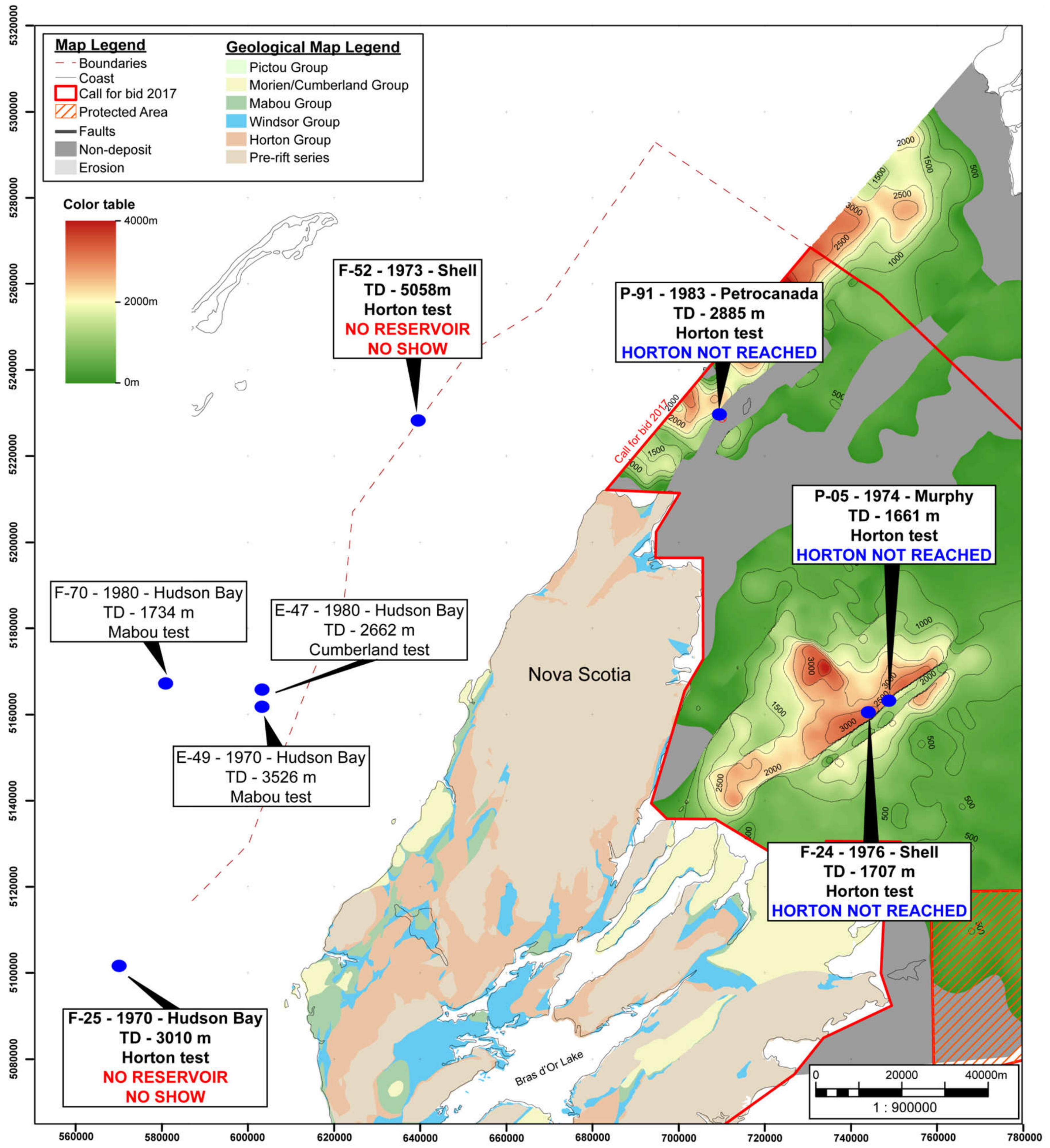


Figure 14: Well failure analysis overlain on the Horton isopach. Note that the Horton Group was not reached in the three offshore wells of the current study. (Isopach map comes from the current study, well data from Hunt and Kendal, 2006).

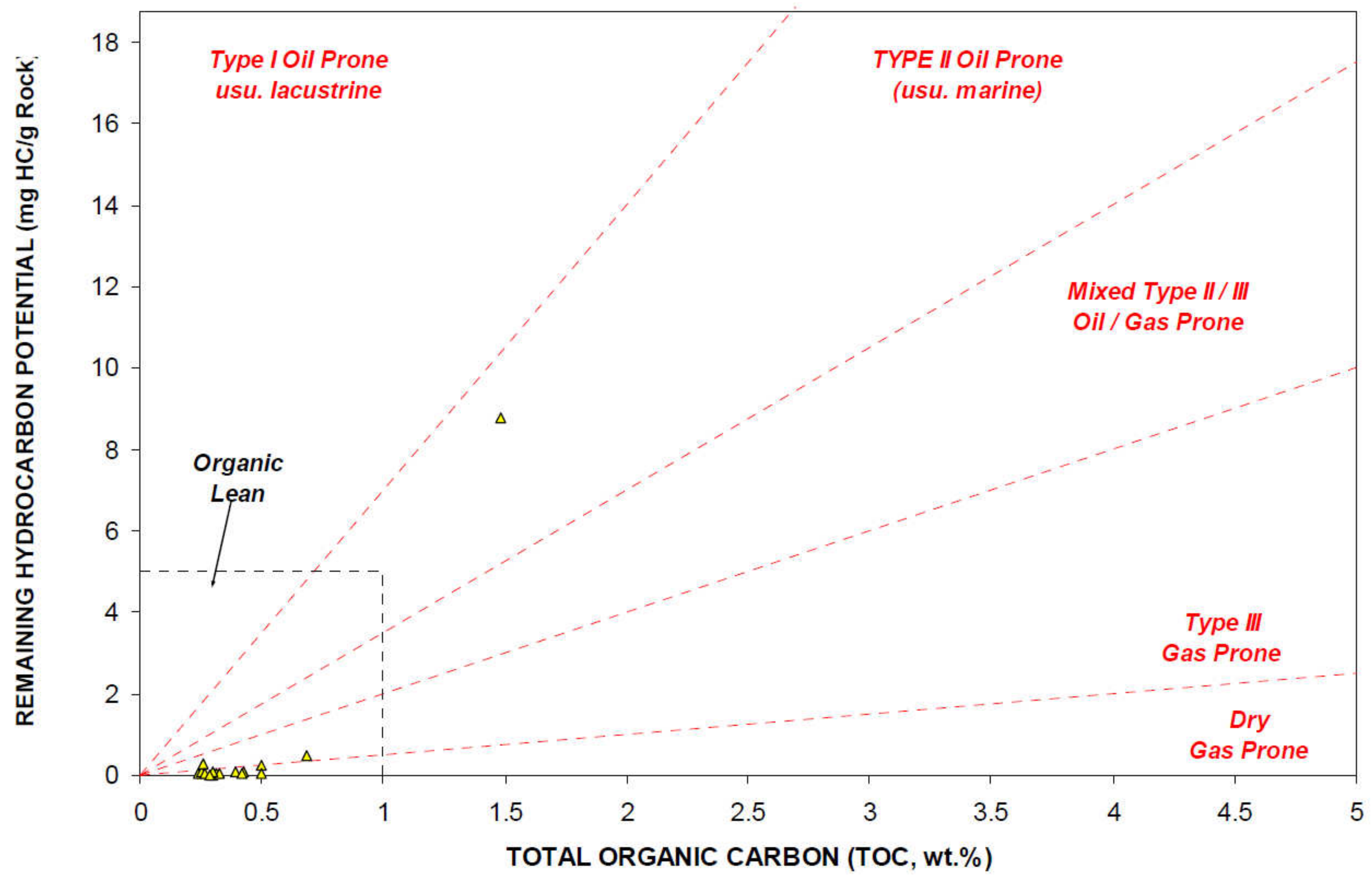


Figure 15: Remaining hydrocarbon potential vs. TOC for the Mabou-Ainslie subbasin; the oil-prone source rock is from Horton Group of Lake Ainslie 88-1 well. Mukhopadhyay (2004)

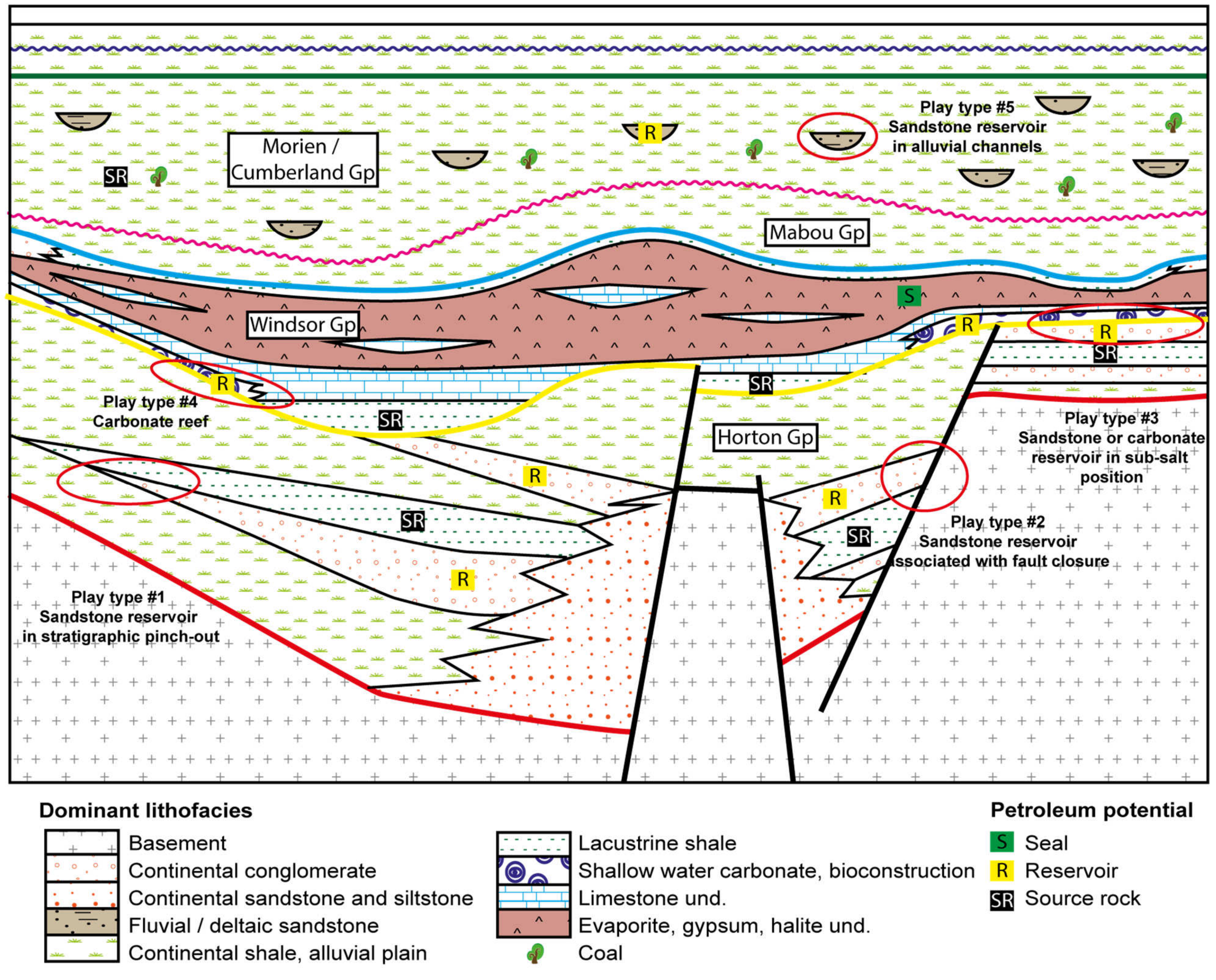


Figure 16: Conceptual diagram of petroleum play types.

