Offshore Newfoundland & Labrador Resource Assessment
Jeanne d’Arc Area NL18-CFB01

An Integrated Project for Nalcor Energy – Oil and Gas Inc.,
and the Department of Natural Resources, Government of
Newfoundland and Labrador

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INTRODUCTION

Nalcor Energy – Oil and Gas Inc. Newfoundland and Labrador’s provincial energy corporation working with the Newfoundland and Labrador Department of Natural Resources (DNR) engaged Beicip-Franlab to conduct an independent resource assessment of the Eastern Jeanne d’Arc Basin area following the resource assessment of the Flemish Pass (NL15_01EN) and Orphan Basin area (NL16-CFB01) in 2015 and 2016.

The East Jeanne d’Arc Basin has demonstrated material potential with several HC indications at wells and a demonstrated efficient petroleum system in the Hebron, Terra Nova, Hibernia and Whiterose field of Jeanne d’Arc Basin.

The objective of this project was to conduct a geological and geophysical interpretation, basin analysis, play risk analysis, and resource assessment for the area subject to the upcoming license round (NL18-CFB01 - November 2018) based on available geological and geophysical data. The final deliverables of this project included a detailed Beicip-Franlab internal report for Nalcor and DNR and this Public Atlas which summarizes the main methodologies and key results of the resource assessment project.

WORKFLOW

1. Database generation and QC
2. Geodynamic and tectonic settings
3. Sedimentology, seismic stratigraphy and geochemistry
4. Gross Depositional Environment (GDE) maps
5. Stratigraphic modelling
6. 2D & 3D petroleum system modelling
7. Play risk analysis, and volumes assessment.

MAIN RESULTS

The Beicip-Franlab petroleum system resource assessment of the East Jeanne d’Arc area demonstrates a potential petroleum system with seven potential reservoirs sourced by three proven source rocks. The timing of burial with respect to traps formation enables hydrocarbons (HC) to be trapped and sealed regionally through rotated Jurassic blocks and potential stratigraphic traps below the Tertiary unconformity. The petroleum system model is calibrated against the presence of nearby discoveries (Dana, and Whiterose) and also, results from well data.
STUDY AREA

The Eastern Newfoundland Region represents part of the North Atlantic Mesozoic rift system. It includes the Jeanne d’Arc, Orphan, and Flemish Pass Basins.

In January 2018, Nalcor Energy and Beicip-Franlab began the resource assessment of the East Jeanne d’Arc area as well as another one in the Orphan Basin.

On April 5, 2018, the Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) announced the Call for Bids NL18-CFB01. The block definition includes 16 parcels of land – with 3 parcels evaluated in this study of the East Jeanne d’Arc area. The land available in the call is under the new Scheduled Land Tenure System:


Interested parties have until 12:00 p.m. NST on November 7th, 2018 to submit bids for the parcels offered in Call for Bids NL18-CFB01. Further detailed information pertaining to this Call for Bids can be found at: https://www.cnlopb.ca/exploration/issuance/#bids-active.
DATA SET

1. **Twenty six (26) wells** were used for the study. Each well contains a set of petrophysical logs, stratigraphic markers, and geochemical reports:
   - Amethyst F-20
   - Archer K-19
   - Aster C-93A
   - Baccalieu I-78 (outside the modelled area)
   - Bonanza M-71
   - Bonne Bay C-73
   - Conquest K-09
   - Dominion O-23
   - Federation K-87
   - Fortune G-57
   - Gabriel C-60
   - Golconda C-64
   - Gros Morne C-17
   - Kyle L-11
   - Lancaster G-70
   - North Dana I-43
   - Panther P-52
   - Searcher C-87
   - South Merasheen K-55
   - South Tempest G-88
   - Trave E-87
   - Trepassey J-91
   - Tuckamore B-27
   - Whiterose A-90
   - Whiterose E-09
   - Whiterose N-22

2. **2D seismic surveys** (regional, 10x10km and 5x5km grids) interpreted by Nalcor and covering an area of 38,000 km² within the East Jeanne d’Arc area (From 2012-2018, Nalcor invested TGS/PGS broadband long offset multiclient NE Newfoundland Slope Seismic Project).

3. **A set of 13 horizons** were interpreted in the 2D surveys and 12 associated isopach maps:
   - Seabed, 0 My
   - C10, Mid Neogene, 10 Ma
   - C24, Top Paleocene, 24 Ma
   - C45, Top Mid Eocene, 45 Ma
   - C54, Top Paleocene/Base Eocene
   - C65, Top Cretaceous, 65 Ma
   - K100, Top Cenomanian, 100 Ma
   - K114, Top Mid Aptian, 114 Ma
   - K137, Top Valanginian, 137Ma
   - J145, Top Tithonian, 145 Ma
   - J151, Top Kimmeridgian, 151 Ma
   - J175, Top Toarcian, 175 Ma
   - Base Mesozoic, 251 Ma

4. **Fault sets** picked for structural evolution and 3D modelling.
   The 2018 East Jeanne d’Arc Basin Resource Assessment study area shares its northern boundary with the 2015 NL15-01 EN Sector and 2018 NL03-EN-01A sector. Nalcor and Beicip-Franlab extended the main structural trends, seismic horizons, and paleogeographic interpretation from the Flemish Pass Basin to the East Jeanne d’Arc Basin to ensure regional consistency.
DATA SET REVIEW AND RELEVANCY

Regional seismic interpretation - The seismic interpretation of the sector covers the entire Jurassic to present day. It is calibrated with the various wells available in the study area.

The regional seismic interpretation based on a 5x5km (approximate) grid is adapted to the play study scale. It identifies the main traps (with a minimum of 8 km²), the main structural features (depocenters, slopes, main regional faults), seismic response of the regional paleo-environment settings, as well as seismic objects and anomalies that may correspond to sedimentary features such as channels, deep sea fans, etc.

This interpretation highlights structural traps with in-place volumes in the order of 80 MMbbl equivalent (~10 Mm³) or higher.

Well geological data - The study also uses the comprehensive well information of 26 wells within the study area and its vicinity. It includes: well logs, paleo-environment data, temperature, pressure, and HC recordings, along with regional geological studies on Eastern NL and existing well correlations. This data provides a reliable framework for the play definition, internal subdivisions, and key characteristics of the wells such as net-to-gross, reservoir intervals, average porosities, carriers, and seals occurrence.

Geochemical and petroleum data - Maturity data recorded in wells are abundant (Ro, Tmax). Maturity data can be correlated to well logs and used for comprehensive building of TOC logs. TOC measurements are acquired from cuttings and cores. The existence of a proven and efficient petroleum system in the neighboring basins (Jeanne d’Arc and Flemish Pass), with similar geologic characteristics, provides a useful analogue for the Kimmeridgian source rock characterization.

Built-on knowledge - As part of previous resource assessments, Beicip-Franlab built on its extensive experience in the NL area and especially within the Flemish and Orphan area (Norris et al. 2018; Gillis et al. 2018, McCallum et al. 2017; Jermannaud et al. 2017, 2016; Le Guerroué et al. 2017, 2016; Stead et al. 2017; Wright et al. 2016)

Reliability and accuracy of the resources assessment - The data quality ensures a reliable and reasonably well-constrained 3D geological model of the area can be built. The corresponding oil and gas resource assessment can be undertaken with greater accuracy covered through the low and high cases, taking into account the petroleum results of nearby discoveries (Whiterose and North Dana)
**HYDROCARBON PLAY RESOURCE ASSESSMENT METHODOLOGY**

- The hydrocarbon (HC) play resource assessment methodology follows the Petroleum Resources Management System (PRMS) Guidelines (2011) for Prospective and Contingent Resource assessment. The 2018 Guidelines include the PODS (Probability of Development success). The PODS was not considered in this study.
- The assessment was based on the deterministic computation of oil and gas volumes in place in the area of interest. The simulation includes 3D numerical geological models of lithofacies distribution (sedimentary system modelling) and of 3D structural oil and gas generation/expulsion/migration and entrapment (petroleum system modelling). The software packages used are DionisosFlow™ (for sedimentation) and TemisFlow™ 3D (for petroleum system).
- The sedimentary system model was calibrated against well data on sand/shale ratio, paleo water depth, and known depositional setting at the wells (shoreface, shelf, slope, etc.). The matching was done at a third order sequence stratigraphic scale resolution. The petroleum system model is calibrated against maturity, temperature, pressure data, oil and gas occurrence, and quality. The matching was done at the resolution of the 3D geological model used in the simulation, and the precision of data (i.e., Vitrinite ±0.15%).
- The calibrated geological model was considered as a Reference Geological Model (RGM) or reference scenario of the various plays.

**Unrisked Volumes**

- The HC charge in a play includes areas with low (residual) and high (concentrated) HC content (in kg/m³). Cutoffs on HC concentration can be selected to define the low, most likely, and high case.
- Some numerical parameters of the Reference Geological Model (RGM) may remain unconstrained while still allowing for a consistent calibration against observed data.
- The computed oil and gas volumes resulting from the RGM numerical simulation are referred to as Unrisked Volumes.

