EXECUTIVE SUMMARY

Introduction

The Paleozoic basins of eastern Canada were among the first to be explored in the world, with drilling activity in New Brunswick beginning as early as 1859. Although most of drilled wells have shown positive indications of oil and gas, production tests have often been disappointing. O&G exploration was never extensive, due to the lack of success stories compared to other parts of North America. In the late 1990s the region saw renewed interest linked to the rapid growth of unconventional resources. Exploration gained momentum with successful wells in western Newfoundland (Deer Lake and Bay St George Basins), and in the 2000s the rebirth of Stoney Creek field and the start of McCully field in New Brunswick. Unfortunately, successive fracking bans have been enacted since 2013, making exploration in Paleozoic basins more difficult. Interest has now shifted offshore in Magdalen Basin where reservoirs are expected to be of better quality and therefore reservoir stimulation might not be required to reach commercial production (see Chapter 1 for more detail on Exploration History).

The Sydney Basin is the least known of the eastern Canadian Paleozoic basins. Only three wells have been drilled offshore between 1974 and 1983 and none of them reached their initial target (Horton Gp). Nonetheless, two of them had shows in upper Carboniferous sandstone (Figure 2). Additionally there is widespread evidence of a working Carboniferous petroleum system, and McCully field (NB) shows that commercial production can be achieved. Thus the area is still a true frontier basin, with very little available knowledge on its petroleum geology. In support of the 2017 Call for Bids (Figure 1; NS17-1; http://www.callforbids.ca/ns17-1-parcels/ns17-1-call-bids-overview), the Nova Scotia Department of Energy and the Offshore Energy Research Association (OERA) have initiated a significant research program to assess hydrocarbon prospectivity in Sydney Basin.

The objective of the current Play Fairway Analysis (PFA) is to build a detailed and comprehensive understanding of the petroleum system in Sydney Basin. Key conclusions from the study are summarized here, with a focus on basin modelling results. Results on geological setting are presented first, followed by a short paragraph on seal capacity and integrity before ending with the Sydney Basin petroleum system assessment.

This PFA Atlas is organized as follows:

- A review of regional exploration history since 1859 (Chapter 1);
- The regional tectonic setting with a focus on the Sydney Basin structural style and evolution (Chapter 2);
- An overview of the geological setting followed by an update of the stratigraphic framework based on well and seismic interpretation (Chapter 3);
- A potential field modelling chapter addressing the issue of pluton signature in the basin (Chapter 4);
- Structural maps resulting from the seismic interpretation are presented in Chapter 5;
- Following the seismic interpretation and stratigraphic sequence work, seismic stratigraphy was performed on three transects. These studies are integrated to generate Gross Depositional Environment maps for each key interval (Chapter 6);
- A seal capacity and integrity study is presented using a combination of stratigraphic modelling and uncertainty analysis assessed via Dionisosflow® and Cougarflow ® (Chapter 7);
- An evaluation of the petroleum system is made using TemisFlow® modelling (Chapter 8)

