Offshore Newfoundland & Labrador Resource Assessment
Orphan Basin 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 south Orphan offshore area (Orphan Basin) following the resource assessments of the Flemish Pass area (NL15-01EN) in 2015 and the Orphan Basin Area NL16-CFB01 in 2016. The Orphan Basin is in an early exploration phase and has recently demonstrated material potential after new regional seismic data uncovered evidence for hydrocarbon entrapment in various Tertiary, Cretaceous and Upper Jurassic leads.

The objective of this project is to conduct a geological and geophysical data interpretation, basin analysis, play risk analysis and resource assessment for the area subject to the upcoming license round (NL18-CFB- 01 November 2018) based on available geological and geophysical data. The final deliverables of this project include 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, sequence 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

Beicip-Franlab petroleum system resource assessment within the Orphan Basin demonstrates a prolific petroleum system with five main plays (reservoirs and associated seals) sourced by four source rocks (Upper Jurassic and Lower Cretaceous). In most cases, the effective charge toward the traps takes place before the trap formation. Some traps in the eastern part of the studied area may have a less favorable HC charge timing, mostly when traps were formed during local structural inversion (Lower Cretaceous).

The reservoir distribution towards the East is closely related to the Jurassic rift structural pattern. Proximal Upper Jurassic to Lower Cretaceous fans are found on the flanks and near the top of rotated blocks. Furthermore, toward the West, deep sea fans and turbidites are widespread during the Lower tertiary near the present day shelf break. As a result, there are superimposed petroleum systems across the study area, and these may contribute to the overall petroleum potential of the area.
The Eastern Newfoundland Region represents part of the North Atlantic Mesozoic rift system which includes the Jeanne d’Arc, Orphan and Flemish Pass Basins.

In November 2015, Nalcor Energy and Beicip-Franlab began the resource assessment of the entire Orphan area. In order to account for recent 3D seismic, heat-flow and sea floor core data, the focus in 2018 was placed on an area of interest (AOI) which included the blocks to be offered in the next bidding round NL18 – CFB 01.

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 6 parcels evaluated in this study of the Orphan basin. The land available in the call is under the new Scheduled Land Tenure System located here: https://www.cnlopb.ca/wp-content/uploads/landissuance/nl1801map.pdf

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. Seven wells were used for the study. Each well contains a set of petrophysical logs, stratigraphic markers and geochemical reports:
   - Cumberland B-55
   - Sheridan J-87
   - Linnet E-63
   - Margaree A-49
   - Lona O-55
   - Bonanza M-71 (outside the modelled area)
   - Great Barasway F-66 (outside the modelled area)

2. 2D seismic surveys (regional, 10x10km and 5x5km grids) interpreted by Nalcor and covering an area of 39,000 km² within the Orphan/Flemish Pass basins (2012-2017 – Nalcor invested TGS/PGS broadband long offset multi-client project).

3. 9836 km² 3D Survey (2017 Nalcor invested TGS/PGS broadband long offset multi-client project).

4. A set of nine horizons were interpreted in both surveys and eight 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 Albion, 100 Ma
   - K114, Top Mid Aptian unconformity, 114 Ma
   - K137, Top Berriasian, 137 Ma
   - J145, Top Tithonian, 145 Ma
   - J151, Top Kimmeridgian
   - J175, Top Toarcian, 175 Ma (partial coverage)
   - Base Mesozoic, 251 Ma

5. Fault sets picked for structural evolution and 3D modelling
Regional seismic interpretation

The seismic interpretation of the sector encompasses the entire Upper Jurassic to present day. It was calibrated on the various wells available for the study area.

The regional seismic interpretation was adapted to the play study scale on an approximate 5x5 km grid. It identified the main traps (with a minimum of 8 km²), the main structural features (depocenters, slopes, main regional faults), the seismic response of the regional paleo-environment settings, as well as seismic objects and anomalies which may correspond to sedimentary features such as channels, deep sea fans, etc.

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

3D seismic data

The study had access to a 3D fast track processed seismic volume in the eastern half of the AOI. The 3D area was penetrated by Margaree A-49 well.

Well geological data

The study also used the comprehensive well information on the 10 wells available within the study area or in its vicinity. These included: logs, paleo-environment data, core, temperature, pressure, HC recordings plus 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 seal occurrence.

Seabed coring and Geochemical data

Maturity data recorded in wells is 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. In addition, headspace gases and heat-flow measurements from seabed shallow cores were used to further calibrate the compositional HC generation model used in the volumetric calculations.

Built-on knowledge


Reliability and accuracy of the resources assessment

The data quality ensured a reliable and reasonably well constrained 3D geological model of the area could be built. This geological model offers a greater precision than the previous resource assessments. The corresponding oil and gas resource assessment can be undertaken within a better accuracy as covered through the low and high cases, and taking into account the petroleum results of nearby wells (Lona O-55 and Margaree A-49).
HYDROCARBON PLAY RESOURCE ASSESSMENT METHODOLOGY

Definitions

- 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 in the area of interest of oil and gas volumes in place. 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/m²). Cutoffs for 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 run outcomes.

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

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 of these wells have been drilled in the Jeanne d’Arc Basin where currently five fields are in production. Production to date has exceeded 1.7 billion barrels of oil. Exploration in the deeper waters of the Eastern Newfoundland Region (Orphan/Flemish Pass Basins) followed the initial exploration on the Grand Banks.

The first well in the assessment area, Gabriel C-60, was drilled in 1979 and encountered Hibernia equivalent reservoir; however, no mature source rock was encountered. The Baccalieu I-78 well (1986) encountered good Early Cretaceous reservoirs and confirmed the presence of good Kimmeridgian source rock. Subsequently, Lancaster G-70 encountered Late Jurassic sandstones and also Kimmeridgian source rock. The Kyle L-11 well, also drilled in 1986, encountered Early Cretaceous reservoir sandstones.