The sensitivity analysis performed on the RGM provides a distribution of computed Unrisked Volumes which can be characterized by the P90, P50, and P10 thresholds on the volume distribution curve obtained from the sensitivity runs outcomes.

The P90, P50 and P10 can also be obtained through direct cut off of HC concentration in the various reservoir plays.

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**PRMS Guidelines 2011:**
EXPLORATION HISTORY

The drilling of Tors Cove D-52 in the early 1960s marked the beginning of hydrocarbon exploration in Newfoundland and Labrador’s offshore. To date, nearly 160 exploration wells have been drilled in Newfoundland and Labrador’s offshore jurisdiction. Many other wells have been drilled in the Jeanne d’Arc Basin related to the development of five producing fields. Production to date has been in excess of 1.7 billion barrels of oil. Exploration in the deeper waters of the Eastern Newfoundland Region followed the initial exploration on the Grand Banks. The Area of Interest (AOI) NL03-EN-01B is situated directly east of the Whiterose producing field in the Jeanne d’Arc Basin, as well as three Significant Discoveries situated on a structural basement high known as the Central Ridge; Trave E-87, North Dana I-43, and South Tempest G-88. Other hydrocarbon shows have been encountered in wells throughout the region, serving as a positive indicator to the potential for a working petroleum system throughout the AOI.

Throughout the 1960’s and 1970’s, exploration within the Newfoundland and Labrador offshore region, focused mainly on the shallow waters of the present day shelf, occurred from southern Newfoundland to the coast of Labrador. In 1979, Chevron et. al drilled the Hibernia P-15 well which encountered hydrocarbons in economic accumulations within the Bernardian aged Hibernia Formation sandstone, as well as the Aptian/Ablbian aged Ben Nevis Formation sandstone, leading to a focus of offshore development within the Jeanne d’Arc Basin.

The Hebron-Benz Nevis oil field was discovered in 1980 by Mobil et. al, with the drilling of the Ben Nevis I-45 well, with development commencing late 2017. This field produces oil from the Aptian/Ablbian aged Ben Nevis Formation. In 1984, with the drilling of the Terra Nova K-08 well by Petro-Canada et. al, the Terra Nova oil field was discovered. This field produces oil from the Tithonian aged fluvial sandstones named the Jeanne d’Arc Formation. The Whiterose oil field was discovered by Husky-Bow Valley et. al in 1984 by the drilling of the Whiterose N-22 discovery well. This well tested oil and gas in sandstones of the Bernardian aged Hibernia Formation, as well as the Aptian/Ablbian aged Ben Nevis Formation. The North Amethyst oil field was discovered in 2008 by the drilling of North Amethyst K-15 well by Husky Oil. This was the first satellite tie-back field in Newfoundland and Labrador’s offshore. This field sits adjacent to the main producing Whiterose field. The North Amethyst field has oil and gas accumulations in the Aptian/Ablbian aged Ben Nevis Formation sandstone, as well as the Bernardian aged Hibernia Formation sandstone.

After the discoveries within the Jeanne d’Arc Basin, seismic acquisition as well as exploration and development within Newfoundland and Labrador’s offshore was almost exclusive to this prolific hydrocarbon production area, with regions outside of the Jeanne d’Arc Basin receiving little in terms data acquisition and particularly the drilling of exploration wells. Within NL03-CFB01, there are four wells drilled. Three of these were drilled in the mid-1980s, with almost 30 years of hiatus until the most recent well drilled in the area. Panther P-52 was drilled by Husky Bow Valley et al. in 1985. This well was drilled on the eastern edge of the Central Ridge structure drilling through passive Tertiary sediments, thin Cretaceous and Tithonian and Kimmeridgian sandstone. Thin reservoir units are present within the Tithonian interval, as well as potential Kimmeridgian source rock was encountered. The well has been plugged and abandoned with no hydrocarbon shows. The Golconda C-64 well was also drilled on the Central Ridge structure by Husky Bow Valley et al. a year following the Panther well, in 1986. This well performed a Repeat Formation Test on a Paleocene interval that resulted in a “gas with an oily skin” (End of Well Report) hydrocarbon show. The well also reported a gas show in the middle Jurassic in the form of rare fluorescence and cut from cuttings samples. This well has been plugged and abandoned. The Lancaster G-70 well was drilled by Petro-Canada in 1986, approximately the same time the Golconda well was being drilled.

This well encountered very thin reservoir in the Berriasian and Upper Jurassic, but encountered the Kimmeridgian interval with Rock Eval data suggestive of 1-4% TOC from cuttings. This source presence proves the regional extent of the Kimmeridgian source potential as this well is drilled on the eastern margin of the NL03-CFB01. There were no hydrocarbon shows and this well was plugged and abandoned. Within the NL03-CFB01 region, there were no wells drilled for approximately 30 years, until Husky Energy drilled the Aster C-93A well in 2014. This well drilled an interval of passive Tertiary, an approximately 800m Lower Cretaceous interval with what appear to be primarily tight sandstone intervals with some thin porous intervals present, terminating in the Middle Jurassic, with no Upper Jurassic present. There were no hydrocarbon shows, and this well has been plugged and abandoned.

With the emergence of Nalcor Energy, Newfoundland and Labrador’s crown energy company, in 2007 a commitment was made to invest in new geoscience data to unlock the next offshore areas that may contain material prospectivity. In late 2010, with Airbus Defense and Space, Nalcor undertook a regional oil seep mapping and interpretation study encompassing all of offshore Newfoundland and Labrador (over 1.5M km²). A subset of the satellite data acquired during this survey imaged areas of potential natural seepage in the Eastern Newfoundland Region, suggesting a regional working petroleum system and, coupled with the adjacent producing fields, as well as the numerous significant discoveries and hydrocarbon shows, highlighted the potential for this area for hydrocarbon exploration.

To better understand the potential nature of prospectivity in this region, in 2012 Nalcor began to invest with global seismic companies TGS and PGS in a long offset broadband 2D multi-client seismic grid of sparse data over the Northeast Newfoundland area mostly focused in the Flemish Pass region, with some coverage over the NL03-CFB01 region. This survey was an extension of the 2011-2012 Nalcor invested TGS and PGS regional 2D seismic program targeting the slope and deepwater areas offshore Labrador.

In 2013, further acquisition in the Flemish Pass Basin region continued into the NL03-CFB01 region. In 2014, the northern extent of the NL03-CFB01 region was covered with 10x10 grid. In 2016, the remainder of the NL03-CFB01 region was infilled and covered with a 5x5 grid. This data forms the foundation for the insights into development of a petroleum system model for the NL03-CFB01 region.
REGIONAL GEODYNAMIC SETTING

The Jeanne d’Arc Basin of the Eastern margin of Canada experienced successive rift episodes associated with the northward opening of the North Atlantic Ocean since Late Triassic times. The continental extension propagated further north, leading to the rifting between Newfoundland and Iberia margins and then Newfoundland and Irish margins. The major rifting phase, which led to the dislocation of the North American and Eurasian plates, was accompanied by a drastic change of the maximum horizontal stress from the northwest – southeast (Phases II and III) to the northeast – southwest (Phase IV; Pichot et al. 2018). Generalized rifting occurred between the Grand Banks Flemish Iberia conjugate margins after the Middle Jurassic (163 Ma; Tucholke et al., 2007) and post-rift sediments indicated the final breakup between 140 and 125 Ma from South to North (Alves et al., 2009). The south of Jeanne d’Arc Basin went through major erosion/non deposition between Kimmeridgian and Aptian (Avalon uplift 151 – 114 Ma; McAlpine, 1990). Rifting occurring between the Flemish Cap-Goban Spur conjugate margins also impacted Jeanne d’Arc basin in the early Barremian (128-126 Ma; de Graciansky et al., 1985) causing fault reactivation and localized inversion capped by Avalon unconformity (114 Ma; McAlpine, 1990).

The Flemish Cap and the Bonavista Platform correspond respectively to the eastern and western limits of the Jeanne d’Arc Basin. In these areas, the continental crust remains relatively unthinned with a thickness of about 30 km. The southern edge of Jeanne d’Arc Basin corresponds to the Avalon Transfer. The Dominion Transfer separates two distinct domains within Jeanne d’Arc Basin. The transition towards Flemish and Orphan Basins occurs along the prominent E-W oriented Cumberland Ridge. In the west (Jeanne d’Arc) and north (Orphan) of the East Jeanne d’Arc, the crustal thickness shows highly thinned areas (less than 7 kilometers).
Welsink & Tankard (2012) report “subsidence in the Jeanne d’Arc Basin was intermittent and controlled by faults rooted in pre-existing basement structures”.

The Late Triassic to Early Jurassic rifting and sag sequences are thought to be related to the opening of the North Atlantic ocean. The Jeanne d’Arc Basin has experienced the effect of this rifting, as it is thought to be the northernmost extent of this tectonic event.

