Call for Bids NS17-1 – Regional exploration history, geological setting, source rocks and exploration potential of Sydney Basin, offshore Nova Scotia

Kristopher L. Kendell*, David E. Brown and Shaun Rhyno (*kkendell@cnsopb.ns.ca)

Canada-Nova Scotia Offshore Petroleum Board, Halifax, Nova Scotia

1.0 Overview

Call for Bids NS17-1 consists of three (3) Board-posted parcels within the Sydney Basin in water depths ranging from 50-450 metres (Figure 1.1). The Sydney Basin is a Carboniferous age sedimentary basin extending from Cape Breton Island to southern Newfoundland. This basin crosses the jurisdictional boundary between the Nova Scotia and Newfoundland and Labrador Offshore Areas. The last Exploration Licences in this region, within the Canada-Nova Scotia Offshore Area, were acquired by Hunt Oil in 1998 and relinquished in 2010 without drilling a well however, seismic data was acquired. Husky Canada recently held an Exploration Licence directly adjacent to the proposed NS17-1 parcels in the Canada-Newfoundland and Labrador Offshore Petroleum Board's jurisdiction. Husky Canada acquired seismic data but no wells were drilled, and the Exploration Licence was relinquished in 2014.

Only two wells have been drilled in the offshore portion of the Sydney Basin, North Sydney F-24 and North Sydney P-05. Both were drilled in the mid-1970's to evaluate shallow targets well above the Early Mississippian Horton Group, which is interpreted to be the most prospective interval in the basin. Both wells encountered gas in shallow Pennsylvanian sandstone formations above the Horton. North Sydney F-24 was flow tested but was unable to flow gas to surface.

The geophysical data in the Sydney Basin consists of widely spaced two-dimensional seismic lines that were predominantly collected in the 1980's or earlier, and apart from one recent survey have poor image quality. Interpretation of this data shows that this basin has all the necessary elements to be prospective, particularly the Horton Group, which has not been penetrated by any of the Sydney Basin wells. The region has potential for both oil and gas, and active oil seeps, from equivalent formations, are present onshore Cape Breton. The primary target formations in the Sydney Basin are analogous to the producing zones in the Stoney Creek oil field and McCully gas field onshore New Brunswick. **This document summarises the* ***Regional Exploration History, Geological Setting, Source Rocks and Exploration Potential*** *sections of the Call for Bids NS17-1 website. Please refer to www.callforbids.ca for the* ***Well Summaries and Petrophysics*** *information.*

2.0 Regional Exploration History

The story of petroleum exploration in the Sydney Basin is best understood in the context of regional historical exploration and specifically for this NS17-1 Call for Bids in the encompassing latest Devonian to Early Permian Maritimes Basin of which the Sydney Basin is its large eastern extension. Though intermittent, petroleum exploration in Atlantic Canada Carboniferous age basins has been ongoing for almost 150 years with two fields discovered in New Brunswick. However, the much larger offshore extensions of the basins are far less explored.It is important to note that except for four wells, the remaining 209 and almost all 2D seismic in offshore regions under Nova Scotia jurisdiction are located in Tertiary-Mesozoic basins. Of these four wells in Late Paleozoic basins, two are in the Sydney and two in the Magdalen. Within the latter that underlays the south half of the Gulf of St. Lawrence, a total of nine wells were drilled between 1943 and 1983 to test mostly salt-related structural traps. Approximately 30,000 km of 2D seismic data was acquired since the mid-1940s to early 1980s. Of the wells, there is one significant gas discovery, The Hudson's Bay-Fina East Point E-49 well. (1970; re-entered for testing in 1974) is located in shallow waters under Prince Edward Island jurisdiction. It tested 5.3 MMcf/d gas over a 12 m thick interval within a fluvial sandstone of Stephanian age. Of additional note is the Hillsborough No. 1 well drilled in 1943-44 by Island

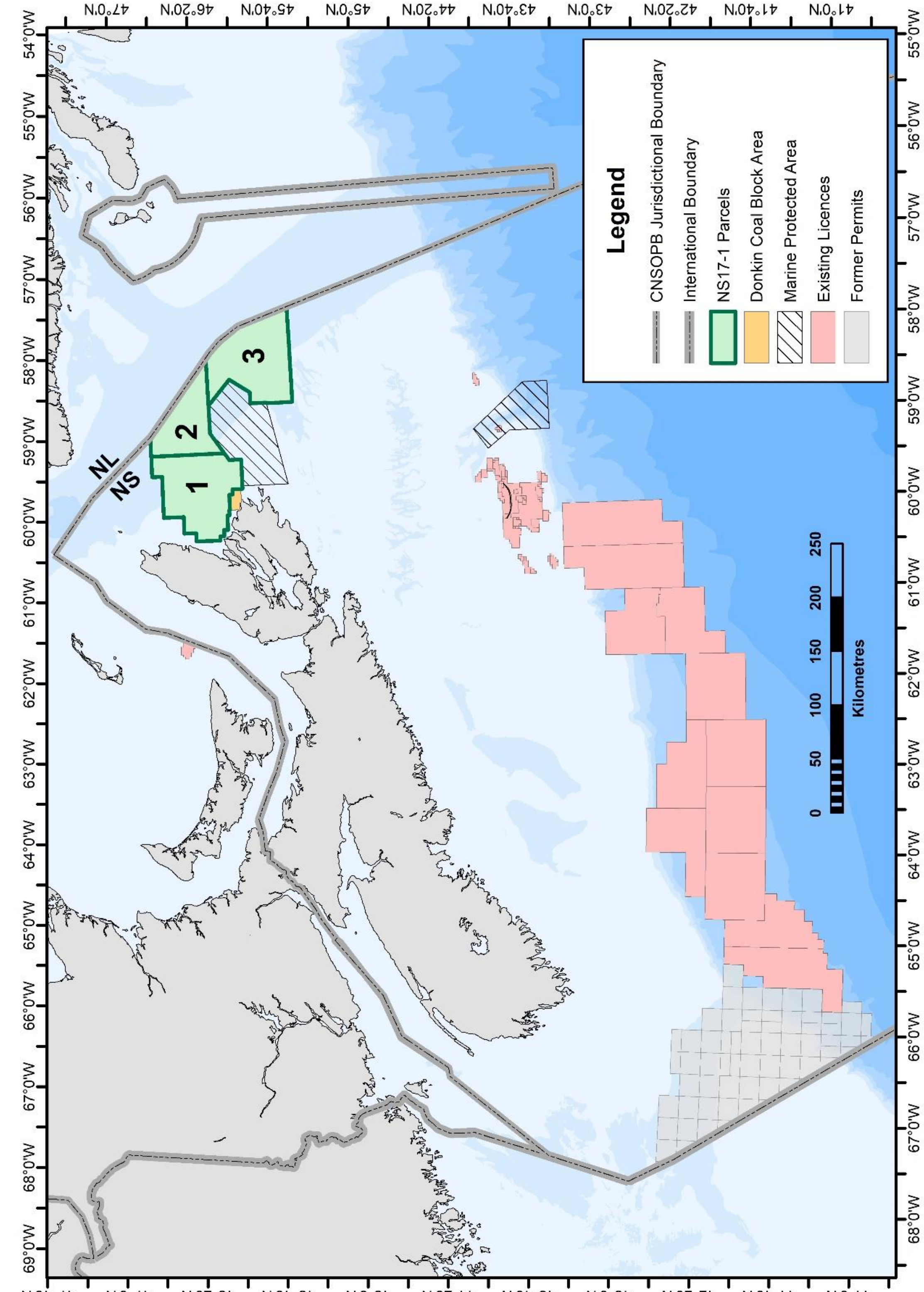


Figure 1.1 Location Map

Development Company - a subsidiary of Socony-Vacuum that later became Mobil. It was the first offshore well drilled in the British Commonwealth and tested drape of Mississippian and Pennsylvanian sediments over a deep salt swell offshore Prince Edward Island.

As of 2017, 209 wells were drilled offshore Nova Scotia with 129 exploration and the remainder either delineation or development wells. Over 401,000 km of 2D and approximately 49,000 km² of 3D seismic data has been acquired offshore Nova Scotia since 1960. This exploration lead to twenty-three significant and eight commercial hydrocarbon discoveries with additional wells encountering numerous oil and gas shows in Cretaceous and Jurassic sediments. Three commercial developments evolved from these discoveries: Cohasset-Panuke (1992-1999; oil), Sable (1999 – present; gas & condensate), and Deep Panuke (2013 – present; gas). There are no significant discoveries in Nova Scotia's offshore Carboniferous basins.

Onshore Exploration – New Brunswick

Carboniferous (Mississippian-Pennsylvanian) strata of the Maritimes Basin blanket a significant portion of the Atlantic provinces of Eastern Canada both on- and offshore (Figures 2.1 and 2.2). They provide significant contributions to their economies through the extraction coal, gypsum, salt, potash, limestone, base metals (Pb-Zn-Ba-Cu-Cs), and, petroleum. Some of the earliest conventional exploration for petroleum in North America began in 1859 in southeastern New Brunswick. Wells drilled near surface seeps in the Moncton Subbasin tested earliest Mississippian oil-prone continental lacustrine sediments of the Horton Group, with a number drilled over the next four decades. Based on this knowledge, drilling of structural configurations in southeastern New Brunswick occurred over the early 1900s. In 1909, the Stoney Creek oil and gas field was discovered near Hillsborough, New Brunswick at the eastern end of the Moncton Subbasin. It is a combined structural / stratigraphic trap of Early Mississippian lacustrine shoreline sandstones and oil shales. Production of oil and gas followed and up into the 1950s with over 150 wells drilled in and around the field, and a number of modern exploration / delineation wells completed over the 1980-2010 period.

In the early 2000s, Contact Exploration re-entered and cleaned up over 40 historic wells and drilled two additional ones in 2006. Production reinitiated in 2007 and the field is currently under production by Orlen Upstream Canada Ltd. producing 37° API paraffinic oil and minor sweet gas. Average field production in 2015 was about 35 Bbls/d, with cumulative oil production from 1909 to the present approximately 980,000 barrels. In 2000, Corridor Resources Inc. discovered natural gas while drilling a water-disposal well for the Potash Corporation's mine near Sussex, New Brunswick (also in the Moncton Subbasin). The gas was trapped in the same tight lacustrine shoreline sandstones and organic-rich lacustrine shales as those at Stoney Creek field about 60 km northeast. The McCully gas field has been in production since 2003 with average daily gas production for 2016 of 5.8 MMscf/d.

The source and reservoir rocks for the New Brunswick fields is the Frederick Brook Member of the Albert Formation (Horton Group). In the Sussex area, this organic-rich lacustrine shale has an estimated maximum thickness of 1100 metres and covers an area of almost 500 km^2. This unit is recognised as a high-ranking resource play with an estimated in-place gas resource of 67.3 Tcf. (Note: The above statistical information from the Government of New Brunswick, 2017.)

Onshore Exploration – Nova Scotia

In Nova Scotia, drilling for petroleum occurred on Cape Breton Island with the first recorded well in 1869 (Bell, 1958). Exploration was concentrated in the Lake Ainslie area on western side of the island where surface seeps were known for centuries. It was soon determined the reservoir-source combination was the same Carboniferous age as those successfully explored in New Brunswick, and intermittent exploration and drilling was undertaken throughout Nova Scotia during the 1900s to 1940s. Although hydrocarbon shows were documented, no commercial discoveries were made.

Following Bell's detailed assessment of Nova Scotia's petroleum potential (Bell, 1958), and perhaps influenced by it, a new period of exploration was initiated by major industry companies such as Imperial Oil, Pacific

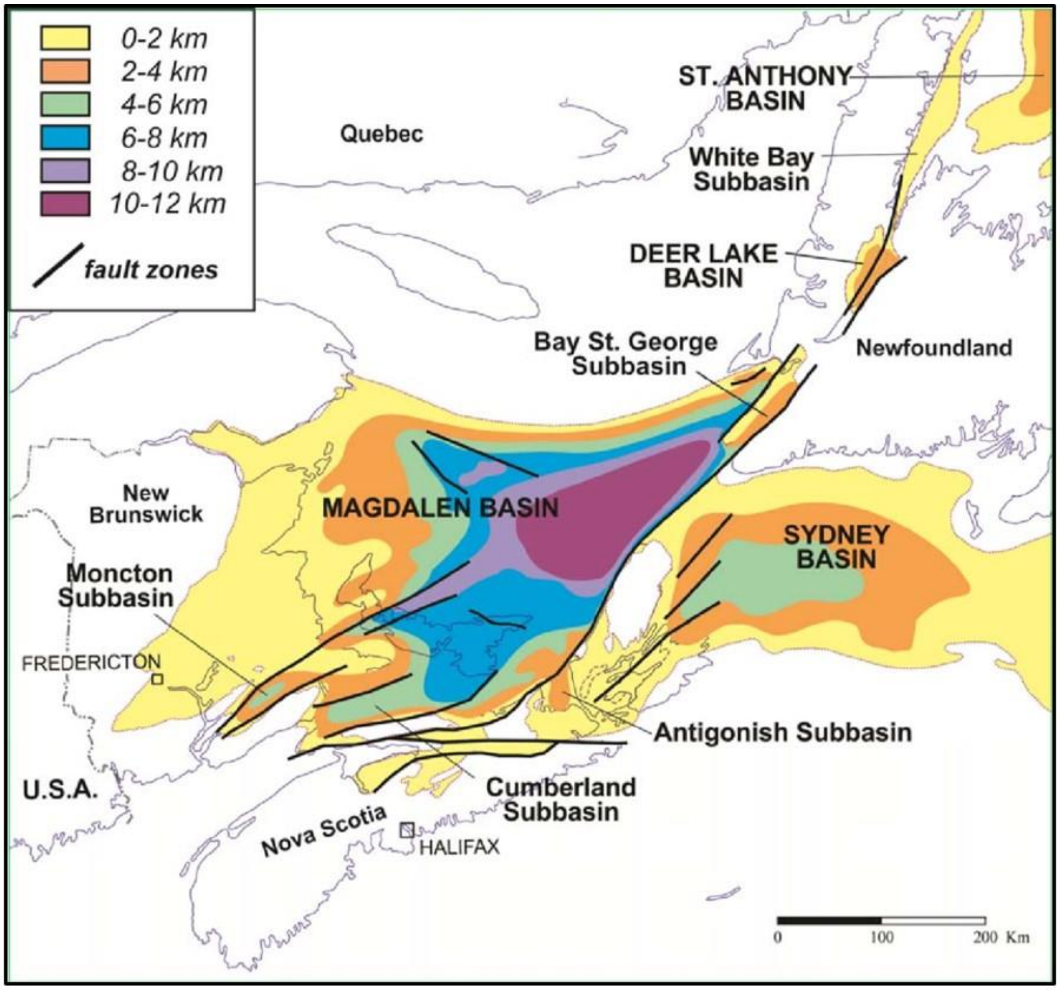


Figure 2.1: Isopach map of the latest Devonian–Early Permian Maritimes Basin in Eastern Canada. A number of regional basins and subbasins are recognized. While hydrocarbons are known through well and surface shows in several basins, only the Moncton Subbasin has commercial oil and gas production. From Jiang et al., 2016.

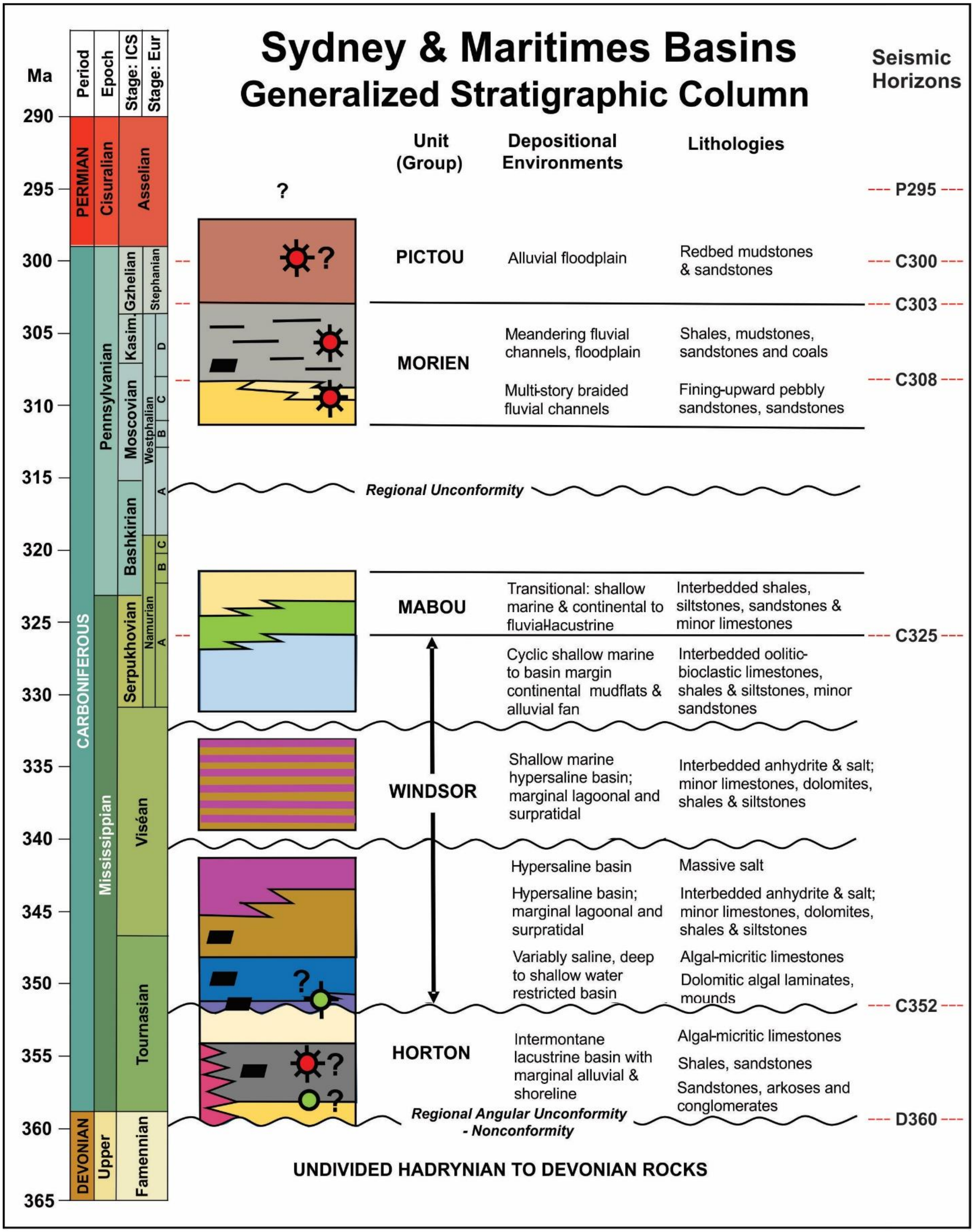


Figure 2.2 Generalized stratigraphic column with approximate locations of mapped seismic horizons

Petroleum, and Murphy Oil. This period is considered the first era of 'modern' exploration utilizing surface geological mapping, seismic, gravity and magnetic surveys. Eleven wells were drilled between 1958 and 1968 with nine in the Lake Ainslie area of western Cape Breton Island, and one on the mainland near Antigonish, all targeting early Carboniferous plays. Several wells at Lake Ainslie had oil shows in Early Mississippian Horton Group siliciclastics though none deemed commercial (McMahon et al., 1986).

The remaining well was the Murphy et al. Birch Grove No. 1 well (1968). It was the first to be drilled in the Sydney Basin in which coal mining existed since the late 1700s with known presence of associated coal bed methane gas. Between 1963 and 1965, Pacific Petroleum Limited acquired 53 km of seismic data and with surface mapping defined a large anticlinal feature. The well was drilled in 1968 with no hydrocarbons encountered, and while additional seismic profiles were acquired several years later, no further drilling was done. The Birch Grove well, and the basin's four others noted below are described in detail with petrophysical analyses in Section 3: Well Summaries.

During the 1970s, a large number of serendipitous petroleum shows were present in many mineral exploration boreholes (see McMahon et al., 1986). This was a period of intense exploration for Mississippian carbonate-hosted base metal (Pb-Zn) and potash deposits in the basal part of the Windsor Group in Carboniferous subbasins throughout Nova Scotia and New Brunswick.

Along the north shore of the Bras d'Or Lake in Central Cape Breton Island, Amax Exploration Inc. drilled 36 bore holes between 1975-1978 to assess the Jubilee Pb-Zn deposit. All had varying degrees of liquid petroleum shows (oil, pyro-bitumen and tar) present in cavities, vugs and fractures within limestones and anhydrites (McMahon et al., 1986). In 1978 Chevron Standard explored for similar deposits 10 km northeast at Malagawatch, and one of six boreholes it drilled had oil shows. A seventh borehole – Chevron Bras d'Or No.3A-78 – was drilled specifically to assess this accidental discovery and had flow to the surface of 40° API oil (McMahon et al., 1986). Further drilling for potash there in 1978-1981 had varying degrees of oil shows in all eleven boreholes. This discovery encouraged Chevron to initiate an exploration program in Cape Breton, though with the collapse of oil prices in the early 1980s no further activity occurred.

Offshore Exploration – Sydney Basin

Industry interest in the offshore part of the Sydney Basin began in the late 1960s during Nova Scotia's first offshore exploration cycle beginning in 1959. Three distinct cycles of exploration activity have occurred in the Nova Scotia offshore since then with the fourth focusing on the deep-water slope starting in 2013.

In the Sydney Basin, the first reconnaissance seismic lines were shot by Texaco Canada in 1969, and then more focused seismic, gravity and magnetic surveys acquired by Murphy Oil Company Limited (1970, 1971) and Texaco (1972-1973) on the Nova Scotia and Newfoundland side of the basin respectively. Murphy had earlier obtained exploration rights for several parcels on the Nova Scotia side of the basin. Prospects were defined through mapping with the largest a long, narrow NE-SW trending anticlinal high being fault bounded on its long sides with simple closure on the ends. The trap was defined as drape over a presumed deep basement ridge. Postulated reservoir targets were early Mississippian Windsor Group porous shallow marine carbonates, and underlying Horton Group fluvial-lacustrine siliciclastics.

The North Sydney P-05 well was drilled to a depth of 1660.8 m and encountered gas-bearing coals and sands of the Pennsylvanian Morien Group. The targeted Mississippian succession was not penetrated and none of the gas zones tested. In 1976, following reassessment of the seismic data, and encouraged by discovery and flow testing of gas by Hudson's Bay Oil & Gas at its East Point E-49 well in the Magdalen Basin to the west, Murphy's partner Shell Canada drilled the North Sydney F-24 well. It was located 5.6 km southwest of P-05 slightly off the crest of the North Sydney feature, and designed to flow test the sandstone F-24 pay zones to determine potential deliverability. P-05 found gas throughout the Morien Group section though log analysis revealed the sands had low porosity and gas was likely sourced from coaly intervals. Nevertheless, two sands, in P-05, were tested that included acidizing and fracking but no gas flowed to surface.