WINDSOR GROUP

The Windsor Group is one of the most important stratigraphic and economic units in the Carboniferous basins of Atlantic Canada. It comprises a complex succession of interstratified evaporites including gypsum, anhydrite, salt and potash, fine and coarse-grained red beds, and fossiliferous marine carbonates (Figure 17; Boehner and Giles, 2008). The Windsor Group is interpreted to have been deposited during a major marine incursion, coming from the east of the Sydney Basin (Figure 17). Towards the top of the Windsor Group, the Windsor sea began to retreat, allowing the deposition of more clastic sediments (Figure 1).

- **Lower Windsor Group:**

The Lower Windsor Group includes in the Sydney Basin, from base to top, the Macumber, Sydney River and Kempt Head Formations (Figure 1). The Lower Windsor Group is not penetrated by the offshore wells studied here, so the lithology encountered is extracted from onshore data, i.e. Cape Breton.

Macumber Formation:
The Macumber Formation is the equivalent of the Gay River Formation in onshore areas of Cape Breton. The Macumber Formation represents deposition during a sudden marine transgression, and is dominated by carbonate deposits (Schenk, 1967).

Sydney River Formation:
In onshore areas of Cape Breton, the Sydney River Formation is an interstratified succession of coarse- to fine-grained, red and grey siliciclastics and evaporites (anhydrite, gypsum and rare salt) with minor thin carbonate interbeds (locally fossiliferous) (Boehner and Giles, 2008).

The Sydney River Formation is interpreted to represent the first sustained phase of major marine basin evaporite deposition from hypersaline Windsor sea in the area. The deposition of the thick section of calcium sulphate (gypsum or anhydrite and followed by minor limestone) is, in part, contemporaneous with the deposition of the basal carbonate (Gays River Formation and others). This major evaporite deposition reflects an increase in the salinity, first indicated by the facies distribution of the basal Windsor Group carbonates (Boehner and Giles, 2008). Several environmental factors can influence and favor the deposition of evaporites, such as an increase in evaporation due to warm climate, a decrease in the influx of water within the basin due to the closure of the basin, and/or the decrease in the clastic sediment influx.

Kempt Head Formation:
In onshore areas of Cape Breton, the Kempt Head Formation consists principally of stratified halite with minor interbeds of anhydrite, grey green siltstone and thin, low grade potash salt zones (sylvite and carnallite). No coarse clastic sandstone is observed within this formation (Boehner and Giles, 2008).

The Kempt Head Formation is interpreted to represent increasingly saline marine evaporite deposition dominated by halite which followed and was, in part, a basinal facies of the basal anhydrite of the Sydney River Formation. The contact is inferred to be gradational both laterally and vertically (Boehner and Giles, 2008).

- **Upper Windsor Group :**

The Upper Windsor Group includes in the Sydney Basin, from base to top, the Meadows Road and the Woodbine Road Formations (Figure 1).

Meadows Road Formation:
In onshore areas of Cape Breton, the Meadows Road Formation is an interstratified sequence of evaporites (gypsum and anhydrite), red and minor green siltstone, with several distinctive fossiliferous marine carbonate members. The carbonate members are typically overlain by, and occasionally underlain by, gypsum and anhydrite. The gypsum is gradational downward through nodules in dolomitic limestone matrix into the carbonate units. The gypsum beds are typically <6 m thick and are the hydrated equivalent of anhydrite which dominates deeper in the subsurface (Boehner and Giles, 2008).

The Meadows Road Formation is interpreted to represent repeated shallow water marine transgressions and regressions that produced cyclic alternations of fossiliferous micritic oolitic and algal carbonate, nodular gypsum and anhydrite and red continental siltstone and shale. More soluble evaporites, including halite and possible potassium salts, may have been deposited in the most saline facies deep in the basin (Boehner and Giles, 2008).

Woodbine Road Formation:
In the Sydney Basin, the Woodbine Road Formation comprises two facies, the marginal conglomeratic facies in the Point Edward area, and the more typical basinal facies. The Woodbine Road Formation is an interstratified sequence of red beds, siltstone and sandstone with local conglomerate and breccia in the marginal areas (Boehner and Giles, 2008).

The depositional model for the Woodbine Road Formation is very similar to that described for the underlying Meadows Road Formation. Evaporite facies are not as extensively developed, but the carbonate members tend to be better developed. The formation is dominated by fine grained red beds deposited in a continental to marginal marine mudflat environment. These are the distal equivalents of coarse grained alluvial fan conglomerates and breccias locally developed at the margins of uplifted basement blocks (Boehner and Giles, 2008).

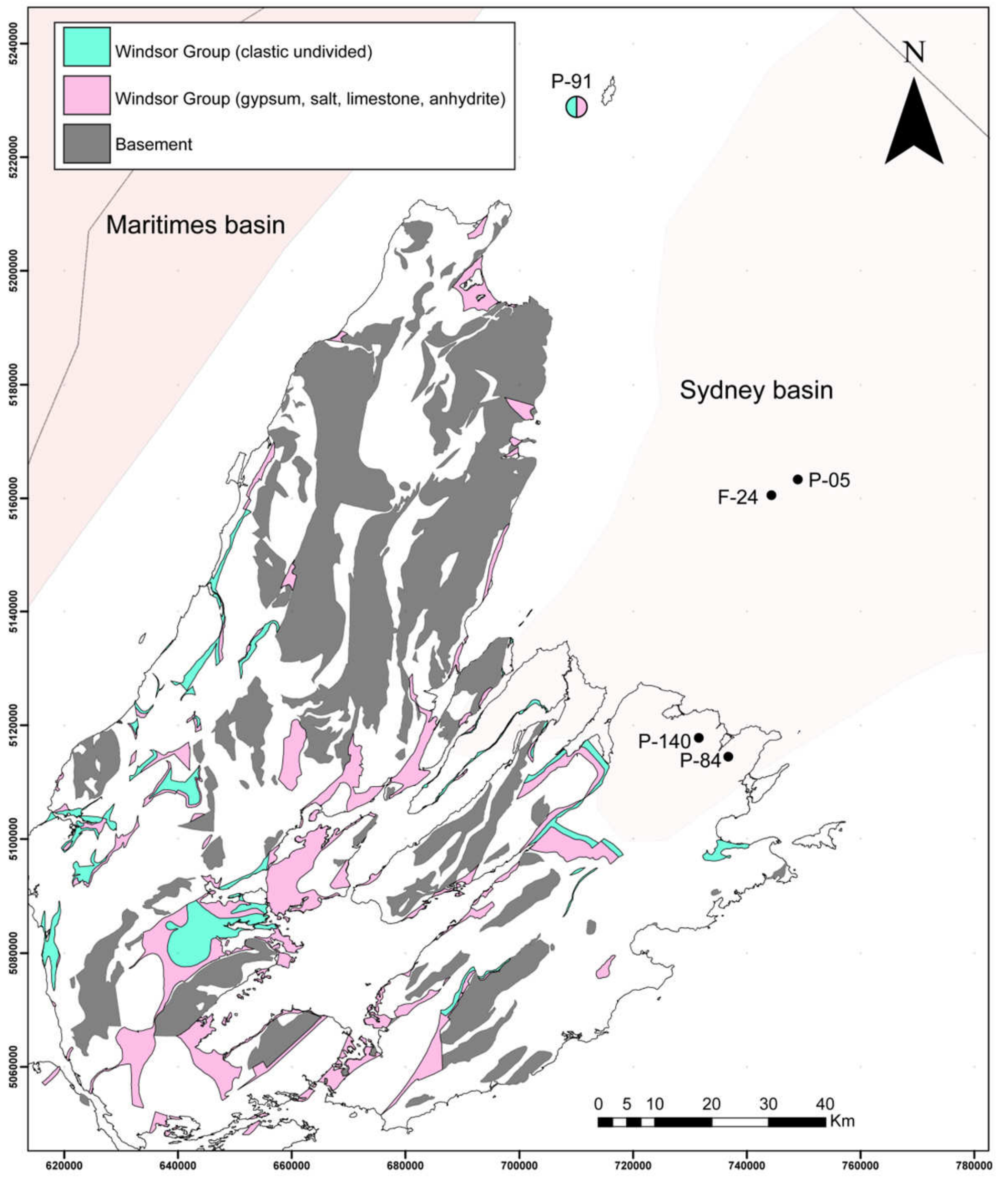


Figure 17: Windsor outcrops in onshore Cape Breton in blue (clastic undivided) and pink (gypsum, salt, limestone and anhydrite) with the basement in grey. Well data are shown where available.