The climax of the deformation runs from Kimmeridgian to Lower Valanginian with an early rifting phase reactivating inherited structures or initiating new half grabens. During this period, subsidence is controlled by rotating blocks along normal listric faults rooted in the crust and antithetic faults rooted either in existing basement structures or in the salt, if present. In the northern part of the NL18-CFB01 study area, this phase is characterized by wide rifting, which continues north into the Orphan and Flemish Pass Basin regions.

Soon after, a second tectonic episode occurs with lesser intensity until Valanginian. Part of the deformation is accommodated on existing structures but new faults are also created. They are rooted into Late Jurassic overpressured shales or in the salt.

NE-SW Valanginian to Aptian extension focused in the Orphan Basin causes localized transpressional reactivation of the main structures throughout the NL18-CFB01 area. Combined with widespread Avalon uplift in the South, this leads to major erosional features throughout Jeanne d’Arc Basin.

In general, the Late Cretaceous (including Albian) sediments are relatively thin throughout the Call for Bids area and show flat-lying succession above the Top Aptian Unconformity, suggesting limited sedimentary influx in this part of the basin.

The Base Tertiary is well defined regionally all over the Jeanne d’Arc Basin and merges with the erosion surface on top of the major tilted or inverted fault blocks. Progressive downlaps overlaying the Base Tertiary record a regional thermal subsidence during the Paleogene, followed by flexural load when sedimentary rate increases during the Neogene.
Ten depth maps were picked from the seismic grid and used to define the skeleton of present-day model geometry. Five are shown here for illustration purposes. In some cases, where surfaces converge, the older surface is replaced by a younger surface and the thickness between these two surfaces becomes zero. For modelling purposes, all surfaces have been mapped to the extent of the modelled regions.
The stratigraphic framework has been updated to tie to well stratigraphic correlations and seismic interpretation. Main time markers (Base Mesozoic, J_175, J_151, J_145, K_140, K_100, C_65, C_54, C_45, C_34 and C_24) were picked guided by biostratigraphic interpretation. Well penetration largely sample the Cretaceous and Late Jurassic levels. Aptian and top Cretaceous erosive events locally remove part of the stratigraphic records.
This comprehensive stratigraphic interpretation served as the framework for the sedimentological input to the Gross Depositional Environment (GDE) mapping. When coupled with thickness maps, these inputs served as the fundamental information for the DionisosFlow™ stratigraphic model.
GEOLOGY SETTINGS

All geological information (markers, well reports and well logs) are integrated and interpreted in terms of sedimentology and petrophysics in order to provide a consistent stratigraphic framework constraining environment of deposition (right) and eventually Gross Depositional Environment (GDE) maps for each seismic sequence.

Depositional and sedimentological observations are obtained from combination of literature, well information and seismic geomorphology analysis. Petrophysical log interpretation provides updated lithological profiles coupled with biostratigraphic analysis to assess the stratigraphic and paleoenvironment settings. This interpretation is used to build the geological models used in the stratigraphic and petroleum system modelling software.

During the Triassic rift episode, the depositional model indicates significant clastic deposition along the margins of the Jeanne d’Arc Basin, with the deposition of the Argo salt centered in the main depocenter of the central Jeanne d’Arc Basin.

During the Early Jurassic, which corresponds to the drowning of the aborted Triassic rift episode, the deposition of carbonate prevails. During the Late Jurassic to Early Cretaceous, large regressive packages are deposited. They correspond to the Hibernia (Berriasian) and Jeanne d’Arc (Tithonian) reservoir intervals.

The transgression during Early Cretaceous records deeper marine sand until the Avalon unconformity (Aptian) resulting in the Ben Nevis deposition.

The Late Cretaceous records a large basin drowning during a maximum of eustasy. Bathyal deposits are spread throughout the study area.
The interpretation, in terms of seismic stratigraphy, aims at identifying sedimentary bodies from seismic data. Two regional seismic cross-sections (see map) were chosen to define the key stratigraphic features of the margin.

The NW-SE section highlights the infill of the depocenter located between the Phoenix Ridge and the Beothuk Knoll (in this section between Bonanza and Kyle wells).

Specifically, this section displays: a) Jurassic continental deposits with alluvial fans and fluvial plain, overlaid by carbonate platform deposits on local highs with fluvial deltaic filling topographical lows, and b) Cretaceous continental and fluvial plain deposits sourced mainly from the rift shoulders overlain by turbidite systems.

A thick Tertiary succession is also noticeable in the northwestern part of the section. Progradation of this interval is toward the southeast.
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**SEQUENCE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS**

**Raw seismic data**

**Sequence stratigraphy** Well + seismic stratigraphy

The NE-SW section highlights the infill of the main depocenter located between the Morgiana Uplift and the Cumberland Ridge. It includes the northern end of the Anson Graben.

Specifically, this section displays: a) Jurassic continental deposits with alluvial fans and fluvial plain, overlaid by carbonate platform deposits on local highs with fluvial deltaic filling topographical lows, and b) Cretaceous continental and fluvial plain deposits sourced mainly from the rift shoulders overlain by turbidite systems. A much thinner Tertiary succession is here preserved.

**Depositional environments** Geology at wells + seismic geomorphology
PETROLEUM PLAY DEFINITION

According to the PRMS definition accepted by the Society of Petroleum Engineers (SPE), a "play or petroleum play" is a model of how a petroleum system (HC charge, reservoir, seal, or trap) may combine to produce petroleum accumulations at a given stratigraphic level (e.g., the Tithonian play). A play may contain prospective resources and reserves (in the economic sense). Seven plays have been defined. Three plays display effective reserves: Tithonian, Lower Cretaceous and Albian-Aptian

Four plays remain hypothetical: Triassic, Early Jurassic, Kimmeridgian and Late Cretaceous.

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<th>Source Rock</th>
<th>Reservoir</th>
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<td>Tithonian Egret</td>
<td>Otter Bay</td>
<td>Dawson Canyon</td>
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<td></td>
<td>Cenomanian Egret</td>
<td>Dawson Canyon</td>
<td>Dawson Canyon</td>
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<td>Albian Aptian</td>
<td>Tithonian Egret</td>
<td>Ben Nevis</td>
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<td>Egret</td>
<td>Jeanne d’Arc</td>
<td>Fortune Bay</td>
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<td>Kimmeridgian</td>
<td>Egret (lateral)</td>
<td>Voyager</td>
<td>Egret</td>
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<td>Early Jurassic</td>
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</tr>
<tr>
<td>Triassic</td>
<td>Egret (lateral)</td>
<td>Eurydice</td>
<td>Argo</td>
</tr>
</tbody>
</table>

Triassic to Cretaceous Wheeler diagram of a representative section through the study area. Same diagram in water depth (below).
Within the NL18-CFB01 license area, there are multiple Cretaceous submarine fan plays. These fans have been imaged over multiple 2D seismic lines within the license area. Many display a type class 2p AVO response when viewed in the gathers and on the near and far angle stacks.

North American polarity convention was used in this study. Increase in impedance (positive amplitude) is blue; decrease in impedance (negative amplitude) is orange.

This particular example of a Cretaceous submarine fan play, named the Bristol's Hope lead, within the license round area displays a brightening negative amplitude response when viewed in the far angle stack.
Within the NL18-CFB01 license area, there are multiple rotated Jurassic fault block plays. These rotated fault blocks have been imaged over multiple 2D seismic lines within the license area. Many display a type class 2p AVO response when viewed in the gathers and on the near and far angle stacks.

North American polarity convention was used in this study. Increase in impedance (positive amplitude) is blue; decrease in impedance (negative amplitude) is orange.

This particular example of a rotated Jurassic fault block play, named the Dublin lead, within the license round area displays a brightening negative amplitude response when viewed in the far angle stack.
GEOLOGY & GROSS DEPOSITIONAL ENVIRONMENT MAPS: TRIASSIC TO TITHONIAN

A set of eight Gross Depositional Environment (GDE) maps spanning the main sequences were built from the stratigraphic/sedimentological information coupled with the seismic data (thickness, structural maps, geomorphological features, and seismic stratigraphy analysis). They represent the paleoenvironments at given ages that serve as input to the stratigraphic basin modelling (DionisosFlow™), specifically to constrain the paleobathymetric/paleoenvironmental changes through time and space and the sedimentary pathways.