In the late 1970s, Petro-Canada acquired a large exploration licence in the northwestern part of the Sydney Basin extending from Nova Scotia to Newfoundland and up to and including the Cabot Strait.

The company acquired a large seismic, magnetic and gravity dataset over its licenses in 1981 and 1983, with the latter including a grid over the North Sydney structure. The operator defined a prospect opposite St. Paul Island located in the Cabot Strait that Murphy originally outlined in 1971. The prospect was a northeast-southwest trending narrow elongate closure bounded on the southeast by a rhombic-shaped structural high. The stratigraphic successions showed steep dips to the north and closure on transverse and normal fault seals. Postulated reservoir zones were within all Carboniferous intervals. The Petro-Canada et al. St. Paul Island P-91 well was drilled in 1984 to a depth of 2883 m and did not find any evidence of hydrocarbons nor sufficient reservoirs, with the Pennsylvanian succession eroded away.

In 1997, the CNSOPB's NS97-1 Call for Bids included five parcels in the Sydney Basin. Hunt Oil Company of Canada was the successful bidder and in 1998 awarded two Exploration Licences (ELs) in the western side of the basin - EL 2364 and EL 2365. Exploration was delayed for a period of time due to environmental and associated licencing issues, with the acquisition of a 2D seismic dataset in 2005. Following assessment of geophysical and geological data, Hunt decided to let its ELs expire and the lands reverted to Crown.

Though not petroleum-related, a recent onshore well has generated geoscience information useful towards understanding the offshore Sydney Basin. Carbon Capture & Storage Nova Scotia – a government-industry-academic consortium – is responsible for research on the potential for onshore CO_2 sequestration and storage. In their initial project phase they assessed the potential of different age geological units throughout the province having sufficient reservoir and seal characteristics. The onshore Sydney Basin near the city of Sydney was determined the best candidate as a thick succession of Carboniferous sediments underlay the region, and a CO_2-generating coal-fired power facility is located at nearly Point Aconi. The second project phase required the drilling of a test well to evaluate viability of the rocks. The Early Mississippian Horton Group was determined to be the best potential storage reservoir and overlying Windsor Group carbonates and evaporites as a seal. In 2014, the Carbon Capture & Storage Nova Scotia (CCSNS) No. 1 well was drilled about 6 km east of the Birch Grove No. 1 well (1968). It penetrated 1372 m of Pennsylvanian fluvial sediments followed by 154 m of presumed basement rocks of possibly late Neoproterozoic age. The expected Horton-Windsor rocks were not present and the well terminated at a total depth of 1527 m.

The most recent period of offshore exploration in the Sydney Basin took place on the northeastern half of the basin in waters under Newfoundland jurisdiction. The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) Call for Bids NL06-2 offered three large parcels for industry consideration (Enachsecu, 2006a, 2006b), and in 2008 Husky Canada was the successful work commitment bidder for the southernmost Parcel 1. There were no historic wells and only limited vintage seismic data in and surrounding their new Exploration Licence - EL 1115. In 2010, Husky completed a large 2D regional seismic survey over and adjacent to their licences that extended across the inter-provincial offshore boundary into Nova Scotia jurisdiction. After assessing the basins' potential, Husky allowed the parcels to revert back to the Crown. Currently, there are no exploration licences within the Sydney basin in either jurisdiction.

4.0 Geological Setting

Study area, data-set and approach

The study area for Call for Bids NS17-1 covers the Sydney Basin and the easternmost portion of the Magdalen Basin. Collectively, these two areas form the eastern extension of the Maritimes Basin (Figure 2.1). An extensive suite of 2D seismic surveys, varying greatly in vintage and quality, forms the main data-set for this study (Figure 4.1.1). The most recently acquired seismic available in the database is the NS24-H6-1E survey, collected by Husky in 2010. All other surveys were collected in the 1980's or earlier. To varying degrees, seismic imaging and artefacts like conventional seafloor and peg-leg multiples present a significant interpretation challenge, in some cases forming the dominant reflections and substantially obscuring primary reflections (e.g. Figure 4.1.4). Substantially improved

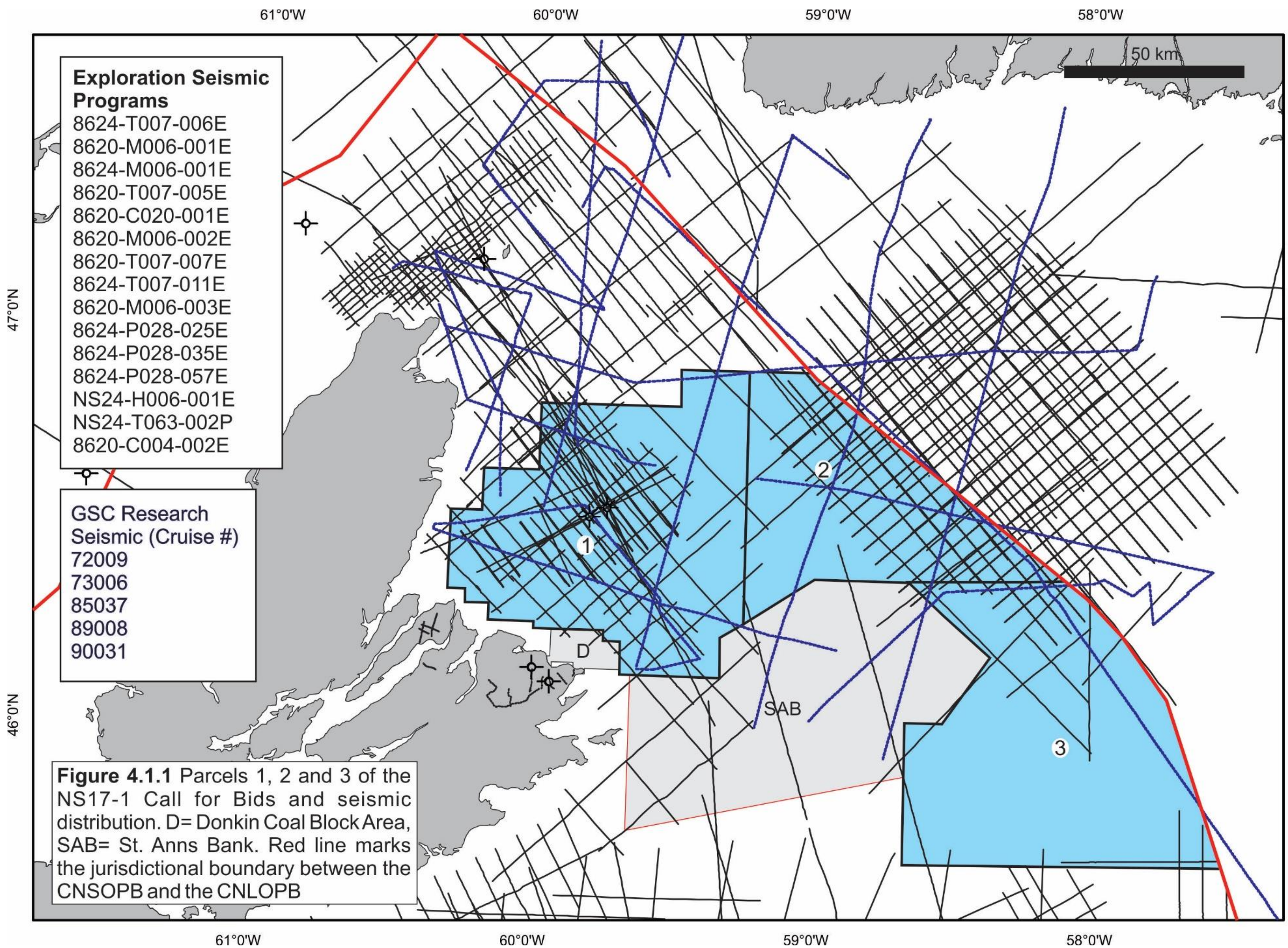


Figure 4.1.1 Parcels 1, 2 and 3 of the NS17-1 Call for Bids and seismic distribution. D= Donkin Coal Block Area, SAB= St. Anns Bank. Red line marks the jurisdictional boundary between the CNSOPB and the CNLOPB

imaging in the 2010 Husky survey provided a higher degree of interpretation confidence, helping guide interpretations in poorer data-quality areas. In addition, different seabed multiple and peg-leg scenarios were calculated and overlain on seismic sections as seismic markers were correlated, in an attempt to minimize interpretation errors associated with seismic artefacts. Shallow high-resolution seismic profiles (available from the Geological Survey of Canada) were also vectorized and used to determine the dip of folded primary reflections in the upper 100 m or so. These profiles helped to confirm the dips of folded strata in areas where poor resolution or near-seabed ringing in conventional industry data obscured the recognition of primary reflections. In some areas these shallow penetrating profiles helped to clearly distinguish higher amplitude layer-cake artefacts on industry profiles, from folded dipping and erosionally truncated Carboniferous and/or Permian strata. Unfortunately, failure to recognize these artefacts has lead to erroneous interpretations in a number of previous studies (discussed later). In addition to the myriad of seismic artefacts, data gaps of 10 km or more are common in the central and southern portions of the study area.

Synthetic seismograms were generated for five wells, Birch Grove No.1, North Sydney P-05, North Sydney F-24, St. Paul P-91 and CCS Nova Scotia No. 1. These wells provide calibration of the seismic stratigraphy, but the calibration is limited to the western and nearshore parts of the study area. There are no well penetrations that calibrate strata older than the upper Windsor Group (discussed in more detail later). Significant efforts were also made to ensure that the shallow offshore geological interpretations are consistent with the stratigraphy exposed along immediately adjacent shorelines on Cape Breton Island and southern Newfoundland (Figure 4.1.2a, b). Several onshore exposures of Mabou and Morien Group strata appear to continue into offshore basins. Likewise, exposed basement terranes in onshore areas were correlated with a moderate degree of confidence into offshore areas, with interpretations bolstered by available gravity and magnetics data-sets, and previously published interpretations (Dehler and Roest, 1998; Barr et al., 2014).

Despite the unique integration of modern topography, surface geology, gravity, magnetics, industry and academic seismic, and information from both onshore and offshore industry boreholes, into a single workstation environment, large data-gaps and extremely poor seismic quality (in particular) lead to a large amount of interpretation uncertainty in some offshore areas. Acquisition of additional modern seismic and other geophysical data-sets will be required to properly evaluate the geology in such areas.

4.1 Basement Architecture

Basement rocks are defined as all formations older than the mid-Devonian McAdams Lake Formation, and the top of basement is represented by the D360 seismic horizon, the deepest mapped surface in this study (Figure 2.2). Defining and correlating pre-Carboniferous basement terranes throughout the Maritimes Basin has been the focus of many previous studies, and while not the primary objective of this study, an understanding of the different terranes and their boundaries is necessary and aided the regional seismic interpretation.

At least four pre-Carboniferous terranes are interpreted to be present across the study area (Williams, 1979; Hibbard et al., 2006; Barr et al. 2014, Waldron et al., 2015) (see Figures 4.1.2b, 4.1.3 , 4.14 and 4.1.5). The Precambrian Mira Terrane of southeast Cape Breton, and its equivalent, the Avalon Terrane in Newfoundland, consist of volcanic, sedimentary and plutonic rocks (Bevier et al., 1992). Offshore, the top of the Mira Terrane is challenging to correlate on seismic profiles (D360 marker), but there are strong indications it was heavily faulted into a series of narrow southwest-northeast trending horsts and grabens that underpin the southern portions of the Sydney Basin. The top of Mira basement was carried below a series of higher amplitude faulted and locally folded reflections believed to correspond to an early period of fill within the Sydney

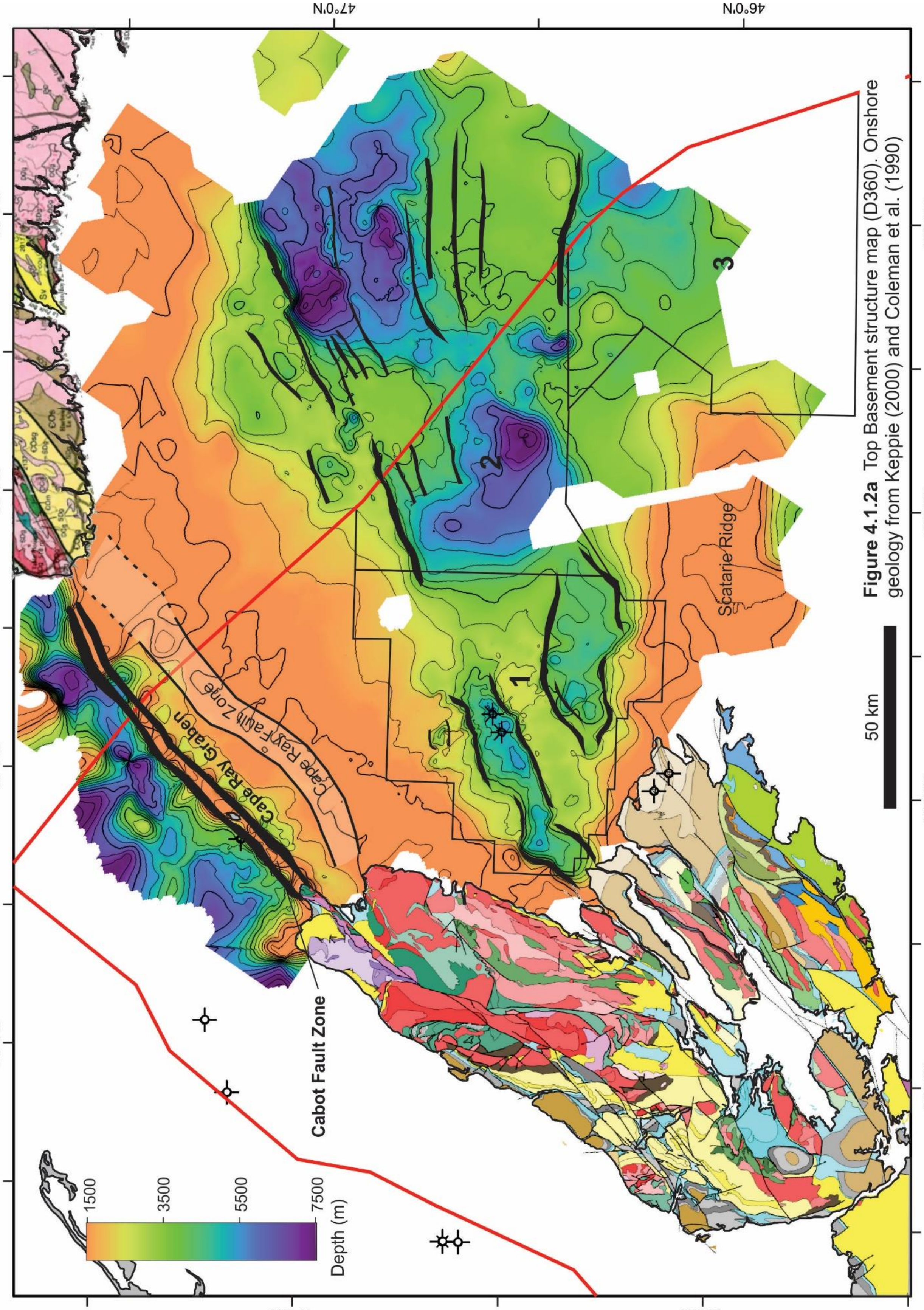


Figure 4.1.2a Top Basement structure map (D360). Onshore geology from Keppie (2000) and Coleman et al. (1990)

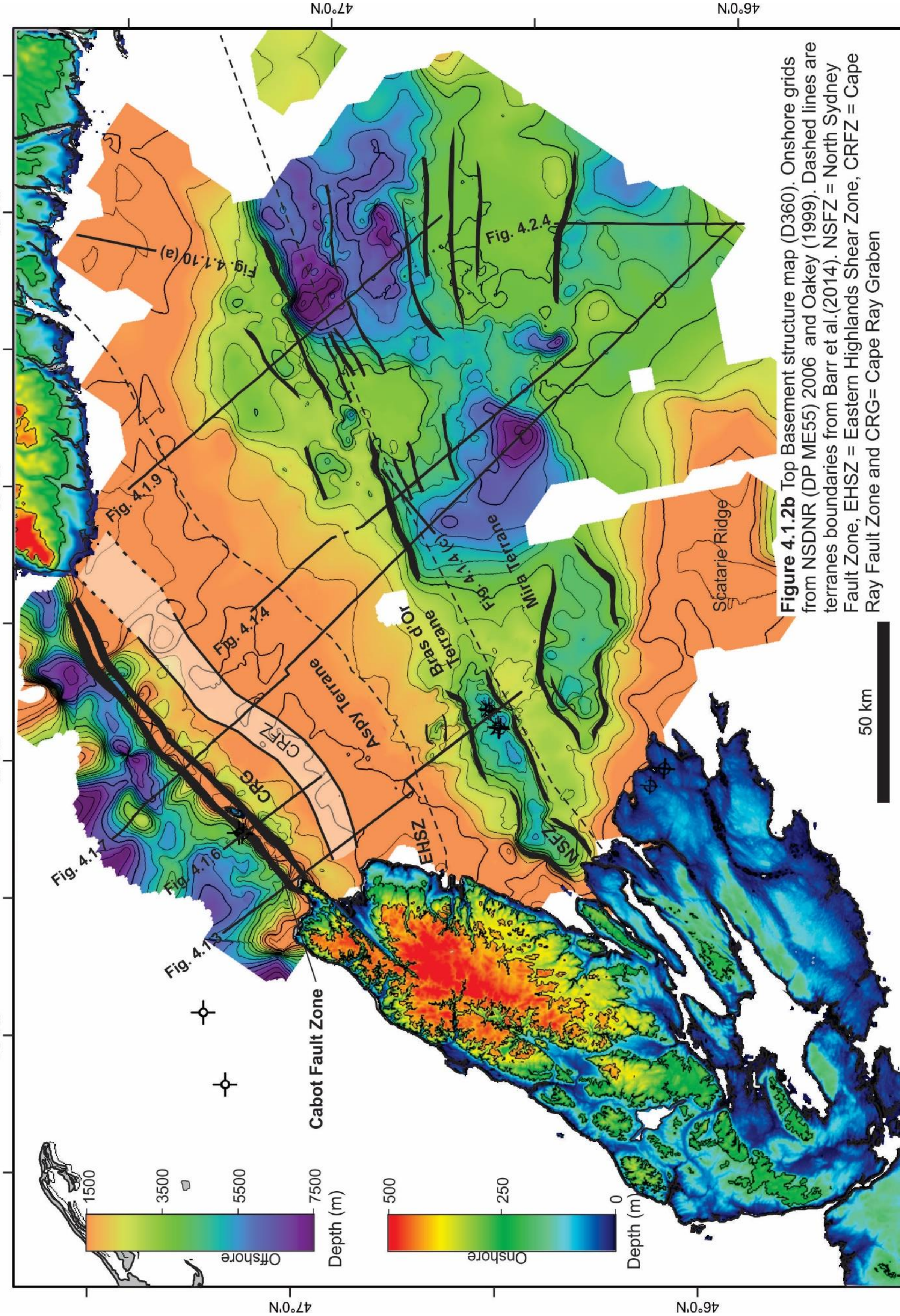


Figure 4.1.2b Top Basement structure map (D360). Onshore grids from NSDNR (DP ME55) 2006 and Oakey (1999). Dashed lines are terranes boundaries from Barr et al.(2014). NSFZ = North Sydney Fault Zone, EHSZ = Eastern Highlands Shear Zone, CRFZ = Cape Ray Fault Zone and CRG= Cape Ray Graben

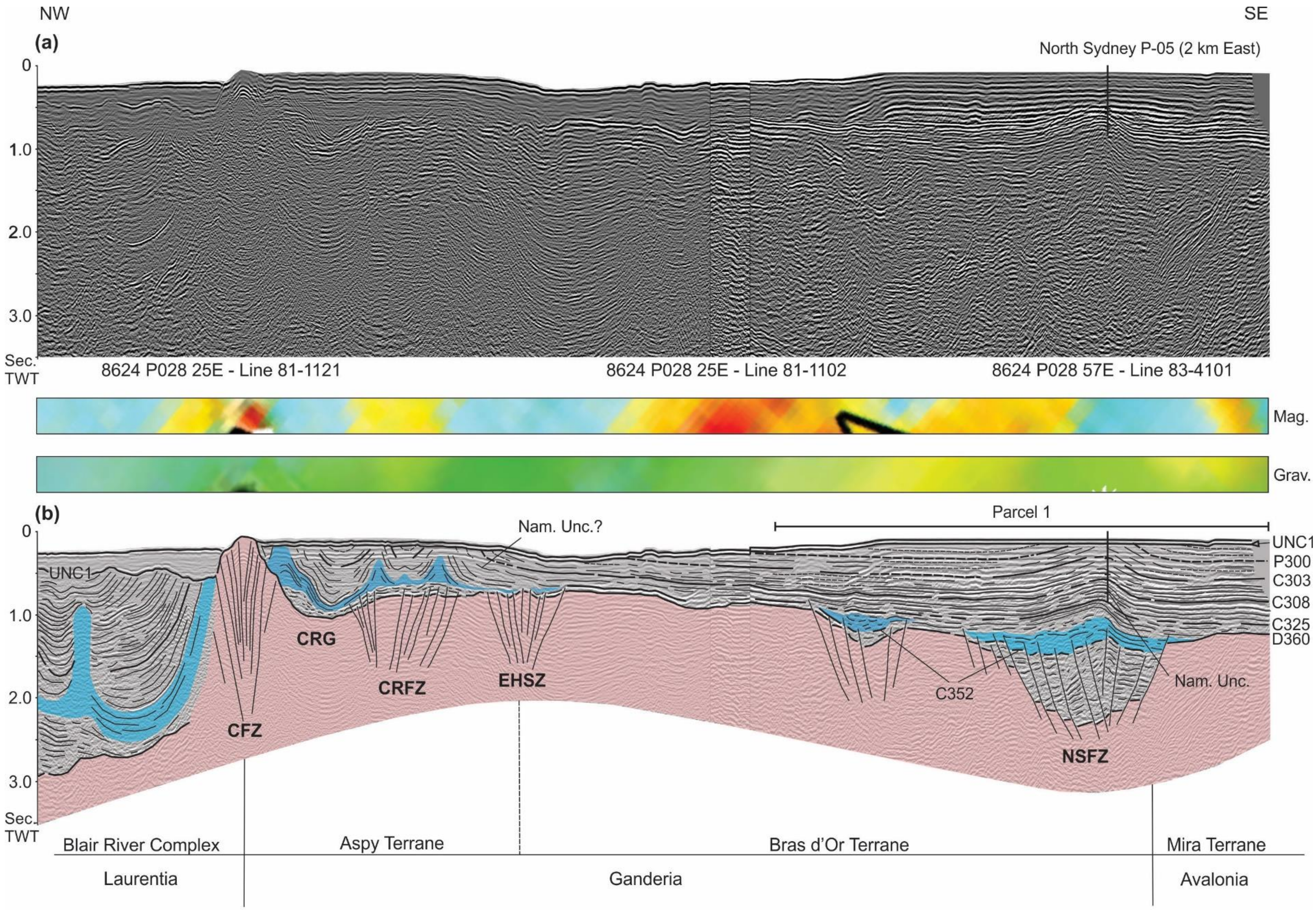


Figure 4.1.3 (a) Uninterpreted composite seismic line **(b)** Interpreted composite seismic line, blue polygons represent potential mobile units within the Windsor Group, pink fill is basement. CRFZ = Cape Ray Fault Zone, CFZ = Cabot Fault Zone, NSFZ = North Sydney Fault Zone, EHSZ = Eastern Highlands Shear Zone, CRG =Cape Ray Graben.