After a decade of no activity, new multi-client, exclusive seismic grids and the first 3D survey were collected. In 2003, Petro Canada et al. drilled Mizzen L-11 and intersected excellent reservoirs in the Early Cretaceous and Late Jurassic. This well had 5m of light oil pay in Early Cretaceous sandstones; however, the resource was deemed non-economic. In the same year, Tuckamore B-27 was drilled by the same companies. Tuckamore drilled through thick Cretaceous sandstone; nevertheless, it was wet and the well was TD’d before reaching the Jurassic interval. However, new 2D seismic over this well location indicates a thick Jurassic aged section.

In December 2008, Equinor (formally known as Statoil) et al. spudded Mizzen O-16 and on April 8, 2009, the company announced an oil discovery. The well tested oil from Late Jurassic sandstone, and the results spurred a renewed interest in the Flemish Pass Basin. Subsequent oil discoveries by Equinor et al. – Harpoon and Bay du Nord (2013) – are surrounded by the parcels included in Call for Bids (NL15-01EN). The Bay du Nord discovery was described as the largest oil find in the world for 2013. In 2016, Equinor et al. announced a new discovery at Baccalieu and Bay de Verde, and in June 2018 filed their project description with the Federal Regulator for the Bay du Nord Project.

On the eastern side of the Orphan Basin, the Great Barasway F-66 well (2006) drilled a thick Jurassic aged section containing Tithonian and Kimmeridgian source rock. Even though this well was unsuccessful in a discovery, it yet again demonstrated the presence of regional source rock. The Lona O-55 well drilled in 2010, although an unsuccessful petroleum discovery, also encountered a thick Jurassic section. The most recent activity in the Orphan Basin was in 2013 where Margaree A-49 became the third deepwater well in the basin. Again this well encountered a Jurassic section, but unfortunately, was unsuccessful in discovering petroleum.

With the emergence in 2007 of Nalcor Energy, Newfoundland and Labrador’s crown energy corporation, a commitment was made to invest in new geoscience data to unlock the next offshore areas which could contain material prospectivity. In late 2010, Nalcor, with Airbus Defense and Space, 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 (Orphan/Flemish Pass Basins), suggesting a regional working petroleum system and, coupled with the recent 2009 Mizzen O-16 discovery, highlighted potential new areas for oil exploration.

To better understand the region’s potential prospectivity, in 2012 Nalcor invested with global seismic companies TGS and PGS in a long offset broadband 2D multi-client seismic grid of 10x10km data over the Flemish Pass area. 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 2014, infilling of the initial 10x10km grid began, resulting in a 5x5km grid over the Flemish Pass and Orphan Basins. With these data, independent resources assessments of the Flemish Pass and Orphan areas were released in advance of the 2015 and 2016 Call for Bids. These land sales resulted in work commitments of $1.2 billion and $514 million respectively.

Continuing the investment with TGS and PGS, additional 10 x 10km 2D infill programs have been completed. Also, two 3D surveys (4600km² and 9800 km²) were acquired pre-bid over portions of the 2016 and 2018 Call-for-Bids respectively. In 2017 Nalcor invested with Fugro and AGI on a 10 000 km² seabed coring study within the Orphan basin focusing on a large portion of 2018 call-for-bids area to assist in providing additional insights into the petroleum system potential of the region.
The Orphan Basin is located at the NE edge of Newfoundland margin. By its geographical position, the Orphan Basin was subject to two consecutive rifting episodes related to the North Atlantic Opening (Pichot et al., 2018):

- first the NW-SE oriented extension in the Late Jurassic - Early Cretaceous related to the rifting between Newfoundland and Iberia (Rift II, III), and
- the NE-SW oriented extension in the Early Cretaceous related to the Newfoundland - SW Irish and Goban Spur margin rifting (Phase IV).

The two consecutive nearly perpendicular extension phases (Upper Jurassic and Lower Cretaceous) have been responsible for the important crustal thinning below the various grabens of the Orphan basin. The crustal thinning results from the combination of pure extensional tectonics and strike-slip movements, which may locally lead to a crustal denudation. The crustal thickness may be as low as 7 km in the thinned parts. The important crustal thinning event has a direct impact of the Late Jurassic Early Cretaceous thermal history.
The Late Jurassic rifting episode has been documented over a broad region of the North Atlantic margins. This phase, characterized by wide rifting, affects Jeanne d’Arc Basin up to the western part of the Orphan Basin. The Top Tithonian lies within the syn-rift sequence. Intense crustal thinning centered in the eastern part of the Orphan Basin has been observed.

Earlier interpretations suggested no Jurassic sediments were present in the western part of the Orphan Basin. However, new data and subsequent interpretations have demonstrated that the impacts of Jurassic rifting has extended further than previously thought, thus allowing for the deposition of Jurassic sediments throughout a large portion of the West Orphan Basin.

The Early Cretaceous rift episode is preferentially localized in the western part of the Orphan Basin. Fault reactivation (strike slip movement) and local transpressional inversion are described during the Cretaceous. In general, the Late Cretaceous (including Albian) sediments are relatively thin throughout the basin and show flat-lying succession above the Top Aptian Unconformity, suggesting regional minor subsidence, except in the easternmost part of the area of interest.