During the Triassic rifting period, the evaporitic sequence within the Jeanne d'Arc basin is dominantly bound by continental environments. The early Jurassic sees the deposition of carbonate environments during the drowning of the aborted Triassic rift episode. The Late Jurassic to Early Cretaceous sees large regressive packages including the Hibernia and Jeanne d'Arc fluvio-tidal reservoir level (Tithonian and Berriasian).
The Early Cretaceous transgression records further basinal sand until the Avalon unconformity (Aptian), resulting in the Ben Nevis deposition. The Late Cretaceous deposits record a large basin drowning during a maximum of eustasy shading bathyal deposits throughout the NL18-CFB01 AOI. A variety of reservoir types can be expected from the Early Cretaceous fluvial deposits, to shoreface and turbidite systems preserved within the Cretaceous basin.
FORWARD STRATIGRAPHIC MODELLING: OBJECTIVES AND WORKFLOW

A forward stratigraphic simulation was performed using DionisosFlow™ (an IFPEN software) to (1) understand better the 3D sedimentary architecture of the basin, (2) quantify the sedimentary volumes at the basin scale, and (3) predict the location of prospective areas in regions with less geological information. This modelling was performed from Late Triassic up to top Cretaceous. Stratigraphic modelling is an integrated model that takes into account accommodation history, sediment supply (siliciclastic source and carbonate production), and transport processes.

- **Accommodation** reflects the available space creation through time that is defined from subsidence maps and global sea level curve.
- **Sediment Supply** is defined by both siliciclastic source and carbonate production. Siliciclastic sources are defined at the edge of the model and varies through time. It corresponds to river insights. Carbonate production is the in-situ production function of ecological parameters (mainly bathymetry, substratum, wave energy, fluvial discharge).
- **Transport processes** are macro-scale sediment transport laws (equation of diffusion). These diffusive equations enable the simulation of the sediment distribution based on its content (grain type and density) and local paleobathymetric variations over tens of kilometres.

Sedimentation or erosion is simulated at each point of the basin using mass balance principles, and is then calibrated by tuning all of the environmental parameters (sources, subsidence map, transport/diffusion).

The main steps of workflow for this stratigraphic modelling consisted of:

- Reproducing regionally the overall basin geometry evolution from Late Triassic to top Cretaceous. This implies (a) a calibration of tectono-stratigraphic sequences with existing structural maps, (b) a reproduction of internal geometries observed on seismic profiles, (c) a reproduction of lithological trend at well location.
- Predicting and quantifying the sedimentological distribution inside described seismic geobodies away from well calibration, and in unexplored areas.
- Extracting refined GDE and lithological 3D volume to be used in the petroleum basin modelling Software (TemisFlow 3D™) and play assessment.

The stratigraphic model extends over 9280km² (116 x 80km) and spans Late Triassic (230 Ma) to top Cretaceous (65 Ma). Time step resolution is 0.2My, for 826 layers. The spatial resolution is 2km. Model calibration is performed based on eight structural maps (seismic horizons) and more than 20 wells.
FORWARD STRATIGRAPHIC MODELLING: SUBSIDENCE HISTORY

In the stratigraphic modelling, subsidence represents the vertical movement of the basement through time. It is key to defining the accommodation space and its variation through time, thus driving in-situ sediment flux. Subsidence evolution is built after reconstructing the main tectono-stratigraphic sequences guided by structural maps (seismic interpretation), taking into account sediment compaction. Eight subsidence maps (at 202, 175, 151, 145, 134, 114, 100 and 65 Ma) have been used to guide the subsidence history of the basin from Triassic to Cretaceous.

Three main tectonic episodes are shaping the final basin geometry. The first tectonic event is an aborted Triassic rift (1) that develops a large subsidence trough around the location of the Jeanne d’Arc Basin, extending to the northeast. The rift elongation is N145° along normal and strike slip faults. The second tectonic event is a Late Jurassic rifting (2) in a N130° direction developing local horsts and grabens with normal and strike slip faults. The third tectonic event corresponds to the Avalon uplift (3) and affects only part of the basin.

The available space curves indicate the available space creation or removal through time (230 Ma to 65 Ma) at specific locations (Conquest K-09 and South-Merasheen K-55). These curves combine subsidence rates extracted from the subsidence maps and global sea level variation rates. The variations highlight the expected stratigraphic sequences in terms of creation or removal of available space for sedimentation.

Both curves show a Triassic to Jurassic long term transgressive system. The curve at Conquest highlights especially the Triassic and Late Jurassic rift events with a large transgressive system that provides conditions of deposition for a Kimmeridgian source rock. The curve at South Merasheen highlights a large regressive system associated to the Avalon Uplift around 120-130 Ma.
FORWARD STRATIGRAPHIC MODELLING: INPUT PARAMETERS

SILICI-CLASTIC SEDIMENT SUPPLY

Four main sources of sediment have been interpreted to feed this area, based on regional paleo-geographic mapping and seismic geomorphological interpretation of objects such as channels, lobes and slope fans. These sources seem relatively steady from the Triassic until the Late Cretaceous originating from the Cumberland Ridge, the Flemish Cap and largely from the Grand Banks.

Sediment sources shed off sediments from existing paleo-highs with intensity varying with tectonic events such as the Late Jurassic rifting and the Avalon uplift.

Volume of sediment (defined as a flux in DionisosFlow) and sand/shale ratio have first been estimated from thickness maps, then adjusted through the forward simulations. Associated fluvial discharge has been estimated from an average value of about 0.35 mg/l.

EVAPORITES

Triassic salt layers are identified southwest of the Jeanne d’Arc Basin within the wells Spoonbill, Cormorant, and Murre. Salt lithologies are intercalated in shales, mudstone, and calcareous shales. Age dating constrains the salt deposition between 215 to 190 Ma.

That time interval corresponds to a low sea level stage during the Late Triassic to very Early Jurassic in the Global Sea Level curve. This lowstand stage isolates the Jeanne d’Arc Basin, thus allowing salt deposition fed from higher frequency (Milankovic) marine incursion.

Salt precipitation in the simulation has been estimated to be around 400m/Myrs.

CARBONATE PRODUCTION

The basin is largely dominated by silici-clastic sediment but several carbonate levels exist especially during the Jurassic and Early Cretaceous such as the Iroquois and Whale Formations in the Early Jurassic, the Rankin Formation during Oxfordian and some thin levels in the Early Cretaceous. Well lithology descriptions (Golconda, Kyle, Bonanza, Fortune) highlighted the presence of bioclastics, ooliths, mollusc fragments, and foraminifera varying from 10 to 100m thick.

DionisosFlow simulations take into account carbonate production rate as a function of bathymetry, wave energy, substratum nature, and fluvial discharge. Carbonate production rate has been defined around 200m/Myrs except for Aptian/Albian/Cenomanian/Turonian times, which is known as the global carbonate crisis, and where production has been limited to 45m/Myrs.

ORGANIC MATTER

The geochemical analyses have established the Kimmeridgian rich organic layers are the main source rock of the region. Nevertheless, its actual distribution is poorly constrained. DionisosFlow is used to predict and delineate rich organic matter content constrained by environmental conditions such as bathymetry, substratum nature, and oxygenation condition.

DionisosFlow simulations take into account primary productivity of organic matter and its subsequent degradation during precipitation and within the substratum. Two models are considered here. An anoxic model (stagnant model) which corresponds to the Triassic-Late Jurassic period and an open marine model that represents time during which the North Atlantic ocean is largely open. For both, primary productivity has been estimated around 5-10m/Myrs.
FORWARD STRATIGRAPHIC SIMULATION: CALIBRATION RESULTS

The calibration phase consisted in testing various scenarios to calibrate both geometry/thickness maps and respect lithologies recorded at well location. The main input parameters used for calibration are source location, fluxes, sand/shale ratio, and timing.

Maps at the right compare interpreted thickness maps (seismic horizons) and simulated sediment thickness. The model shows a good consistency. Wells below highlight how trends are matched between simulated clastics and carbonate ratio with the observed lithology.
FORWARD STRATIGRAPHIC MODELLING:
LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS MODELLING

Environmental parameters such as the paleobathymetries and the lithological content are used to define the paleoenvironments.
FORWARD STRATIGRAPHIC SIMULATION : SEISMIC STRATIGRAPHY CALIBRATION

Seismic control of the general (thickness) and specific geobodies and stratal terminations (such as onlap, toplap and truncation geometries) were reproduced. A random line is displayed below.
FORWARD STRATIGRAPHIC MODELLING: METHODOLOGY FOR MAPPING DEPOSITIONAL ENVIRONMENTS AND LITHOLOGY DISTRIBUTIONS

The grid below (1) illustrates the simulated stratigraphic model with lithology properties (or dominant lithology). For each layer, a set of more than 15 output properties can be extracted. They include paleoenvironment conditions (2a), such as bathymetry, water flow, and wave energy; and lithologies (2b) such as sand, shale, mudstone, carbonate, evaporites, and organic matter.

**1- 3D Stratigraphic Model Grid**

To give a more representative mapping of actual stratigraphic sequences, groups of layers corresponding to two to four million years are selected.

The depositional environments maps (3) and the lithology distribution maps (4) are built by combining the previous properties for each sequence.

The maps shown on the next pages are chosen for the representability of specific tectono-stratigraphic events.