Kendell et al. 2017

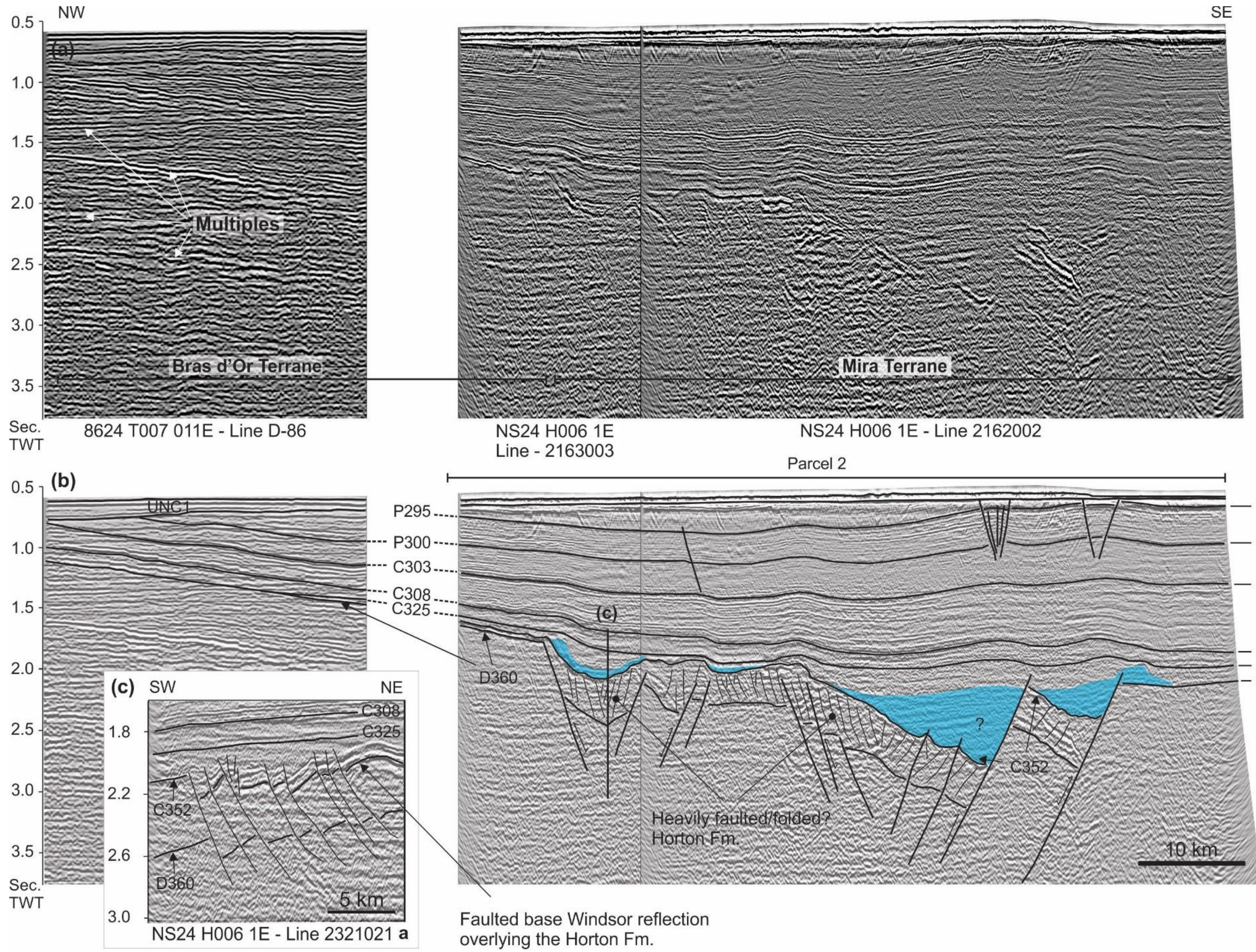


Figure 4.1.4 (a) Uninterpreted composite seismic line highlighting multiples and terrane boundaries. **(b)** Interpreted composite seismic line, blue polygons represent potential mobile units within the Windsor Group **(c)** portion of a strike line that intersects the graben noted on image (b)

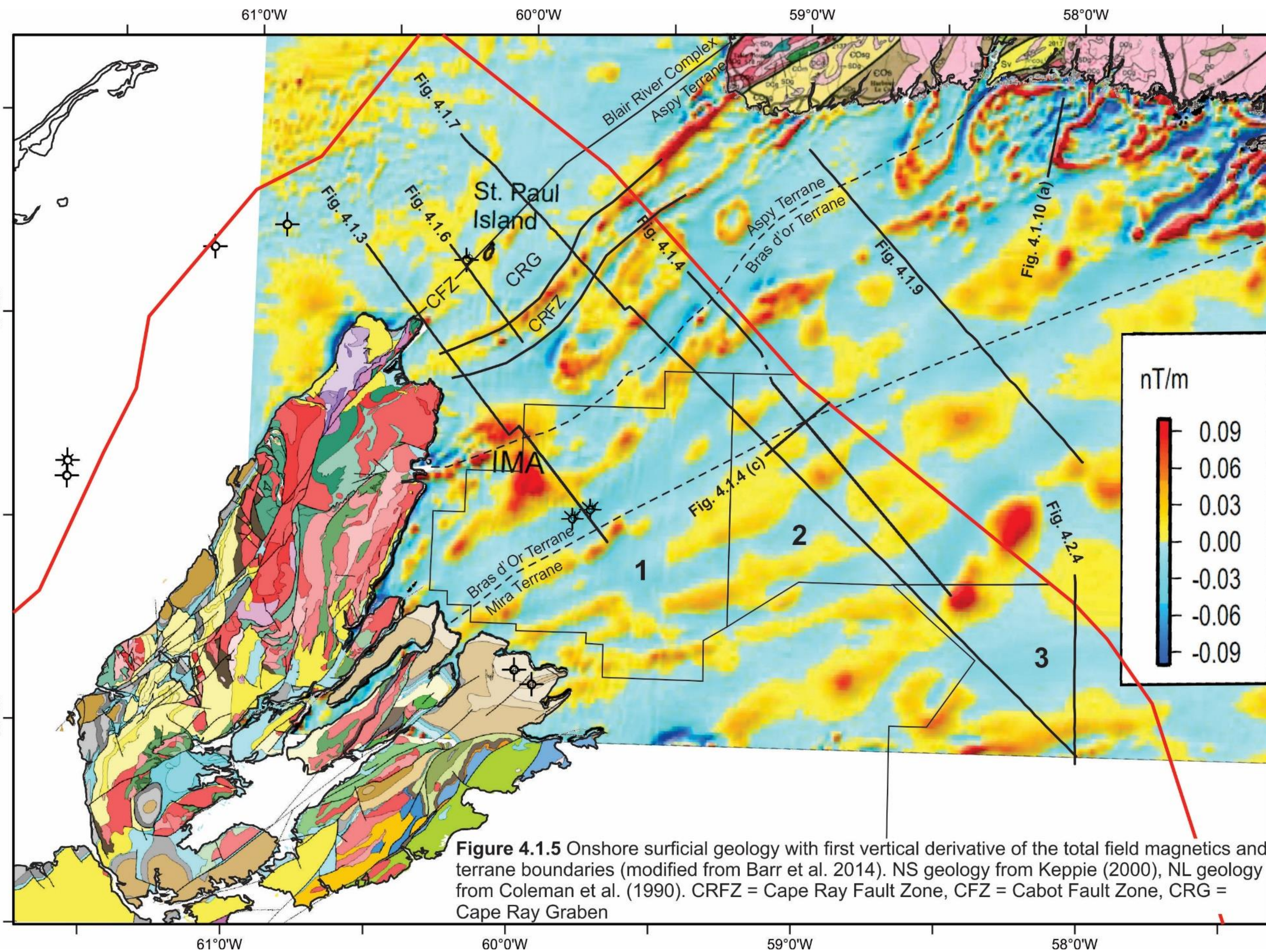


Figure 4.1.5 Onshore surficial geology with first vertical derivative of the total field magnetics and terrane boundaries (modified from Barr et al. 2014). NS geology from Keppie (2000), NL geology from Coleman et al. (1990). CRFZ = Cape Ray Fault Zone, CFZ = Cabot Fault Zone, CRG = Cape Ray Graben

Basin, but there is no distinct 'top basement' reflection here (Figure 4.1.4).

The offshore boundary between the Mira Terrane and the Bras d'Or Terrane to the west was defined by Barr et al. (2014) on the basis of potential fields data (Figure 4.1.5; see also their Figure 10) and coincides closely with the North Sydney Fault Zone (NSFZ) defined by Pascucci et al. (2000). Relative to the top basement surface mapped in this study (D360 marker; Figure 4.1.2b), the terrane boundary tracks along the southern border faults of a narrow inverted graben penetrated by the North Sydney wells (coincident with the "Boisdale Anticline" of Hacquebard, 1983), and skirts along the northern border faults of the westernmost grabens of the Mira Terrane (Figure 4.1.2b). The boundary coincides with a number of large-offset, basement faults that likely formed initially during the Acadian Orogeny, and were later reactivated to create accommodation space for mid-Devonian McAdams Lake Formation and earliest Mississipian Horton Group strata.

As defined by Raeside and Barr (1990), the Bras d'Or Terrane consists of pre-Middle Devonian gneisses, Proterozoic clastic-volcanoclastic-carbonates, late Proterozoic to Cambrian intrusives and Ordovician/Devonian intrusives. On offshore seismic lines, the number of faults progressively decreases towards the northwest, away from the Mira Terrane, where the basement marker forms a topographic high. Here, Bras d'Or basement has a "smooth" character and lacks any coherent internal reflectivity on seismic profiles. The interface between the Bras d'Or Terrane and the sedimentary section above it commonly produces a high-amplitude seismic reflection that is easily identified throughout this part of the Sydney Basin (and below which multiple peg-leg multiples commonly ring) (Figures 4.1.3 and 4.1.4). The D360 surface along this topographic high is generally no deeper that 1 sec (twt) and correlated with a high degree of confidence. The high-amplitude character of the D360 surface here is probably in response to the acoustic impedance contrast between the overlying sedimentary section and high-velocity basement rocks of the Bras d'Or Terrane (granites?), though no wells penetrate basement in the Sydney Basin.

The Aspy Terrane is composed of predominantly Ordovician- Silurian metavolcanic and metasedimentary rocks (Lin, 1993). Like the Bras d'Or Terrane, the D360 marker across the Aspy Terrane forms a high amplitude reflection mapped with a high degree of confidence except where it approaches the Cabot Fault zone (CFZ) along its western edge (where the marker deepens). The Aspy Terrane is bisected by a number of tightly spaced faults corresponding to the CRFZ defined by Langdon and Hall (1994). These probable strike-slip faults form a positive flower structure across most of the study area (Figures 4.1.3 and 4.1.7) with a slight negative expression near the St. Paul well (Figure 4.1.6).

The western boundary of the Aspy Terrane corresponds to the CFZ, a prominent strike-slip terrane boundary described in previous studies (Langdon and Hall, 1994; Pascucci et al., 2000) The offshore boundary between the Bras d'Or and Aspy terranes has been defined previously on the basis of potential fields data (Figure 4.1.5; e.g. Figure 10 of Barr et al. 2014) and coincides closely with the Eastern Highlands Shear Zone (EHSN) defined by Raeside and Barr (1990). Relative to the top basement surface mapped in this study (D360 marker; Figure 4.1.2b), the terrane boundary has no obvious structural expression, and instead generally bisects the broad basement high that forms the offshore extension of the Cape Breton Highlands. Similarly, aside from Figure 4.1.3, most seismic profiles show little cross-sectional expression of this terrane boundary.

The reader should note that in previous studies (e.g. Langdon and Hall, 1994; Pascucci et al., 2000), the high amplitude response of the D360 marker across the Bras d'Or and Aspy Terranes was instead interpreted as a regionally extensive Namurian (i.e. "Mississippian-Pennsylvanian") unconformity. However, a well tie with new biostratigraphic data from Weston et al. (2017) and, more importantly, differentiating seismic multiples from real seismic events (assisted in particular by the use of high resolution, shallow penetrating seismic data, e.g.

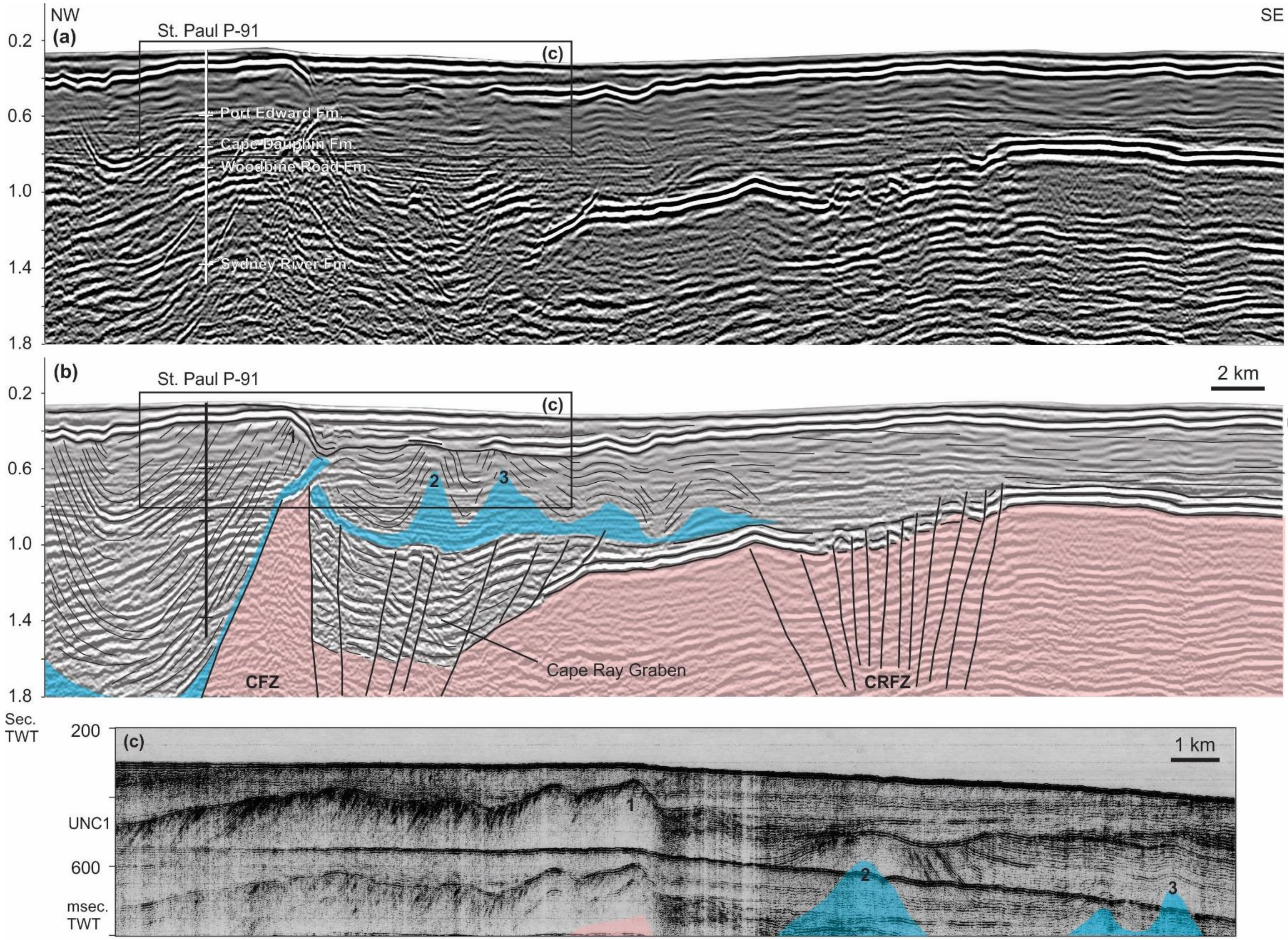


Figure 4.1.6 (a) Uninterpreted seismic line 81-1171 from survey 8624-P028-25E that intersects the St. Paul well. **(b)** interpreted version of (a), blue polygons represent mobile Windsor Group evaporites, pink fill is basement. **(c)** high-resolution seismic data near-parallel to line 81-1171. CRFZ = Cape Ray Fault Zone, CFZ = Cabot Fault Zone. 1, 2 and 3 label equivalent features on high resolution data and industry seismic

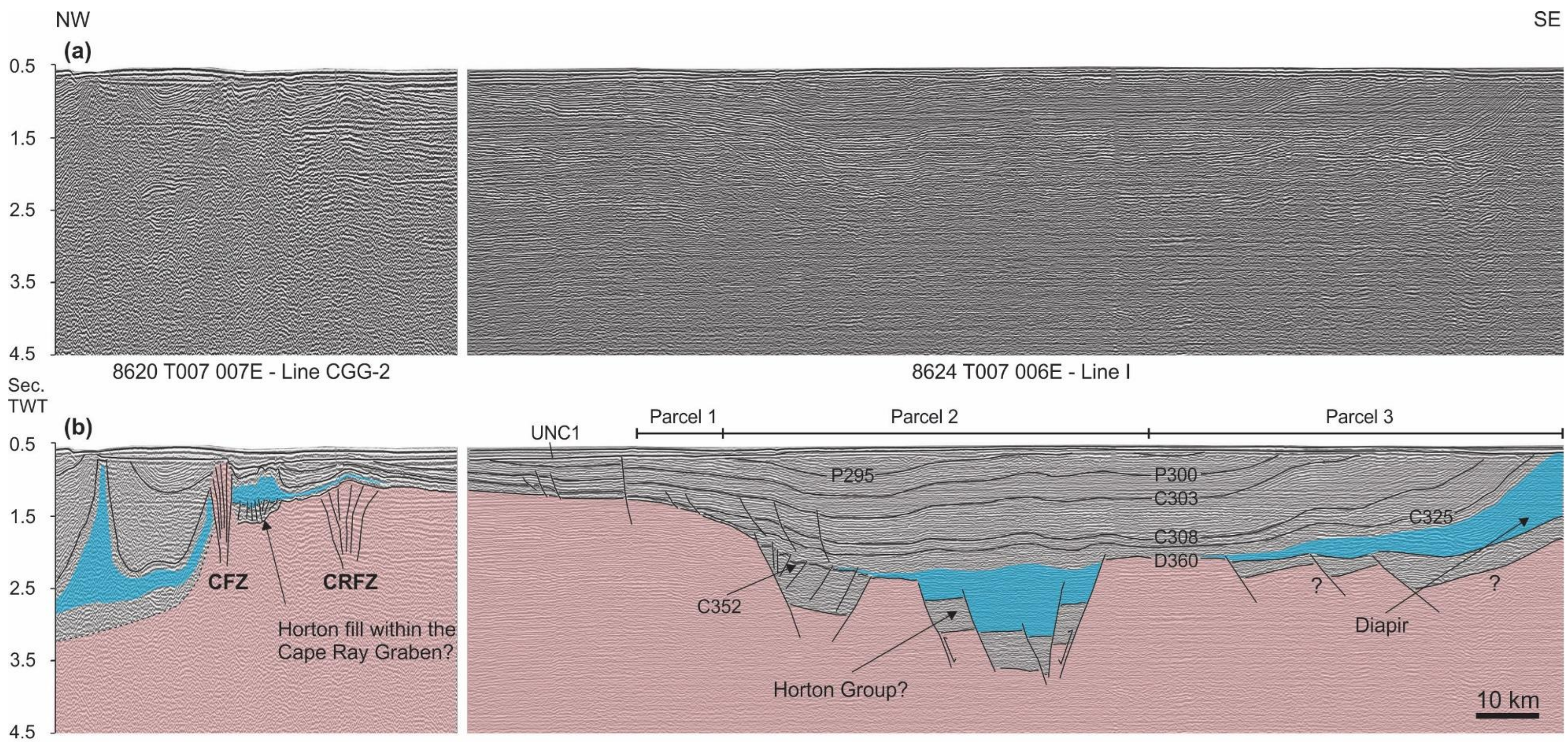


Figure 4.1.7 (a) Uninterpreted composite seismic line **(b)** Interpreted composite seismic line, blue polygons represent potential mobile units within the Windsor Group, pink fill is basement.

Figure 4.1.6) has led to a much different interpretation in this study. Here, we carry the Namurian unconformity shallower, above the D360 marker. North of the North Sydney P-05 well, the seismic event corresponding to the Namurian unconformity shallows and crops out at the seafloor near the CRFZ. The marker is located above what appear to be Visean (Windsor Group) salt diapirs identified on a number of seismic profiles along the western boundary of the Aspy Terrane. Additional salt diapirs are also recognized in the Cape Ray Graben (CRG)(CRG; Langdon and Hall, 1994) where the basement marker deepens (Figures 4.1.3, 4.1.6 and 4.1.7). Likewise, onshore exposures of Windsor Group strata in Aspy Bay support the presence of Windsor Group strata within the CRG. A Namurian aged unconformity cannot underlie these diapirs as previous interpretations have done, unless these diapirs correspond to post-Namurian evaporites, which to date have not been recognized in the basin.

The fourth terrane within this study is the Blair River Complex, which is found north of the CFZ. This region was not extensively mapped as it extends into the Magdalen Subbasin and is outside of the study area, but basement deepens dramatically and there is an abundance of salt diapirs that inhibit imaging of the top basement surface.

Gravity and Magnetic Expression of the Bras d'Or and Aspy Terranes

As described above, this study carries the top basement D360 marker much shallower across the Aspy and Bras d'Or Terranes than interpreted in previous studies. It was also carried shallower than the depth Barr et al. (2014) used in their potential field modeling. One explanation for the preference for carrying basement deeper across these terranes in previous studies is the pronounced, east-west, oval-shaped gravity low across this region (Figure 4.1.8). A shallow basement pick would not be favoured across a region that forms a gravity low, because in many cases gravity lows correspond to regions with thick, less dense sedimentary cover.