The Base Tertiary is well defined regionally over the Orphan Basin and merges with an onlapping surface on tops of the major tilted fault blocks. Progressive downlaps overlaying the Base Tertiary illustrate a regional thermal and flexural subsidence of the basin in the Early Tertiary time.
The Orphan basin lithostratigraphy has recorded the main extensional/transtensional events occurring in the western North Atlantic. During the initial NW-SE opening (Kimmeridgian/Tithonian), extensional tectonic features are created (tilted blocks and horsts/grabens). The troughs are filled up with marine clastic sediments (to the east) and alluvial type deposits (to the west).

During the subsequent NE-SW extension (Lower Cretaceous), the Orphan basin deepens and the overall transgressive period records mostly shaly sedimentation. Near the end of the Lower Cretaceous (Aptian unconformity), local inversion features related to the transtensional and transpressional stress regime are formed. These features constitute some major traps. They may be eroded at their crest down to the Kimmeridgian units.

After the mega regional unconformity at the end of the Cretaceous, the passive margin sedimentation records the progradation of massive shoreface deposits from the west toward deeper turbiditic deposits to the east.
Twelve depth maps were picked from the depth-converted seismic grid and used to define the skeleton of present day model geometry.

Six 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 region.

The present day shelf break has prograded since the Tertiary from the west to its present location.

The well section flattened at the Tertiary boundary (C-65), shows the variations between Tertiary basin thinning westward and the horsts and grabens system in Upper Jurassic, progressively filled in during the Cretaceous.
Depositional and sedimentological observations are obtained from combination of literature, well information and seismic geomorphology/stratigraphic analysis.

3D seismic cube located in the eastern portion of the study area provides more detailed analysis of the sedimentary objects, especially for the syn-rift intervals. This interpretation is used to build the conceptual Gross Depositional Environment maps and to feed the geological model used for the stratigraphic and petroleum system modelling.

Those geological and gross depositional environments are detailed in the next figures.
In terms of seismic stratigraphy, the interpretation follows the criteria for the recognition of sedimentary bodies from seismic data. For the purpose of the present evaluation, two regional seismic cross-sections (see map) were chosen to define the key stratigraphic features of the margin.

The seismic stratigraphy interpretation workflow is adapted from P. Jermannaud et al., 2010.

The West-East-oriented section highlights the Jurassic rifting leading to high tectonic subsidence and sedimentation toward the east and northwestern part of the study area with significant amount of marine sand deposited in the graben. Those sediments are sourced by the erosion of neighbouring horsts.

The section also displays the turbiditic systems developing during the Eocene/Oligocene (passive margin stage) and supplied by the western prograding Bonavista platform.
This section crosses the Cumberland ridge, which remains a paleo-high until the Paleocene. The syn-rift Late Jurassic sandy deposits are visible within the study area, as well as the locally inverted Upper Jurassic and lower Cretaceous series during Cretaceous transpressional regime (Lona and other anticline visible to the South of Margaree A-49).
Five main plays are considered in the AOI of the Orphan basin, from top to bottom:

- **Eocene/Paleocene**: The Eocene Paleocene play consists of deep marine sands sourced from the western shelf, and is sealed by basin shales. The reservoirs are not connected directly to the Upper Jurassic and Lower Cretaceous sources. Oil has been found in similar sands in the Jeanne d’Arc Basin to the SW.

- **Upper Cretaceous**: Locally, this play can display deep marine reservoir sands to the East of the AOI, resulting from source from the Orphan Knoll, inverted structures and related erosive features (Margaree canyon?). The Upper Jurassic Kimmeridgian, Tithonian and Lower Cretaceous marine source rocks can effectively charge the sands.

- **Lower Cretaceous**: This play displays marine turbiditic reservoir sands, mostly in the eastern part of the AOI, sealed by basinal shales, and directly sourced by the Kimmeridgian/Tithonian source. It corresponds to the Hibernia play in the Jeanne d’Arc Basin.

- **Tithonian Play**: The Tithonian reservoirs are marine sands concentrated in the eastern part of the AOI. They are partly sealed by the shale that is linked with the Upper Tithonian transgressive events. These reservoirs can be sourced by the Kimmeridgian shales, and laterally by the Tithonian source rocks. HC shows have been reported in Margaree A-49 in the Tithonian.

- **Kimmeridgian Play**: The Kimmeridgian play corresponds to the sandy shoreface and marine sands reservoirs, deposited in the troughs during rifting. These were subsequently uplifted during the Lower Cretaceous transtensional period. They are self-sourced reservoirs, sealed locally by marine shales. Oil shows have been reported in some wells in the Jeanne d’Arc Basin.
Within the NL18-CFB01 license area, there are multiple Jurassic tilted fault block plays. These structural plays exhibit a classic architecture, and were first imaged over two or more 2D seismic lines within the license area. The 3D seismic survey further resolves a number of these leads and has allowed for additional leads within this play type to be identified. Many display an AVO response when viewed in the gathers and on the near and far angle stacks.

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

This particular example of a Jurassic structural play within the license area shows an increase in amplitude strength updip in the far angle stack.
Within the NL18-CFB01 license area, there are a number of structural/stratigraphic plays. These plays are large in scale and were first imaged over two or more 2D seismic lines within the license area. The 3D seismic survey further resolves a number of these leads and has allowed for additional leads within this play type to be identified. Many display an 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 is orange.