**2- Output properties**

2a - Paleoenvironment conditions

- Bathymetry
- Wave Energy
- Water Flow

2b - Lithologies

- Shale
- Carbonate
- Sand

**3- Depositional Environment Maps**

Paleoenvironments:
- Bypass Erosion
- Alluvial fan
- Fluvial plain
- Fluvial channel
- Lacustrine
- Shoreface
- Tidal
- Inner carb platform
- Outer carb platform
- Evaporitic
- Inner Neritic
- Outer Neritic
- Bathyal

**4- Lithology Distribution Maps**

Lithologies:
- Bypass Erosion
- Sandstone
- Siltstone
- Silty-shale
- Shale
- Carbonate
- Marlstone
- Mudstone
- Evaporites
FORWARD STRATIGRAPHIC MODELLING: DEPOSITIONAL ENVIRONMENTS & LITHOLOGY DISTRIBUTION

1. Triassic Salt Basin: The Triassic aborted rift develops a deep basin in the west of the study area (Jeanne d’Arc Basin) extending towards the northeast. Depositional environments evolved from mostly continental/lacustrine at the beginning of the rift (Early Late Triassic) to a marine environment with episodic isolation from the main ocean between the eustatic drop (=216 to ≈196 Ma). The depositional environment and lithology maps show transitional environment from bypassed paleo-highs to the evaporitic basin in the lowest area. High sand content exists around highs, fluvial plain environment dominates in the northeastern region and thick salt is deposited in Jeanne d’Arc Basin.

2. Voyager Equivalent Middle Jurassic: The Voyager Formation develops during a lowstand sequence in a dominated shallow water environment, which is favorable to mixed carbonate/clastic environments. Small carbonate patches can be found while the interval remains mostly dominated by silici-clastic sediments.
FORWARD STRATIGRAPHIC MODELLING: DEPOSITIONAL ENVIRONMENTS & LITHOLOGY DISTRIBUTION

3. Rankin Equivalent (Oxfordian): This interval corresponds to a highstand system track in a transgressive sequence favorable to carbonate development. The continental and fluvial plain sedimentation transitions to shoreface environment around preserved paleo-highs. A small carbonate platform with bioclasts is locally developing away from fluvial discharge. Accommodation space generally increases due to global sea level rise and the Late Jurassic rifting that reactivates basin faults.

4. Egret Equivalent (Kimmeridgian): This interval reflects the transgressive to maximum flooding event of the Late Jurassic sequence. Accommodation space reaches a maximum, allowing very rich organic matter preservation in a shale to mudstone environment. Most of the basin is flooded and a shoreface to fluvial plain environment is limited to the paleo-highs. Some small carbonate bioclastics can exist when the fluvial system moves southward.
FORWARD STRATIGRAPHIC MODELLING: DEPOSITIONAL ENVIRONMENTS & LITHOLOGY DISTRIBUTION

5. Jeanne d’Arc Equivalent (Tithonian): This interval is one of the main reservoirs in the area. It corresponds to a lowstand system track that provides good quality fluviodeltaic sand over the study area. Large volumes of sediment sourced from the south and east develop a prograding system into the basin. Accommodation space decreases during this time, due to the sediment discharge. Some turbidite systems may develop further in the basin.

6. Flooding event (Late Tithonian): A transgressive period that follows the Jeanne d’Arc Formation deposition sees the development of a potential seal over a significant part of the basin. This event represents potential rich organic matter deposited across a limited area compared to the Kimmeridgian. This is due to a shorter transgressive period during late Tithonian. Some small bioclastic carbonate patches can develop but in very limited extent.
FORWARD STRATIGRAPHIC MODELLING: DEPOSITIONAL ENVIRONMENTS & LITHOLOGY DISTRIBUTION

7. Hibernia Equivalent (Berriasian/Valanginian): This interval is also one of the main reservoirs in the area. It corresponds to a lowstand system track that provides a thick unit of well sorted sand, especially in the southern half of the study area. A deltaic system progrades towards the northeast into the basin. Accommodation space decreases and enables turbidite systems to fill the deeper basin.

8. Ben Nevis Equivalent (Aptian/Albian): The Avalon Uplift event affects part of the basin with fault reactivation and regional uplift. It represents the last tectonic event that shapes the basin. Sediments previously deposited are re-transported into the lows and then re-sorted within the shoreface sand of the Ben Nevis Formation. The northeast portion of the study area is drowning.
FORWARD STRATIGRAPHIC MODELLING: DEPOSITIONAL ENVIRONMENTS & LITHOLOGY DISTRIBUTION

Late Cretaceous: This sequence of deposition shows a very low sedimentation rate. Structural highs are progressively eroded and eventually flooded. The study area is evolving to a broad bathyal environment and sand distribution seems to be very limited. Chalk is deposited as a pelagic product, mainly in the lows.

9. Late Cretaceous sample map at 74 Ma
SOURCE ROCK DEFINITION: CHARACTERIZATION AT WELLS

In the studied area, Total Organic Content (TOC) and Rock Eval data allowed for characterization of key parameters of source rock intervals at well locations. In addition, the regional extent of source rock was assessed through a Carbolog® approach to constrain the petroleum modelling. With this approach, the TOC was computed from the combined log response between the sonic, density, neutron, and resistivity. From well data within the study area, the source rock evaluation shows:

- A hypothetic Toarcian source rock, not sampled at wells within the area, but inferred from regional stratigraphic settings and global sedimentary trends.
- The existence of a proven Kimmeridgian source rock (main source rock in the Jeanne d’Arc Basin).
- The existence of a rich TOC interval at the top of the Tithonian in Great Barasway, Baccalieu and Lancaster wells (around 3%) and a Kimmeridgian source rock potential distributed over a large thickness (>200m) with TOC ≥ 1%. (see 2015 Flemish Pass Basin resource assessment available at Nalcor energy: https://goo.gl/OYG0tr).
- The Cretaceous level (Turonian-Cenomanian) presents a source rock potential, illustrated here at Great Barasway and Sheridan, and which is supported by the stratigraphic forward modelling that highlights local “ponds” favorable to the preservation of organic rich sediments.
- The Paleocene interval displays a regionally consistent level of rich TOC values constituting a potential source rock. Its average TOC is in the order of 2-5% depending on the basinal settings.
- Finally, another potential TOC rich level is recorded around 45 Ma (Eocene) with a fair lateral consistency. This source rock is not sufficiently buried in the basin to represent a significant contribution to the petroleum system.

IFPEN patented methodology to estimate the organic content of potential source rocks. From Carpentier et al., 1991.
SOURCE ROCK DEFINITION: FORWARD STRATIGRAPHIC MODELLING COMPUTATION

Geochemical analyses demonstrated that Kimmeridgian rich organic layers are the main source rock of the functioning petroleum system in the Jeanne d’Arc Basin. Its actual distribution over the study area is poorly constrained by well data. In that sense, DionisosFlow is used to predict and delineate rich organic matter content based on environmental conditions such as bathymetry, substratum nature, and oxygenation conditions. Measured values at well locations (mainly Rock Eval data) are used as a reference to adjust the primary productivity.

**Methodology:** DionisosFlow simulations take into account primary productivity, degradation, and preservation of the organic matter, which are conditioned by the environmental conditions imposed on the model. Degradation of organic matter occurs, first during precipitation, and then, in the substratum. Its preservation and dilution are related to the sedimentation rate. Moreover, regional or global anoxicity events are taken into account to modulate the preservation process. At the end of process, DionisosFlow estimates an initial TOC. TOC volumes within the sediment are converted into masses of TOC for comparison with well data and petroleum system modeling.

**Application to the study area:** Two general models are considered for this basin based on its tectonostratigraphic evolution: (1) an anoxic model (stagnant model) that corresponds to the Triassic-Late Jurassic period when the North Atlantic ocean is not very well connected and (2) an open marine model when the North Atlantic ocean is largely open with a connection from the north to the south Atlantic (Page 24).

TOC measurements at well locations (mainly Rock Eval data and calculated TOC, Page 34) are used as a reference to calibrate the primary productivity through several scenarios. For both models, primary productivity is estimated around 10m/Myrs.

Bathymetry, sedimentation rate, and facies distribution maps (examples below), resulting from the stratigraphic model simulation, constrain organic matter deposition, and the preservation process.

The cross section, presented below, is an extraction of the model showing a vertical distribution of TOC%. It helps to highlight the stratigraphic position of the richer organic matter layers. The Kimmeridgian source rock is clearly identified as thick and rich. Tithonian source rock potential is present in thin stringers. According to this simulation, the Toarcian may present rich organic layers, but without well data as evidence to support this, the Toarcian source will not be included as a contributing source rock during volume calculations.