Our interpretation suggests basement is shallow here and veneered by a relatively thin sedimentary cover that is counter to the gravity data. However, the onshore gravity expression of the Exploits Zone of central Newfoundland (equivalent to the Aspy Terrane) is also low, and corresponds to low-density granitic plutons (Figure 4.1.10b). Similarly, shallow penetrating high-resolution seismic profiles across a gravity low immediately offshore from these gravity lows reveal thinning of coherent Carboniferous strata above a strong basement marker interpreted as a granitic pluton (Figure 4.1.10a). The D360 marker was tied to this line from nearby deeper industry seismic lines, and is overlain by coherent reflections of the Pennsylvannian Sydney Mines and South Bar formations. The basement rocks beneath these formations subcrop at the seafloor where they have a chaotic, high-energy reflection character interpreted to represent a granitic body. This potential pluton is directly offshore from known onshore granites within the Exploits subzone of Newfoundland and also corresponds to a gravity low. Furthermore, low-density granites that produce gravity lows are known to exist elsewhere in the region. The South Mountain Batholith onshore Nova Scotia (Benn et al., 1999) and New Brunswick's Saint George Batholith (King and Barr, 2003) are two examples of significant gravity lows produced by low-density Devonian granitic plutons. As such, the offshore gravity low across the Aspy and Bras d'Or terranes could reflect the presence of similar low-density plutons beneath a thin veneer of Carboniferous strata. Seismic lines across this feature consistently show Carboniferous sediments onlapping and thinning onto the D360 seismic marker as it shallows northward toward the CRFZ (Figures 4.1.3, 4.1.4, 4.1.7 and 4.1.9), consistent with Carboniferous strata that onlap a pre-existing (mid-Devonian or older) sequence of rocks.

Evidence for intrusive granites are also noted on the magnetic data, where circular, magnetic high "halos" are present throughout the Aspy Terrane (Figure 4.1.5). Barr et al. (2014) suggested that these "halos in the Exploits (Aspy) subzone are probably caused by Silurian-Devonian plutons like those in the Burgeo Intrusive Suite". Therefore, we interpret the gravity low feature represents pre-Carboniferous intrusives, with most of the overlying sedimentary section mapped as thinning onto it.

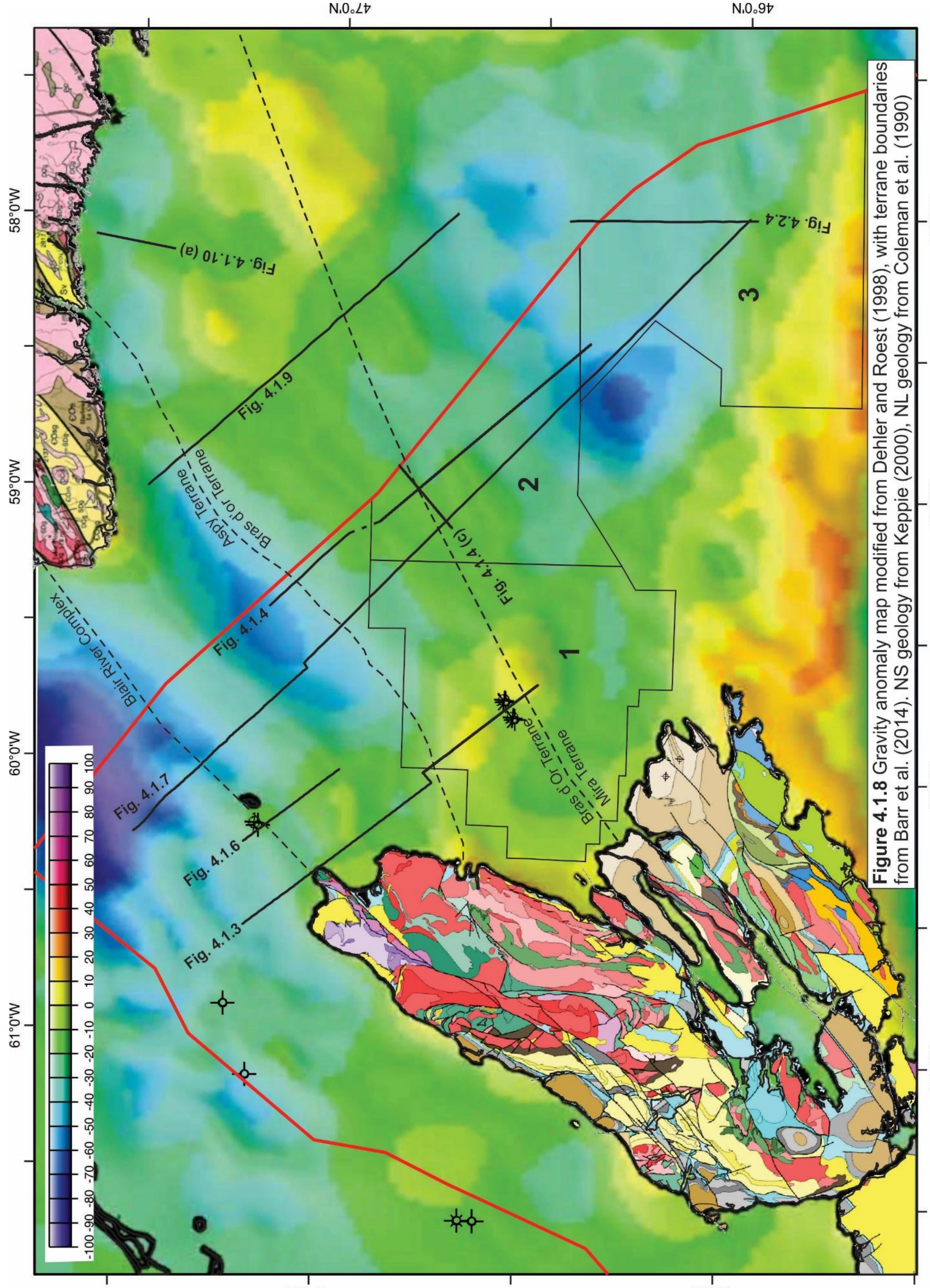


Figure 4.1.8 Gravity anomaly map modified from Dehler and Roest (1998), with terrane boundaries from Barr et al. (2014). NS geology from Keppie (2000), NL geology from Coleman et al. (1990)

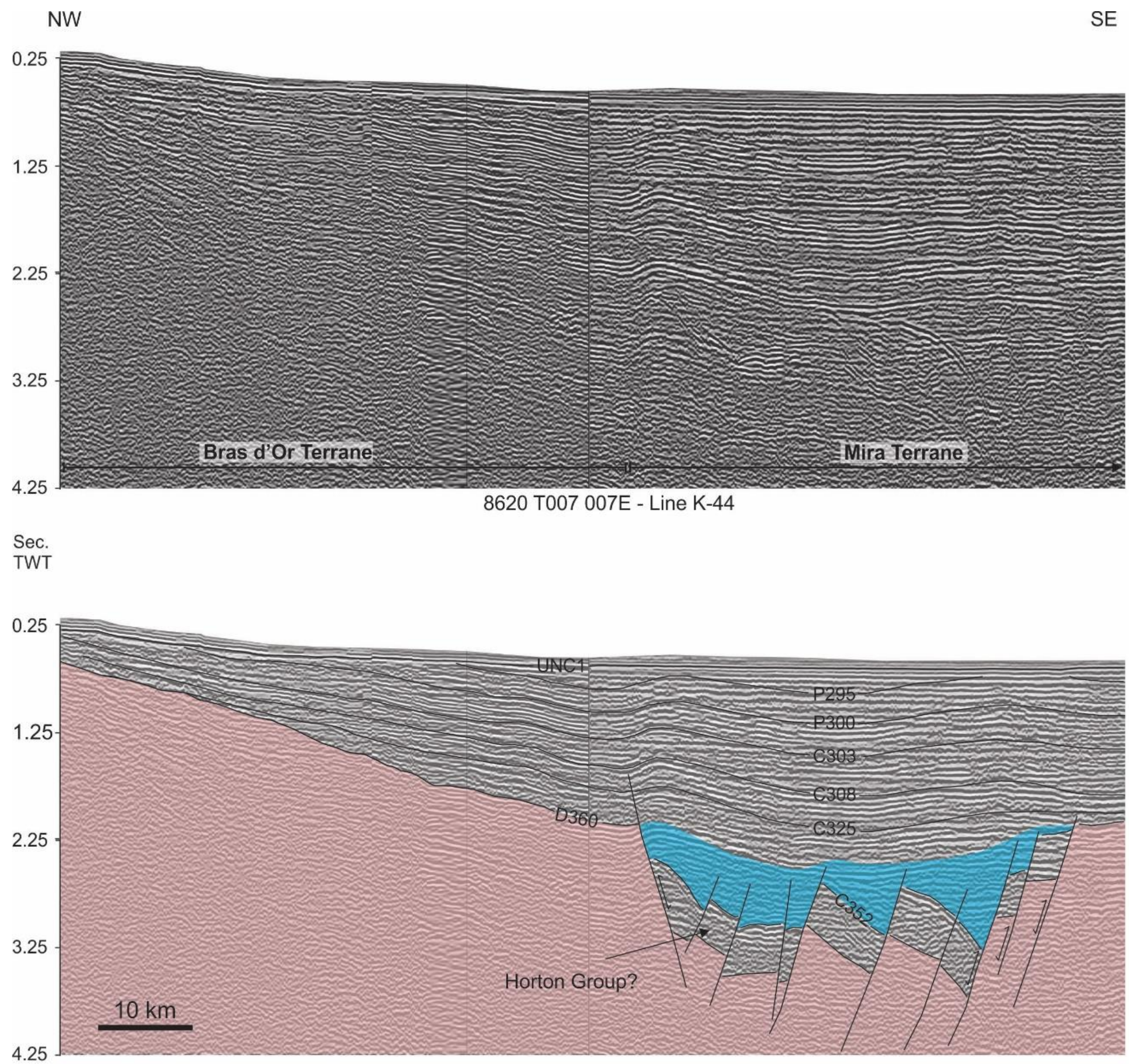
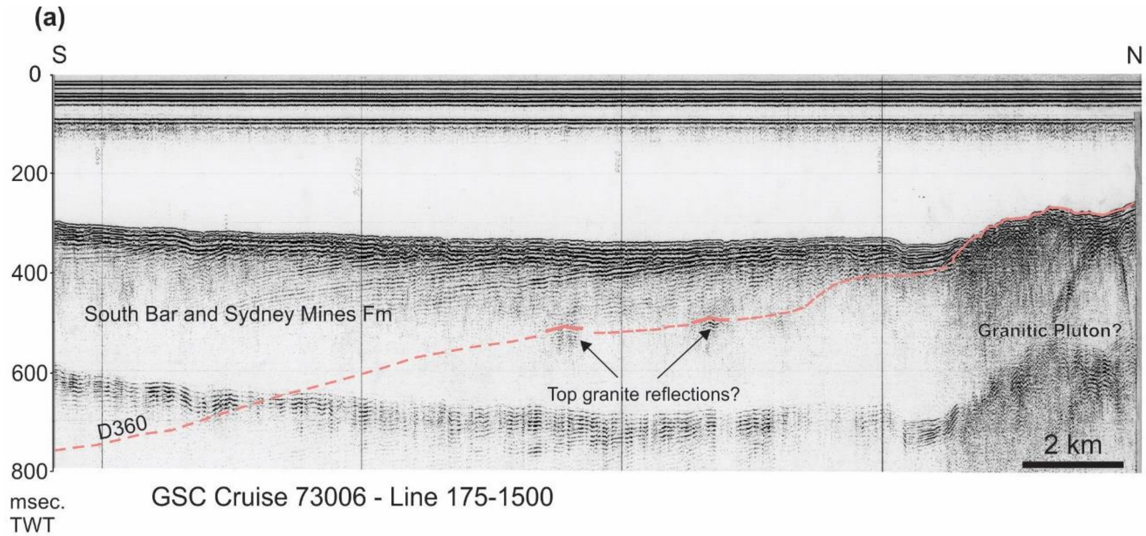
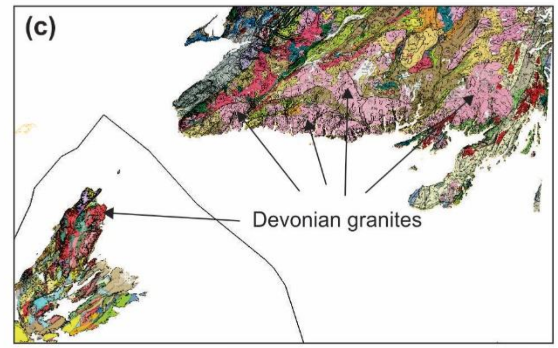


Figure 4.1.9 Seismic line from the Newfoundland and Labrador side of the Sydney Basin, blue polygons represent potential mobile units within the Windsor Group, pink fill is basement.





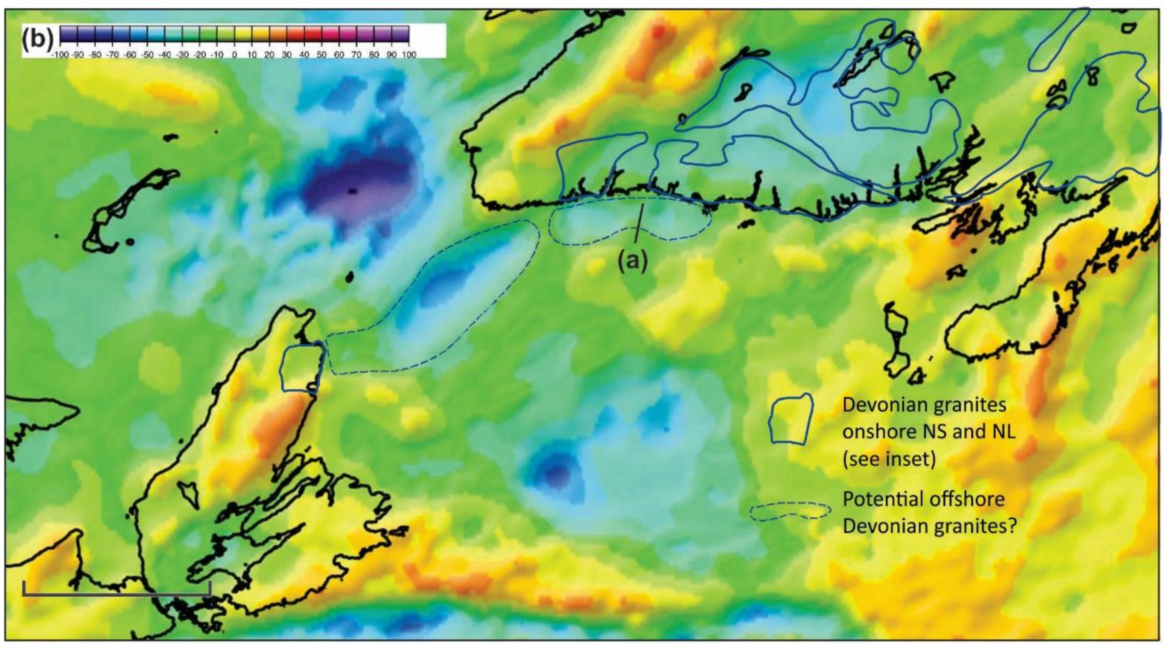


Figure 4.1.10 (a) High resolution seismic line (see (b) and Figure 4.1.8 for line location) **(b)** Gravity anomaly map with polygons drawn from (c) to note the location of onshore Devonian granites. Dashed blue lines represent possible gravity expressions from offshore granites. Gravity anomaly map modified from Dehler and Roest (1998) **(c)** Surficial geology map of southern Newfoundland and Cape Breton Island with arrows noting the locations of low density granites. NS geology from Keppie (2000), NL geology from Coleman et al. (1990)

4.2 Structure and Stratigraphy

A total of 9 seismic markers were correlated across the study area (Figure 2.2). A velocity model was built to depth convert mapped seismic markers, to produce isopachs and correct a number of velocity artifacts produced by the Laurentian Channel and recent Quaternary glacial deposits. North Sydney F-24 and North Sydney P-05 (see Figure 4.2.1 for well locations) were used to generate the time-depth relationships for the model. These wells are 6 km apart and only penetrate the upper 1700 meters of the Sydney Basin which is shown to be up to 7 km thick. Although the wells are representative of only a small portion of the basins stratigraphic succession they do provide time-depth curves for the Mabou Group and shallower intervals. A linearly increasing velocity was used for the section below the well TD, Windsor and Horton groups, reaching a maximum of 4500 m/s at the D360 seismic marker.

The D360 seismic marker, as described earlier, is below the drilling depths of all offshore wells, and can be difficult to identify on some seismic lines. In the southern regions of Sydney Basin the exact boundary between the Horton Group (or older Devonian McAdams Lake Fm.) and basement is uncertain (Figure 4.1.4). South-southeast of the North Sydney wells the D360 horizon marks the base of reflectivity within faulted blocks. This is based on an assumption that the loss of reflectivity below this marker represents the Mira basement terrane, while layered reflections above the D360 are sedimentary rocks of the McAdams Lake Formation and/or Horton Group.

The C352 seismic horizon marks the Windsor-Horton contact (Figure 2.2). Where possible, it is interpreted at the base of a high-amplitude doublet that likely represents the basal anhydrites of the Windsor Group (Figure 4.1.4(c)). This basal Windsor reflection is well documented throughout the Maritimes Basin. The faulted/deformed nature of this doublet is consistent with interpretations that benefit from Windsor and Horton well control in other basins; e.g. Kennetcook Basin (Waldron et al., 2010) and Magdalen Basin (Durling and Marillier, 1990; Durling and Marillier, 1993). A potential alternate scenario is that the C352 marker represents the boundary between Horton and the Mira basement, and that any coherent reflections below C352 are actually meta-sedimentary rocks within the Mira Terrane. In this study, C352 is the preferred boundary between Windsor and Horton and when mapped as such, the distribution of the Horton Group is as shown in Figure 4.2.2. The Tournasian Horton deposits of predominantly lacustrine shales and sandstones are confined to the central and southern regions of Sydney Basin but may also be present within the CRG.

Figure 4.2.3 is a grid of the diachronous C325 seismic horizon. Near the wells, C325 represents the top of the Windsor Group, which although not penetrated in the two the North Sydney wells is assumed to be just below their TDs. Away from the wells, the uncertainty for what this seismic horizon represents increases. The seismic marker stays above all identified salt diapirs, and below the Namurian unconformity, although the latter is not well defined on seismic. Therefore, in most scenarios the C325 is a top Windsor seismic horizon but in some areas may also represent the Namurian Unconformity and/or the top of the Mabou Group. The C325 to C352 (Windsor to Horton) interval is a marine unit, with deep marine evaporitic deposits at its base that transition upwards to interbedded, shallow water, bioclastic limestones, siltstones and shales near its transitional boundary with the overlying Mabou Group (Boehner and Giles, 2008).

Historically, it has been difficult to determine if Windsor Group salt is present within the offshore Sydney Basin. The existence of this Visean salt would improve confidence that there is adequate seal in place for trapping migrating hydrocarbons sourced from the underlying Horton shales. Webb (1973) noted a potential diapiric salt structure in the southern region of Sydney Basin (Figure 4.2.4). This diapir/salt wall is in Parcel 3 underlies an east-west trending fold visible on multiple structure maps (Figures 4.2.3 and 4.2.5) This diapiric feature is mappable across multiple seismic profiles and likely extends further to the east beyond the current seismic data coverage.

Throughout Parcels 1 and 2 Windsor salt is likely present

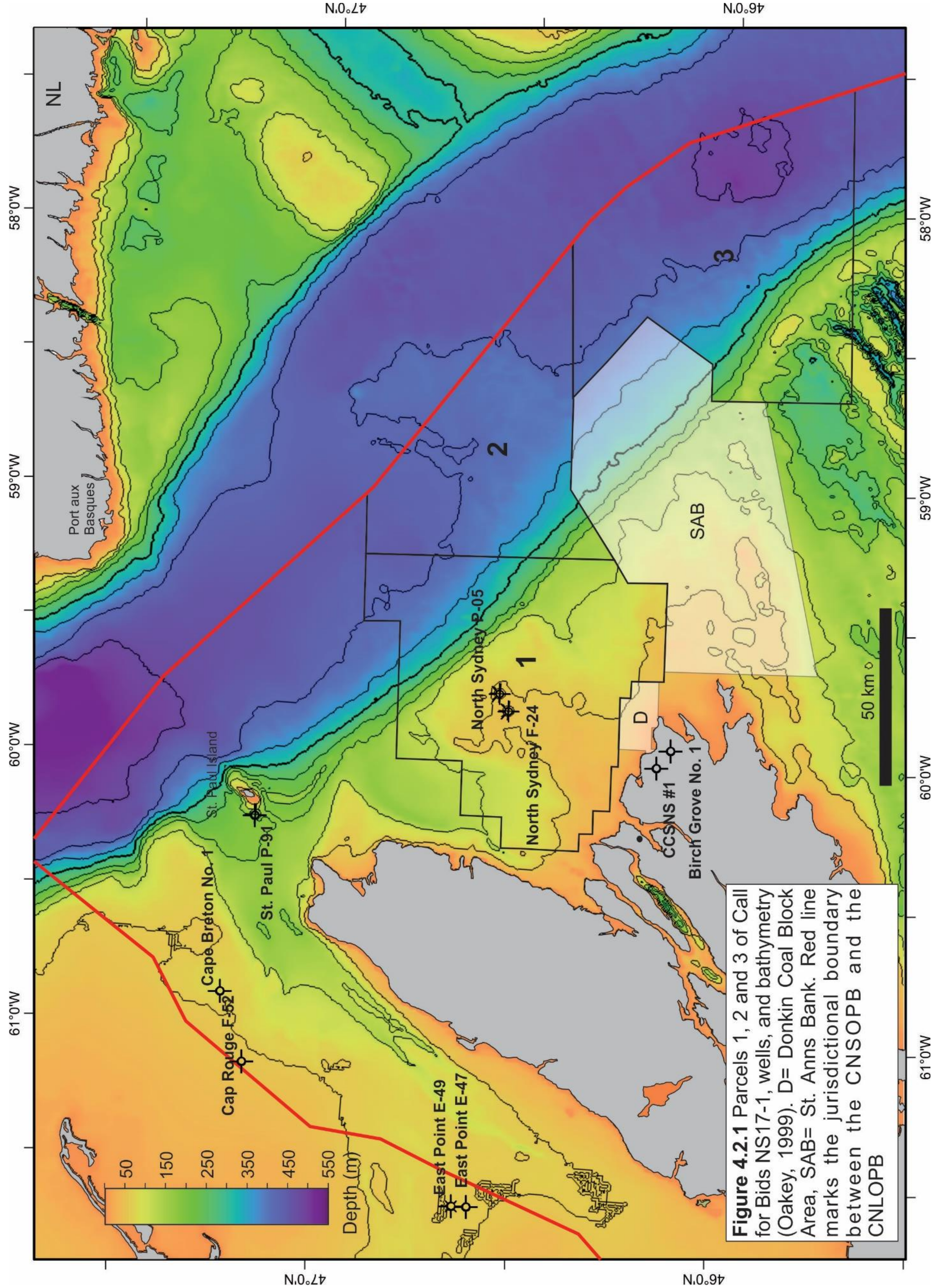


Figure 4.2.1 Parcels 1, 2 and 3 of Call for Bids NS17-1, wells, and bathymetry (Oakey, 1999). D= Donkin Coal Block Area, SAB= St. Anns Bank. Red line marks the jurisdictional boundary between the CNSOPB and the CNLOPB