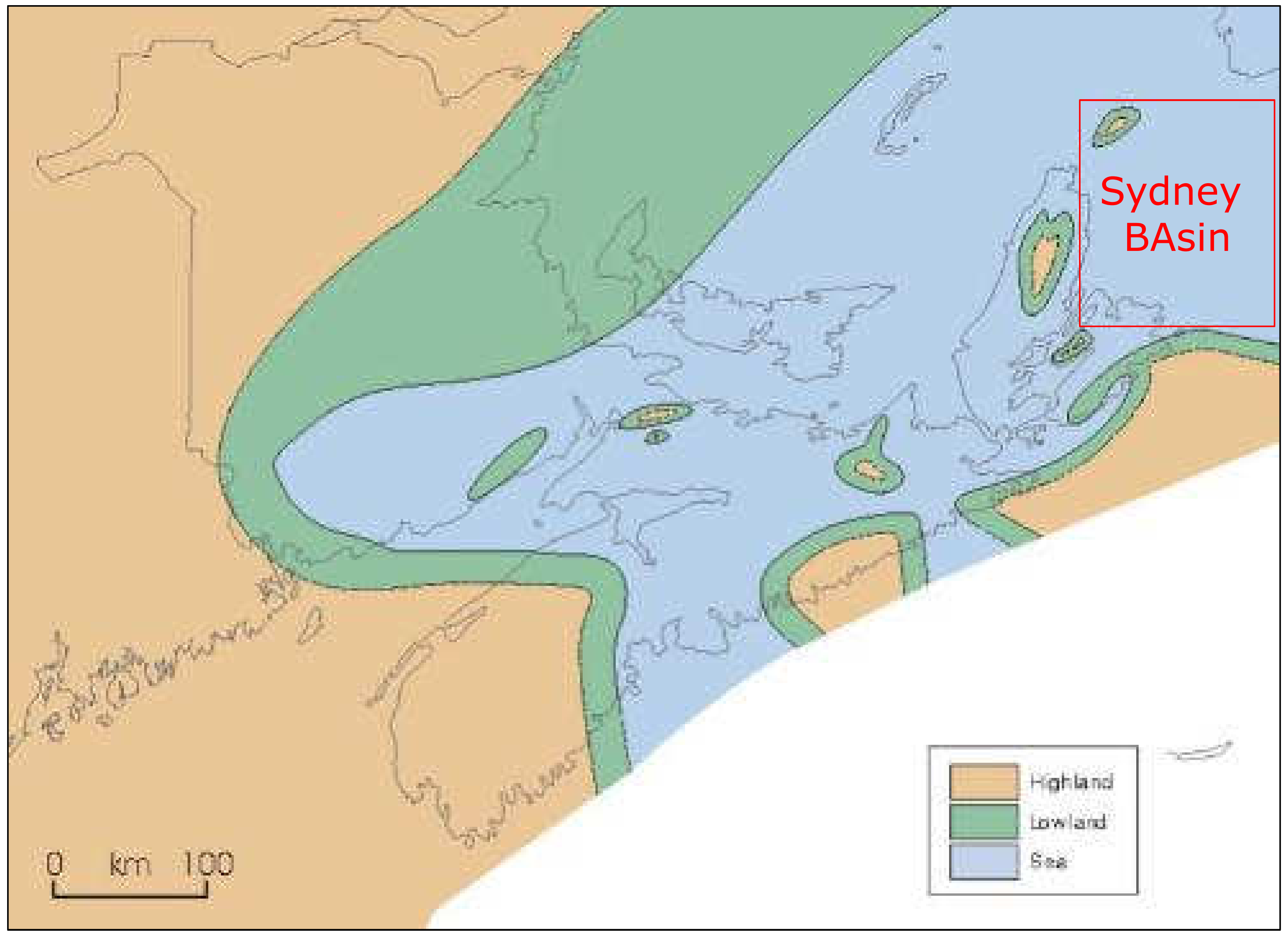


Figure 18: Regional paleogeography at the time of the Windsor Sea, in the Early Carboniferous, about 335 million years ago.

Figure 19: Windsor Group carbonate reservoir with crude oil, well ATG-8-76 (Jubilee area)

Figure 20: Saint Croix gypsum cliffs, Nova Scotia.

PETROLEUM POTENTIAL OF THE WINDSOR GROUP

The Windsor group comprises potential source rock, reservoir and seal.

Source rock potential

Windsor Group carbonates and calcareous shales contain Type II and III organic matter with up to 5% TOC (Mossman, 1992; Dietrich et al., 2011; Fowler, 2017), and in the Sydney Basin is assumed to have TOCs ~1.2% to 2.6%. The cumulative effective thickness ranges from 10 to 50 m (onshore/offshore) and its SPI (Source Potential Index) from 0.1 to 0.6 Tons/m2.

Reservoir potential

The Windsor Group has a reservoir potential in its lower part: the Macumber Formation (Figure 19). Outcrops show reservoirs with potentially good porosities (Enachescu, 2008) but well data suggest a tighter reservoir. For instance Enachescu (2008) suggests that Windsor carbonates have good porosities in onshore areas, but CCSNS-1 P-140 well onshore shows tight carbonate. The main issues regarding the reservoir potential of the Windsor Group come from a lack of data to refine the distribution of facies (reefs are patchy) and the structural stress (to help locate fractured reservoirs – Figure 19).

Seal capacity potential

The Windsor Group is a potential major seal as it comprises thick layers of salt (up to 1500 m in places). The main issue regarding the seal integrity comes from the alternation of salt and carbonate layers. The Windsor Group is studied in greater detail here to better constrain the distribution of key facies (see Chapter 7 for more details).

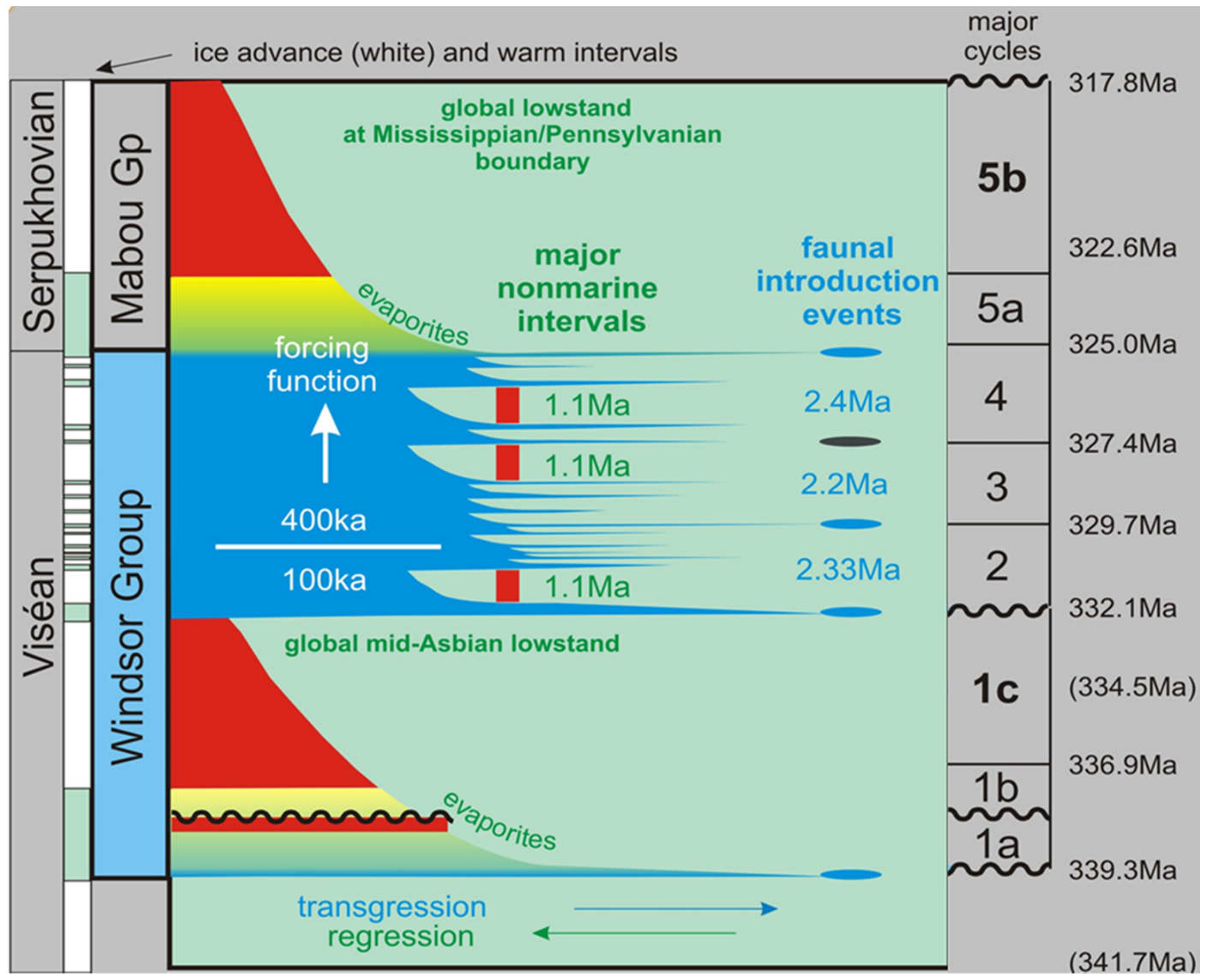


Figure 21: Potential forcing during the deposition of the Windsor Group. From Lavoie et al., 2009.

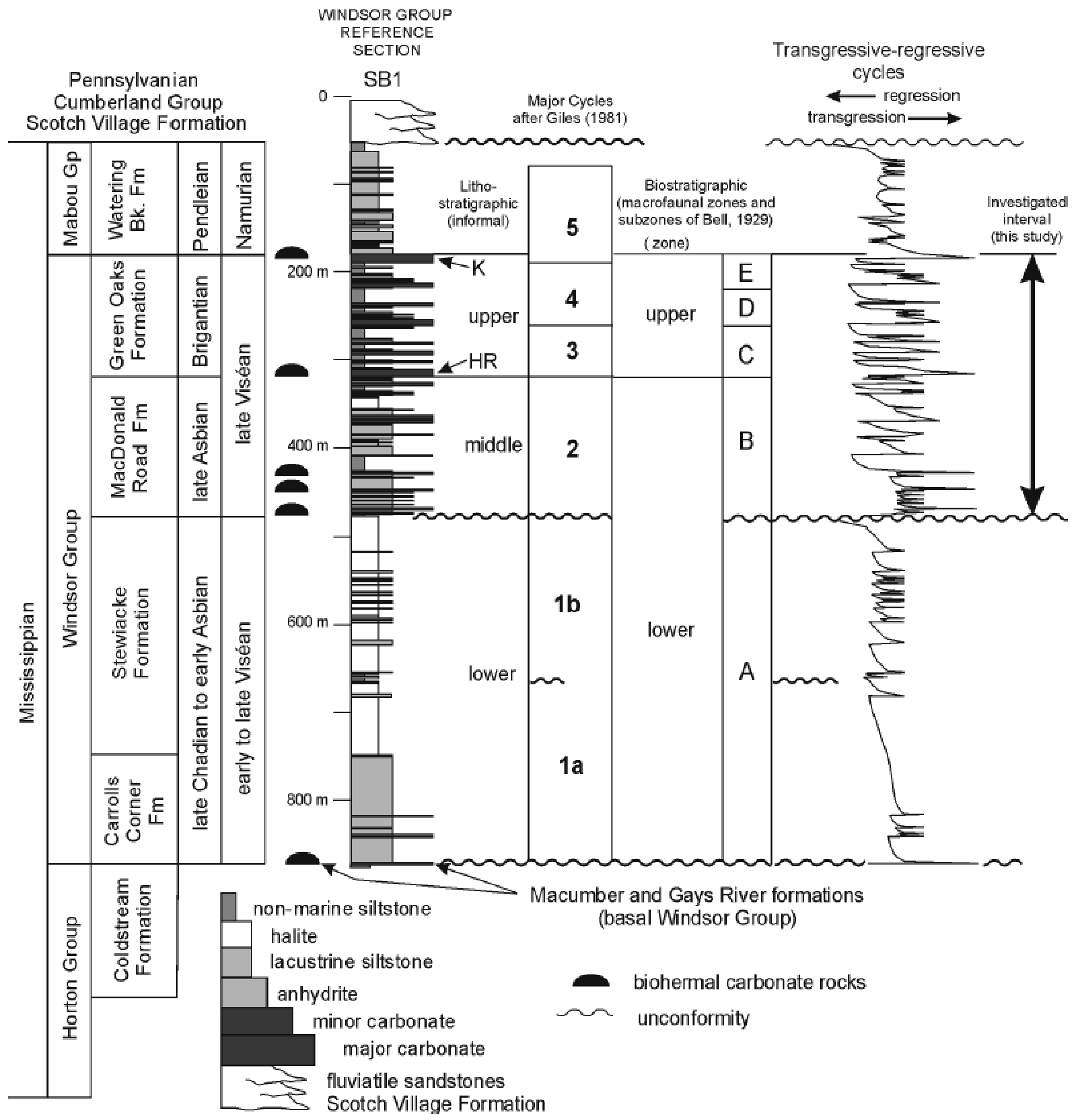


Figure 22: Carboniferous litho- and biostratigraphy of the section cored in SB1. The transgressive-regressive cycles are schematic only; relatively deep-water carbonates are shown as the maximal transgressive events, ranging through shallow-water oolitic and peritidal carbonate rocks to subaqueous evaporates to Sakha evaporates, and finally to non-marine red beds at maximal regression. From Giles, 2009.