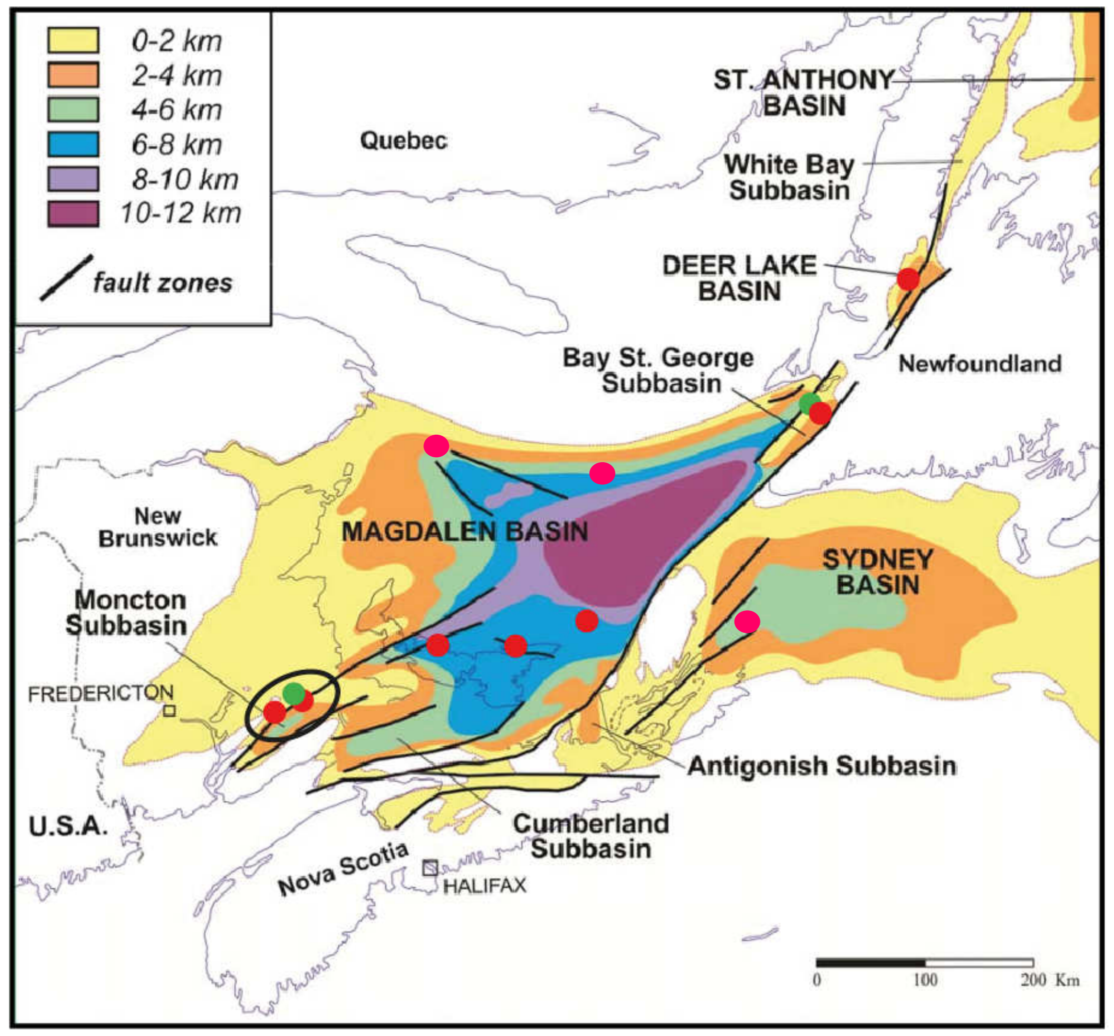


Figure 2: Regional hydrocarbon distribution from wells. Green dots are oil discoveries, red dots are gas discoveries, pink dots are gas shows. Note that in Sydney Basin two wells were drilled at the same location and both had gas shows.