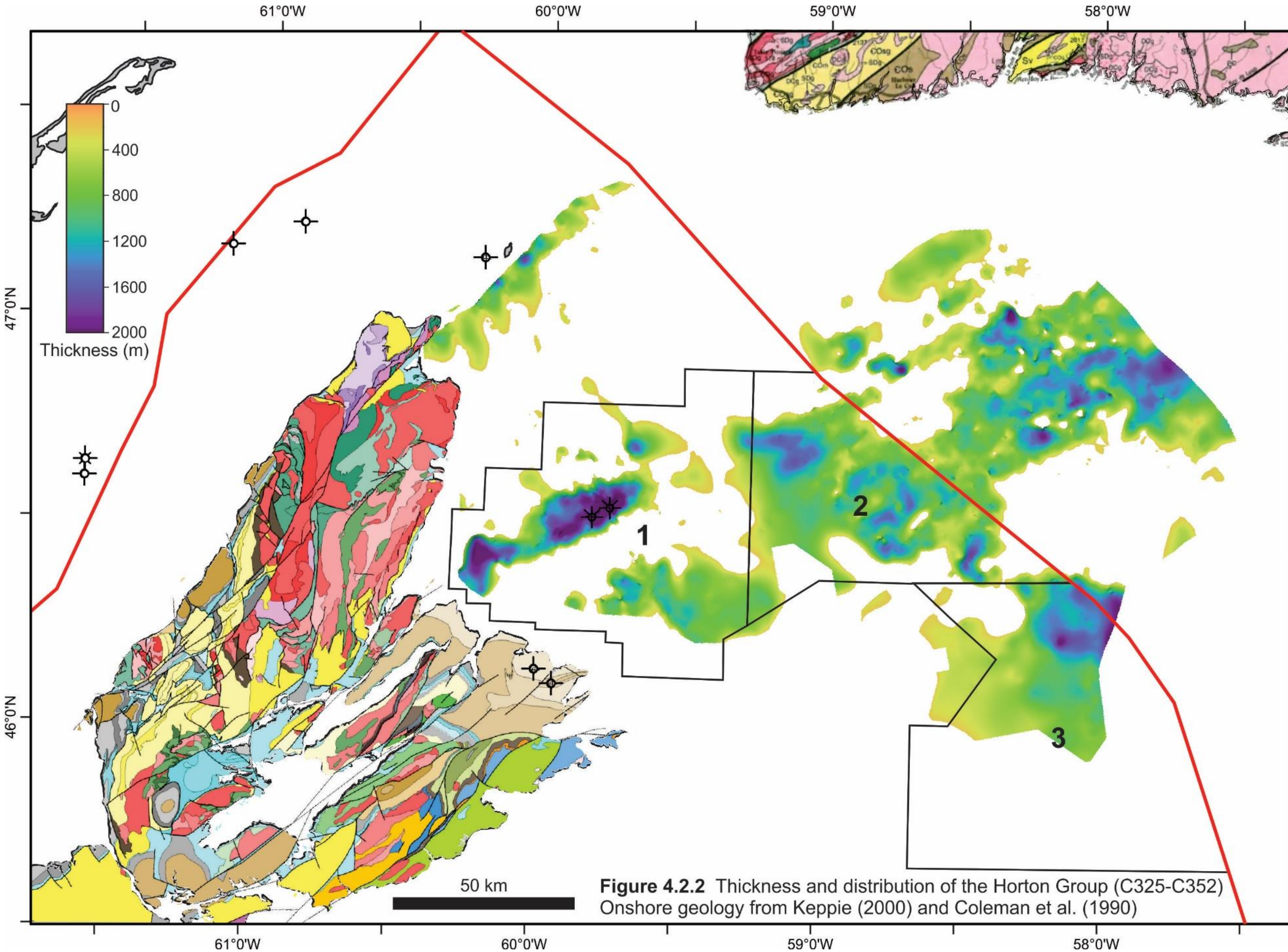


Figure 4.2.2 Thickness and distribution of the Horton Group (C325-C352) Onshore geology from Keppie (2000) and Coleman et al. (1990)

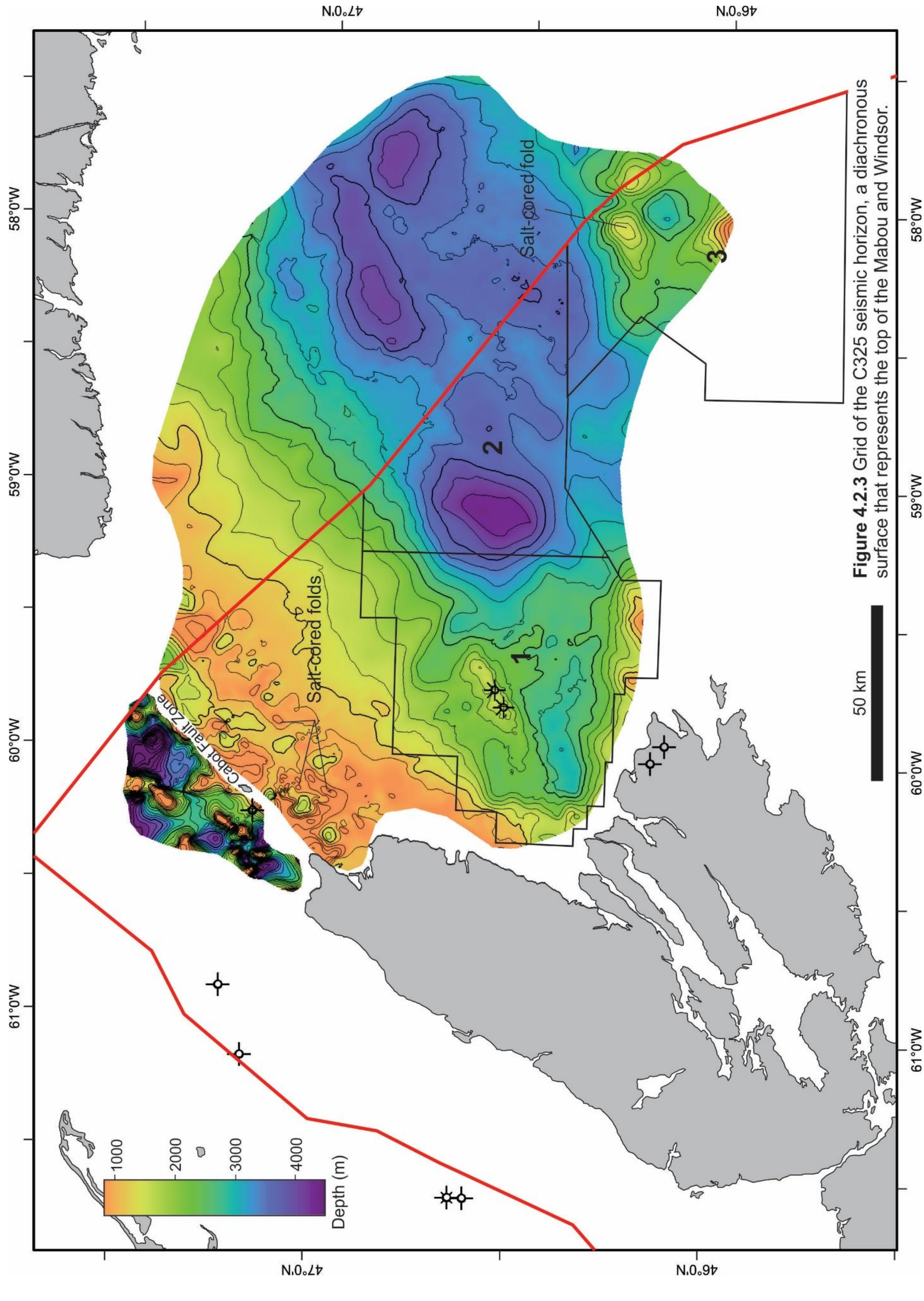


Figure 4.2.3 Grid of the C325 seismic horizon, a diachronous surface that represents the top of the Mabou and Windsor.

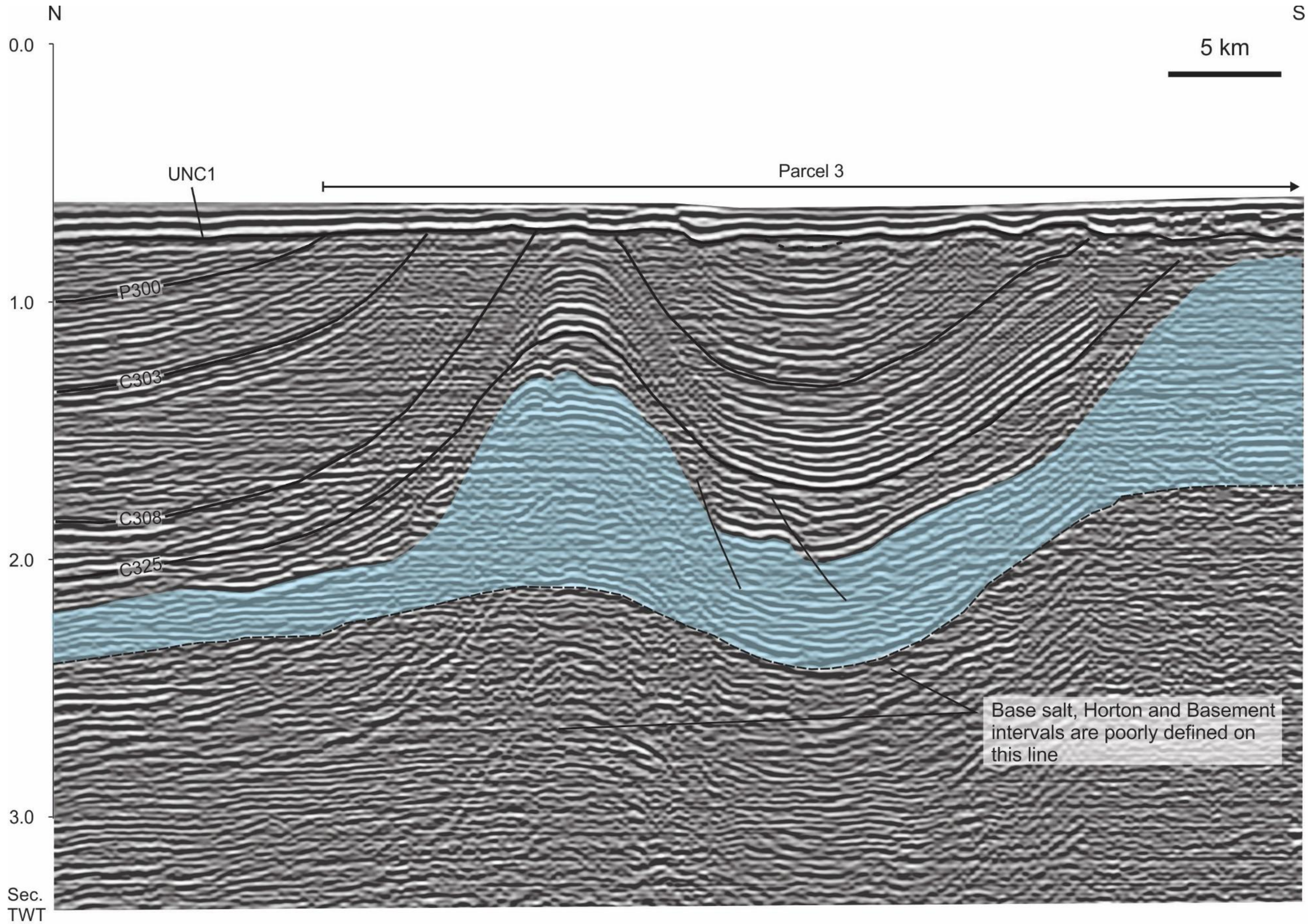


Figure 4.2.4 Seismic line F from survey 8624-T007-006E, illustrating diapiric structure within Parcel 3. Horizons deeper than Windsor are challenging to interpret on this line and not represented.

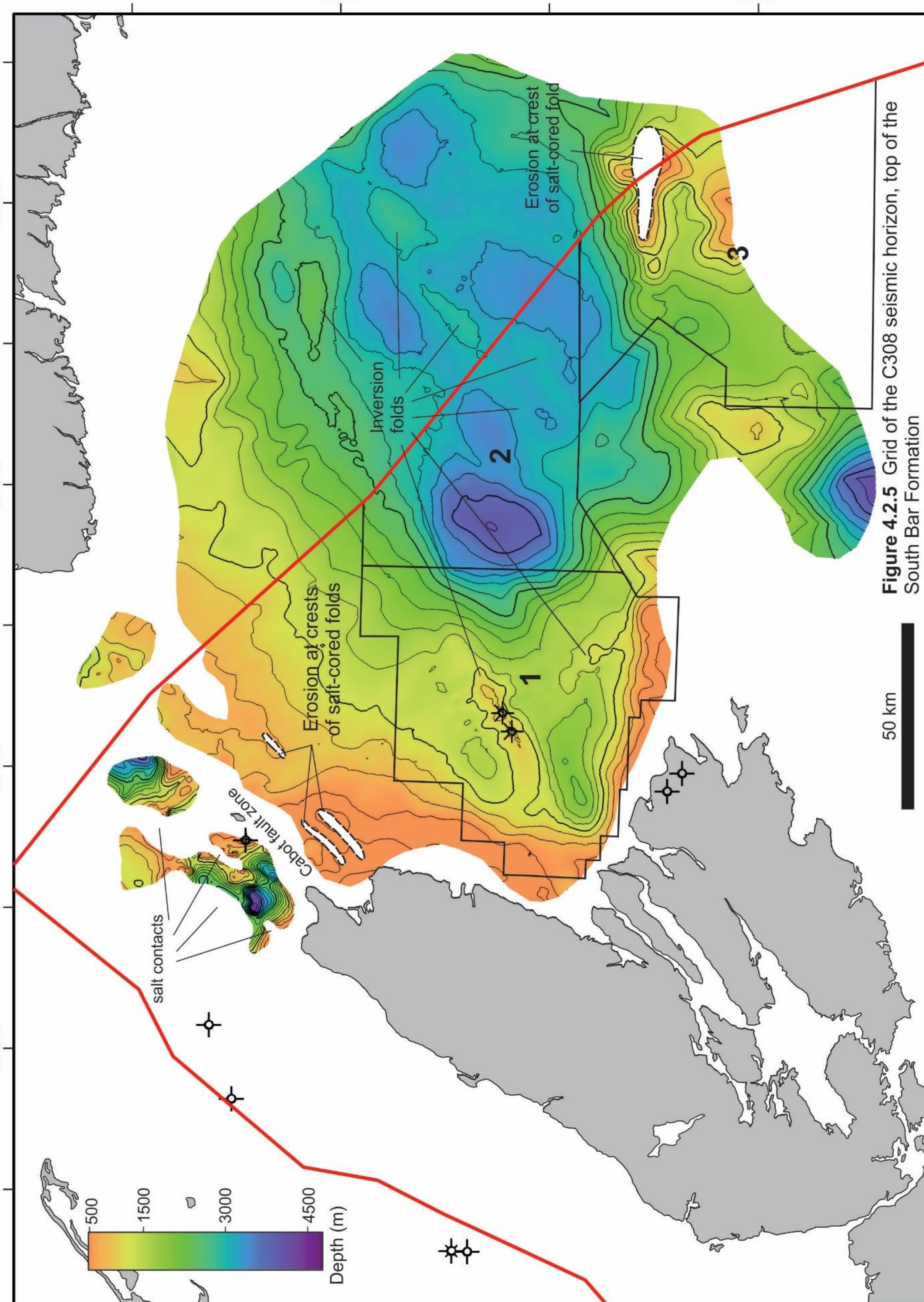


Figure 4.2.5 Grid of the C308 seismic horizon, top of the South Bar Formation

but there is no strong evidence for diapiric structures. The Windsor Group here would have filled paleo-topographic lows created by earlier movement along faults that offset both the Mira basement and the Horton Group (Figures 4.1.3, 4.1.4 and 4.1.7 and 4.1.9). The blue polygons in these seismic profiles outline what appear to be mobile units with the Windsor Group. This unit is noted to deform, accommodate younger loading and in some cases rise up along bounding footwalls. All evidence that the strata within the blue polygons could be composed of a mobile facies (i.e. Windsor evaporites)

North of Parcels 1 and 2 but south of the CRFZ, diapiric salt structures, or any potential mobile Windsor units, are not recognized on the current seismic datasets. This is the region where the Bras d'Or and Aspy Terranes are quite shallow (perhaps existing as long-lived paleo-high?) and like the Horton Group, Windsor strata would likely be very thin to nonexistent here.

North of the basement high, probable salt diapirs/walls are interpreted in the CRG (Figures 4.1.3, 4.1.6 and 4.1.7). Dip lines through this graben show faint, folded and dipping reflections that are interpreted to represent folded strata overlying the diapirs (Figure 4.1.6). Previous authors' interpretation in this graben follow the flat-lying reflections that are most likely a combination of conventional seafloor and peg-leg multiples; and thus not valid seismic events. The wide spacing of the dip-oriented seismic lines make this difficult to confirm on the industry seismic data. However, high resolution Geological Survey of Canada research shallow seismic data also cross this graben and were used to confirm the presence of dipping reflections (Figure 4.1.6(c)). This confirms that the dipping seismic reflections are present; and that previous interpretations on the "flat" reflections (multiples) are not representative of the geology in the CRG. These folded events can also be mapped to the northeast on neighboring seismic lines throughout the CRG which suggests these features are linear salt-cored walls that trend southwest-northeast.

Correlation to onshore outcrops also support the interpretation that these folded strata are likely diapirs. Line 81-1121 (the line shown in Figure 4.1.3) is a dip line located just offshore of Aspy Bay. Both Horton and Windsor groups outcrop in Aspy Bay, making it very plausible for the mobile units of the Windsor Group to be present a few kilometers offshore. Previous studies place Pennsylvanian strata at this elevation within the graben. A tie to the onshore outcrops in this scenario is less straightforward, and a large offset, north-south trending fault would be necessary. A fault of such large offset may be possible, but the required north-south trend is unlikely given the predominant east-west trend of the major strike-slip faults in the region.

The C308 seismic horizon marks the top of the South Bar Formation of the Morien Group (Figure 2.2 and 4.2.5). The South Bar Formation is a fluvial unit that is predominately composed of sandstones (Boehner and Giles, 2008). Some of these sandstone units are gas-charged in the anticline tested by the North Sydney wells. The South Bar Formation reaches burial depths of 4 km within Parcel 2 and shallows to the north and south. Locally, the uppermost parts of this surface is eroded over the crest of diapirs. The mid-lower section of the South Bar unit is still present overlying the salt diapir in Parcel 3 and is a potential reservoir unit here.

The C303 structure map for the comformable overlying Sydney Mines Formation is very similar to the South Bar (Figure 4.2.6). Its deepest burial depth is within Parcel 2 and it shallows to the north and south where it is eroded near the seafloor by an unconformity (UNC 1 on all figures). The precise age of this erosion is unknown, but it is no older than Permian and possibly as young as Mesozoic. It's likely that this UNC 1 seismic horizon represents a merger of many different aged unconformities, potentially as old as Permian and others as young as the recent glacial events (Holocene).

The Pictou Group consists of alluvial deposits of red mudstones and sandstones (Figures 2.2 and 4.2.7). A precise "top" of the Pictou Group is not present in the wells but recent biostratigraphy (Weston et al, 2017) determined that this unit is present at the top of the North Sydney wells. The C300 seismic marker is within Permian aged strata and marks a notable seismic boundary between a higher amplitude, channelized unit (above C300) and a low amplitude seismic facies with

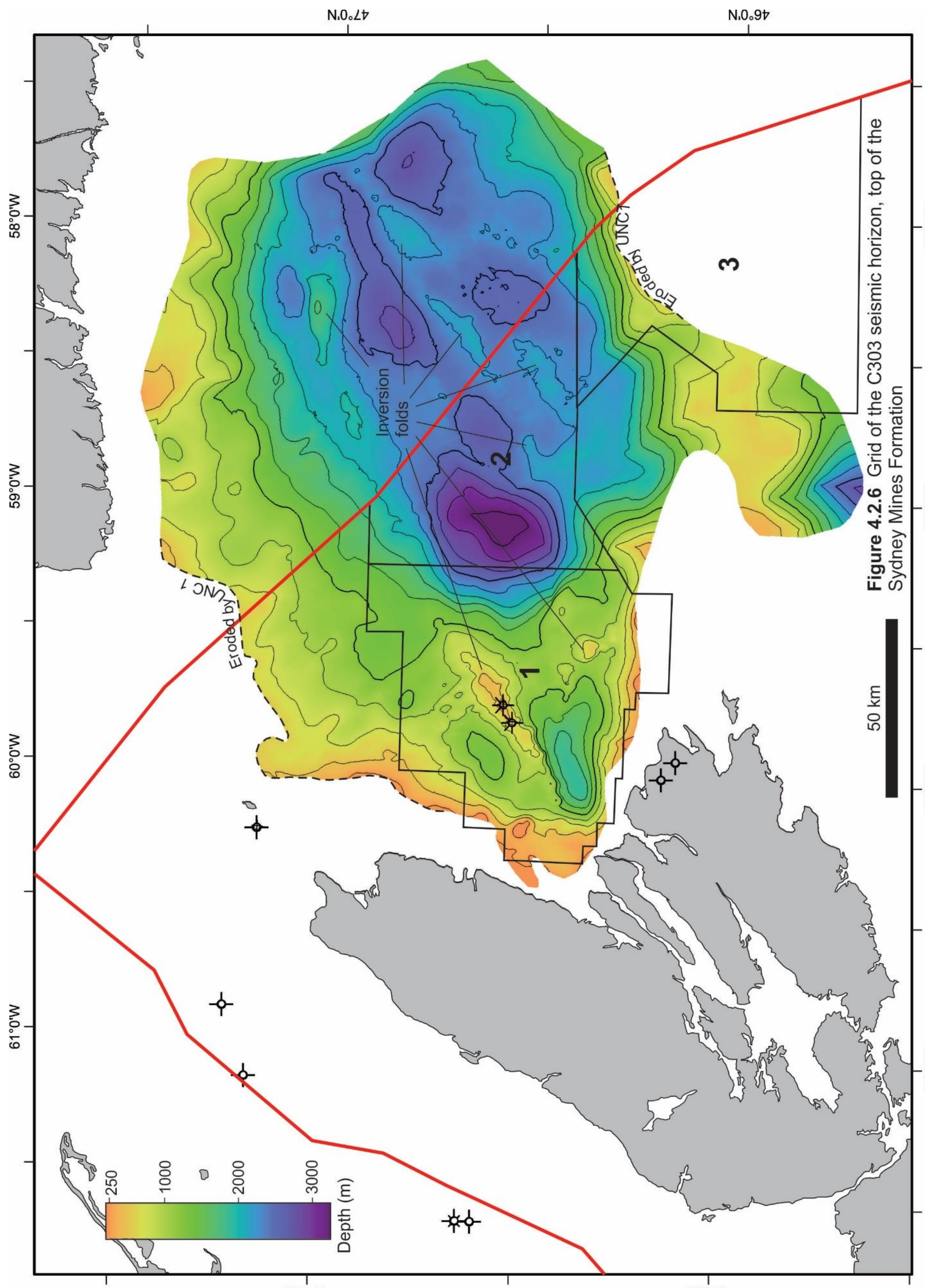


Figure 4.2.6 Grid of the C303 seismic horizon, top of the Sydney Mines Formation

predominantly parallel seismic reflectors (below C300) (Figure 4.1.4). Within this study, the C300 arbitrarily represents the Top of the Pictou Group, while the shallower P285 represents a second intra-Permian unit, with a distinctly different seismic facies (Figure 4.2.8). This upper interval (P295-C300) may be equivalent to the Permian sandstones identified in multiple Magdalen Basin wells by Giles and Utting (1999). The P295 is only present/preserved in the central Sydney Basin, within Parcel 2 and at the eastern edge of Parcel 1.