This particular example of a Cretaceous Structural/Stratigraphic play within the license round area displays an AVO supported lead.
Within the NL18-CFB01 license area, there are Eocene Fan plays. These fans are large in scale and 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.
The initial phase of rift opening and associated sedimentary filling occurs during the Early Upper Jurassic. The active tectonic subsidence, which is linked with crustal thinning in the Eastern part, leads to the formation of very segmented systems of horst and grabens. Those grabens are fed with clastic material produced by the erosion of neighboring horsts. Gilbert type delta clinoforms are formed at the edge of those mini basins, while slope/basin floor fans are deposited in the basinal parts, along fault escarpment. Those sediments are deposited in marine conditions with early oceanic connection to the south and the east, while the western part remains continental.
During Tithonian, the rift opening continues with higher tectonic subsidence propagating to the northwest. Marine conditions prevailed toward the whole region, with the exception of horst structures remaining above sea level. The Cumberland ridge starts to break up in the central part of the area, leading to the connection with southern Jeanne d'Arc basin. Gilbert type deltas and associated turbiditic systems are still present, and are progressively drowned at the end of the Tithonian.
The stress regime drastically changes during early Cretaceous, when the main extension direction is shifted to NE-SW. There are several local tectonic inversions affecting the eastern part of the area, as a consequence of a local transpressional tectonic regime. Those inversions occurred in a shallow to open marine context, leading locally to the erosion and reworking of Jurassic and lowermost Cretaceous sediments. The connection with open ocean also leads to eustatic influence resulting in successive periods of transgression and regression. During transgression and highstand, pelagic sedimentation prevailed in the Orphan basin lows, with potential deposition of organic rich material, whereas, turbiditic sand rich systems developed during lowstand intervals.
Following the Aptian, the oblique transpressional regime decreases to the east, and remained still active in the central part. This tectonic stage ended in the late Cretaceous with continental breakup separating Newfoundland and Irish conjugate margins. The increased thermal subsidence in the eastern region, and at lower level to the northwest led to the increase of paleoslopes around the Central Orphan high, and the development of turbiditic systems flowing from the Orphan Knoll high, down to the subsiding eastern and western sub-basins. Those systems are the ones described around Margaree A-49 (local incisions/pathways and slope fans).
During the Tertiary, passive margin state prevailed, with source of sediment located in the southern and western Bonavista platform. Giant contouritic ridges developed to the south and along the Flemish pass to the east, with the onset of oceanic bottom current during Paleocene. Turbiditic systems are successively oriented from the SE to the NW (Paleocene) and from west to east (Eocene/Oligocene) with still topographic constrain due to Cumberland ridge paleohigh.
FORWARD STRATIGRAPHIC MODELLING: OBJECTIVES AND WORKFLOW

A forward stratigraphic simulation was performed using DionisosFlow™ (an IFPEN software) in order to (1) better understand 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 the base of the Oxfordian, up to the base of the Cenozoic, in sequential time steps. For each time step, three main environmental parameters were taken into account:

- The Accommodation (corresponding to subsidence and eustasy) reflects the space available for sedimentation. This information is provided by the combination of structural/depth map and paleobathymetry maps, which leads to the computation of Subsidence/Accommodation maps.
- The Sediment Supply, which may correspond to an external input (with added in situ erosion of local highs with associated drainage basins), or to in situ marine carbonate or pelagic rain production. The sediment supply can be tuned by defining clastic sources at the edge of the model, which reproduce the sediment and water fluxes evolution through time and space.
- The quantification of Sediment Transport, using 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 and erosion were simulated at each point of the basin using mass balance principles, and then calibrated by tuning all of the environmental parameters (sources, subsidence map, transport/diffusion). While carefully considering the interplay between these three parameters, the main steps of the stratigraphic modelling analysis consisted of:

- Reproducing regionally the overall basin geometry evolution from Late Jurassic to Top Cretaceous. This implies (a) a calibration of regional sequence thickness with existing structural interpretation and sequence stratigraphic definition; (b) a reproduction of internal geometries observed on seismic profiles and (c) a reproduction of sand probability estimated from GDE maps and section dressed with facies.
- Reproducing lithological vertical succession observed at the four available well locations.
- 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 the petroleum basin modelling Software (TemisFlow 3D™) and play assessment.

The simulation time ranges from the base of Rifting (~161 Ma) to the top Oligocene (~24 Ma). The time step used in the simulation is 0.1 Ma. The final 3D cube model comprises 960 layers in the Mesozoic, and 380 layers in the Tertiary. The six main seismic stratigraphic sequences (J161-J151-K145-K137-K114-K100-C65) served as the key input for building the stratigraphic reference model.
FORWARD STRATIGRAPHIC SIMULATION: CALIBRATION RESULTS

The calibration phase consisted of a step-by-step setting of each time interval in between the five selected time horizons. This phase calibrates both geometry/thicknesses for each one of the five intervals (seismic thicknesses), matching shale/sand ratios recorded at the study wells. The thickness calibration was controlled by the difference between the input thickness and the simulated thickness. Errors were then minimized by modifying the sediment supply and the source locations.

Both markers and $V_{shale}$ logs were used for calibration of the stratigraphy and the shale lithology at Margaree A-49 location. The model produced good thickness calibration of simulated markers between the well and input markers. The main lithologies observed at wells were also matched in the simulated results.
SIMULATED ACCOMODATION SPACE HISTORY

The stratigraphic modelling simulation, once calibrated, provides a detailed history of the successive phases of available space creation or removal at each point of the study area. Those phases reflect the main tectonic events starting during the early late Jurassic. A cell history extraction at the Margaree well position of cumulated accommodation gives some clues on rift opening tectonic subsidence, successive pulses of local transpressional inversion, and passive margin thermal and flexural subsidence:

1: Phase III rifting: Flemish Cap - Galicia opening
2: Phase IV-V rifting: Orphan Knoll – Goban Spur opening
3: Phase V rifting and post rift: Labrador-Greenland opening
4: Passive margin
FORWARD STRATIGRAPHIC MODELLING RESULTS - FACIES MAP DISTRIBUTION OF OXFORDIAN/KIMMERIDGIAN FORMATION (SAMPLE MAPS)

The facies model inputs were set as a function of percentage of clastic lithologies (percentage of sand and shales), percentage of organic matter (pelagic mud deposition) and paleoenvironmental data (paleobathymetry and water flux on the horst slopes). Fourteen individual facies were distinguished at relevant stratigraphic intervals based on main tectono-stratigraphic system tracks, such as highstand and lowstand to capture large scale lithological variation spatially and vertically.