VISEAN T-R CYCLES

During the deposition of the Windsor Group, several authors (see Lavoie et al., 2009 for a detailed review) suggest forcing cycles of 100-400 kyr (Figure 21).

It is believed that bioconstructions start early on but quickly stops in the early Visean due to rapid appearance of anhydrite. The bioconstructions reappear in the upper Visean, interbedded with siliciclastics (Giles et al, 2009, figure 22)

MABOU GROUP

The Mabou Group comprises a succession of grey and red brown fluvial and lacustrine strata dominated by grey mudrocks and red sandstone and mudrock. It conformably overlies the Windsor Group and is overlain unconformably by a sequence of grey and red fluvial sandstone and mudrock of the Morien / Cumberland group (Boehner and Giles 2008). The Mabou Group is widely distributed throughout much of the Sydney Basin, but it rarely outcrops because of its poorly indurated nature.

Across Cape Breton island, the Mabou Group has a total maximum thickness of 700 m (Hamblin, 2001).

Cape Dauphin Formation

The Cape Dauphin Formation comprises interbedded grey shale, gypsum and anhydrite, and minor thin, light grey to white limestone. The gypsum and anhydrite occur in the lower part of the section and are known only in drillhole sections. The formation is dominated by grey mudrocks with thin (10-30 cm) interbeds of limestone and silty limestone. The limestones typically are laminated to domal (locally convoluted) algal stromatolites. Red or green siltstone occurs in the upper part of the formation (Boehner and Giles 2008).

The Cape Dauphin Formation conformably overlies the Windsor Group and is conformably overlain by the Point Edwards Formation. The Westphalian / Namurian unconformity, representing the base of the Cumberland / Morien Group, can erode down to the Cape Dauphin Formation.

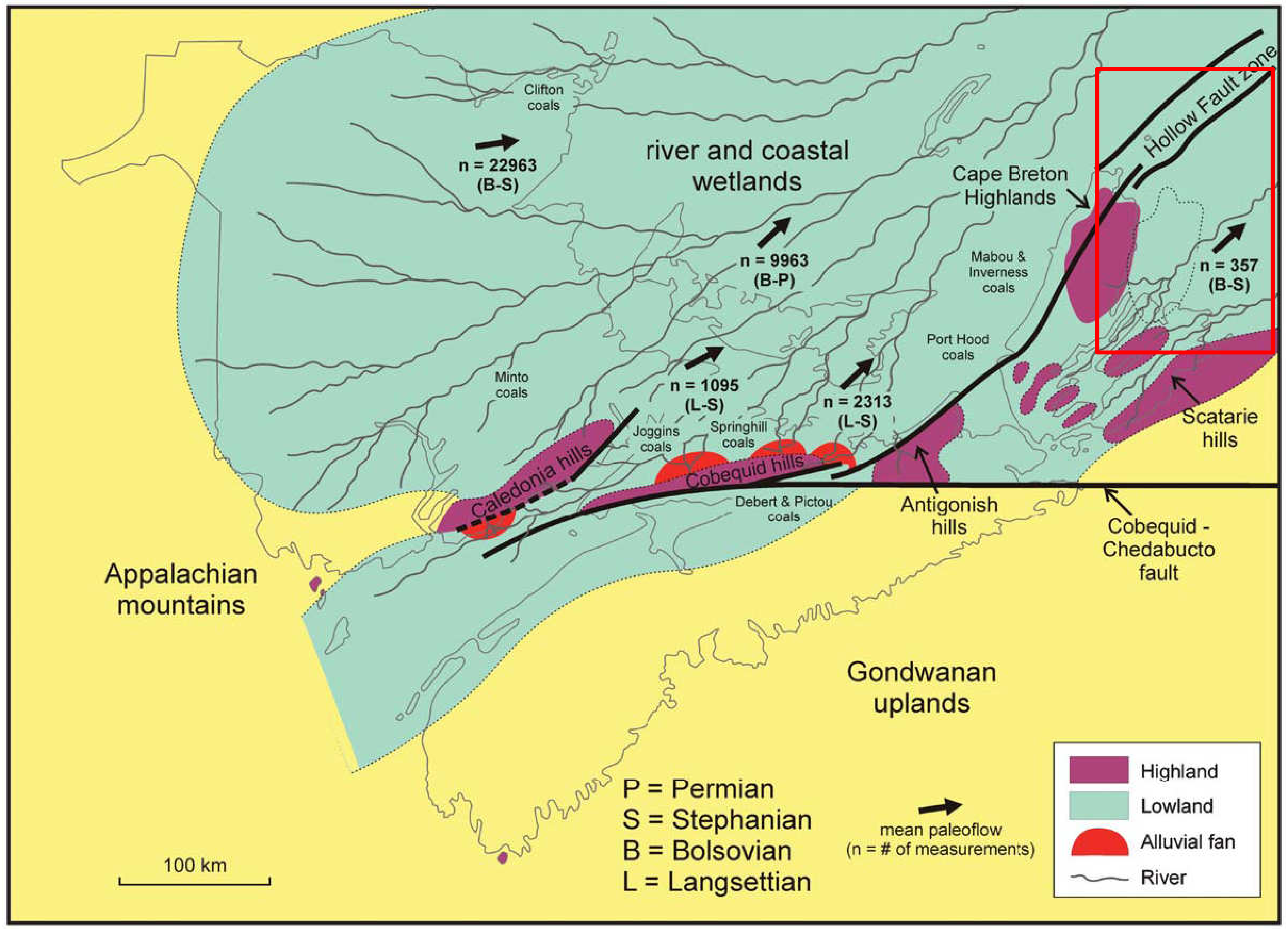


Figure 23: Regional paleogeography in the early Carboniferous, about 310 million years ago. (Gibling et al. 2008). The western part of the study area lies within the red box.

Point Edwards Formation

The Point Edwards Formation comprises a complex sequence of interbedded red and mottled grey-green and yellow-brown and minor grey siltstone, sandstone and shale with minor intraformational breccia and conglomerate. Limestone occurs as thin (<20 cm) interbeds and as nodules within the mudrocks. The basal part of the section consists of red to green siltstone. The upper parts of the unit consist of a mixture of red mudstone, sandstone and conglomerate (Boehner and Giles 2008).

The fine grained red beds, pedogenic carbonates and related mottled siliciclastics comprising the formation reflect a change from continental lacustrine deposition in the underlying Cape Dauphin Formation to a predominantly subaerial fluvial mudflat environment with minor sustained standing water deposition (Boehner and Giles 2008). Arid to highly seasonal climatic conditions probably existed which may reflect inherited evaporitic conditions similar to the underlying Cape Dauphin Formation.

The Point Edwards Formation conformably overlies the Cape Dauphin Formation and is unconformably overlain by the Westphalian / Namurian unconformity, representing the base of the Cumberland / Morien Group.

Cape Dauphin Formation

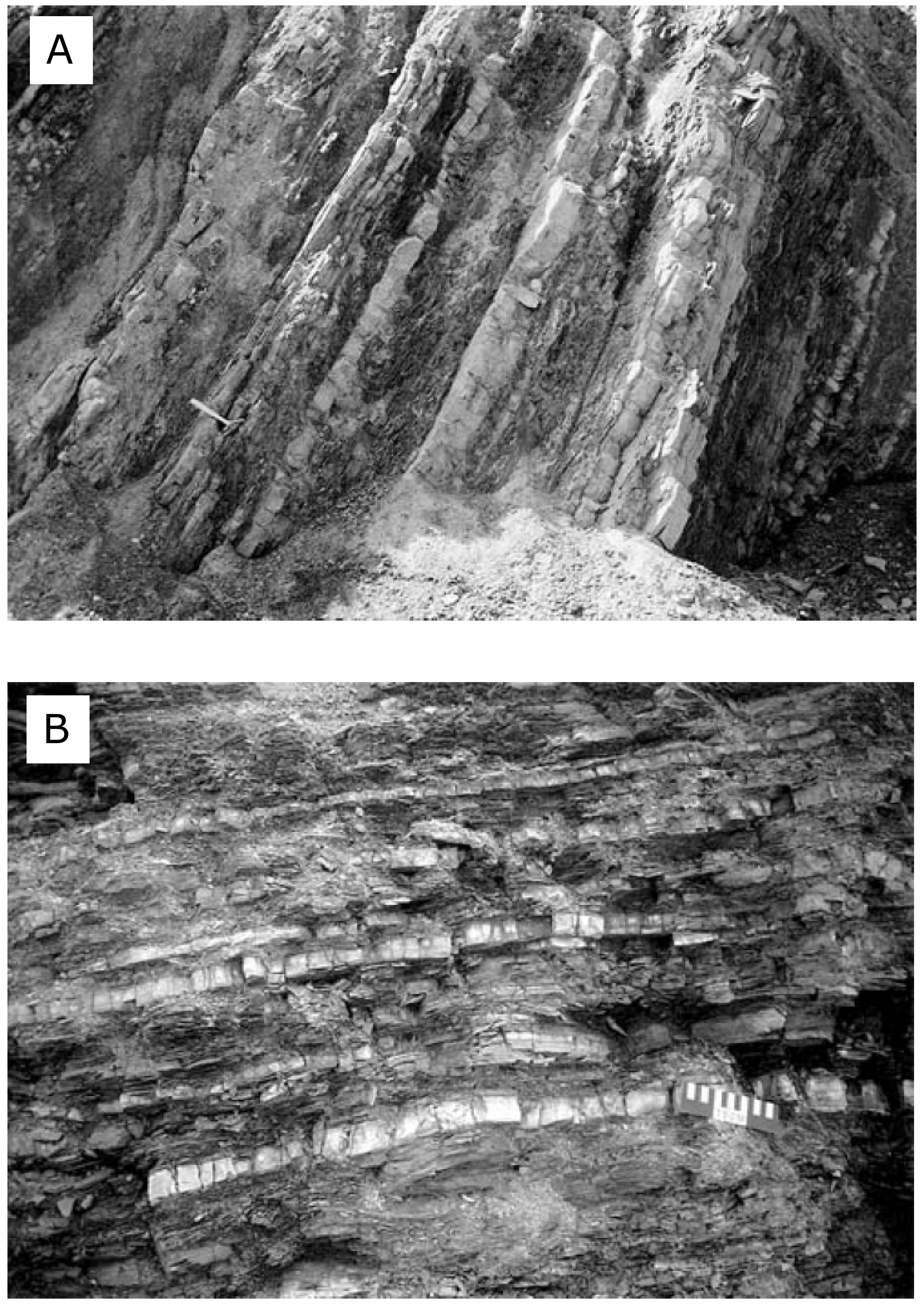


Figure 24: A. Coarsening-upward sequence, Cape Dauphin. Top is to the left. B. Thin calcisiltite beds in grey, bioturbated mudstone, Broad Cove. (Hamblin, 2001)