Isopach Maps and Summary of Tectonic Events

The total thickness map shows deep depocenters (7 km or more) in the south-central part of Sydney Basin (Figure 4.2.9 a,b). The initial strata within these depocenters are the Late Devonian to Early Carboniferous McAdams Lake, Horton and Windsor groups. These formations infilled the rifted Mira (Avalon) Terrane basement rocks. The early rifting, that is primarily focused in the Mira Terrane is likely related to the middle-late Devonian Acadian orogeny (Pascucci et al., 2000). The post-Windsor Late Carboniferous successions of fluvial, floodplain and alluvial deposits subsequently filled the basin once the Acadian related rifted topography had been infilled. Localised depocenters are not present in the Late-Carboniferous, and thickness maps of these sequences display a broad-scale regional thickening to the south (Figure 4.2.10). This thickening trend is likely related to both regional subsidence (thermal relaxation?) and salt withdrawal. This Late Carboniferous loading of underlying Windsor units formed the east-west trending salt wall that is present in the southern part of the basin. An apparent lack of thinning near the crests of multiple folds on seismic lines and late Carboniferous thickness maps, is evidence that this inversion-related folding throughout the basin occurred very late, likely in the Permian or later (Figures 4.2.3, 4.2.4, 4.2.7, and 4.2.10). The mechanism for this late inversion event is most likely a strike-slip and/or reverse reactivation of the older Acadian faults, possibly related to the initial phases of rifting in the Central Atlantic region starting in the Middle Triassic.

5.0 Source Rocks

Within the onshore Maritimes Basin, known and potential source rocks exist in rocks ranging from Early Devonian to Late Pennsylvanian age, and believed to extend into the adjacent offshore regions Table 5.1). While extensive studies were completed in the former, the small number of wells (11), depth of penetration, and sampling issues together constrains confidence in their characteristics and extent there. There have been a number of studies and analyses on potential source rocks. As related to the Sydney Basin, Mukhopadhyay (2004) and most recently Fowler and Webb (2017) provide compilations, and new analyses of source rocks in Cape Breton Island's onshore and offshore basins.

There are only two wells in the offshore portion of the Sydney Basin. Neither penetrate the known rich oil- and gas-prone Horton Group lacustrine successions nor confirmed the presence of younger Windsor (restricted marine) and Mabou (lacustrine) source intervals. Evidence reveals the presence of some organic-rich rocks in shallower sediments. Tables 5.2 to 5.8 are compilations of geochemical analyses by group and formations for all five wells in the Sydney Basin. Note that not all wells are included in each table. This is because either well did not penetrate the respective formation, and/or no analyses were performed (e.g. CCS-NS No.1). For the two North Sydney wells, kerogen type was not defined in their tabulated analyses, but was identified as type III based on descriptions and commentaries in the reports. The coarse sampling procedures (decametres) limits the identification, physical characteristics and analysis of organic-rich intervals or beds. Electric logs have also not identified such intervals. Nevertheless, useful information on the sections penetrated and their potential does exist.

5.1 Devonian – Guysborough Group

The oldest potential source rock in the Sydney Basin is

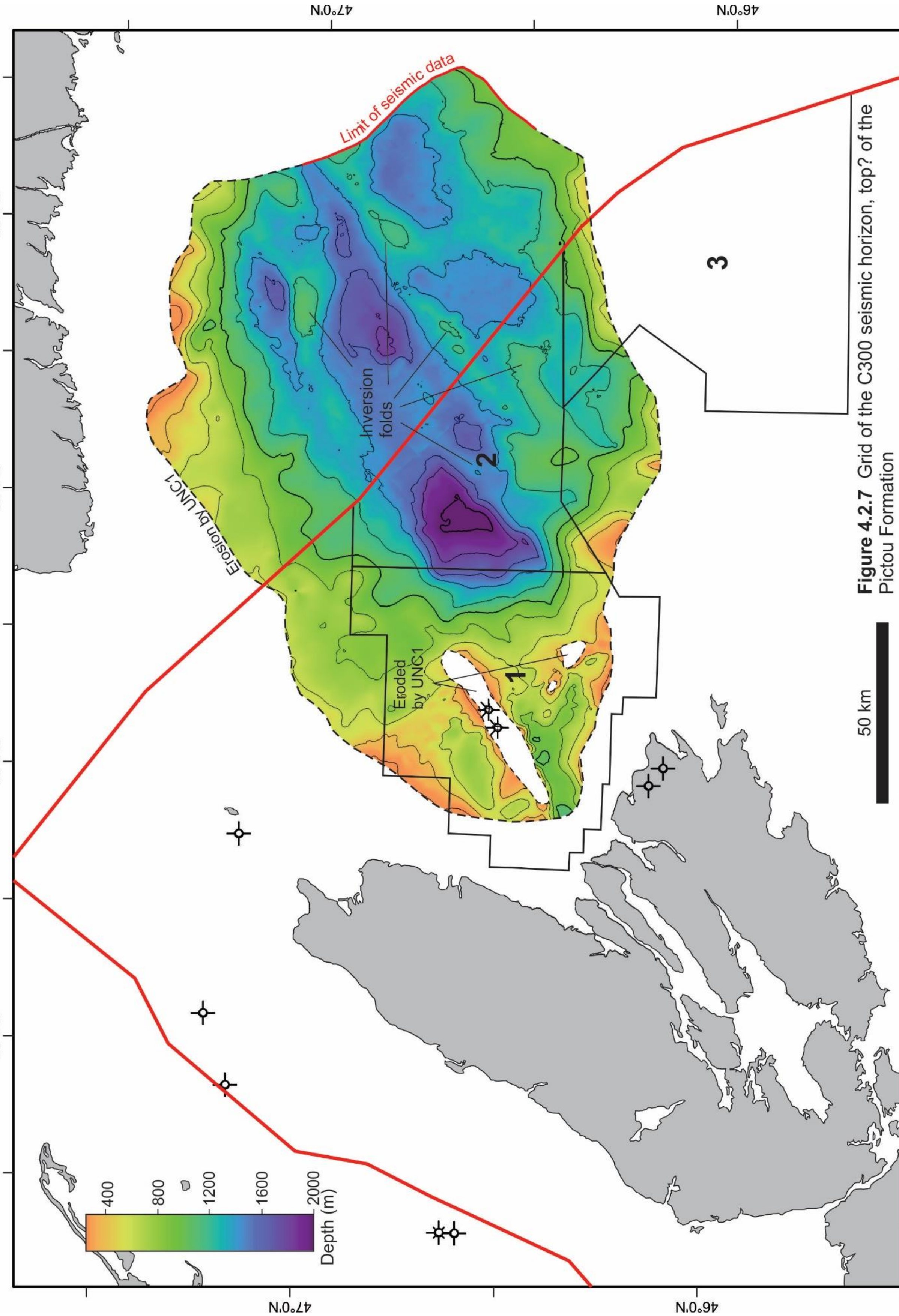


Figure 4.2.7 Grid of the C300 seismic horizon, top? of the Pictou Formation

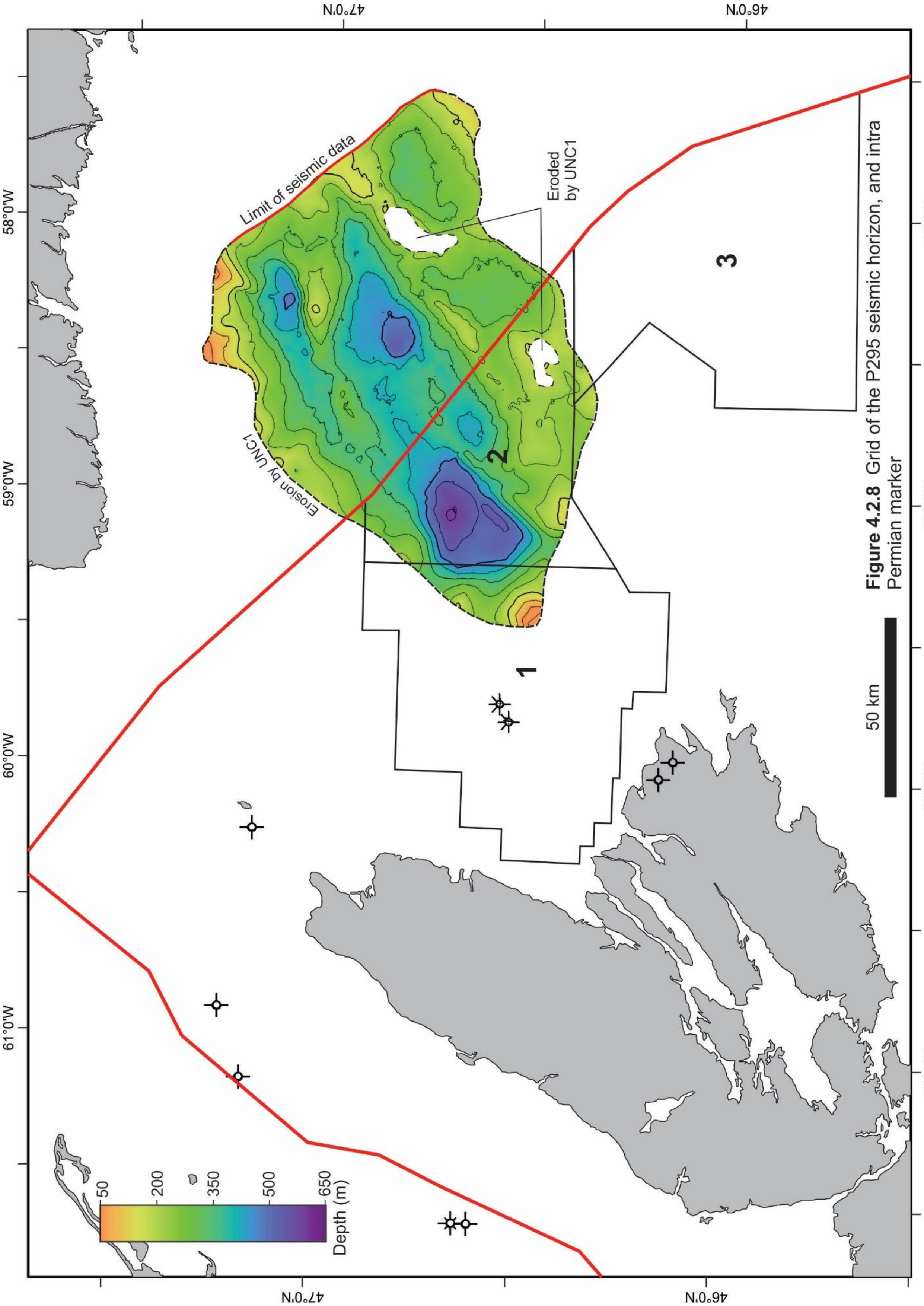


Figure 4.2.8 Grid of the P295 seismic horizon, and intra Permian marker

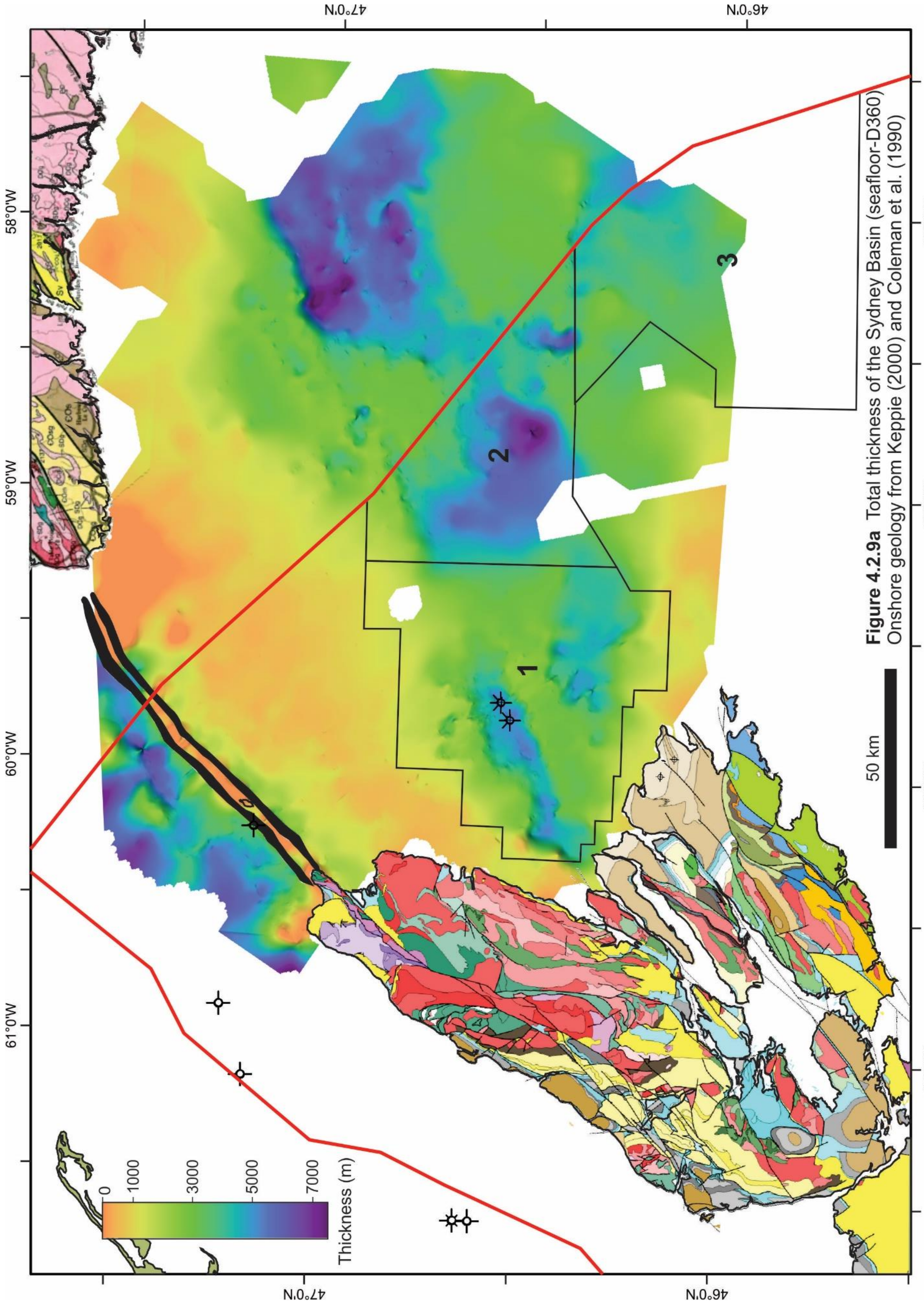


Figure 4.2.9a Total thickness of the Sydney Basin (seafloor-D360)
Onshore geology from Keppie (2000) and Coleman et al. (1990)

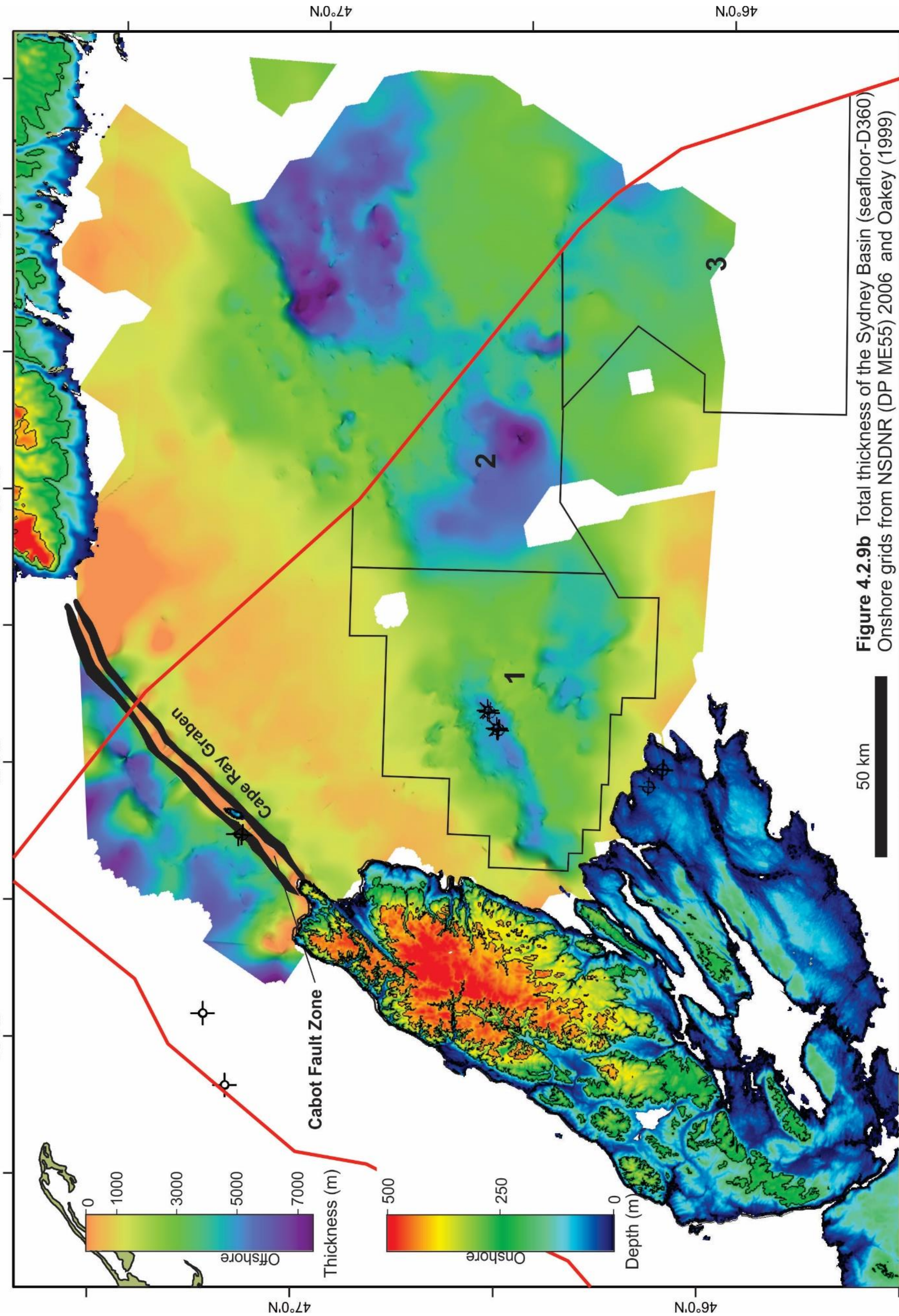


Figure 4.2.9b Total thickness of the Sydney Basin (seafloor-D360) Onshore grids from NSDNR (DP ME55) 2006 and Oakey (1999)

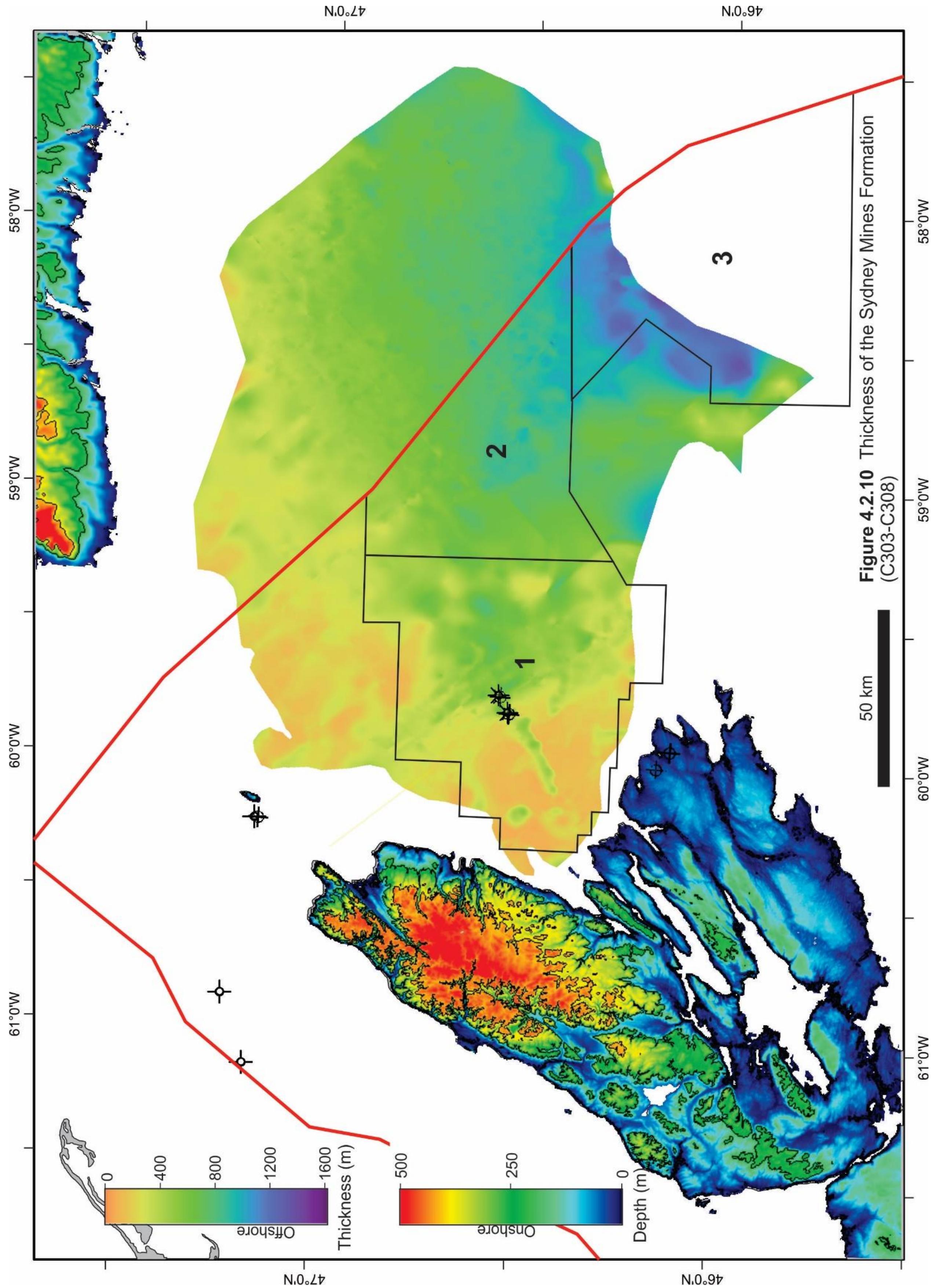


Figure 4.2.10 Thickness of the Sydney Mines Formation (C303-C308)

Table 5.1: Proven and potentail source rock intervals in the Sydney Basin.