From the base of rift to the top Kimmeridgian, 100 layers (time steps) were simulated in the stratigraphic forward model.

Six gross depositional maps were then vertically upscaled and integrated in the TemisFlow™ modelling as lithology properties (three are pre-Kimmeridgian and three within the Kimmeridgian).

Those maps are representative of the diachronous rift opening (phase III) with successive opening and connection to the global ocean of the Easternmost and Northernmost region during early Upper Jurassic, followed by central part of the region.
FORWARD STRATIGRAPHIC MODELLING RESULTS - FACIES MAP DISTRIBUTION OF TITHONIAN FORMATION (SAMPLE MAPS)

The facies model inputs were set as a function of percentage of clastic lithologies (percentage of sand and shales), percentage of organic matter (pelagic mud deposition) and paleoenvironmental data (paleobathymetry and water flux on the horst slopes and from the border of the model). Fourteen individual facies were distinguished at relevant stratigraphic intervals based on main tectono-stratigraphic system tracks such as, highstand and lowstand to capture large scale lithological variation spatially and vertically.

During the Tithonian, 60 layers (timesteps) were simulated in the stratigraphic forward model.

Four gross depositional maps were then vertically upscaled and integrated in the TemisFlow™ modelling as lithology properties.

Those maps are representative of the late phase III rift opening with a regional connection to the global ocean, drowning of the main grabens, and dislocation of the South eastern part of the Cumberland Ridge.

A contribution from a Northern clastic source (ie. Orphan Knoll structure) has to be considered in order to honor the high sedimentation rate in the Eastern grabens during this period.
FORWARD STRATIGRAPHIC MODELLING RESULTS - FACIES MAP DISTRIBUTION OF LOWER CRETACEOUS FORMATION (SAMPLE MAPS)

The facies model inputs were set as a function of percentage of clastic lithologies (percentage of sand and shales), percentage of organic matter (pelagic mud deposition) and paleoenvironmental data (paleobathymetry and water flux from the edge of the model). Fourteen individual facies were distinguished at relevant stratigraphic intervals based on main tectono-stratigraphic system tracks such as highstand and lowstand to capture large scale lithological variation spatially and vertically.

During the Lowermost Cretaceous, 80 layers (timesteps) were simulated in the stratigraphic forward model.

Four gross depositional maps were then vertically upscaled and integrated in the TemisFlow™ modelling as lithology properties. Those maps are representative of the initial phase IV rift opening with a local structural inversion affecting mostly the eastern part of the area. Clastic sedimentation is induced by erosion of transpressional structures, which reworks the Upper Jurassic sedimentary material.

The Berriasian/Valanginian intervals are mostly regressive and followed by an overall transgressive and highstand trend during the Barremian/Aptian interval.
The facies model inputs were set as a function of percentage of clastic lithologies (percentage of sand and shales), percentage of organic matter (pelagic mud deposition) and paleoenvironmental data (paleobathymetry and water flux from the edge of the model). Fourteen individual facies were distinguished at relevant stratigraphic intervals based on main tectono-stratigraphic system tracks such as highstand and lowstand to capture large scale lithological variation spatially and vertically.

During the Lowermost Cretaceous, 490 layers (timesteps) were simulated in the stratigraphic forward model. Eleven gross depositional maps were then vertically upscaled and integrated in the TemisFlow™ modelling as lithology properties.

Those maps are representative of the late phase IV rift opening and following post-rift phase. Structural Inversion areas are still noticeable toward the central part of the area. The clastic sedimentation is induced by the erosion of transpressional structures, which reworks the Upper Jurassic sedimentary material.
FORWARD STRATIGRAPHIC MODELLING RESULTS - FACIES MAP DISTRIBUTION OF TERTIARY FORMATION (SAMPLE MAPS)

The facies model inputs were set as a function of percentage of clastic lithologies (percentage of sand and shales), percentage of organic matter (pelagic mud deposition) and paleoenvironmental data (paleobathymetry and water flux from the edge of the model). Fourteen individual facies were distinguished at relevant stratigraphic intervals based on main tectono-stratigraphic system tracks such as highstand and lowstand to capture large scale lithological variation spatially and vertically.

The tertiary maps are an update of the 2016 study, thus explaining the partial covering of this 2018 study area. From the Base Paleocene to the top Oligocene, 380 layers (timesteps) were simulated in the stratigraphic forward model.

Nine gross depositional maps were then vertically upscaled and integrated in the TemisFlow™ modelling as lithology properties. Those maps are representative of the passive margin state following late Cretaceous post-rift. Silty to sandy turbiditic systems are deposited in the offshore during highstand and lowstand time intervals. Orientation of such systems are alternating from southeast to northwest during the Paleocene with sediments coming from the Jeanne d’Arc area, to west to east during Eocene, with the progradation of the Bonavista platform and enhanced thermal subsidence of the northern part of the study area.
FORWARD STRATIGRAPHIC MODELLING: TOC MAP COMPUTATION

The geochemical analysis shows that several organic-rich layers exist and may act as major source rock within the study area. Nevertheless, their distribution within the basin away from wells is not very well known. The Stratigraphic modelling tool DionisosFlow has been used to predict and delineate preserved organic-rich depocenters, which are constrained by environmental conditions such as bathymetry, substratum nature and oxygenation condition.