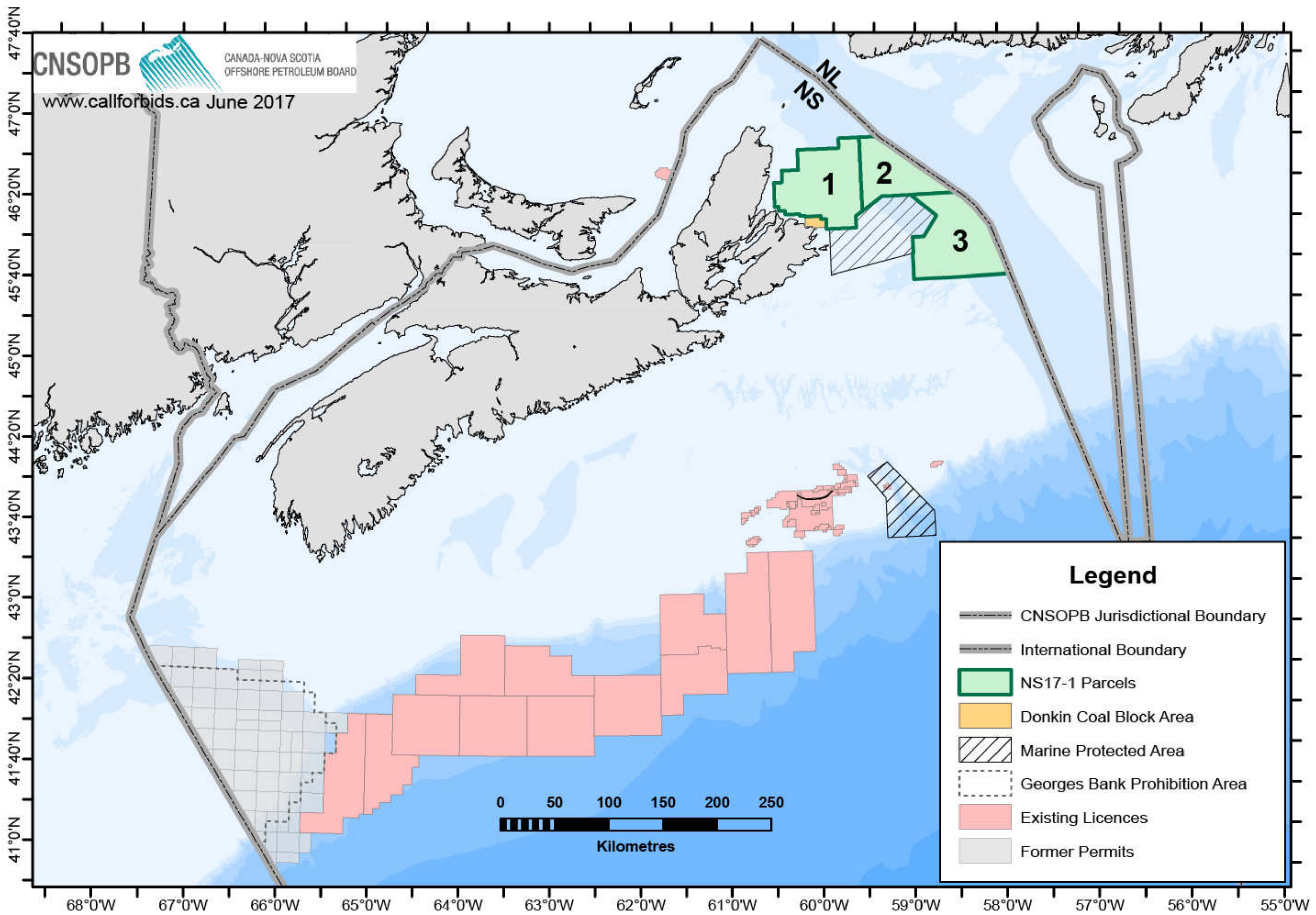


Figure 1: CNSOPB offshore area and 2017 Call for Bids NS 17-1 parcel locations in green (http://www.callforbids.ca/ns17-1-parcels/ns17-1-call-bids-overview)

Geological Setting and Reservoir Properties

In the Sydney Basin area, the pre-Carboniferous basement corresponds to only two orogenic units: the Salinic and the Acadian orogens. These units are bordered by 3 major faults:

- The Cabot fault (this fault or fault zone is the main oceanic suture corresponding to the closure of the Iapetus paleo-ocean)
- The Dover fault considered as a suture zone corresponding to the closure of the Acadian seaway
- The Cobequid Chedabucto fault that separates the Meguma paleo continental block from the Avalonia block. This fault was reactivated as transtensional sinistral strike slip fault during the Mesozoic opening of the Atlantic, creating the Orpheus pull-apart basin.

The pre-Carboniferous basement of the Sydney Basin is mainly composed of:

- Metasediments with various grade of metamorphism from very high grade to locally poorly metamorphosed sediments in the Acadian orogen.
- Intrusive plutons of various natures in all the tectonic units.

From the work completed on tectonic setting and structural style, the main conclusion that can be drawn is that the Sydney Basin is located in a zone that has suffered relatively little major structural deformation in spite of being located at the center of major global tectonic events. Somehow the actual basin location has remained relatively stable for a very long time and the Permian compression has only modestly impacted the lower to mid-Cretaceous series. Most of the normal faults ceased their activity at the transition between the Horton and Windsor Gp. and acted as reverse faults during the Permian compression.

Reservoir properties

Paleozoic reservoirs are largely considered to be tight reservoirs, although most of the hydrocarbon discoveries have been tested without reservoir stimulation. Measured values of reservoir porosity and permeability are wide ranging from very tight to very good reservoirs (Table 1). Nonetheless, petrophysical properties of the lower Carboniferous sandstones in the Sydney Basin are uncertain due to the absence of wells. Overall the main uncertainty is diagenesis; reservoir quality in eastern Canada can be considerably influenced by diagenesis and the impact can be significantly more critical than sand cleanliness. The favorable conditions for porosity development include:

- shallow burial (preservation of significant primary porosity);
- early calcite cementation sufficient to strengthen the framework against physical compaction but which does not completely to occlude primary porosity (Chapter 1, Figure 17A); and
- significant dissolution of calcite cements and framework grains which generate significant secondary porosity.