Point Edwards Formation

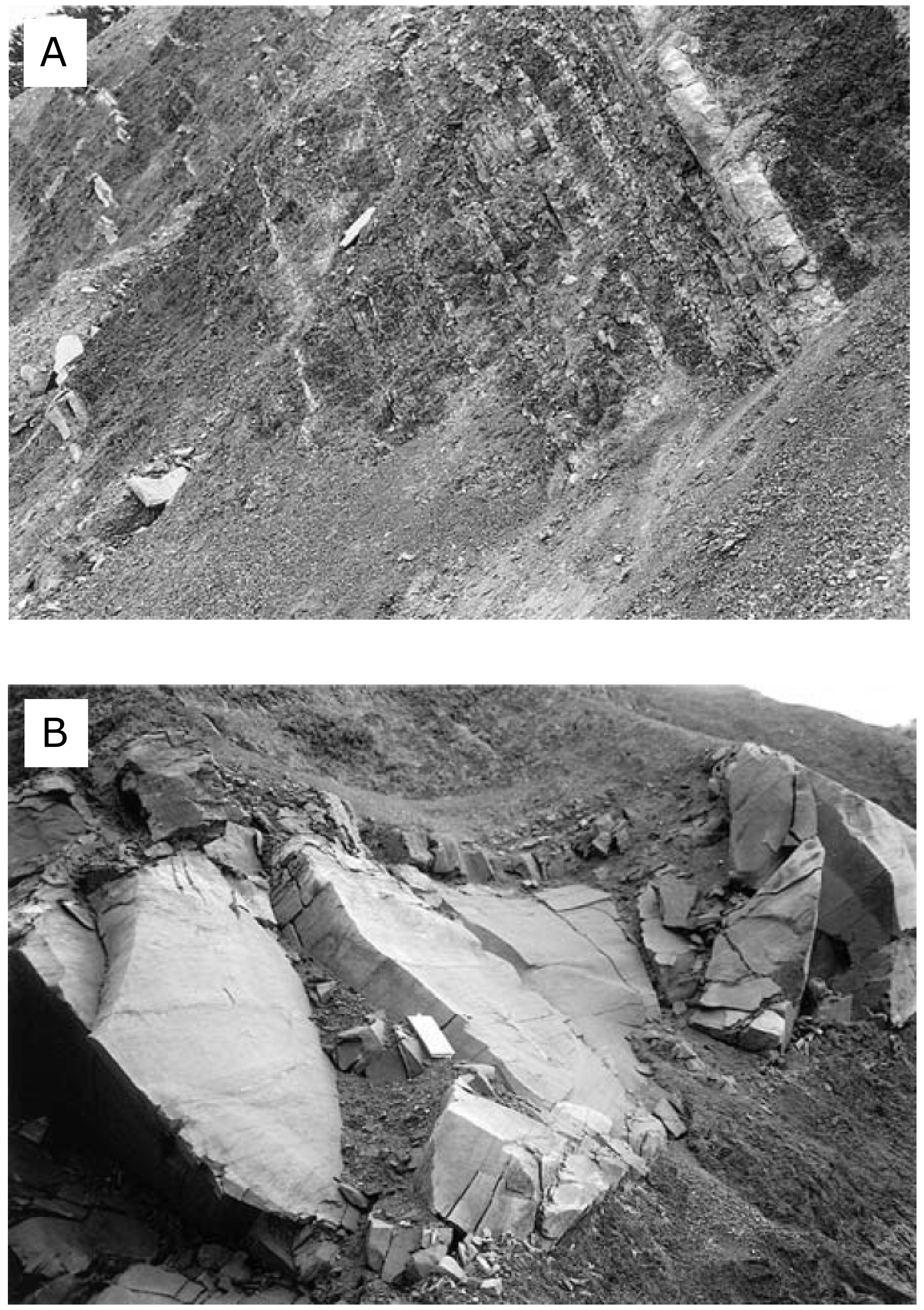


Figure 25: A. Coarsening-upward sequence of red pedogenic siltstone grading up into interbedded sandstone and siltstone, Ragged Point. Top is to the right. B. Lens-like sandstone channel-form, thinning from base, Broad Cove. (Hamblin, 2001)

MORIEN OR CUMBERLAND GROUP

The Morien / Cumberland Group is one of the most significant economic units of the Carboniferous basin-fill of the Maritimes Basin. It contains the bulk of the mineable coal resources in the region and has been an active producer for more than 200 years (Boehner and Giles 2008).

The Morien / Cumberland Group ranges in thickness from 1500-1800 m in the onshore and near shore parts of the Sydney Basin. Across the offshore Sydney Basin, the Morien / Cumberland Group conserves roughly the same thickness. Paleocurrent indicates flow direction to the northwest (Figure 26).

The base and top surfaces of the Morien / Cumberland Group are two unconformities. The basal surface is the Westphalian / Namurian unconformity, which erodes the major part of the Mabou Group, and even the Windsor Group in onshore outcrop sections. The top surface is the Westphalian C-D unconformity, which delineate the Morien / Cumberland Group from the Pictou Group.

The Morien / Cumberland Group is Westphalian in age, and ranges between Westphalian A to Westphalian C (Figure 1).

South Bar Formation:

The South Bar Formation comprises an interstratified sequence of medium- to coarse-grained, grey to grey-brown sandstone, pebbly sandstone, conglomerate with subordinate (10-15% maximum) grey to locally reddish mudrocks and rare thin coals. Plant debris is locally abundant, especially in conglomeratic channel lags at the base of major sandstone units (Boehner and Giles 2008).

The South Bar Formation is the most widely distributed subdivision of the Morien Group in the Sydney Basin map area, and occurs extensively in the subsurface in the northerly and easterly extensions of the Basin (Boehner and Giles 2008).

The overall fining upward nature of the formation is attributed to the proximal-distal evolution in an extensive braid plain environment. The lower part of the formation, more massive, coarser-grained and thicker bedded, is interpreted to represent moderately confined, proximal and intermediate braided rivers. The upper part of the formation, which is finer grained and contains more sedimentary structures, is interpreted the distal reaches of the braided river system (Boehner and Giles 2008).

The abundance of coaly material throughout the South Bar Formation indicates that a moderate climate with abundant rainfall existed, allowing the ephemeral development of interchannel vegetation and the local development of peat mires.

Waddens Cove Formation:

The Waddens Cove Formation is distinctive in that it displays lithology and sedimentology intermediate between the sandstone dominated South Bar Formation beneath, and the overlying mudrock dominated coal measures of the Sydney Mines Formation. It is a transitional unit comprising an interstratified sequence of medium to fine-grained, grey to grey-brown and red sandstone occurring as narrow channels and as more laterally persistent sheets (levees or crevasse splays), and subequal red to grey mudrocks (Boehner and Giles 2008).

The Waddens Cove Formation is only locally present in both onshore and offshore areas of the Sydney Basin. The contact between the underlying South Bar and the Waddens Cove Formations is the Westphalian B-C unconformity.

The depositional environment of the Waddens Cove Formation is interpreted to be generally similar to the overlying Sydney Mines Formation (Boehner and Giles 2008). They recognized the distinctiveness associated with fluvial channel and adjacent alluvial components. These features included the extensive reddening of the typically grey strata, abundance of extensive siliceous duricrusts, and the consequent channel sandstone bodies localized in incised valleys.

Sydney Mines Formation:

The Sydney Mines Formation comprises an interstratified sequence of grey to locally reddish mudrocks with subequal medium to fine-grained, grey to grey-brown sandstone. The section contains numerous economically significant coal seams, and thin stromatolitic limestones. Key coal seams of economic significance include in ascending order: Gardiner, McRury, Emery, Phalen, Backpit, Bouthillier, Harbour, Hub, Lloyd Cove, Point Aconi and Murphy seams (Boehner and Giles 2008).

The Sydney Mines Formation conformably overlies lower units of the Morien Group including the South Bar Formation in the central to western parts of the Basin and the Waddens Cove Formation in the eastern areas. The Sydney Mines Formation is unconformably overlain by the Pictou Group (Boehner and Giles 2008).

The overall environment for the formation is attributed to predominantly alluvial deposition on a meandering fluvial floodplain (Figure 25). Mudrocks and finer sandstones were deposited as levee and crevasse splay deposits adjacent to the river channels as well as in lakes within the flood basins between the major meandering sandstone channels (Boehner and Giles 2008).

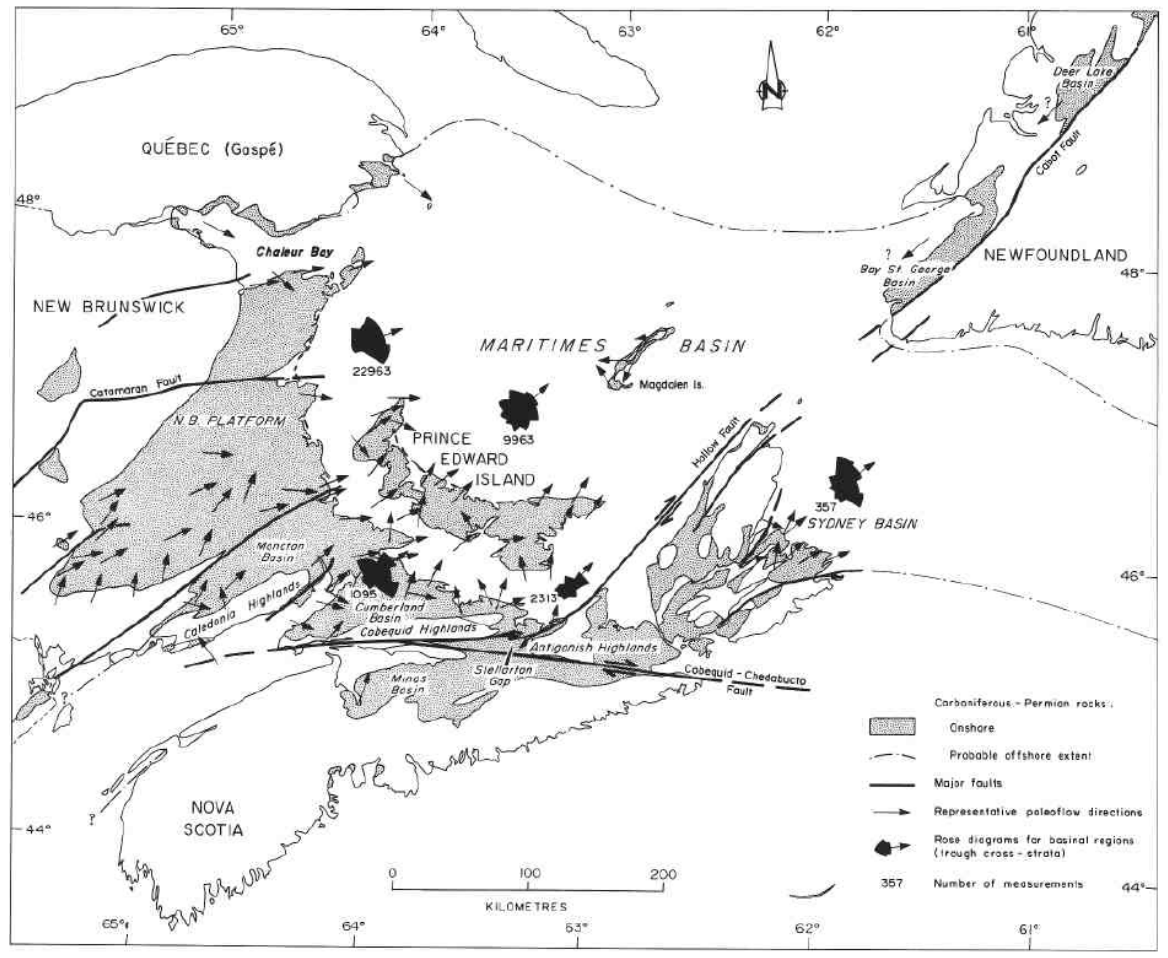


Figure 26 Summary paleoflow map for Late Carboniferous (late Westphalian A) to Early Permian strata of the Maritimes Basin. Solid arrows show representative paleoflow directions. Rose diagrams show all measurements of trough cross-strata within local areas of the basin. Note the predominantly northeasterly paleoflow, subparallel to the line of major faults. (Gibling et al. 1992)