**GEOLOGICAL CONTEXT + MODEL SIMULATION**

Primary productivity of organic matter versus depth is an input of DionisosFlow. Two successive organic matter depositional environments are considered:

- stagnant endoreic syn-rift environment, followed by
- an open marine post-rift environment.

**INPUT**

- Considered Paleobathymetry

**RESULT**

- Facies map

**MODEL POST-PROCESSING**

Burial preservation of organic matter depending on sedimentation rate

DionisosFlow simulation takes into account the primary productivity of organic matter and its subsequent degradation during precipitation and in the sedimentary substratum.

Two models have been assumed during this study. First, an anoxic model (stagnant model) has been assumed for Late Jurassic rifting event when endoreic condition prevailed.

Second, a more open marine model was then considered for the Cretaceous when the Orphan basin had broader Atlantic connection (epireic system).

The main results are initial TOC maps for the four main organic rich stratigraphic interval that could act as major source rocks.
Four source-rocks have been considered in the petroleum system model. The Upper Jurassic source-rocks (Tithonian and Kimmeridgian) are regionally known. The Cretaceous source-rocks (Barremian, Albian, Turonian) source-rocks are less known, but likely in the Orphan basin environment.

1. The Kimmeridgian source-rock is proven at Great Barasway and Flemish pass wells. According to the source-rock depositional model, the organic matter rich levels (mixed terrestrial/marine) are located in ‘pods’ corresponding to stagnant water in the lows. Conversely, the organic matter rich layers are absent on the local highs (horsts).

2. The Tithonian source-rock is also recorded in the Flemish pass basin. According to the model, it is deposited in ‘pods’ corresponding to stagnant water in the lows. The OM-rich layers are more widespread than the Kimmeridgian OM-rich layers and may locally display high SPI (>4 Tons HC/m²).

3. The Lower Cretaceous OM-rich deposits have equivalent regionally (Bjarni Fm. In Labrador) and have been deposited in shallow marine environment. According to the depositional model, they may reach up to 3 Tons HC/m² potential.

4. The Aptian-Albian source-rock is also regionally known in open marine environment in the North Atlantic (black shales). Their potential remains low to fair.

5. The Turonian source-rock is regionally known but appears to be immature over most of the studied area. However, as outlined in the 2016 Orphan Basin resource assessment (https://goo.gl/CFK8e2), this source rock matures in the west to north-west areas of the basin.

Type IV AVO seismic responses of OM rich layers has been investigated. When confidence is high, the extent of these AVO anomalies have been compared to the source-rock depositional model results.
The forward stratigraphic model reproduces the main depositional events, associated sedimentary bodies and play elements, as well as structural trends, driven by accommodation history.

The Jurassic sandy series are locally interfingered with stringers of organic rich deposits. The inversion of those sediments are locally visible and well reproduced in the stratigraphic model in the central to Eastern part of the study area.

Lower Cretaceous sediments are alternating from lowstand fans and sandy turbiditic channels (Valanginian/Berriasian) to locally organic rich pelagic sediments in the lows (Hauterivian to early Albian).

Bonavista prograding platform and associated lowstand fans are clearly reproduced in the model to the south-west during the Paleogene.
FROM SEDIMENTOLOGY / STRATIGRAPHY TO LITHOFACIES DISTRIBUTION FOR 3D MODELLING

StudY Area

Seismic horizons
- Sea bottom
- C_10
- C_24
- C_45
- C_54
- C_65
- K_100
- K_114
- K_137
- J_145
- J_151
- Basement

% Sand

Lithofacies legend
- Silty fluvial (fluvial)
- Shaly fluvial (swamp)
- Heterolithic alluvial fan
- Shaly prodelta
- Silty deltaic
- Silty turbidite
- Sandy shoreface
- Sandy turbidite
- Sandy lobe
- Shaly turbidite
- Silty offshore
- Shaly offshore
- Pelagic mud
- Chalk
- MTD
- Not simulated in the stratigraphic model

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

3D Forward Stratigraphic Model
(sand proportion over 1100+ layers; 2x2 km grid)

3D Forward Stratigraphic Model Facies Distribution
(Over 1100+ facies maps)

3D Petroleum System Model
(38 upscaled facies layers in 0.5x0.5 km grid)
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 hydrocarbon generation, expulsion, migration and entrapment, from the source rock until the reservoirs were simulated, taking into account both the paleo-geometry, the thermal state, fluid flow and the rock 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 TemisFlow™ with the structural depth maps used to create the present day model geometry with additional subdivisions from DionisosFlow™. The 3D stratigraphic cube with lithological and source rock distribution maps was populated using gross facies 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 history 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 (dray 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 id computed through the multiphase Darcy Law flow. It simulates the Pressure regime (HC pressure and water pressure), capillary forces retention effect and buoyancy forces.

This models assumes 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 toward the traps.

The models offers also the option of instantaneous HC migration toward the traps (Trap Charge Assessment module TCA). The TCA module is used as a complement to the Darcy modeling since it allows for a higher horizontal resolution of the model.
The 3D petroleum system model (built from 12 seismic horizons) has been subdivided in 38 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 above), the 3D stratigraphic model (DionisosFlow™) was then upscaled from the interval between the base of rifting to present day maintaining regional geological context and keeping the highest degree of information.
**TEMPERATURE DATA**

In the studied area of the Orphan basin, the present day temperatures, measured on the shelf wells and deep water (Great Barasway), display an average geothermal gradient of 28-to 34°C/km., with an average of 31°C. The Cumberland, Sheridan and Linnet shelf wells display a slightly lower gradient (28°C/km) than at Great Barasway and Margaree (31°C/km).