Unit (Fm. / Gp.)	Age	Source Rock	Depositional Environment	Cumulative Thickness (m)	Av TOC %	OM Type	Original HI (mg/g)	Comments
				PENNSYLVANIAN				
Sydney Mines Fm. (Morien Gp.)	Westphalian D - Stephanian	shales	fluvial floodplain: lacustrine & coal swamp	15	55	III-IV	200	Source of gas, probably as CBM - resource potential previously assessed.
Sydney Mines Fm. (Morien Gp.)	Westphalian D - Stephanian	oil shales	as above	2	10	II-III	450	A number of thin intervals with about 2 m cumulative thickness (Gibling and Kalkreuth, 1991).
Sydney Mines Fm. (Morien Gp.)	Westphalian D - Stephanian	dull coals	as above	1	55	II	500	Probably less than 1 m thickness (Marchioni et al., 1994).
				MISSISSIPPIAN				
Windsor Group	Early Visean	carbonates, evaporites & shales	deep marine evaporitic	5?	3	II	450	Macumber Formation (basal Windsor) not yet observed in the Sydney Basin, but present elsewhere onshore Cape Breton Island. Thin high-TOC shaley and dolomitic intervals within overlying evaporites are known elsewhere but with lower HI than suggested. Liquid oil has been observed/recovered from borehole cores (McMahon et al., 1986).
Strathlorne Fm. (Horton Group)	Mid Tournasian	shales	lacustrine	>5 to 100+ - use average of 30 m?	5	I-III	500	Proven oil and gas source rock in the Maritimes Basin but not yet observed in the Sydney Basin. Thickness varies widely between different onshore subbasins. Varying proportions of Types I and II OM.
				DEVONIAN				
McAdams Lake Fm. (Guysborough Gp.)	Latest Emsian - Early Eifelian	shales	lacustrine	5	5	I-III	400	Historically mined as an oil shale (Smith & Naylor, 1990). Thickness based on NSDME #2 drillhole. HI estimated only (Fowler and Webb, 2017).

Source: *Via M. Fowler. Modified after Summary Table based on report by Fowler and Webb, 2017: "Sydney Basin Petroleum Systems - Synthesis of Historical and New Geochemical Data", Applied Petroleum Technology (Canada) Ltd., 276 p. Annex to Offshore Energy Research Association "Sydney Basin - Play Fairway Analysis", 2017.*

the McAdams Lake Formation. It is found in a narrow, elongate, northeast-southwest trending half graben formed at the fault boundary between two Avalon composite terranes – the Mira and Bras d'Or – at the southwestern end of the onshore Sydney Basin (White and Barr, 1998). The formation is unconformably overlain by alluvial fan conglomerates of the Tournasian Horton Group (Grantmire Formation), with a time gap of about 40 Ma spanning the unconformity. Plant and palynology date the formation as latest Emsian to Early Eifelian (latest Early to Middle Devonian). Mapping and drilling of the succession reveals a thickness of about 1000 m, and post-deposition it underwent a period of compressive deformation with related folding.

The McAdams Lake Formation represents deposition in a rifted continental setting, with two sequences defined: a lower unit with siliciclastic deposition in a shallow lacustrine setting with proximal alluvial fan deltas, and an upper unit represented by prograding alluvial fan deltas and associated braided streams possible due to rift margin uplift. Within the upper unit were periods of possible basin subsidence (and climatic changes?) whereby lakes expanded and transgressed over coarser grain marginal facies (White and Barr, 1998).

The depositional setting and lithofacies is similar to that of the younger Horton Group, with the middle Horton having well defined oil- and gas-prone source rocks elsewhere in the various onshore subbasins of the Maritimes Basin, and is the source for hydrocarbon production in southeastern New Brunswick (see Section 2). Within the McAdams Lake's lower unit there are carbonaceous to coaly shale beds 0.6-3.0 m thick informally described as 'oil shales' (citations in Smith and Naylor, 1990). Limited mining and assessments were undertaken with liquid petroleum generated from the rocks, but with no commercial production.

In an assessment of potential oil shale resources in Nova Scotia, Smith and Naylor (1990, p. 11) quoted assessments completed by others that revealed the shales were "…thermally mature (within the oil window)", and with Ro of 0.86-1.06. Total organic carbon (TOC) content ranged from 2.5 to 18.5%. Hydrocarbon indices were not quoted by these authors, though they stated that the organic carbon was derived from humic (Type III) rather than algal sources.

Mukhopadhyay (2004) analysed three samples from a borehole with results similar to those quoted by Smith and Naylor (1990) with shale samples thermally mature (Ro 0.74-0.87), and TOCs from 1.67-9.28 though with the Type III kerogens having quite low hydrogen indices (13.71 mg HC/g TOC). Fowler and Webb (2017) undertook analyses of outcrop and borehole samples. The former were had very low TOCs thought due to the weathered nature of the outcrop. Better results were obtained from borehole samples. The shales were organic-rich with TOCs from 2.07-41% with low hydrogen indices (43-124 mg HC/g TOC), and revealed to be mature (Ro 0.92-1.00%). The authors suggest the observed low HIs could be the result of elevated maturity and migration of most hydrocarbons, therefore original HIs are estimated to originally been significantly higher with good potential for liquid hydrocarbon generation (see Table 5.1).

The McAdams lake Formation could have good potential as a source rock. Its presence in a half graben formed adjacent to a terrane boundary and lacustrine-alluvial stratigraphic succession mirror that of the younger Horton Group that has known excellent petroleum source rocks, occurrences, and hydrocarbon production. However, the McAdams Lake has limited areal extent though its presence in the basin beneath Mississippian and younger strata is unknown. In its marginal setting, it is thermally mature, and in distal deeper parts of the basin would have higher maturation. Furthermore, following deposition it underwent moderate compressional deformation followed by a period of erosion with ca.40 Ma elapsed time before buried by earliest Mississippian Horton Group sediments. Over such an extended time, any existing traps and migration pathways for possible hydrocarbons generated could have been breached / eroded. Distal basin accumulations may have had a better chance of preservation but in turn deeply buried in the Carboniferous with commensurate elevated thermal maturity.

5.2 Mississippian – Horton, Windsor & Mabou Groups

The Tournasian Horton Group is found in all four Atlantic Canadian provinces, and is the first post-Acadian Orogeny sedimentary succession extending across all Appalachian terranes in the region. It was deposited in an inter-montane setting created through complex transtensional tectonism within which were rapidly subsiding grabens and half grabens. Though there are local variations, in a broad sense, the group displays a tripartite subdivision with a basal alluvial-fluvial succession, followed by underfilled deep lake systems, and capped by fluvial strata.

On Cape Breton Island, the Horton is subdivided in ascending order into the Craignish, Strathlorne and Ainslie formations respectively. However, in the Sydney Basin, Horton sediments are limited to the basin margin conglomeratic alluvial fan facies of the Grantmire Formation (Boehner and Giles, 2008). The Grantmire is most probably a diachronous succession, and laterally equivalent to the three basinal units. These probably exist in the subsurface there, though the paucity of onshore seismic lines has yet to confirm this.

As summarized by Fowler and Webb (2017; Table 5.1), Horton (Strathlorne) lacustrine successions on the Island can be up to 300 m thick. The formation is composed mostly of grey to dark grey mudstones with lesser amounts of fine grain sandstones and rare thin carbonates. Beds within the mudstones can be very rich, with TOC ranges from 2-20% with Types I and II kerogens. Hydrogen indices can be high where it remains immature.

Horton sediments are the proven and most prolific source interval in the Maritimes Basin (Dietrich et al., 2011; Fowler and Webb, 2017). In southeastern New Brunswick's Moncton Subbasin it is the source for the McCully field's gas production, and current and historic oil and gas production at the Stoney Creek field (see Section 2: Exploration History). In various locations throughout the region, especially rich intervals are recognized as oil shales and were mined for petroleum extraction. In the Lake Ainslie area of west-central cape Breton, oil shows from Horton sediments are known from oil seeps, well bores and outcrops (Bell, 1958; McMahon et al., 1986).

Liquid petroleum is associated with several base metal deposits in Nova Scotia preserved in inclusions and porous rocks of the basal Windsor Group carbonate, the Macumber Formation (Sangster et al., 1998). For example, at the Walton Ba-Pb-Zn-Cu-Ag deposit on the mainland, its Horton source is confirmed through geochemical analyses and was formed by thermal maturation of proximal Horton organic rich source rocks by hot mineralizing fluids (Kontak and Sangster, 1995). A similar situation is recorded at the Jubilee Pb-Zn deposit in the Bras d'Or Lake region of central Cape Breton (Rogers and Savard, 2002).

Fowler and Webb (2017) sampled and analysed Strathlorne shale lithologies from several locations at the northern tip of Cape Breton Island in the Cape St. Lawrence area and compared them with earlier assessments (references therein). The rocks were found to have TOCs mostly greater than 1.00% (~0.27-6%) but variable HIs (<100-354 mg HC/g TOC) and S2 values. Those with elevated Tmax values (~450-485°C), low S2 and HI values indicated thermally maturity to overmaturity (Meat Cove and Salmon River). Conversely, samples from another site (e.g. Bay Road Quarry) were less mature with higher parameter values. Biomarkers confirmed Type II and some Type I kerogens from algal-rich lacustrine facies.

Though not penetrated in the on- and offshore parts of the Sydney Basin, Horton Group sediments most probably exist in the basin. Development of the Middle Horton's Strathlorne Formation lacustrine facies (or its equivalent) is uncertain, though if present would be an excellent source rock prone to generating liquid hydrocarbons, and gas with increasing maturity. Its distribution is confined to faulted depositional lows that through time may have become interconnected. However, consideration must be given to the fact that the Horton has undergone several tectonic events since its deposition: burial, faulting, uplift, faulting / folding, erosion, burial. All would have an impact on its burial history and timing of maturation and migration into coeval / adjacent or overlying reservoirs. Early inverted Horton basins adjacent to local and/or major faults would offer the best potential for retention of organic matter and attenuated maturation over time.

It should also be noted that the Horton outcrops described above are located in small depositional troughs within the Cabot Fault System. This terrane-bounding fault system extends across the Cabot Strait to Newfoundland and separates the Sydney and Magdalen basins. Its positive expression within the Strait was the target of the Petro-Canada St. Paul P-91 well (see Section 2: Exploration History). It is thus difficult to determine which basin these outcrops are associated with. Biostratigraphy has confirmed that the well did not penetrate any Horton or younger Windsor group sediments (Weston et al., 2017).

Windsor Group

Strata of the Viséan Windsor Group conformably to unconformably overly the Horton Group, with the latter having in some cases near active faults undergone modest deformation. Its areal extent is greater that the Horton and displays an onlapping relationship with underlying and marginal rocks. The Windsor records the first – and only – significant marine incursion into the Maritimes Basin with sediments recording deposition in deep water to peritidal settings.

The Windsor Group is divided into five major depositional cycles and grouped into a lower (2) and upper (3) successions, and like the Horton shows some lateral variability in the different subbasins of the region. The lower Windsor records rapid filling of the (likely) sub-sea level basins and transgression of the basal carbonate – the Macumber and Gays River formations – reflecting deposition in deep water slope to below wave-base outer shelf environments respectively (Lavoie and Sami, 1998). This was followed by deposition of thick anhydrites and later salt, both under deep water conditions with the basin rapidly shallowing due to evaporative filling (Lavoie, 1995). The Macumber has not yet been discovered in the Sydney Basin though the four remaining depositional cycles are present with a maximum thickness of 1500 m (Boehner and Giles, 2008). The Upper Windsor represents deposition in the now shallow water and gently subsiding basins, with three cycles defined represented by a series of thin cyclic, transgressive-regressive carbonate-siliciclastic (and occasionally evaporitic) successions. Their formation is probably due to orbital forcing and related Gondwanan glaciation (Giles, 2009). Contact with the overlying Morien Group is generally transitional and conformable.

Potential source rocks are present within the entire Maritimes Basin Windsor succession though are volumetrically small with minor organic shales present in the upper Windsor with very good potential (Fowler & Webb, 2017). In such cases, the beds' areal extent is not known and could have limited local expression. In the onshore Sydney Basin, a review of previous analyses and new analyses from borehole samples by Mukhopadhyay (2004) inferred such rocks contained Types II-IV kerogens (mostly III-IV) with low TOC values. Fowler and Webb's review of his (ibid) generally concurred with this assessment though their analysis of several samples showed better potential. New sampling and analyses of borehole cores and outcrops of upper Windsor rocks by Fowler and Webb (ibid) found that they generally composed of Type III kerogens with low-moderate TOCs (1-2.5%), low to fair HIs (100-200) and variable maturities.

Only the St. Paul P-91 well penetrated about 700 m of the Windsor that was limited to the Upper Windsor (equivalents to the Woodbine Road and Kempt Head formations). Analysis of recovered lithologies by Kendall and Altebaeumer (1984) indicated that all successions drilled had reached a very high level of thermal maturity with little to no generative potential for hydrocarbons (Tables 5.2 and 5.3)

The better source rocks are present in its lower part: the Macumber and overlying evaporite succession. The Macumber contains thin-bedded limestones and dolomites with organic-rich shale beds. It has a regional distribution throughout the Maritimes Basin though is relatively thin with variable thicknesses (3-30 m; Lavoie and Sami, 1998). However, in the undrilled deepest parts of the Maritimes and Sydney basins it could be thicker. As shown in Table 5.1, they are composed of Types I and II kerogens (in varying proportions), with have high average TOC (5%) and hydrogen indices (450). Thin (cm) organic-rich dolomite and shale beds are common within the overlying thick anhydrite and salt interval and observed in outcrops, quarries and mines (salt) with in some cases liquid petroleum. Their contribution to known petroleum systems is modest though should be greater in the centre of the Maritimes Basin salt province offshore western Cape Breton Island.

Oil staining is common in Windsor group onshore Cape Breton Island, and there are a significant number of documented oil shows with a selected examples described in Section 2: Exploration History (see also McMahon et al., 1986; Mukhopadhyay, 2004). Numerous seeps and shows have been reported from outcrops, water wells, and mineral exploration borehole cores (Bell, 1958, McMahon et al., ibid). The latter are associated with Pb-Zn (plus other base metals) hydrothermal mineral deposits in the region hosted within the basal carbonate Macumber Member. In central Cape Breton, the Jubilee deposit is the best documented (Rogers and Savard, 2002). Indeed, the majority of such oil discoveries were inadvertent during exploration for these mineral deposits.

Analysis of oils and staining found in presumably Macumber carbonates from borehole cores from a number of locations in Cape Breton (e.g. Lake Ainslie, Jubilee Pb-Zn deposit, Malagawatch) was done by Mukhopadhyay (2004) and Fowler and Webb (2017). They reached broadly similar conclusions that these hydrocarbons had a terrestrial lacustrine source, with some biomarker evidence to suggest a contribution from a potential hyspersaline source (i.e., lower Windsor evaporites). Their character is very similar to those from the Horton (Albert Formation) in New Brunswick – the source of oils for the Stoney Creek oil field – having Types I II (and III) kerogens with high TOCs and HIs. Fowler and Webb (2017) also reviewed analyses of interpreted Windsor age source intervals in the offshore Sydney Basin wells. However, recent work by Weston et al. (2017a, b, and c) places these units in the younger Mabou Group, thus confirming the wells did not penetrate Windsor Group sediments (see below).

As confirmed through analyses, petroleum shows in Windsor Group rocks are sourced from lacustrine sediments in the underlying Horton Group, with modest contributions from the lower Windsor (Macumber and evaporites). Most are the result of normal burial diagenesis of organic-rich source rocks. Those oils associated with base metal deposits were created through heating of hot mineralizing (basin- or basement-derived?) fluids migration through and/or adjacent to organic rich lacustrine shale beds were undisturbed in deeper basin settings, Windsor source rocks could be thicker with higher organic content and greater petroleum generative potential. However, in such a setting very deep burial over time would exhaust its ability to create oils, and then gas. Attenuating its maturation through inversion of the rock column along basin-bounding faults could retain its potential and that on the underlying Horton.

Mabou Group

The Windsor Group is transitional into and conformably overlain by the Mabou Group. This is a transitional succession recording the Maritimes Basin's change from a marine to terrestrial depocentre. The late Viséan to Early Namurian Mabou is present throughout Cape Breton's Carboniferous basins and in the Sydney Basin and between 1 and 2 km thick deposited in a slowly subsiding basin with minor faulting along its margins. It is subdivided into two principle formations: the Cape Dauphin and Point Edward. The former is composed of shales, evaporites and minor carbonates recording the transition from a mixed marine-lacustrine to saline depositional environment in a continental setting (Boehner & Giles, 2008). The latter formation is transitional with interbedded varicoloured shales, siltstones, sandstones and minor conglomerates deposited in a subaerial lacustrine-fluvial setting with fluvial facies more common in its upper part.

The Mabou is present in all five wells in the Sydney Basins and outcrops onshore. Analyses of a limited number of samples from the three offshore wells indicates a low potential with Type III kerogens dominating, and though mature, the rocks appear to have had low original hydrogen indices (Tables 5.4 and 5.5). Mukhopadhyay (2004) considered the succession to have good source rock potential. A review by Fowler and Webb (2017) suggests that the Mabou has little petroleum potential due to low TOCs and HIs dominated by Type II gas-prone kerogens. The authors make an interesting observation regarding the possible potential in the lower Cape Dauphin. Similar age rocks in the Deer Lake Basin of southwestern Newfoundland are recorded to have very organic-rich and oil-prone lacustrine shales. Likewise across the Atlantic in Scotland a similar age unit contains oil shales composed of Types I and II kerogens with impressive TOCs approaching 15% with some hydrogen indices HI>900 mg HC/g TOC. The onshore Deer Lake Basin is on the northeastern margin of the Sydney Basin. Fowler and Webb (2017) speculated that if a similar depositional setting existed in the deeper parts of the basin, and if mature, it would be a significant oil-prone source rock.

5.3 Pennsylvanian – Riversdale, Morien & Pictou Groups

Riversdale Group

Within the onshore Carbon Capture & Storage Nova Scotia No. 1 well, Weston et al. (2017d) discovered an approximately 80 m thick sequence of thick fluvial sandstones and minor shales dated as Westphalian A (Langesettian). It was bounded above by the Westphalian B/A unconformity, and below by the major mid Carboniferous (Westphalian-Namurian) regional unconformity. Lithological correlations extended it into the nearly (9 km) Birch Grove No. 1 well. The lithologies are similar to the Silver Mine Formation defined by Boehner and Prime (1993) and are also of Westphalian A age. It is not observed in any of the offshore wells.

A similar aged and unconformity-bounded succession is present on the Nova Scotia mainland originally designated as the Riversdale Group. Boehner and Giles (2008) note that the revisions in Carboniferous stratigraphy had the Riversdale had long been incorporated into the underlying Mabou Group (Belt, 1964; 1965). For sake of convenience, these rocks are placed under the old Riversdale Group nomenclature. Regarding their source rock potential, the unit's dominantly sandstone lithologies and thin nature negate its potential, at least in the region surrounding the well. Its existence, facies development, and source potential elsewhere in the basin is unknown.

Morien Group

A major unconformity divides the Mississippian and Pennsylvanian successions in Atlantic Canada region. It was a precursor to the subsequent Alleghenian Orogeny, and representing a period of regional transpression and erosion, also coinciding with global sea level lowering related to Gondwanan glaciation (Gibling et al., 2008). Basin-bounding faults were re-activated with associated normal and thrust faulting, and structural inversion of some basins or parts thereof. Though variable depending on location and basin, the maximum amount of erosion encapsulates sediments of late Namurian A to early Westphalian B (approximately late Serpukhovian – late Bashkirian). Older strata exhibit several degrees of angular discordance though locally near active faults could be significant. This is the case over the Pennsylvanian in the Sydney Basin, with unconformities / faunal breaks recorded in the early Westphalian B/A, and late Westphalian C/B.