The maps, presented below, are an extraction of the resulting source rock map for the Kimmeridgian stage. It shows both initial TOC% distribution (average TOC) and net thickness (TOC above a threshold value) that could be used for petroleum system analysis.
SOURCE ROCK DEFINITION:
SYNTHESIS

Five known, hypothetical or speculative, source rocks have been considered for the petroleum system modelling of the Jeanne d'Arc Basin:

1. The Toarcian calcareous shale and claystone (post early rift) in an epeiric marine setting is only penetrated in Golconda C-64 with no clear potential. However, speculative potential is supported by the sedimentary model and evidence of widespread anoxic event at that time. This has not been modelled as a contributor to hydrocarbon migration due to the speculative nature of this source rock.

2. The Kimmeridgian Egret Fm. is sampled in numerous wells displaying marine rich organic matter with good to excellent potential, deposited regionally in deep marine conditions. The potential diminishes laterally toward the eastern extent of the study area.

3. An upper Toarcian source rock very similar to the characteristics of the Kimmeridgian.

4. The Late Cretaceous source rock develops during the drowning of the Jeanne d'Arc Basin in the northern part of the study area. Its potential is limited at the well locations but can increase towards the center of the basin.

5. Additionally, a Paleocene source rock, which is penetrated by wells on the shelf, is postulated in the deeper basin but its interest for the petroleum system modelling is limited by the burial within this study area.
The Wheeler diagram reflects the paleo environment setting as a function of geological time. The environments within the Triassic and Middle Jurassic change from evaporitic/shaley depocenter toward carbonate and clastic conditions on the basin edges. The main Late Jurassic and Early Cretaceous reservoirs are located on the edges of the basins.
FROM SEDIMENTOLOGY / STRATIGRAPHY TO MODELLING

Initial Seismic and Stratigraphic Interpretation
(Seismic interpretation & GDE mapping)

3D Forward Stratigraphic Model
(sand proportion over 826 layers; 2x2 km grid)

3D Forward Stratigraphic Model
Lithology Distribution

3D Petroleum System Model
(33 upscaled facies layers in 1x1km grid)

Not modeled in DionisosFlow

Interval modeled with DionisosFlow

Reconstructed from paleobathymetries

Lithologies
- Continental shale
- Continental sandstone
- Submarine sandstone
- Marine Heterolithics
- Marine Shale
- Alluvial fan
- Deep Fine Carbonate
- Deep Heterolithic Carbonate
- Carbonate shoal
- Platform Carbonate (Chalk)

Bonanza M-71
North Dana I-43
Kyle L-11

North Dana I-43 (proj.)
PETROLEUM SYSTEM MODELLING

The basin and petroleum system modelling used the present day information (geometry, facies, and source rock properties) and the conceptual basin evolution (sequence stratigraphic analysis, and mainly paleo-environment and basin tectonic evolution) to reproduce the physical, thermal, and chemical processes that occurred during its deposition.

The generation, expulsion, migration, and entrapment of hydrocarbons from the source rock to the reservoirs were simulated, taking into account both the paleo-geometry, the thermal state, fluid flow, and the rock's petrophysical properties.

1D modelling: A first understanding of the geothermal context and pressure field was rapidly assessed by a series of 1D models at key well locations, helping to evaluate oil and gas generation timing in the various Jurassic source rock candidates.

3D Model construction: The 3D static petroleum system model was built using DionisosFlow™ with the structural depth maps used to create the present day model geometry with additional subdivisions from TemisFlow™. The 3D stratigraphic cube with lithological and source rock distribution maps was populated using gross lithofacies maps extracted from the DionisosFlow™ results.

2D Basin Modelling Calibration: Two 2D sections were extracted from the 3D framework to perform the calibration of the thermal and pressure regimes. The sections were chosen for their representativeness of the petroleum system (passing through the source rock kitchen) and to include key wells with relevant data for calibration. The model boundary conditions through time were defined. This enabled the thermal calibration of the model for both historical and present day temperature. The model properties, especially the fine tuning of facies distribution and permeability parameters, were taken into account for pressure calibration.

3D Hydrocarbon migration calibration: The hydrocarbon generation and migration simulation was performed using Full Darcy Compositional Migration in TemisFlow™ and taking into account the results of 2D modelling. Source rock type and richness were also defined in the model. The known oil and gas accumulations and shows (including sea bottom seeps) and their properties were used to calibrate the model and understand its limitations.

The model uses a compositional description of the HC (dry gas, wet gas, condensate light oil, intermediate, and heavy oil). The HC chemical composition depends on the kerogen compositional kinetics and HC product cracking.

The hydrocarbon saturation within the source rock during HC generation generates an increase of the source rock capillary pressure, and consequently, the expulsion of hydrocarbons. The model assumes that a minimal saturation is needed to trigger the expulsion.

The evaluation of charge within main plays was calculated by taking into account the physical processes governing the migration of hydrocarbon fluids.

The HC fluid flow is computed through the multiphase Darcy Law flow. It simulates the Pressure regime (HC pressure and water pressure), capillary forces retention effect, and buoyancy forces.

The models assume that a minimal saturation within the HC migration pathways (carrier beds, faults conduits) is needed to proceed. No movement occurs until the HC saturation reaches the minimal residual saturation. Consequently, the long distance HC migration models predict a lower migration efficiency towards the traps.

The models also offer the option of instantaneous HC migration toward the traps (Trap Charge Assessment [TCA] module). The TCA module is used as a complement to the Darcy modelling since it allows for a higher horizontal resolution of the model.
**3D BLOCK BUILDING**

The initial 3D petroleum system model (11 seismic stratigraphic layers, arrows) has been subdivided in 41 layers, enabling the identification of the main components of the petroleum system, while preserving the main regional lithological and sequence stratigraphic events.

To create this petroleum system model (shown below), the 3D stratigraphic model (DionisosFlow™) was then upscaled from 546 to 32 layers for the interval between Base Mesozoic and C65 (Top Cretaceous) maintaining regional geological context and keeping the highest degree of information.

---

**3D (fence diagram) stratigraphic view considering the final block layering**

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</tr>
</thead>
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</tr>
<tr>
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<td>J151</td>
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**Dominant petroleum system element**
- **Source rock**
- **Seal**
- **Reservoir**

**Seismic horizons**
TEMPERATURE DATA

In the studied area of the East Jeanne d’Arc Basin, the present day temperature measured in the shelf wells and deep water display a range of geothermal gradients of 30 to 35°C/km, with an average of 33.7°C.

The wells in areas with highly thinned basement (Conquest, Adolphus, Dominion, South Tempest) display a relatively high thermal gradient. It suggests the thinned crust and normal crust thermal regimes are slightly different.

The above observations are used to calibrate the thermal regime of the East Jeanne d’Arc Basin.

VITRINITE REFLECTANCE DATA

The percentage Ro measurements are displayed on the graph at right for fourteen wells, which are of different vintages and from multiple geochemical laboratories. A wide range of values may be found for a given burial depth and a given well, while maturity trends with depth are quite similar between wells and/or laboratories.

Data evidence at present day display the beginning of oil window between 2500 and 3000 m, although these conditions have varied in the past (shallower depth).

The effect of late Aptian erosion is not visible in the maturity data because of scarce spatial sampling. Part of the wells display continuous Mesozoic sedimentation in the troughs. For the others, the amount of erosion vs pre-erosion burial was not sufficient to impact the maturity trend (i.e., this thermal episode is overprinted by later burial).
THERMAL RIFT EVOLUTION

Heat flow evolution in the Jeanne d'Arc Basin is controlled by heat transfer through evolving thinning continental crust and synchronous disposition of sediments. Heat flow transfer varies through time and position in the basin controlled by the following factors:

- Thickness and type of crust directing radiogenic heat production of continental crust.
- Sedimentation rate impacting basin burial history.
- Bulk thermal conductivity of sediments controlled by compaction and type of lithology.
- Radiogenic heat production of sediments.
- Temperature and depth of Lithosphere-Asthenosphere Boundary (1333 °C).

Rifting is handled through a thinning factor of the continental crust calculated from an assumed pre-Triassic thickness of 35 km. Maximum values are reached in Jeanne d'Arc area (> 4) whereas in most of the area it is lower than 2.5.

Polyphased rifting took place between Late Triassic and late Early Cretaceous. Total thinning is thus distributed into two main rifting phases (1: Triassic to Early Jurassic and 2: Late Jurassic to Early Cretaceous) in between which an intermediate crustal thickness is recalculated.

Crustal thinning is used to compute variation of basal heat flow through time and space in response to successive rifting phases.

The crustal thinning results in a drastic rise of the top asthenosphere (1333 °C isotherm) and an increase of temperature in the crust and the sediments leading to warmer conditions (i.e. shallower hydrocarbon generation windows during Triassic to Early Cretaceous).

During the late Early to Late Cretaceous post-rift phase, top asthenosphere isotherm depth gradually decreases until heat flow equilibrium is reached. In addition, a high Cenozoic sedimentation rate over the depocenters contributes to the decrease of the heat flow.
**Vitrinite Ro (%) - At Present Day for Selected Source Rocks**

The present-day source rock maturity expressed in Equivalent Vitrinite Reflectance (VRo%) shows Jurassic source rocks highly mature (wet and dry gas window) to overmature in deepest syn-rift depocenters, whereas in low sedimentation rate areas with less burial, maturity remains in the oil window if those intervals are preserved.