Preservation of the porosity through the development of specific diagenetic events is a possibility in the Horton Formation in the Sydney Basin. However, an extensive understanding of the diagenetic processes and the sedimentary sources of the basin (diagenetic processes influenced by mineral composition of the rock) is needed in order to predict the type and development of diagenesis and its influence on porosity. Retained parameters for the present PFA are listed in Table 1 below.

Group	Formation	Petrophysical Properties Considered for Sydney Basin					
		Effective Porosity (%)		Total Porosity (%)		Permeability (mD)	
		Max	Avg	Max	Avg	Max	Mode
Pictou	Pictou	10%	0,8%	21%	6,1%	100	0,2
Cumberland	Sydney Mines	10%	1,0%	23%	6,4%	30	0,1
	Waddens Cove	10%	2,7%	19%	6,4%		
	South Bar	10%	2,7%	19%	5,7%		
	Silver Mines	10%	0,8%	17%	6,5%		
Mabou	Point Edward	10%	1,5%	24%	5,7%	0,15	0,1
	Cape Dauphin						
Windsor	Woodbine Road	-	-	17%	8%	0,2	0,1
	Meadows Road						
	Sydney River						
	Macumber						
Horton	Upper Horton	-	-	10%	5%	1*	0,05*
	Middle Horton	-	-				
	Lower Horton	-	-				

Table 1: Petrophysical properties defined for Sydney Basin

Seal capacity and integrity

The main regional seal is expected to be the Windsor Gp, which is largely composed of an evaporitic succession including thick halite and potash formations. These lithologies act as a seal for the main petroleum system that is the Horton Gp. The absence of geological information regarding the Horton and Windsor series in the Sydney Basin implies using an innovative solution to assess the presence and extent of a seal at a regional scale, and then to be able to estimate its sealing capacity and integrity. Because of the level of uncertainty, using stratigraphic modelling alone is insufficient. To quantify the uncertainties on sealing presence and integrity, we have used a multi – realization workflow using CougarFlow ®. A multi-realization workflow allows the generation of alternative scenarios according to an Experimental Design which explores uncertain input parameter ranges and assesses the impact of main influential parameters on thickness and facies calibration (see Chapter 7).

103 alternative simulations were tested against the reference model from DionisosFlow®. Results are expressed in a mean salt thickness map of the Middle Windsor and its associated standard deviation which permits an evaluation of the seal capacity and integrity and highlights possible leakage areas (Figure 3).

From computed maps, seal capacity and integrity seems good to excellent in the majority of the Sydney Basin as mean salt thickness ranges from 200m to 1100 m with a normalized standard deviation at 25% of the salt thickness. An exception is to be noticed around actual onshore limits and around the Cabot fault area as salt thicknesses are good but standard deviation is higher than 100% of the salt thickness. Leakage areas are assessed in the north western part of the block around actual onshore Newfoundland and Nova Scotia. Nevertheless, onshore Nova Scotia presents a lower risk as Windsor salt outcrops can be observed in the adjacent onshore region and these observations cannot be directly included in the modelling.