The slight difference may be related to the crustal and lithospheric nature between deep water environment (thinned continental crust, uplifted mantle) and shelf environment (thick crust and stable lithosphere).

The above observations are used to calibrate the thermal regime of the Orphan basin.

**VITRINITE REFLECTANCE DATA**

The average burial depth at which the 0.6% Ro threshold (top oil window) is reached is around 3200m, in line with a 28°C/km to 31°C/km average geothermal gradient, assuming that present day temperature corresponds to the maximum paleotemperature.

The Great Barasway Ro measurements (from various laboratories) indicate a higher maturity in the Tithonian units (1900-2800 m burial) and Kimmeridgian units (> 2800 m).

The maturity trend in the Jurassic levels of Great Barasway is shifted vertically by 1500m to 1800m toward higher maturities with respect to shelf wells Ro (Linnet, Sheridan). This shift might be related to an erosion of the Upper Jurassic during a high geothermal gradient period during Lower Cretaceous (maximum burial before erosion and end of rift period). In addition pyrolysis data and oil extracts form Great Barasway well indicate a medium maturity within the oil window.
The Heat flow evolution in the AOI within the Orphan basin is controlled by heat transfer through evolving hyper-extended/thinned crust margin 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).

Rift propagation took place during the Upper Jurassic / Lower Cretaceous. Rifting is handled through a thinning factor of the continental crust calculated from an assumed pre-rift thickness in unthinned crust in sounding areas. The continental crust appears to be highly thinned in the eastern part of the AOI, below the Jurassic grabens. Herein the corresponding total crustal thinning factor is above ~8. In the western part of the AOI, the continental crust is moderately thinned (total crustal thinning factor ~2). The crustal thinning results in a rise of the top asthenosphere (1333 °C isotherm) and an increase of temperature in the crust and the sediments.

The thermal history of the AOI is highly variable depending on location. Near the present day shelf (d location), the heat-flow increases slightly during the syn-rift period. It remains lower than in other locations as a consequence of a lower crustal and lithospheric heat-flow component, as shown by the observed geothermal gradients in nearby wells.

In the other locations (a, b and c), the heat-flow significantly increases during the syn-rift period. In the thinnest crust location (a), the maximum heat-flow is nearly twice the present day heat-flow.

The high syn-rift heat-flow in the thinned crust locations in the grabens causes an early HC generation from the Kimmeridgian source-rock.
The present day temperature regime resulting from the lithospheric thermal model fits the observations within the studied area (well temperatures and seabed coring measurements).

In the deepest part of the depocenters near the eastern shelf, the temperature reaches 250°C. The maximum simulated temperature is 230°C for the Kimmeridgian source rock interval, 215°C for the Tithonian source rock, and 168°C for the Cretaceous source rock interval.

The overall reservoir temperatures are above 80°C at present day. Early migrated oil may have been biodegraded as reservoir temperature could be below 80°C (Pasteurization temperature) at the time of filling. In the western part of the section, reservoir temperature reaches levels allowing secondary cracking of oil into gas.
Thermal gradients are a function of heat flow and thermal conductivity of sediments throughout the thermal evolution of the basin ($T_{grad} = \text{Heat Flow} / \text{Conductivity}$).

Variations of thermal gradients in time and space are observed as a consequence of tectonic thermal events and sedimentary input into the basin.

The geothermal gradient maps are visualized through the computed average gradient between 0 and 2000 m burial for present day and Early Cretaceous (end of extensional rift).

At present day, average thermal gradient lays between $30^\circ\text{C/km}$ to $36^\circ\text{C/km}$ over the AOI and decreasing towards the southwest.

Near the end of the extensional rift phase (Early Cretaceous), the geothermal gradient can reach nearly the double of the present day value ($65^\circ\text{C/km}$) in the eastern part of the AOI, where the crustal thickness is minimal.

The occurrence of the syn-rift thermal event has a significant impact on the temperature history of the deepest syn-rift sediments (Kimmeridgian).

In the western part of the AOI, the burial and thermal history lead to a continuous increase of the syn-rift sediments up to present day.

In the eastern part of the AOI, the Kimmeridgian layers reach a first temperature maximum at 137 Ma, which is ultimately exceeded during Eocene time after a minimum at the end of Tertiary.

The deepest Kimmeridgian layers have reached $160^\circ\text{C}$ at 137 Ma. The deepest Kimmeridgian source-rock levels are therefore fully mature and may have expelled most of their potential.

As a consequence, the traps generated at, or later than 137 Ma in the eastern part of the AOI, may not be charged by these deepest Kimmeridgian source-rocks. This situation may have prevailed at the location of Great Barasway F-66, which is further North of the AOI.
The present day maturity over the studied area shows that the Kimmeridgian deep source-rocks are within the dry gas window. The Tithonian source-rock is within the oil or gas window depending on its present day burial. The Barremian and Albian source-rocks are within the light oil condensate window to the West, and in the oil window to the East.
To the east, most of the maturity is reached in the Lower Cretaceous due to high thermal gradients during end of crustal rift phase. To the west, the maturity starts after the Lower Cretaceous, and increases progressively until present day.
The Tithonian source-rock maturity starts after the Aptian times (100 Ma), following the main structuration period. It increases progressively all over the studied area until present day.
The Barremian-Aptian source-rock maturity starts during Miocene times (24 Ma), after the main structuration period. It increases progressively until present day in the western part and to the south of the studied area.
The Albian source-rock maturity starts during Miocene times (24 MA), after the main structuration period. It increases progressively until present day in the western part and to the south of the studied area.
Pore pressure and overpressure (above hydrostatic) are driven by the average sedimentation rate since the Tertiary.

Mild overpressure can be expected in the Western part, below the slope.