Younger Cenomanian and Paleocene source rocks are only mature below the thick prograding Bonavista Platform. Timing and synchrony of liquid hydrocarbon migration was favorable for trap charge and preservation from the deeper organic-rich intervals (see following slides).

<table>
<thead>
<tr>
<th>Source Rock</th>
<th>Vitrinite Ro (%) - at 0.0 Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kimmeridgian SR</td>
<td>1</td>
</tr>
<tr>
<td>Tithonian SR</td>
<td>2</td>
</tr>
<tr>
<td>Cenomanian SR</td>
<td>3</td>
</tr>
<tr>
<td>Paleocene SR</td>
<td>4</td>
</tr>
</tbody>
</table>
Maturity expressed in Vitrinite Reflectance was calculated for the Kimmeridgian source rock layer through geological time. The early oil window (VRo% > 0.6) appears during the Late Jurassic to Early Cretaceous in deepest depocenters due to higher burial rate and high geothermal gradients during rifting phase. The oil window (0.6 – 1.1 VRo%) prevailed in almost all the basin area until the latest Cretaceous, with the exception of deepest depocenters which reached the gas window from the Valanginian. A steep, regional increase of maturity occurred after the Cretaceous, due to higher sedimentation rate and burial, preserving overmature gas areas throughout the basin with the exception of the southern and eastern edge of the Jeanne d’Arc Basin that remained in immature to early generation window.
Maturity expressed in Vitrine Reflectance was calculated for the Tithonian source rock layer through geological time. The early oil window (VRo% > 0.6) appears during the Early Cretaceous in deepest depocenters due to higher burial rate and high geothermal gradients during late rifting phase. The oil window (0.6 – 1.1 VRo%) prevailed in almost all the deepest depocenters until the latest Cretaceous, with the exception of western and northeastern areas and which reached the gas window after the Barremian. A steep, regional increase of maturity occurred after the Cretaceous due to higher sedimentation rate and burial, causing the appearance of gas generation and overmature areas in the north and west. The southern and eastern edge of the Jeanne d'Arc Basin remained in immature to early generation window.
Maturity expressed in Vitrine Reflectance was calculated for the Late Cretaceous source rock layer through geological time. The early oil window (VRo% > 0.6) appears progressively during the Paleogene due to higher sedimentation rate and burial. The oil window (0.6 – 1.1 VRo%) prevailed in almost all the Bonavista Platform progradation area until present day, with the exception of the northwestern area which reached the gas window after the Miocene.
Maturity expressed in Vitrine Reflectance was calculated for the Paleogene source rock layer through geological time. The early oil window (VRo% > 0.6) appears progressively during the late Paleogene due to higher sedimentation rate and burial. The oil window (0.6 – 1.1 VRo%) prevailed in almost all the Bonavista Platform progradation area until present-day.
PRESSURE MODELLING

A NW-SE transect is used to describe the petroleum system as it intersects most of the depocenters relevant for analyzing the petroleum systems of the study area.

The top section displays in 2D, the upscaled results of lithology modelling used as input for thermal and migration modelling. Potential source rock intervals are highlighted with dashed lines.

The main regional pressure boundaries lie within the Jurassic, Cretaceous, and the Paleogene in relation with regional shale or chalk units that appear to be relatively continuous at basin scale. These regional shale units also correspond to the main organic-rich layers within the Mesozoic.

The first pressure jump occurs below Late Cretaceous deep carbonates. The most important pressure jump occurs below the Kimmeridgian source rock. The presence of overpressure below the Kimmeridgian source rock level is a regional feature that tends to disappear laterally as sand content, and thus vertical and lateral connectivity, increases.

Deeper low permeability intervals such as Late Toarcian and Triassic evaporites also cause significant over pressure increase.
THERMAL MODELLING

In the deepest part of the depocenters, the temperature reaches more than 250°C. It is highly probable that most of the deepest troughs of Jeanne d’Arc area are already in low pressure, high temperature metamorphism.

The two Jurassic source rocks (proven Kimmeridgian and Tithonian) all lie at temperatures higher than 140°C, equivalent to highly mature to overmature source rocks throughout this section.

Cretaceous and Paleogene source rocks are found within oil window (vitrinite reflectance comprised between 0.7 and 1.3% Ro).

The overall Jurassic reservoir temperatures are above 120°C at present day, along this cross section, meaning that only light oil, condensate, and gas could be preserved.

The Cretaceous sedimentary interval is found at the lower maturity interval, along this cross section, so early migrated oil and late gas could coexist.
In the deeply buried depocenters, the kerogen Transformation Ratio of the two assessed Jurassic source rocks comprises between 80 and 95%, depending on their reactivity and burial history vs position in the rift.

Cretaceous kerogen transformation can reach 75% west of the Bonanza basement high. Paleocene kerogen transformation never exceeds 50% along this section. Cretaceous and Paleocene source rock transformation is directly related to Neogene burial.

Expelled masses are sensitive to the thickness and richness of the source rocks (i.e., their potential depending on effective thickness in the model, porosity, bulk density, initial TOC, and initial Hydrogen Index), and the transformation ratio. The Kimmeridgian source rock has expelled large amounts of hydrocarbons (up to 10 t/m² where sedimentologic conditions are the most favorable for deposition and preservation of organic matter).

Other Jurassic source rocks are minor contributors to the system, with the main uncertainty being their richness and extent.

Cretaceous and Paleogene source rocks have not expelled significant amounts of hydrocarbons within the study area.

The timing of kerogen transformation and expulsion are presented for four representative locations on the inset map and charts below, of East Jeanne d’Arc area.
PETROLEUM SYSTEM MODELLING

Migration modelling allows for the reproduction of the main discoveries and producing fields in 3D. The model is also able to explain fluid escape pattern such as the one observed on top of Bonanza basement high.

The model shows an efficient lateral migration process throughout the study area. One should note that lateral migration process is enhanced by Cenozoic westward tilting of the Jeanne d'Arc Basin, caused by the flexural load of the Bonavista Platform.

The HC quality was computed from the HC composition in oil (C6+) and gas (C1-C5). Gas and locally condensate are predicted over most of the area.

TIMING OF MATURATION VERSUS EROSION

The timing of hydrocarbon maturation, illustrated by the age at which the main source rock level in the study area reaches 0.7%Ro (equivalent to early oil generation for a Type II kerogen), is in competition with erosion related to the Avalon Uplift.

This may lead to significant loss of the early generated hydrocarbons along the main uplifted areas that bound the AOI. Fainted colors represent the areas where post-erosion generation is likely to provide significant hydrocarbons after regional reservoir seal and reservoir deposition.
The 3D reference petroleum system model is built on the basis of a calibrated lithofacies geocube, coming from stratigraphic modelling.

Distribution and observed fluid properties are then properly reproduced:

- Hydrocarbon discoveries* such as North Dana or Whiterose demonstrate efficiency of petroleum system components within the study area.
- Those direct observations, combined with hydrocarbon occurrence detection such as gas chimneys and AVO response, were analyzed and used to constrain the reference geological model.

In the 3D image, the maturity of the Kimmeridgian source rock is displayed as a background map in vitrinite reflectance equivalent.

The blue lines indicate drainage lines from “kitchens” to structural highs. Hydrocarbon migration pathways are represented by black vector arrows for a given time, indicating lateral and vertical migration processes.

Blue bodies represent potential traps and their structural closures independently from hydrocarbon charge.

* [https://www.nr.gov.nl.ca/nr](https://www.nr.gov.nl.ca/nr)
UNRISKED VOLUMES FOR NL18-CFB01

Volumes contained in the 3 parcels (14, 15 & 16)

The unrisked volume of hydrocarbons corresponds to the amount of oil (in Bbbl), gas (Tcf), and oil+gas (in Bboe) that can be present in the plays (expressed as high, average, and low scenario) according to one reference geological scenario.

Uncertain variables such as TOC, seal retention capabilities, and oil and gas saturation cutoffs have been accounted for.

The reference scenario also honors the observations on pressure, temperature, and oil accumulations within the resolution of the geological model and within the uncertainties on measurements/observations. The volumes described here are aggregate, summed volumes for the three blocks, and they do not include additional volumes outside of the blocks but which are within the study area.

The impact of the uncertain variables is evaluated through a sensitivity analysis.