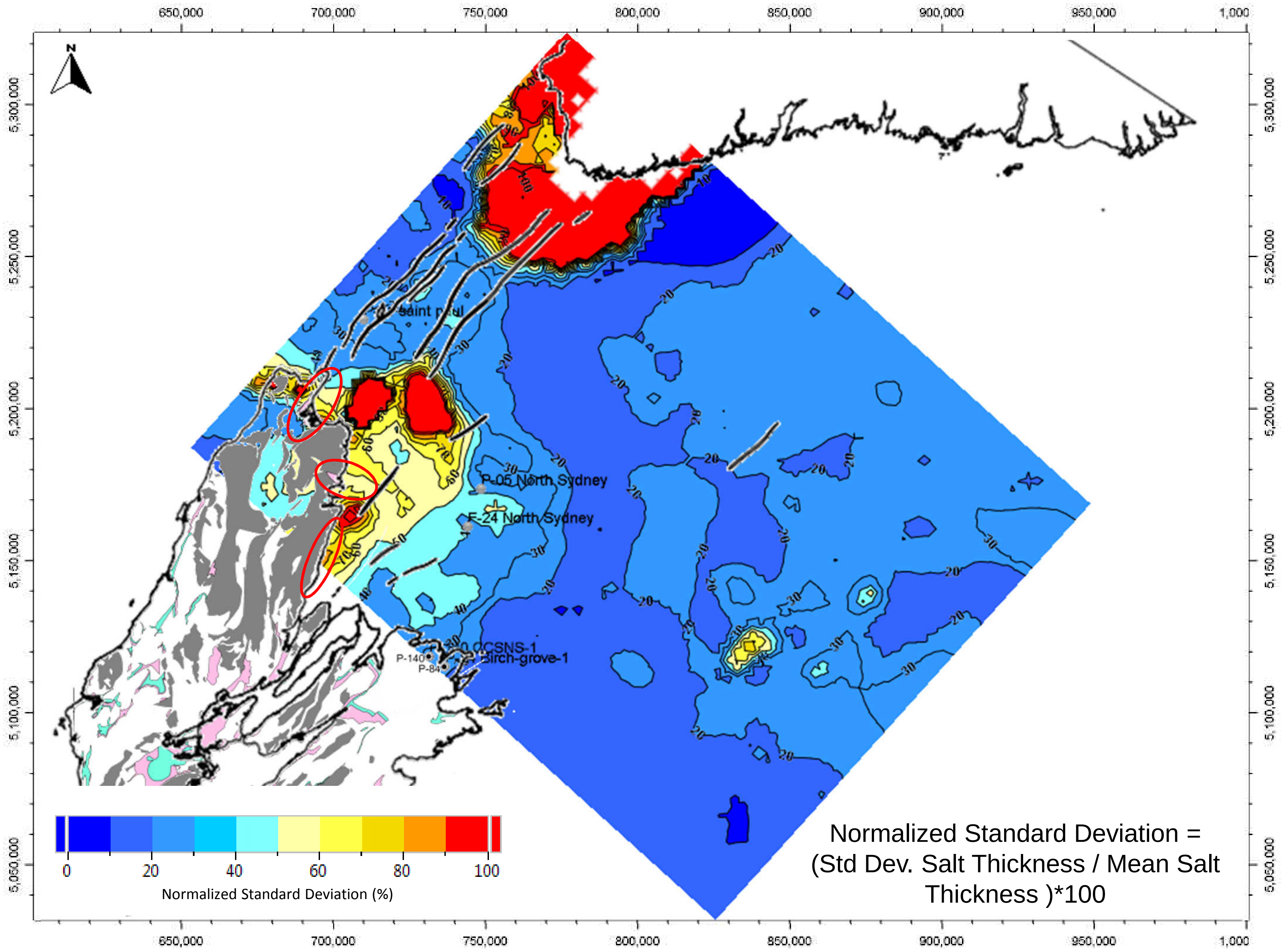


Figure 3: Normalized standard deviation of salt thickness for the Middle Windsor interval highlighting high risk areas in the northwest part of the map from Nova Scotia to Newfoundland.

Sydney Basin Petroleum System Assessment

The source rock model shows that the best source rock in the Sydney Basin is the type I/II Horton lacustrine shale (Table 2). The Mabou Fm is also considered to be a potential source rock with an alternative scenario from type III/II to type I/II. This alternative scenario in the basin modelling suggests oil accumulation where oil seeps have been observed (Chapter 8).