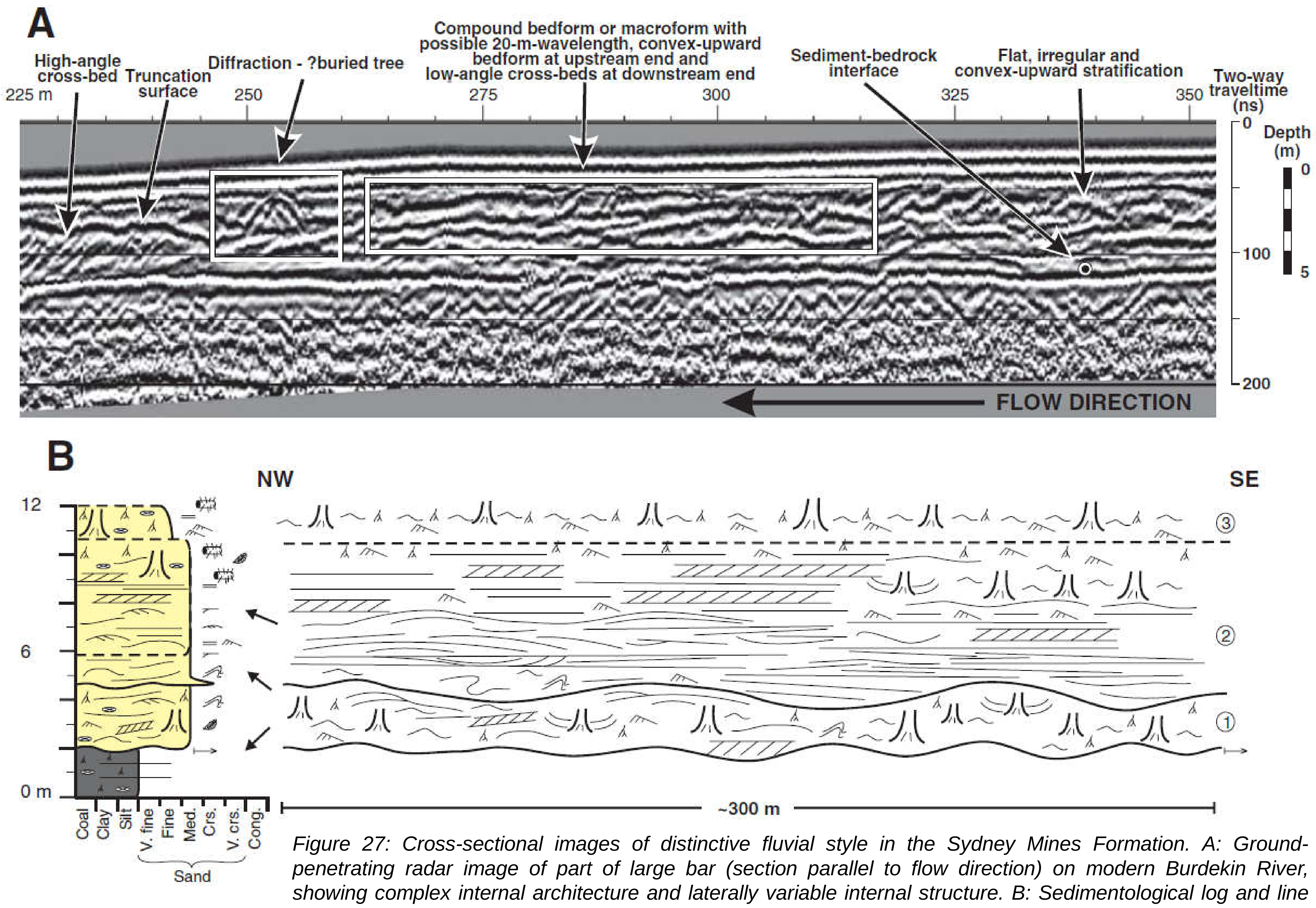


Figure 27: Cross-sectional images of distinctive fluvial style in the Sydney Mines Formation. A: Ground-penetrating radar image of part of large bar (section parallel to flow direction) on modern Burdekin River, showing complex internal architecture and laterally variable internal structure. B: Sedimentological log and line drawing of part of channel body in Sydney Mines Formation near Morien, Nova Scotia, showing complex lateral and vertical facies variability, abundance of high flow stage sedimentary structures, and evidence for in situ tree preservation within channel body. Circled numbers refer to storeys. Arrows to right of graphic log show paleocurrent data, oriented such that north is directly upward. V—very, Med.— medium, Crs.—coarse, Cong.—conglomerate. (Fielding et al. 2009)

Figure 28: Outcrop of the Morien / Cumberland Sydney Mines Formation at the Point Aconi Seam, Nova Scotia (photo by Rigel, M.C – Wikipedia)

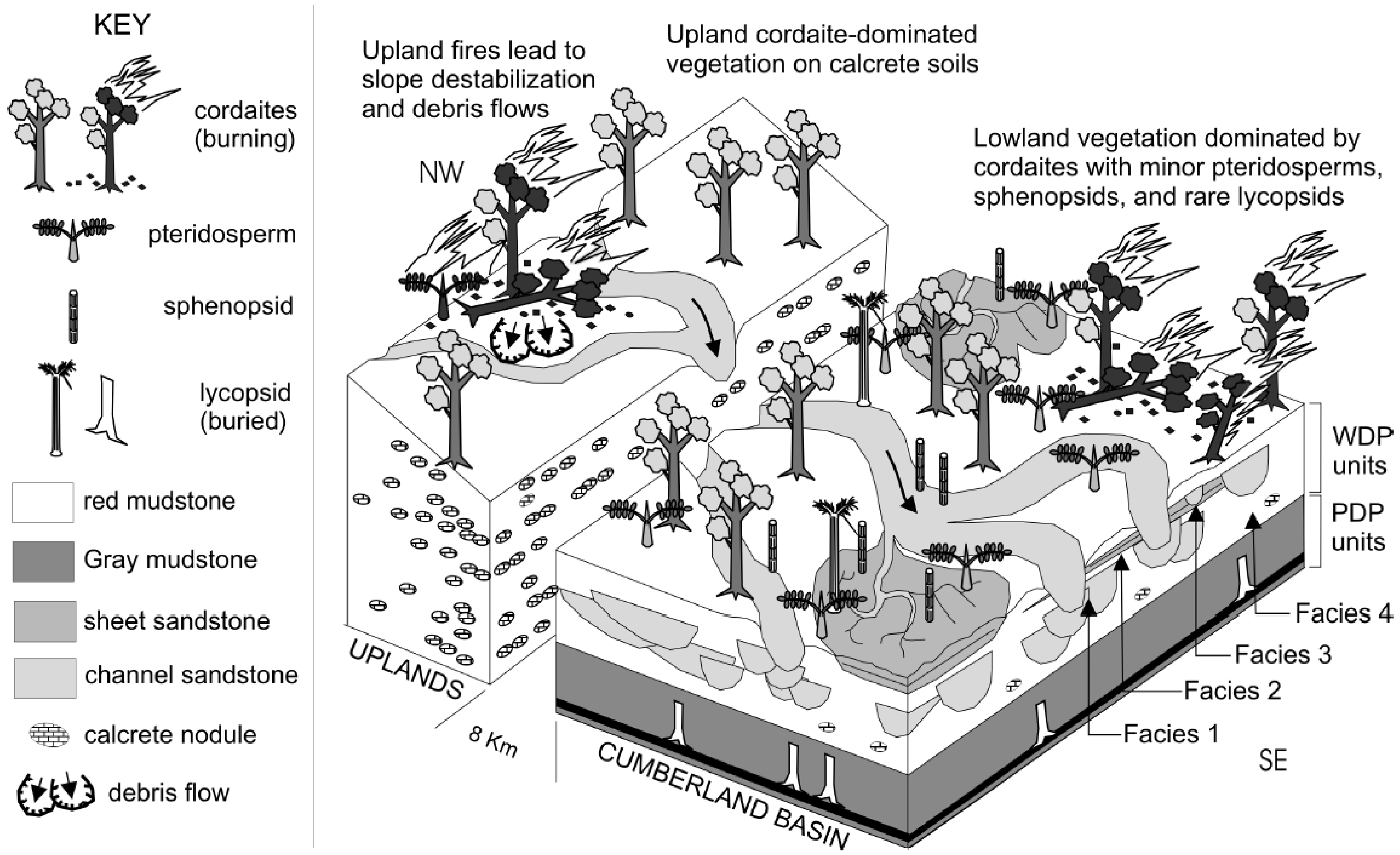


Figure 29: Summary of Joggins well-drained alluvial plain (WDP) paleoenvironments and fire-prone cordaite-dominated plant communities. PDP indicates poorly drained coastal-plain units underlying WDP units. Upland zone represents the Minudie Anticline, 8 km upstream of the Joggins Basin. Falcon-Lang, 2003

PETROLEUM POTENTIEL OF THE MORIEN / CUMBERLAND GROUP

The Morien / Cumberland Group is prospective with the Sydney Mines Formation representing a potential source rock, and the sand-rich South Bar Formation a potential reservoir.

Source rock potential
Thick, widespread coal measures in the Morien / Cumberland have been observed to have significant petroleum source potential (Gibling and Kalkreuth, 1991; Macauley and Ball, 1984; Mukhopadhyay, 1991). The coal measures contain Type II and III organic matter, with TOC values up to 40% (Dietrich et al., 2011), The predominance of Type III organic matter indicates the coal measures have major natural gas source potential. The Cumberland Group coal measures are up to 2200 m thick in the onshore Cumberland Sub-basin and the Pictou Group coal measures up to 5000 m thick in the offshore Magdalen Basin (Lavoie et al., 2009a). The generation of natural gas from coal measures is documented by the numerous gas shows in exploration wells drilled through coal-bearing sections (Grant and Moir, 1992). In terms of thickness and areal distribution, the coal measures are the most abundant source rocks in the Maritimes Basin.

Reservoir potential
The South Bar Formation represents a potential reservoir. However, well data show that the reservoir is locally tight. Away from well data, no information is available about the real potential of this reservoir.

Seal capacity potential
The Morien / Cumberland Group does not yield any characteristics of potential seal.