<table>
<thead>
<tr>
<th>Oil Equivalent</th>
<th>Unrisked Volumes in place (Bbbl)</th>
<th>Jurassic</th>
<th>Cretaceous</th>
<th>Tertiary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Early Jurassic Middle Jurassic Late Jurassic Early Cretaceous Late Cretaceous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P90 Low scenario</td>
<td>0.24 0.74 0.11 0.54 0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P50 Most likely scenario</td>
<td>0.38 0.95 0.7 1.86 1.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10 High scenario</td>
<td>0.44 1.06 1.22 3.60 2.27</td>
<td></td>
<td></td>
<td>1.19</td>
</tr>
</tbody>
</table>

Gas Unrisked Volumes in place (Tcf)

<table>
<thead>
<tr>
<th></th>
<th>Early Jurassic</th>
<th>Middle Jurassic</th>
<th>Late Jurassic</th>
<th>Early Cretaceous</th>
<th>Late Cretaceous</th>
<th>Oligocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>P90 Low scenario</td>
<td>0.66 3.73 0.42</td>
<td>1.73 0.3</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>P50 Most likely scenario</td>
<td>1.05 4.76 2.51</td>
<td>5.77 3.15</td>
<td>2.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10 High scenario</td>
<td>1.21 5.25 4.30</td>
<td>11.85 6.19</td>
<td>3.42</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Oil Unrisked Volumes in place (Bbbl)

<table>
<thead>
<tr>
<th></th>
<th>Early Jurassic</th>
<th>Middle Jurassic</th>
<th>Late Jurassic</th>
<th>Early Cretaceous</th>
<th>Late Cretaceous</th>
<th>Oligocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>P90 Low scenario</td>
<td>0.12 0.09 0.04</td>
<td>0.24 0.10</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P50 Most likely scenario</td>
<td>0.20 0.13 0.27</td>
<td>0.87 0.50</td>
<td>0.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10 High scenario</td>
<td>0.23 0.16 0.48</td>
<td>1.56 1.20</td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
UNRISKED VOLUMES FOR NL18-CFB01 Volumes contained in the 3 parcels (14, 15 & 16)
Sensitivity analysis

The unrisked volumes are presented as high, most likely, and low cases with sensitivity deriving from the geological reference model (previous page) for main plays. Their distribution is presented.

The volumes described here are aggregate, summed volumes for the three blocks and do not include additional volumes outside of the blocks but which are within the study area.

<table>
<thead>
<tr>
<th></th>
<th>Total Oil (Bbbl)</th>
<th>Total Gas (Tcf)</th>
<th>Total Oil &amp; Gas (BOE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P90 Low case</td>
<td>0.7</td>
<td>7.7</td>
<td>2.1</td>
</tr>
<tr>
<td>P50 Most likely</td>
<td>2.4</td>
<td>19.8</td>
<td>5.8</td>
</tr>
<tr>
<td>P10 High case</td>
<td>4.2</td>
<td>32.2</td>
<td>9.8</td>
</tr>
</tbody>
</table>
RISK ANALYSIS

Probability of Geological Success \( \text{POS} = \text{Phc} \times \text{Ps} \times \text{Pr} \times \text{Pt} \)

Leads and prospects
The probability of geological success is separated into four main independent terms
- \( \text{Phc} \) = HC charge probability
- \( \text{Ps} \) = Seal presence and efficiency
- \( \text{Pr} \) = Reservoir presence and quality
- \( \text{Pt} \) = Trap existence (in the case of regional 2D seismic grid and interpretation)

Leads and prospects may be mutually dependent. For each dependent lead, the \( \text{POS} \) in the case of success or failure will be higher or lower respectively than the independent \( \text{POS} \).

RISK EVALUATION AND POS

The risk analysis defines semi-quantitative thresholds on the \( \text{POS} \) of the petroleum system components applicable over the studied area.

The HC charge thresholds are defined by average amount of charge HC/km² (e.g., > 500 kg/m²) in the play or play sector (accumulated over the source rock vertical thickness).

The reservoir risk was defined by threshold on estimated net thickness and individual sand layer thickness (Total > 100 m, 1 individual sand layer > 5 m).

The seal risk was defined by threshold on the seal thickness and continuity (faulted and < 10m, unfaulted and > 50m).

The trap risk was defined by trap volume threshold and fill spill analysis (number of traps with porous volumes > 10, 50, or 100 million m³ resulting from the fill spill analysis). In the fill-spill analysis, the excess charge of individual traps filled up to spill point may charge a trap updip. In this case, the individual traps may be merged into a single larger trap.

Risk maps of the individual petroleum system components are known as Common Risk Segment (CRS) maps.

The global exploration risk for the play is defined as Composite Common Risk Segment map (CCRS) and is obtained by superimposing the individual CRS maps.

CCRS multiplay maps may also be built to evaluate the global exploration risk.

RISK SCALE

- High risk that the petroleum system component is not efficient (or low probability that it is efficient)
- Medium risk
- Low risk

Play POS
A play \( \text{POS} \) can be considered. It is defined as the product of \( \text{Phc} \), \( \text{Ps} \) and \( \text{Preservor} \) depending on the risk level (low, best, high)

Risked volumes are the product of:
\( \text{Ps} \times \text{Phc} \times \text{Pr} \times \text{Pt} \) UNISKED volumes at a given probability (e.g., P50)

In this approach, the risked volumes are lower than the \( \text{Prospective Oil Initially In Place (OIIP)} \) and \( \text{Gas Initially In Place (GIIP)} \) resources, and will not correspond to actual volumes to be expected during the exploration of the traps and leads. The risked volumes are used to rank the blocks or sectors between themselves. The plays can also be ranked by adding all risked volumes.
**PETROLEUM SYSTEM ELEMENTS RISKING**

Common Risk Segment (CRS) mapping was performed, based on the reservoir and seal elements, and it considered their presence and efficiencies. Using the full resolution, forward modelling, stratigraphic 3D grid (one play example presented here) the CRS maps took into account elements such as net sands and net shale and the thickness of vertically continuous beds.

For example, the low risk reservoir areas are characterized by net sand thicker than 100m with at least one vertically continuous bed > 20m. A good seal is characterized by at least 20m of continuous shales. The risks are classified as low, medium, or high.

The HC charge risk map was derived from the computed HC charge within a given play through petroleum system modelling. (HC volumes present in traps - structural and/or stratigraphic).

The HC charge risk has been evaluated in the Beicip-Franlab Internal Nalcor/DNR report and is not shown here. A random example is presented here.

For each play, HC Composite Common Risk Segment (CCRS) maps were obtained by combining the HC charge (expulsion and migration) with the geological CRS maps. These CCRS maps express the relative exploration risk throughout the acreage for a given play (Beicip-Franlab Internal Nalcor/DNR report).

<table>
<thead>
<tr>
<th>Lithology</th>
<th>&gt; 50% Sh</th>
<th>&gt; 50% Sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>Sand thickness in at least 1 bed (m)</td>
<td>0</td>
</tr>
<tr>
<td>Seal</td>
<td>Net Sand (m)</td>
<td>0</td>
</tr>
<tr>
<td>Seal</td>
<td>Net Shale (m)</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Seal</td>
<td>Capillary pressure (Mpa)</td>
<td>&gt;0.45</td>
</tr>
</tbody>
</table>

Reservoir CRS

Seal CRS

Reservoir + Seal (from Forward Stratigraphic Modelling)

Charge (from Petroleum System Modelling)

CCRS
INDIVIDUAL PROSPECT/LEAD AVERAGE SUCCESS RATE

For a given lead containing significant HC volumes (in the order of 0.3 Bboe best estimate per lead), the average success rate (individual Probability of Success [POS]) may vary from 6% to 27% depending on the play (Early Jurassic, Late Jurassic or Cretaceous) and the trap type (faulted blocks, stratigraphic, etc.). The POS estimates are derived from the play risk maps and geophysical evidence.

The average success rate per significant lead is evaluated to 11% for all plays.

CUMULATIVE PROBABILITY OF GEOLOGICAL SUCCESS

The Cumulative Probability of Success quantifies the chances of success to find at least a given HC volume in the exploration blocks as a whole. This volume is the combination of individual unrisked volumes in the various leads.

EVOLVING POS WITH ADDITIONAL DATA

The POS is directly dependent on the amount and quality of data. 3D seismic as well as new well information may significantly change the POS estimates.
PETROLEUM SYSTEM CHART

A synthetic petroleum chart illustrating the petroleum components and timing of the generation, expulsion, migration, and entrapment of hydrocarbon is proposed:

- The main and proven source rocks (Kimmeridgian and Tithonian) are generating oil during the Early Cretaceous and are starting to expel oil a few million years later.
- The Cretaceous (Cenomanian-Turonian) and Paleogene source rocks are generating during late Eocene and expulsion is still ongoing. Expected maturity levels are low but hydrocarbon generation is possible if burial is sufficient.

The Kimmeridgian source rock appears to yield the highest oil and gas volumes in place due to an efficient vertical migration from the source and significant lateral migration within the lower Tithonian interval.

Main reservoirs are deposited during active tectonic phases (rifting or uplift). Early expelled and migrated hydrocarbons are thus likely to be lost during Aptian unconformity.

However, delayed migration from the deepest kitchens combined with a secondary generation and expulsion pulse of lately buried peripheral depocenters during the Cenozoic can lead to efficient charge of the main structures after seal deposition.
REFERENCES