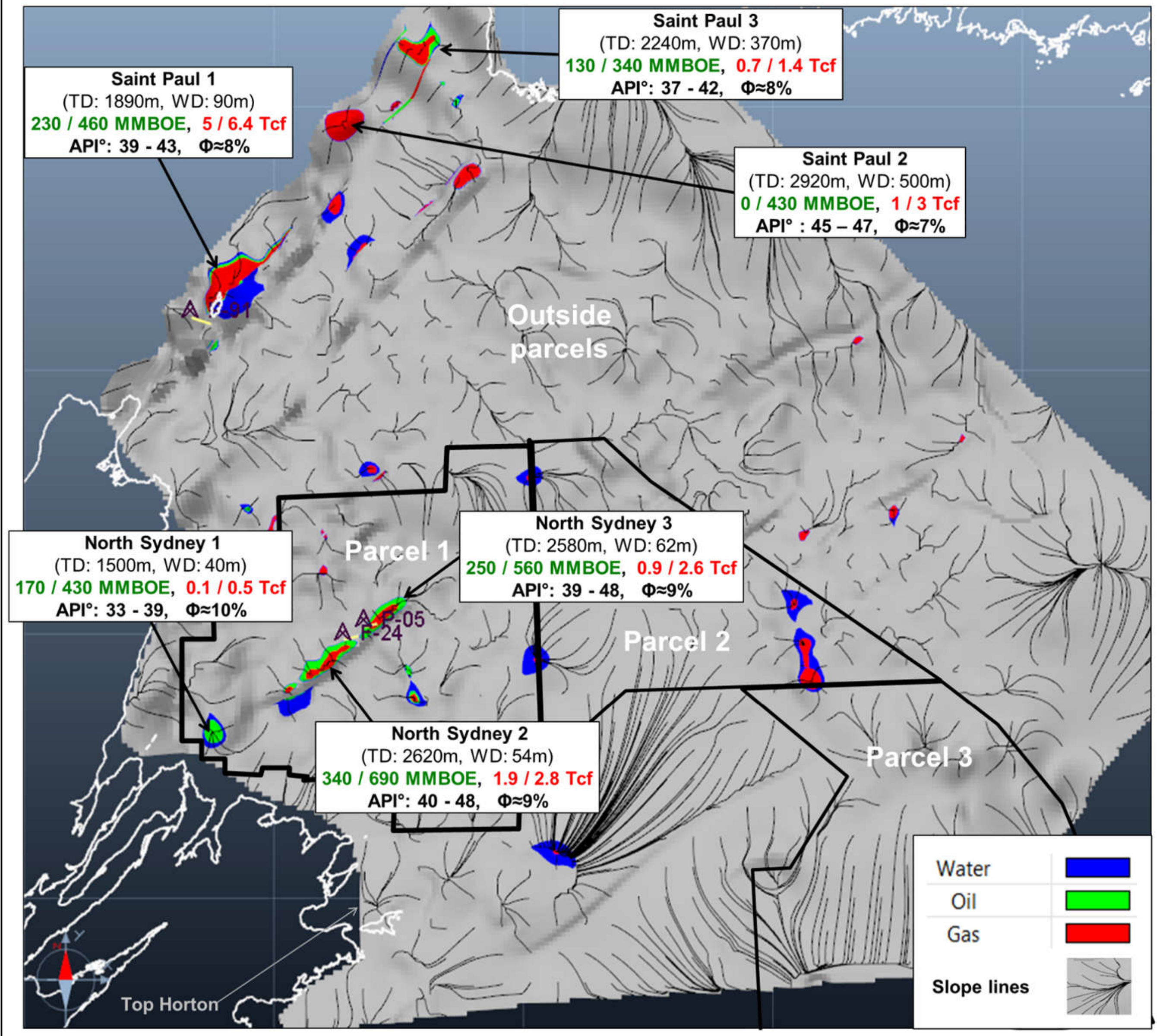
According to basin modeling and assumptions on source rock characteristics, the Horton play constitutes the most likely effective working play in the Sydney Basin (Figure 4; Chapter 8). Scenarios helped to give a range for oil and gas volumes mainly based on uncertainties in migration properties. The different leads identified are very prospective with 1 to 2 Tcf and 400 to 700 MMbbl of oil on average. Some parts of the basin do not show significant accumulations while showing large drainage areas and related hydrocarbon flows. This is related to reservoir configurations in the 3D cellular model. It is probable that with a different configuration those structures could be charged.

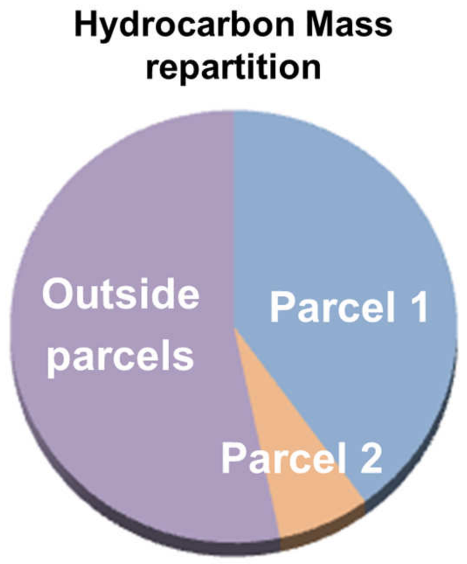
Source Rock	Lithofacies	Avg Effective thickness (m)	Avg TOC0 (wt%)	Kerogen type	Avg HI0 (mgHC/g)	SPI (T/m2)
Sydney Mines	Flood plain and Shallow Lakes	6 m	10%	III / II	450	0.6
Source Rock	Lithofacies	Avg Effective thickness (m)	Avg TOC0 (wt%)	Kerogen type	Avg HI0 (mgHC/g)	SPI (T/m2)
Mabou	Organic-lean shales	30 m	2.5%	III / II	300	0.4
Source Rock	Lithofacies	Avg Effective thickness (m)	Avg TOC0 (wt%)	Kerogen type	Avg HI0 (mgHC/g)	SPI (T/m2)
Lower Windsor	marine shales/evaporites	10 m	3%	II	500	0.3
Source Rock	Lithofacies	Avg Effective thickness (m)	Avg TOC0 (wt%)	Kerogen type	Avg HI0 (mgHC/g)	SPI (T/m2)
Horton	Lacustrine shales	50 m	7%	I / II	650	5.2