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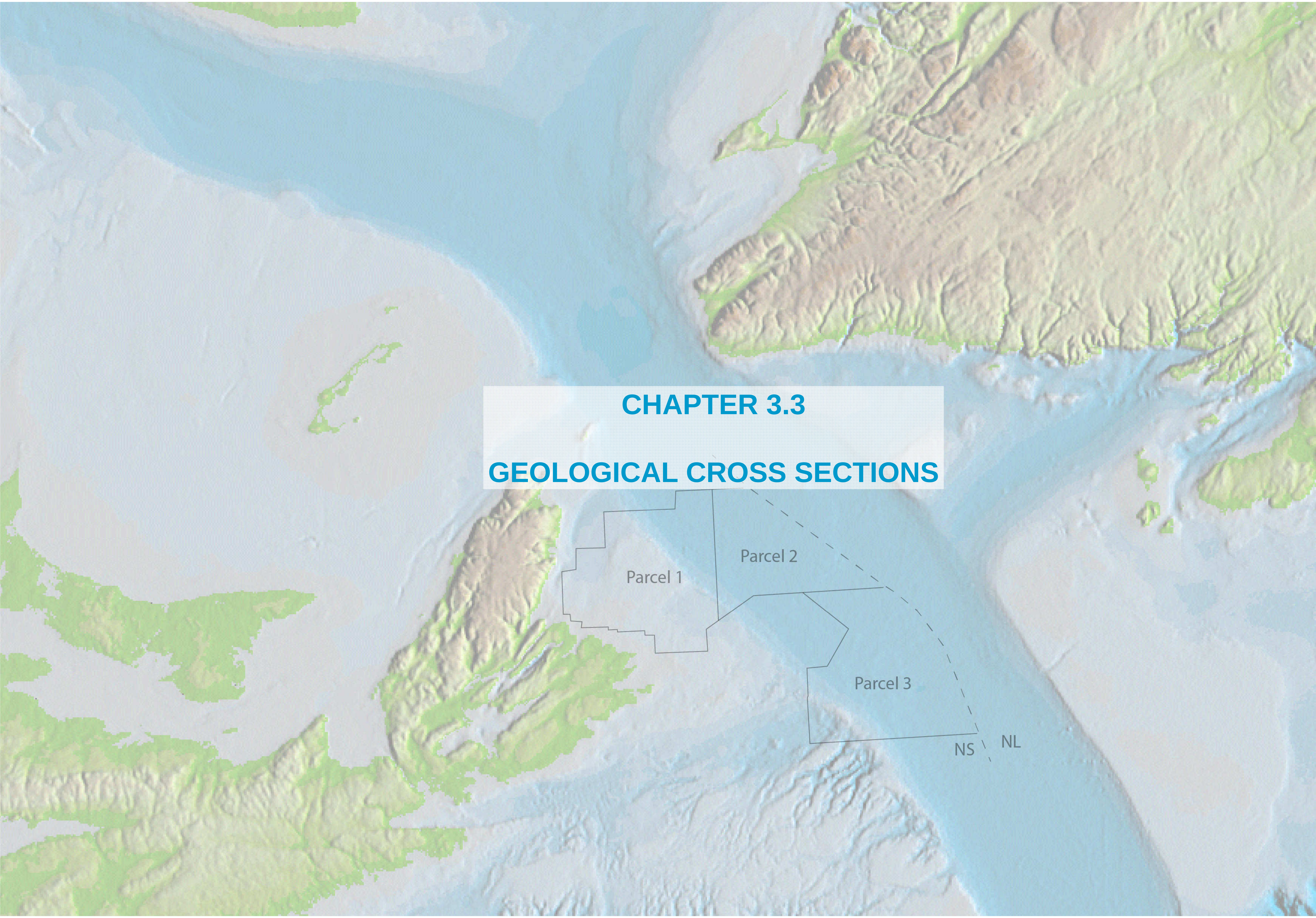
CHAPTER 3.3

GEOLOGICAL CROSS SECTIONS



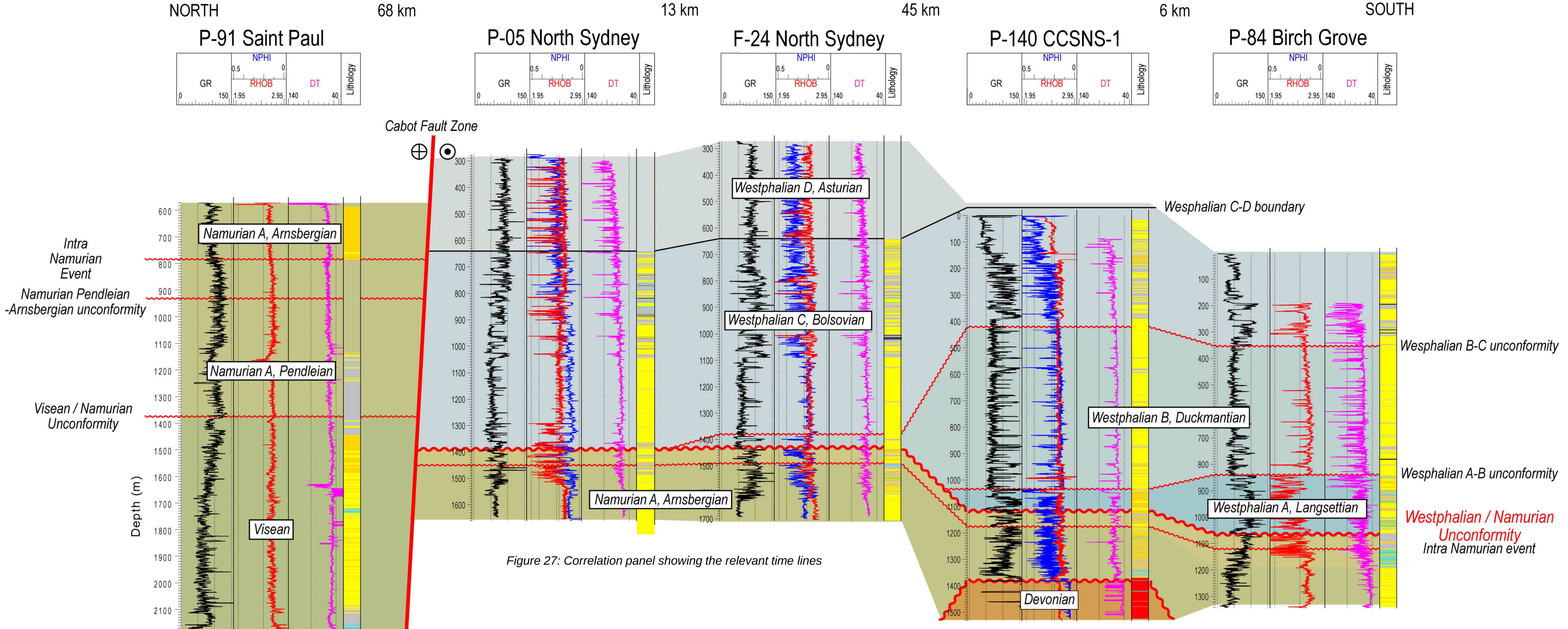


Figure 27: Correlation panel showing the relevant time lines

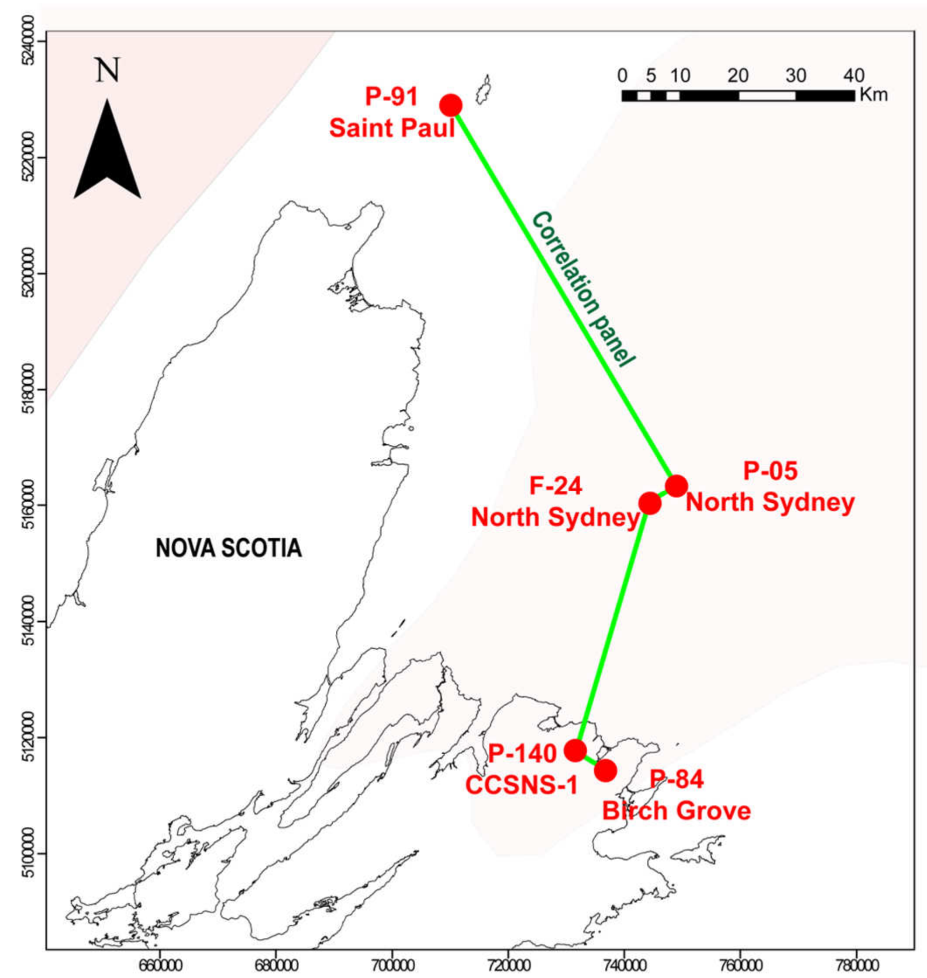
This correlation panel highlights the key time lines through the five studied wells. They are based on the biostratigraphic analyses conducted by RPS in early 2017.

The Devonian basement is only penetrated within well P-140 CCSNS-1 (onshore Nova Scotia). In this well, a significant time gap is noted between Devonian deposits and Namurian A deposits.

The Visean succession is recorded only within well Saint Paul P-91; the base of the Visean succession was not penetrated and the top surface is the Visean / Namurian unconformity.

The Namurian deposits are the only ones present in all five wells. An intra-Namurian unconformity, of Namurian A (Arnsbergian) age can be correlated across the five wells.

The Westphalian succession is recorded in the four Sydney Basin wells, with deposits becoming older going offshore.