The Morien Group defines a period of alluvial, fluvial and lacustrine sedimentation with the succession fining upward over time. It represents long-lived regional drainage system sourced from the southeast that filled the Maritimes Basin that was tectonically stable and undergoing gentle thermal subsidence (Rust et al., 1987; Gibling et al., 1992). The succession in the Sydney Basin is up to 1.8 km thick onshore and at least 2.5 km thick offshore (Boehner and Giles, 2008). Sediment loading in the region contributed to salt diapirism of the lower Windsor Group. The basal South Bar Formation is

WINDSOR GROUP / Meadows Road Formation (Upper Viséan)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (Range)**	**Average S2 (range)**	**Tmax (C)**	**Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
St. Paul Island P-91	0.15	80.0	126.7	0.12	421	3.19	III	1	Kendall & Altebaeumer, 1984

Table 5.2: Meadows Road Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

WINDSOR GROUP / Woodbine Road Formation (Upper Viséan)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (range)**	**Average S2 (range)**	**Tmax (C)**	**Average Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
St. Paul Island P-91	0.35 (0.06-2.01)	70.3 (1.59-704)	122.0 (20.7-538.5)	0.44 (0.01-5.85)	388-514	1.55-3.09	III	16-35	Kendall & Altebaeumer, 1984

Table 5.3: Woodbine Road Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

MABOU GROUP / Cape Dauphin Formation (Namurian A)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (range)**	**Average S2 (range)**	**Tmax (C)**	**Average Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
St. Paul Island P-91	0.41 (0.16-1.03)	24 (14.0-45.7)	71.7 (14.3-195.0)	0.13 (0.07-0.21)	459-462	1.35-1.70	III	4-8	Kendall & Altebaeumer, 1984

Table 5.4: Cape Dauphin Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

MABOU GROUP / Point Edward Formation (Namurian A)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (range)**	**Average S2 (range)**	**Tmax (C)**	**Average Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
North Sydney F-24	0.96 (0.35-0.86)	75 (30-135)			-	0.99-1.02	III	3-5	Cooper et al. (1976)
	0.46 (0.29-0.73)	60.9 (27.03-88.68)	59.8 (41.1-83.78)	0.36 (0.10-0.55)	480-486	0.94-1.03	III	4-7	Mukhopadhyay, 2004
North Sydney P-05	0.23	60			-	1.61	III	2	Cooper et al. (1974)
	0.19 (0.08-0.36)	66.67	75.00	0.24	493	0.9_-1.01	III	1-4	Mukhopadhyay, 2004
St. Paul Island P-91	0.30 (0.12-0.58)	15 (8.3-20.0)	61.3 (15.63-208.0)	0.7 (0.01-0.11)	469-483	0.97-1.59	III	4-16	Kendall & Altebaeumer, 1984

Table 5.5: Point Edward Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

MORIEN GROUP / South Bar Formation (Westphalian A-B)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (range)**	**Average S2 (range)**	**Tmax (C)**	**Average Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
Birch Grove No.1	-	-	-	-	-	0.94-1.19	-	-	Hacquebard, 1973
North Sydney F-24	0.87 (0.09-2.62)	90 (20-255)	-	-	-	0.93-1.00	III	4-5	Cooper et al. (1976)
	2.8 (0.46-5.51)	92.5 (56.8-149.7)	30.3 (13.4-53.7)	3.0 (0.37-6.48)	447-482	0.95-1.04	III	5	Mukhopadhyay, 2004
North Sydney P-05	0.75 (0.34-1.38)	101 (30-15)	-	-	-	0.95-1.77	III	4	Cooper et al. (1974)
	1.62 (0.46-2.80)	106.65 (66.67-115.22)	51.55 (34.59-80.43)	1.49 (0.53-2.69	450-456	0.92-0.96	III	3	Mukhopadhyay, 2004

Table 5.6: South Bar Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

MORIEN GROUP / Waddens Cove Formation (Westphalian B-C)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (range)**	**Average S2 (range)**	**Tmax (C)**	**Average Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
Birch Grove No.1	-	-	-	-	-	n/a	-	-	Hacquebard, 1973
North Sydney F-24	1.04 (0.47-1.96)	97 (40-155)	-	-	-	0.98	‘III’	2	Cooper et al. (1976)
	1.80	91.67	56.11	1.65	449	0.81	III	1	Mukhopadhyay, 2004
North Sydney P-05	0.59	50	-	-	163	1.13	III	1	Cooper et al. (1974)
	11.38 (1.65-211.11)	142.87 (67.27-218.47)	18.39 (5.87-30.91)	23.61 (1.11-46.12)	450-451	0.94-0.97	III	2	Mukhopadhyay, 2004

Table 5.7: Waddens Cove Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

MORIEN GROUP / Sydney Mines Formation (Westphalian C – Stephanian)									
Well	**Average % TOC (range)**	**Average HI (ppm) (range)**	**Average OI (ppm) (range)**	**Average S2 (range)**	**Tmax (C)**	**Ro (%)**	**Kerogen Type**	**Total Samples**	**Reference**
Birch Grove No.1	-	-	-	-	-	0.85-0.88	-	-	Hacquebard, 1973
North Sydney F-24	1.27 (0.16-3.52)	125 (75-290)	-	-	-	0.75-0.97	III	6	Cooper et al. (1976)
	19.6 (3.15-36.4)	132.9 (69.5-196.3)	13.3 (11.1-15.6)	36.9 (2.19-71.5)	432-443	0.68-0.71	III	2	Mukhopadhyay, 2004
North Sydney P-05	0.44 (0.08-1.01)	30 (25-35)	-	-	-	0.78-0.98	III	5	Cooper et al. (1974)
	18.35 (5.38-12.97)	178 (156.51-199.85)	10.9 (8.48-13.38)	17.2 (8.42-25.92)	442-444	0.55-0.67	III	2	Mukhopadhyay, 2004

Table 5.8: Sydney Mines Formation source rock characteristics from wells in the NS17-1 Call for Bids region.

composed of thick, stacked fining upward cycles of grey sandstones with minor shales and rare though significant coal beds deposited by braided river systems over a broad, sandy braidplain. The upper Sydney Mines Formation reflects the transition to a muddy alluvial floodplain with large meandering rivers, lakes and coal swamps, with some minor marine influences (Rust et al., 1987). Its strata are composed of repeating cycles of grey to red mudrocks, fine grain grey to brown sandstones and thick coals. Between the South Bar and Sydney Mines is the Waddens Cove Formation. It is a transitional unit between the two formations and present only on the eastern side of the basin (Boehner and Giles, 2008).

The two onshore wells in the basin were spudded in and penetrated a near-complete Morien Group section. No hydrocarbon shows were recorded and no geochemical analysis completed. Offshore, the North Sydney P-05 and F-24 wells penetrated the entire Morien succession, though it is thinner since here it overlies an uplifted horst block of possibly Horton Group sediments (this report). In both wells significant gas shows were present in the Morien Group, and are believed sourced from associated coal seems (this report). Several analyses were done for these wells but limited to a handful of samples from each formation (Tables 5.6 to 5.8). Overall, they indicated the selected shale samples to have variable TOCs (<1.0-18, average ~ 1.5%) with Type III kerogens. They were generally all within the oil window, and commensurately mature based on the stratigraphic position, but had low hydrogen indices.

Fowler and Webb (2017) reviewed these data from previous workers studying onshore exposures, boreholes and mine workings, and grouped the analyses of Sydney Mines samples based on lithology: coals, coaly shales and shales. They are summarized in Table 5.1. Within coal seams are thin beds – 'dull coals' – that are organic rich high in lipitinites (Type II kerogens) with high HIs though are cumulatively thin. Likewise, some shales (oil shales) associated with coals have very hi TOCs and related properties (high HIs). These could have significant oil potential, though volumetrically are low, at least as expressed in onshore exposures. The best potential sources are lacustrine shales. These have a greater cumulative thickness and are composed of Type III terrestrially-derived kerogens with low TOCs and moderate HIs. They are the probable sources of gas encountered in wells and mine workings. These potential source rocks likely have significant areal extent and probably greater thicknesses in the basin depocentre, and could be a significant source of gas.

Pictou Group

Sediments of the Stephanian to Middle(?) Permian Pictou Group conformably overlie the Morien from which it is transitional. Its upper age and original thickness are unknown due to significant erosion. It is made up of alluvial and eolian redbeds and found only offshore in the Sydney Basin being penetrated by the two North Sydney wells. It crops out onshore in northern Nova Scotia, Prince Edward Island and from seismic data estimated to be about 6 km in the offshore Magdalen Basin. It is essentially barren of organic material though its sandstones are porous with good reservoir potential.

6.0 Exploration Potential

The hydrocarbon potential of the Sydney Basin and other Paleozoic basins is eastern Canada was the focus of multiple recent studies. Within these studies, Hu and Dieterich (2010), Dieterich et al. (2011), Hannigan and Dieterich (2012), all conclude that all necessary elements are in place for a working petroleum system within Sydney Basin. The seismic mapping within these studies also supports these conclusions and helps to illustrate a number of play types. The two North Sydney wells, in the offshore Sydney Basin, did not penetrate the Horton Group which is the interval interpreted to have the greatest hydrocarbon potential and only evaluated the shallower Late Carboniferous formations. Both North Sydney wells have proven gas charge in Late Carboniferous reservoir sandstones. In the North Sydney F-24 well, two zones with limited porosity were flow tested with no recovery. It should be noted, that the porosity of the sands tested in F-24 are lower than the porosities encountered in the equivalent formations in the North Sydney P-05 well. Flow testing of these higher quality reservoir sands, in P-05, may have resulted in a successful test. Other inversion-related anticlines are present within Parcels 1 and 2 (Figures 4.2.5, 4.2.6 and 4.2.7). The subtle folds within Parcels 2 overlie the thicker main depocenter of the Sydney Basin, and are believed to contain intervals with more favorable reservoir properties (Figure 4.1.4). Intra-Horton faulted traps and stratigraphic plays are interpreted to have greater oil and gas potential than the shallower intervals that have been evaluated to date. A clear understanding of the inversion history of the basin may locate regions where the burial depths of the oil and gas prone Horton and McAdams Lake lacustrine shales were suppressed and the units remained within the oil window. Where this setting exists, oil-charged plays are possible, with sandstone units of the Horton Group being a potential reservoir (Figure 4.1.4 (b) and (c)). Horton shales will act as intra-formational seals for this play. There is seismic evidence that Windsor evaporites are present in the CRG, and a diapir is also noted within Parcel 3. (Figures 4.1.3 and 4.2.4). The identification of these salt features prove that Windsor evaporites were deposited within Sydney Basin, and may also be considered a sealing unit to the underlying Horton plays within Parcels 1, 2 and 3.

The Windsor Group's Gays River Formation reefs may also be a potential reservoir for Horton generated hydrocarbons. These reefs would be localised, and potentially difficult to identify on the current seismic data, but are likely present. Onshore, these reefs are common where the Gays River Formation oversteps basin bounding topography.

Acknowledgements – Brian Altheim and John Martin are thanked for compiling and organising the seismic database used within this study. Colleen Menard is thanked for logistical support, and the Resources Group at the CNSOPB are acknowledged for providing a thorough review of the NS17-1 geoscience content. Acknowledgment is also given to Natural Resources Canada (particularly Bob Courtney) for access to the database of NRCAN's marine geophysical data and for providing the program to convert images to segy files (Register JP2000).

Recommended citation:

Kendell, K. L., Brown, D.E. and Rhyno, S. (2017) Call for Bids NS17-1 – Regional exploration history, geological setting, source rocks and exploration potential of Sydney Basin, offshore Nova Scotia. CNSOPB Geoscience Open File Report 2017-001MF, 50 p.

References

Barr, S.M., Dehler, S.A., and Zsámboki, L. (2014) Connecting Cape Breton Island and Newfoundland, Canada: Geophysical modelling of pre-Carboniferous 'basement' rocks in the Cabot Strait area. Geoscience Canada, vol. 41, no. 2, p.186-206, http://dx.doi.org/10.12789/geocanj2014.41.041

Bell, W.A. (1958) Possibilities for Occurrence of Petroleum Reservoir in Nova Scotia. Province of Nova Scotia Department of Mines, 177p.

Belt, E.S. (1964) Revision of Nova Scotia Middle Carboniferous units. American Journal of Science, vol. 262, p.653-673.

Belt, E.S. (1965) Stratigraphy and paleogeography of Mabou Group and related Middle Carboniferous facies, Nova Scotia, Canada. Geological Society of America Bulletin, vol. 76, p. 777-802.

Benn, K., Roest, W.R., Rochette, P., Evans, N.G., and Pignotta, G.S. (1999) Geophysical and structural signatures of syntectonic batholith construction: the South Mountain Batholith, Meguma Terrane, Nova Scotia. Geophysical Journal International, vol. 136, no. 1, p. 144-158.

Bevier, M.L., Barr, S.M., White, C.E., and MacDonald, A.S. (1993) U-Pb geochronological constraints on the volcanic evolution of the Mira (Avalon) terrane, southeastern Cape Breton Island, Nova Scotia. Canadian Journal of Earth Sciences, vol. 30, no. 1, p. 1-10.

Boehner, R.C., and Giles, P.S. (2008a) Geology of the Sydney Basin, Cape Breton and Victoria Counties, Cape Breton Island, Nova Scotia. Nova Scotia Department of Natural Resources, Mineral Resources Branch, Memoir ME 11, 99p.

Boehner, R.C., and Giles, P.S. (2008b) Map ME 1986-1 - Geology Map of the Sydney Basin, Cape Breton Island, Nova Scotia, scale 1:50 000. http://novascotia.ca/natr/meb/data/pubs/memoir11/Memoir11_Map1986-001.pdf

Boehner, R.C., and Prime, G. (1993) Geology of the Loch Lomond Basin and Glengarry Half Graben, Richmond and Cape Breton Counties, Cape Breton Island, Nova Scotia. Nova Scotia Department of Natural Resources, Mines & Energy Branches, Memoir 9, 52p. Plus two appendices and map.

Coleman-Sadd, S. P,Hayes, J.P, and Knight, I. (2000) Geology of the Island of Newfoundland, Map 90-01.

Cooper, B.S., Barnard, P.C., Fisher, M.J., and Butterworth, J.S. (1974) Report on a petroleum geochemical evaluation of the Shell et al. North Sydney G-24[sic] well, Sydney Basin, offshore Nova Scotia, East Canada. Robertson Research International Limited Report No. 4007P. Canada-Nova Scotia Offshore Petroleum Board File D163, Well History Report Appendix 6.11 – Geochemistry Report, 30p. Available online from the CNSOPB Data Management Centre.

Cooper, B.S., Barnard, P.C., Coleman, S.H., Darlington, C., and Butterworth, J.S. (1976) Report on a maturation and source rock evaluation study of the Murphy et al. N. Sydney P-05 well, Sydney Basin, offshore Nova Scotia. Robertson Research International Limited Report No. 2780. Canada-Nova Scotia Offshore Petroleum Board File D134, Well History Report Appendix – Geochemistry Report, 38p. Available online from the CNSOPB Data Management Centre.

Dietrich, J., Lavoie, D., Hannigan, P., Pinet, N., Castonguay, S.,Giles, P., and Hamblin, A. (2011) Geological setting and resource potential of conventional petroleum plays in Paleozoic basins in eastern Canada; Bulletin of Canadian Petroleum Geology, v. 59, no. 1, p. 54-84.

Durling, P., and Marillier, F. (1993) Tectonic setting of Middle Devonian to Lower Carboniferous rocks in the Magdalen Basin. Atlantic Geology, vol. 29, no. 3, p.199-217

Durling, P., and Marillier, F. (1990) Structural trends and basement rock subdivisions in the western Gulf of St. Lawrence, Northern Appalachians. Atlantic Geology, vol. 26, no. 1, p.75-95.

Enachescu, M.E. (2006a) Call for Bids NL06-2 – Sydney Basin Government of Newfoundland and Labrador, Department of Natural Resources, 51 p.

Enachescu, M.E. (2006b) Call for Bids NL06-2 – Sydney Basin Government of Newfoundland and Labrador, Department of Natural Resources, PowerPoint presentation, 98 p. http://www.nr.gov.nl.ca/nr/invest/cfb_nl06_02_sydney.pdf

Fowler, M., and Webb, J. (2017) Sydney Basin petroleum systems: Synthesis of historical and new geochemical data. Applied Petroleum Technology (Canada) Ltd. Report, 276p. Appendix _ in Offshore Energy Research Association (OERA), Play Fairway Analysis Atlas - Offshore Sydney Basin, Nova Scotia. Nova Scotia Department of Energy.

Gibling, M.R., Calder, J.H., Ryan, R., van der Poll, H.W. and Yeo, G.M. (1992) Late Carboniferous and Early Permian drainage patterns in Atlantic Canada. Canadian Journal of Earth Sciences, vol.29, no.2, p.338-352.

Gibling, M.R., Culshaw, N., Rygel, M.C, and Pascucci, V. (2008) Chapter 6 - The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea In: A.D. Maill (Ed.), Sedimentary Basins of the World, Volume 5: The Sedimentary Basins of the United States and Canada, Elsevier, p.211-244.

Giles, P.S. (2009) Orbital forcing and Mississippian sea level change: time series analysis of marine flooding events in the Viséan Windsor Group of eastern Canada and implications for Gondwanan glaciation. Bulletin of Canadian Petroleum Geology, vol. 57, no. 4, p. 449-471.

Giles, P.S., and Utting, J. (1999) Maritimes Basin stratigraphy – Prince Edward Island and adjacent Gulf of St. Lawrence. Geological Survey of Canada, Open File 3732, cross section with explanatory notes.

Hacquebard, P.A. (1983) Geological development and economic evaluation of the Sydney Coal Basin, Nova Scotia. In: Current Research, Geological Survey of Canada, Paper 83-1A, p. 71-81.

Hacquebard, P.A. (1973) Birch Grove No. 1 Well Maturation Geological Survey of Canada, EPGS-DOM-HACQ'73, 1p

Hannigan, P.K. and Dietrich, J.R. (2012) Petroleum resource potential of the Laurentian Channel area of interest, Atlantic Margin of Canada; Geological Survey of Canada, Open File 6953, 32 p. doi:10.4095/289846

Hibbard, J., van Staal, C., and Williams, H. (2006) Geology, lithotectonic map of the Appalachian Orogen, Canada-United States of America. Geological Survey of Canada, Map 02096A, 2 sheets, scale 1:1,500,000.

Hu, K., and Dieterich, J. (2010) Petroleum reservoir potential of upper Paleozoic sandstones in the offshore Maritimes Basin, Eastern Canada; Geological Survey of Canada, open File 6679, 16 p.

Kendall, S., and Altebaeumer, F. (1984) Final Report: Geochemical evaluation of Petro-Canada St. Paul P-91 600-2883m (TD). Canada-Nova Scotia Offshore Petroleum Board File D235, Well History Report Geochemistry Report (92 p.). Available online from the CNSOPB Data Management Centre.

Keppie, J.D. (compiler) (2000) Geological map of the province of Nova Scotia; Nova Scotia Department of Natural Resources, Minerals and Energy Branch, Map ME 2001-1, scale 1:500000

King, M.S., and Barr, S.M. (2003) Magnetic and gravity models across terrane boundaries in southern New Brunswick, Canada. Canadian Journal of Earth Sciences, vol. 41, no.9, p.1027-1047.

Kontak, D.J., and Sangster, D.F. (1995) Aqueous and liquid petroleum inclusions in barite from the Walton deposit, Nova Scotia, Canada: A Carboniferous carbonate-hosted Ba-Pb-Zn-Cu-Ag deposit. Economic Geology, vol. 93, p.845-868.

Langdon, G.S., and Hall, J. (1994) Devonian-Carboniferous Tectonics and Basin Deformation in the Cabot Strait Area, Eastern Canada. American Association of Petroleum Geologists Bulletin, vol. 78, no.11, p.1748-1774.

Lavoie, D., and Sami, T. (1998) Sedimentology of the lowest Windsor carbonate rocks: Base metal hosts in the Maritimes Basin of Eastern Canada. Economic Geology, vol. 93, p. 719-733.

Lavoie, D. (1995) Circum-Euramerica Early Carboniferous (Viséan) basins: Evidence for a salinity stratified ocean. Geological Society of America Annual Meeting, Abstracts with Programs, vol. 27, p.A-451.

Lin, S. (1993) Relationship between the Aspy and Bras d'Or "terranes" in the northeastern Cape Breton Highlands, Nova Scotia. Canadian Journal of Earth Sciences, vol. 30, no.10, p.1773-1781.

McMahon, P., Short, G., and Walker, D. (1986) Petroleum Wells and Drillholes with Petroleum Significance Onshore Nova Scotia. Nova Scotia Department of Mines and Energy, Information Series No.10, 194p.

Mukhopadhyay, P.K. (2004) Evaluation of petroleum potential of the Devonian-Carboniferous rocks from Cape Breton Island, onshore Nova Scotia. Nova Scotia Department of Energy, 245p. https://energy.novascotia.ca/sites/default/files/Evaluation_of_Petroleum_Potential_CB_Report.pdf

Oakey, G.N. and Dehler, S.A. (2004) Atlantic Canada Magnetic Map Series;Atlantic Canada, Geological Survey of Canada, Open File 1813, 1:300000

Pascucci, P. Gibling, M.R. and Williamson, M.A. (2000) Late Paleozoic to Cenozoic history of the offshore Sydney Basin, Atlantic Canada. Canadian Journal of Earth Sciences, vol.37, no.8, p.1165-1165.

Raeside, R.P., and Barr, S.M. (1990) Geology and tectonic development of the Bras d'Or suspect terrane, Cape Breton Island, Nova Scotia. Canadian Journal of Earth Sciences, vo.27, no.10, p.1371-1381.

Rogers, K.M., and Savard, M.M. (2001)Geochemistry of oil inclusions in sulfide-related calcites: fingerprinting the source of the sulfate-reducing hydrocarbons of the Pb-Zn carbonate-hosted Jubilee deposit of Nova Scotia, Canada. Applied Geochemistry, vol. 17, p.69-77.

Rust, B.R., Gibling, M.R., Best, M.A., Dilles, S.J., and Masson, A.G. (1987) A sedimentological overview of the coal-bearing Morien Group (Pennsylvanian), Sydney Basin, Nova Scotia, Canada. Journal of Sedimentary Petrology, vol. 60, no. 4, p.540-548.

Sangster, D.F., Savard, M.M., and Kontak, D.J. (1998) A genetic model for mineralization in Lower Windsor (Viséan) carbonate rocks of Nova Scotia, Canada. Economic Geology, vol. 93, p.932-952.

Smith, W.D., and Naylor, R.D. (1990) Oil Shale Resources of Nova Scotia. Nova Scotia Department of Natural Resources, Economic Geology Series 90-3, 73p.

Waldron, J.W.F., Roselli, C.G., Utting, J., and Johnston, S.K., (2010) Kennetcook thrust system: Late Paleozoic transpression near the southern margin of the Maritimes Basin, Nova Scotia. Canadian Journal of Earth Sciences, vol. 47, no. 1, p.137-159.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., and Hibbard, J. (2015) Late Paleozoic strike-slip faults in Maritime Canada and their role in the reconfiguration of the northern Appalachian orogen. Tectonics, vol. 34, no. 8, p.1661-1684, DOI: 10.1002/2015TC003882

Webb, G.W. (1973) Salt structures east of Nova Scotia. In: P.J. Hood (Ed.), Earth Science Symposium on Offshore Eastern Canada, Geological Survey of Canada, Paper 71-23, p.197-218.

Weston et al. (2017a) Enclosure 5: North Sydney P-05 Summary Chart Enclosure 6: North Sydney P-05 Palynology Range Chart Sydney Basin Play Fairway Analysis, OERA, two charts.

Weston et al. (2017b) Enclosure 3: North Sydney F-24 Summary Chart Enclosure 4: North Sydney F-24 Palynology Range Chart Sydney Basin Play Fairway Analysis, OERA, two charts.

Weston et al. (2017c) Enclosure 7: St. Paul P-91 Summary Chart Enclosure 8: St. Paul P-91 Palynology Range Chart Sydney Basin Play Fairway Analysis, OERA, two charts.

Weston et al. (2017d) Enclosure 1: CCSNS No. 1 (Carbon Capture & Storage Nova Scotia) Summary Chart Enclosure 2: CCSNS No. 1 (Carbon Capture & Storage Nova Scotia) Palynology Range Chart Sydney Basin Play Fairway Analysis, OERA, two charts.

White, C.E., and Barr, S.M. (1998) Stratigraphy and tectonic significance of the Lower to Middle Devonian McAdams Lake Formation, Cape Breton Island, Nova Scotia. Atlantic Geology, v.34, no. 1, p.133-145

Williams, H. (1979) Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, vol. 16, no. 3, p.792-807.