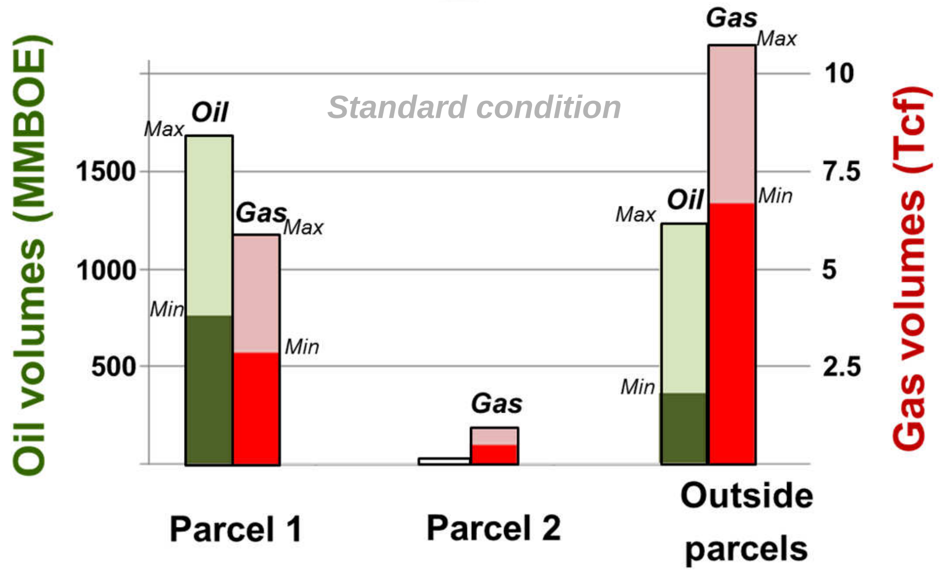
Table 2: Source rock characteristics used in Basin modelling for Sydney Basin.