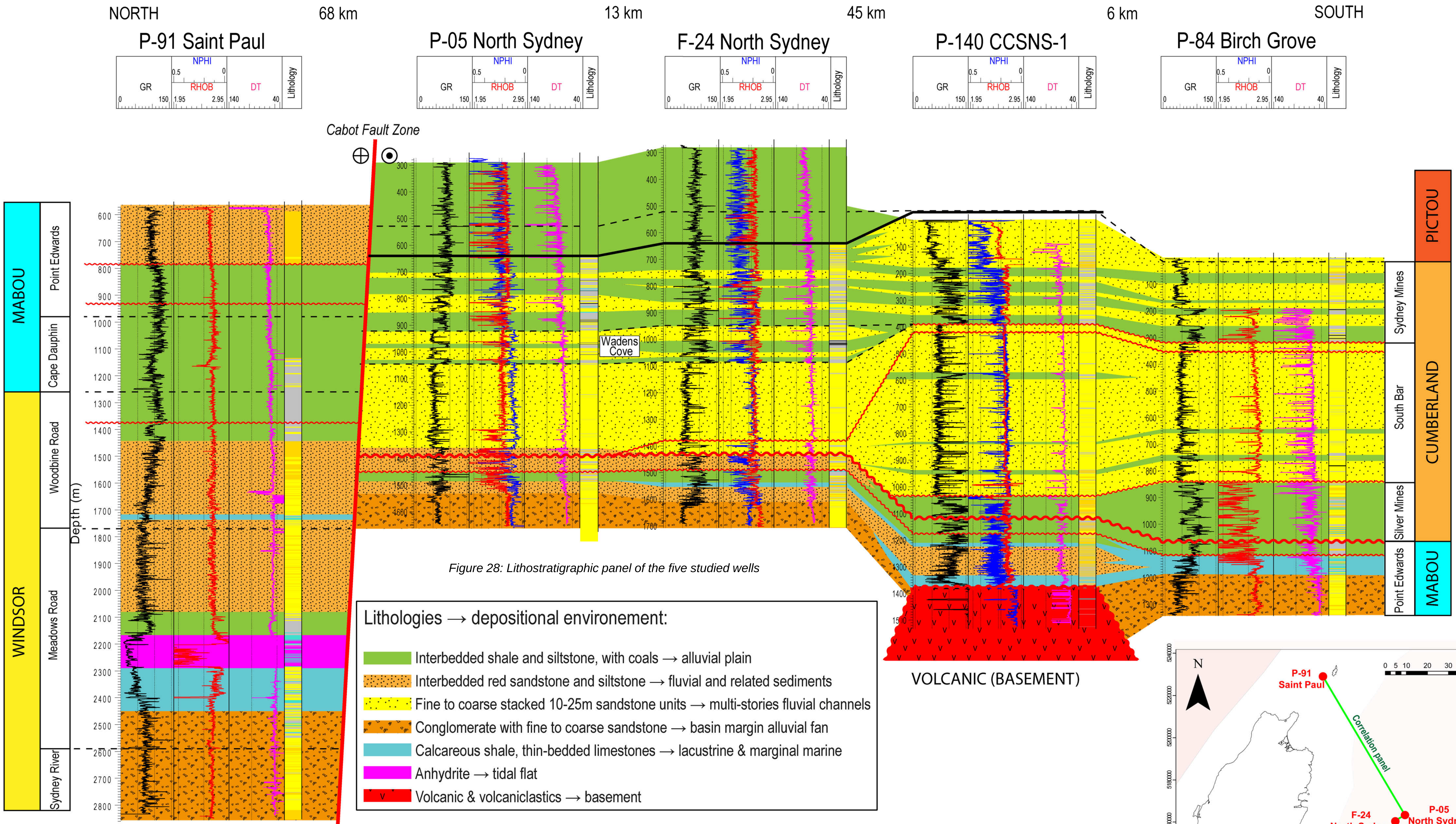
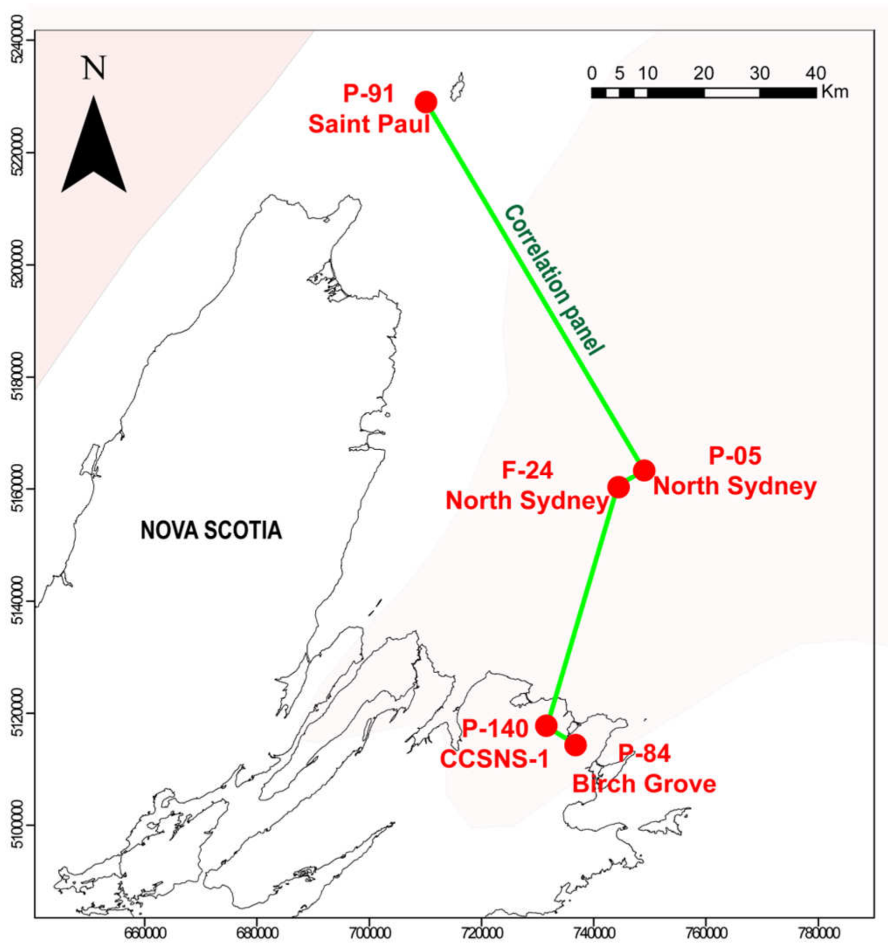


Figure 28: Lithostratigraphic panel of the five studied wells



Lithostratigraphic correlation panel across the five studied wells. The lithology comes from cuttings data. It includes clastic sediment ranging from conglomerate to shale, carbonates and volcanic rocks. The dominant depositional environment is also noted here and illustrates environments ranging from continental and lacustrine to shallow marine.

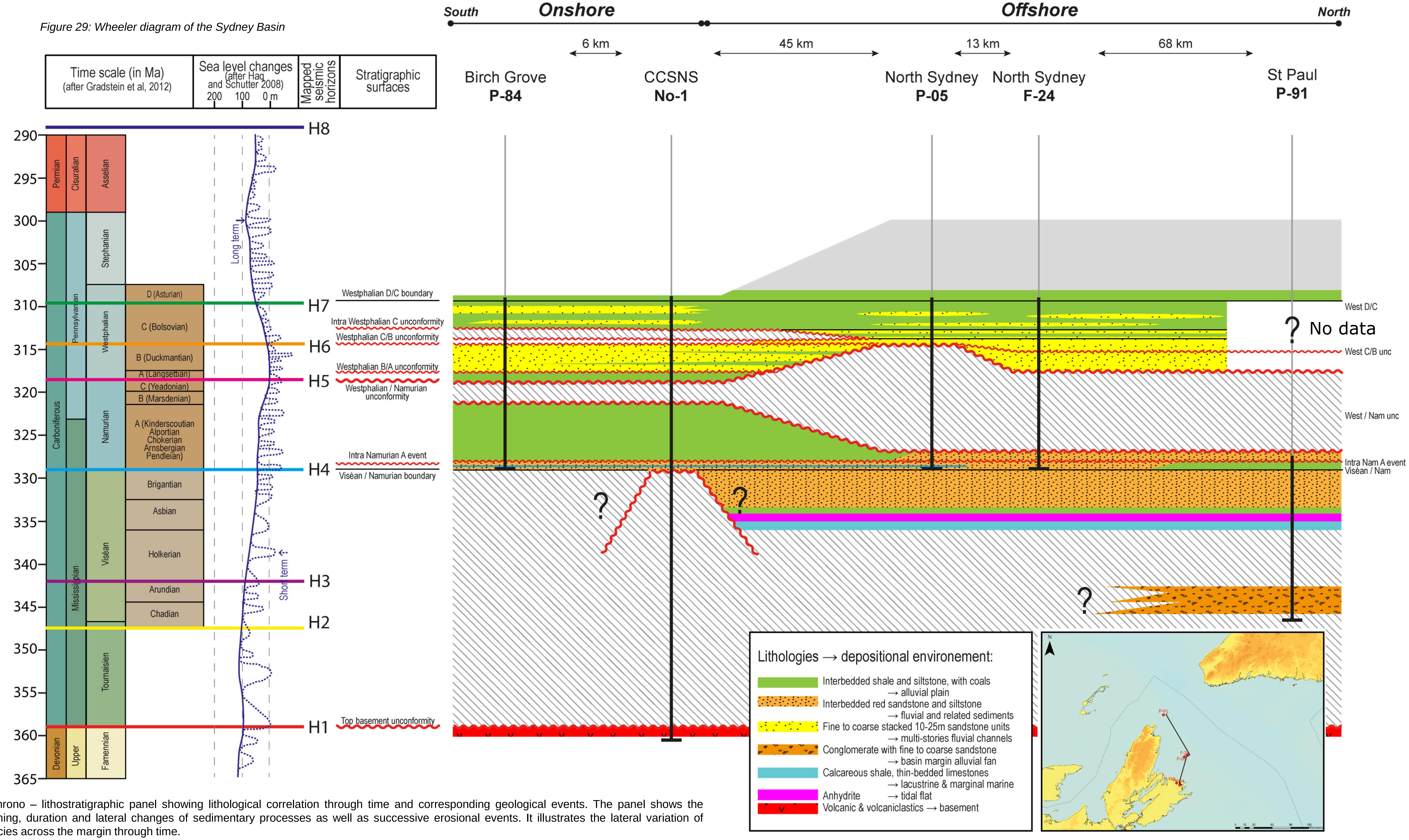
Well CCSNS-1 P-140 is the only well that penetrated the upper part of the basement. In this well, the basement is dominated by volcanic and volcanoclastic rocks.

Well Saint Paul P-91 records the upper part of the Windsor Group. Here, the Sydney River (Lower Windsor Group) Formation consists of conglomerate, interpreted to be deposited in basin margin alluvial fan. The Meadows Road (Upper Windsor Group) alternates carbonates and anhydrite. Conglomerate and sandstone are also present, and illustrates the close proximity of faulted margins.

The Mabou Group is recorded in all five wells. In P-91, it consists dominantly of shale and sandstone, while in P-84, P-140 and F-24, thin layers of carbonates are also recorded. The carbonates imply a marginal marine environment.

The Morien – Cumberland Group is sand-rich, dominated by thick stacks of multi-stories fluvial channels. The South Bar Formation is characterized by a higher net to gross compared to the Waddens Cove and Sydney Mines Formation. However, continuous shale rich intervals can be observed throughout the succession.

Figure 29: Wheeler diagram of the Sydney Basin



Chrono – lithostratigraphic panel showing lithological correlation through time and corresponding geological events. The panel shows the timing, duration and lateral changes of sedimentary processes as well as successive erosional events. It illustrates the lateral variation of facies across the margin through time.

An important time gap is shown here between the top basement and the Visean. The reason is the shallow penetration of the wells, which means the presence of Horton Group across the Sydney Basin was not captured. The Visean can, such as in well CCSNS-1 P-140, directly overlay the Devonian basement, and hence illustrating a large time gap in the record of the sedimentary succession.

The second time gap highlighted here is the Westphalian – Namurian unconformity. The upper part of the Namurian is very poorly recorded, being eroded away in most parts of the basin.

Finally, the youngest time line recorded in the wells is the Westphalian D/C boundary. This implies that the Permian and Quaternary succession is not recorded in these five wells although these strata are inferred elsewhere in the basin. In summary, the wells studied here only show a limited section of the sedimentary succession present in the basin.

Note that well Saint Paul P-91 only records the Visean succession. Since the well is located on a structural high, the upper succession is not recorded. Therefore, predicting the Westphalian succession is hazardous.