Conclusion

The Horton Play

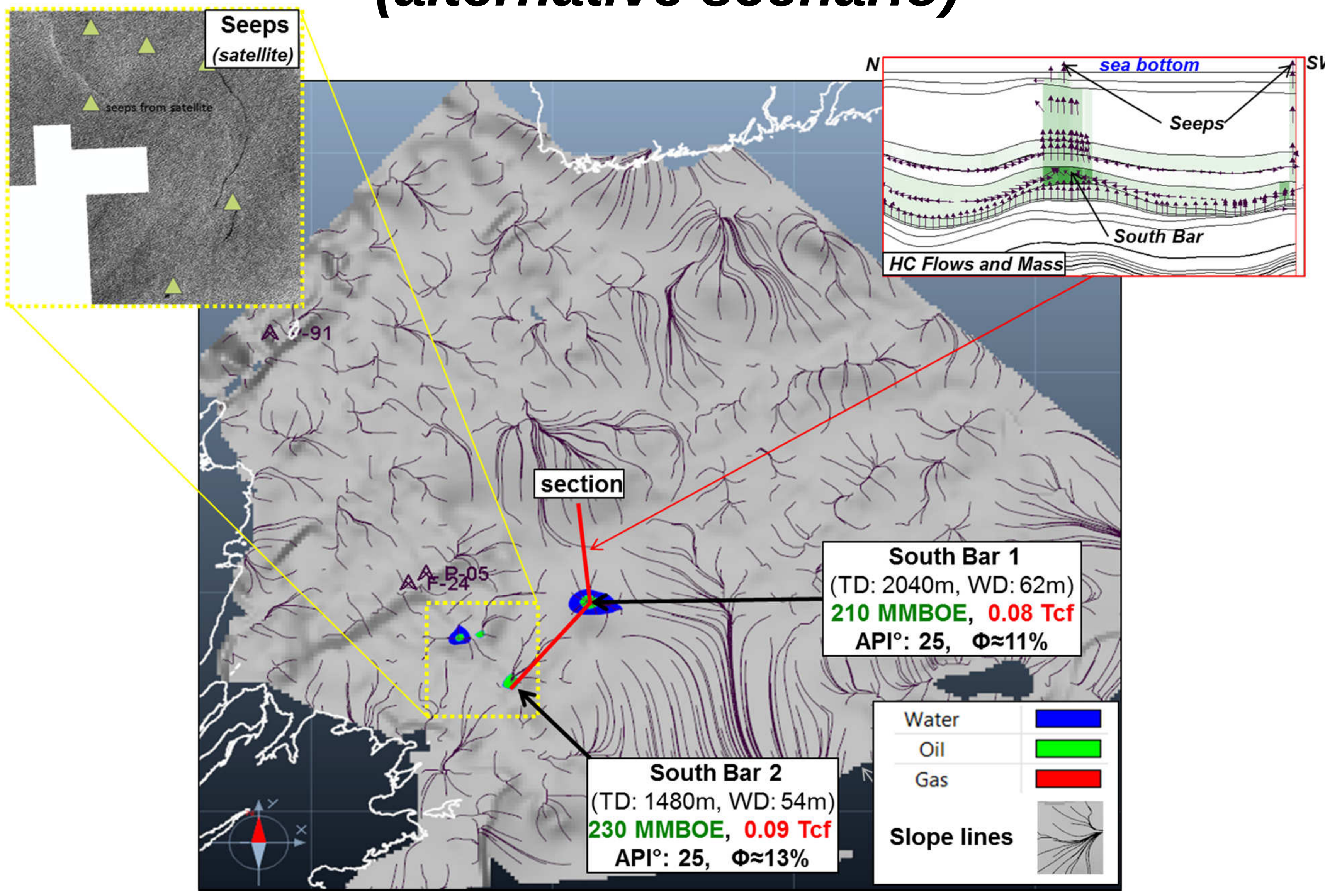






Mabou /South Bar Play

(alternative scenario)



- In conclusion, the under-explored Sydney Basin may host significant hydrocarbon accumulations, particularly in the Horton play. Two drilled wells (F-24 and P-05) were stopped just above likely hydrocarbon accumulations located several hundred meters below, in the Horton Formation. In addition, well P-91 was very close to a probable large gas accumulation near Saint-Paul Island.

- Sydney Basin is composed of Paleozoic formations with four main plays from base to top: the Horton, Windsor, Mabou/SouthBar and Sydney Mines plays. The Horton Formation, deposited in a half graben, has the best source rock potential while the other formation have only very low potential. Peak hydrocarbon generation occurred in the early Triassic just before regional uplift associated with approximately 2-3 km of erosion.

- The main risks in the basin are hydrocarbon preservation through the Mesozoic and Cenozoic erathems, seal integrity, reservoir quality and tectonic timing. These risks were assessed during the study. Tectonic timing and deformation style were studied in the regional tectonic section (Chapter 2). Reservoir qualities were estimated by petrophysical study and regional data (Chapter 3). Seal integrity was evaluated in forward stratigraphic modeling simulations (Chapter 6) and hydrocarbon charge and preservation were assessed by Darcy flow migration modeling through basin modeling technology (Chapter 8).

- Results of the basin modeling show that the Horton play is the only working play in Sydney Basin given the stated assumptions of source rock inputs and basin modeling results. The reference model shows that Windsor seal integrity has been maintained until the present day. The northern sector of the basin is more gas prone than further south due to its higher state of maturity (burial effect). The total hydrocarbon volume for the Horton play is 2900 MMBOE of oil at 33 to 48° API° with largest accumulations around 500 MMBoe, and 17 Tcf of gas. Alternative scenarios were used to assess the uncertainties associated with the estimated oil and gas volumes.

- Surface seeps observed in the southern Sydney Basin prompted the consideration of an alternative scenario for Mabou source rock properties. In this scenario, significant hydrocarbon accumulations can be identified in the southern parts of the basin as well.

- Horton-derived hydrocarbon accumulations are linked principally to Mississippian graben structures identified in the seismic interpretation. Due to the variable quality of the seismic data used in this project, different seismic interpretations are possible for significant parts of the Sydney Basin, especially through the Mississippian section (See for example CNSOPB Call for Bids interpretation). Based on the basin modeling results presented herein, all Mississippian grabens could be expected to host significant hydrocarbons if interpreted in additional locations.