In the central and eastern part of the AOI, the pressure regime remains approximately hydrostatic.

The porosity of Tithonian reservoirs is mostly related to the burial. Fair to good porosities can be expected in the eastern part of the AOI.

**Depositional environments**

**Overpressure**

**Facies - Tithonian reservoir**

**Porosity - Tithonian reservoir**
TIMING OF PEAK OIL EXPULSION

The HC generation/expulsion history varies greatly over the studied area in function of variable burial histories and recorded past thermal gradients of source rocks.

For Upper Jurassic-lowermost Cretaceous reservoirs, the corresponding HC charge vs. trap formation timing will drive the charge risk, depending on the trap location.
HYDROCARBON MIGRATION MECHANISMS & COMPOSITION

The HC migration pattern is driven by the multiple local HC kitchen around the numerous traps. Herein, relative short distance lateral up-dip migration occurred and trapped below seals.

The migration model indicates that the charged traps (in horsts, tilted blocks crests or inverted horsts) may leak toward the sea bottom as observed in escape seismic features.

The HC retention remains efficient enough to preserve HC accumulation within the main Upper Jurassic, Cretaceous and Lower Tertiary reservoirs. Timing of charge preserves liquid phase hydrocarbons (medium to light oils). Depending on present day depth, some gaseous phases may be expected in the traps. The majority of traps contain a liquid phase.
HYDROCARBON MIGRATION MODELLING & HYDROCARBONS OCCURRENCE DETECTION

The 3D reference petroleum system model is built on the basis of a calibrated lithofacies geocube coming from stratigraphic modelling. The distribution and observed fluid properties are then properly reproduced:

- Hydrocarbon shows, such as seafloor seepages, or those detected in residual gas shows in Margaree A-49, demonstrate an active petroleum system within the study area.
- These direct observations, combined with hydrocarbon occurrence detection such as gas chimneys, or AVO response, were analyzed and used to constrain the reference model.

In the 3D image, the fence diagram corresponds to the 2D section stratigraphic display. The maturity of the Tithonian source rock is displayed as background map in vitrinite reflectance equivalent.

Blue lines indicate drainage lines from “kitchens” to structural highs. Hydrocarbon migration pathways are represented by black vector arrows indicating lateral and vertical migration. Blue/green bodies represent potential traps and their structural closures.

There is evidence of AVO anomalies, that can be related to the presence of HC fluids. Several fluid escape features are visible on the seismic right above the apex of some structures. AVO anomalies are useful for basin modeling because they serve to delineate hydrocarbon migration pathways (residual HC micro seepage) and outline bypassed hydrocarbons.
The call for bids area includes the exploration well, Margaree A-49. This well was drilled in 2013; with the objective to explore a deep Mesozoic target within the frontier Orphan Basin. Learnings from this well were critical in furthering the understanding of the basin.

Margaree A-49 drilled into large Late Jurassic structure of Tithonian age. Paleoenvironment reconstructions have been completed that incorporate the data from this well and demonstrate the presence of Tithonian reservoir resulting from adjacent rift horst erosion. The structure is slightly transpressional, and was formed during the Lower Cretaceous SW-NE extensional phase (between 137 and 100 Ma).

In the Margaree well area, the HC charge originates from the deep Kimmeridgian source and appears to be active between 137 Ma and 100 Ma. Based on seismic imaging from the 2017 Long Range 3D acquisition and constrained by the Margaree well data, it appears that a large incision of mid Cretaceous age was active during the time of charge and has breached the top of the Tithonian interval.

The basin model built for this resource assessment relied on the well results to calibrate the model. The basin model with the incorporation of Margaree data is showing that the HC amount charged remains limited, as the drainage area is small and far from a rich source rock ‘pod’ accumulation. However, the residual low saturation HC are of light oil type (32-36 API).

The analysis of the previous exploration results have greatly increased knowledge of the Jurassic source rock in this area, and highlighted the importance of the source rock distribution and HC charge timing for the deeper Kimmeridgian interval.

The area of interest for this basin model does show a variety of situations involving the source rock potential, HC charge timing and HC migration pathways up to the Late Jurassic, Cretaceous and Cenozoic reservoirs. It appears that numerous interpreted leads do correspond to favorable situations regarding these petroleum system components.
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 geological reference case scenario.

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

The reference case scenario also honours the observations on pressure, temperature, and oil and gas 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 six blocks and do not include additional volumes outside of the blocks but within the study area.

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

### Oil Equivalent Unrisked Volumes in place (Bboe)

<table>
<thead>
<tr>
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<th>Jurassic</th>
<th>Cretaceous</th>
<th>Tertiary</th>
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<tr>
<td></td>
<td>Kimmeridgian</td>
<td>Tithonian</td>
<td>Lower Cretaceous</td>
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<tr>
<td>P90 Low scenario</td>
<td>1.1</td>
<td>3.9</td>
<td>2.5</td>
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<tr>
<td>P50 Most likely scenario</td>
<td>2.0</td>
<td>6.8</td>
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<tr>
<td>P10 High scenario</td>
<td>3.7</td>
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### Gas Unrisked Volumes in place (Tscf)

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<td>P50 Most likely scenario</td>
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<td>P10 High scenario</td>
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### Oil Unrisked Volumes in place (Bbl)

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<th>Jurassic</th>
<th>Cretaceous</th>
<th>Tertiary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kimmeridgian</td>
<td>Tithonian</td>
<td>Lower Cretaceous</td>
</tr>
<tr>
<td>P90 Low scenario</td>
<td>0.6</td>
<td>2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>P50 Most likely scenario</td>
<td>1.0</td>
<td>3.6</td>
<td>2.7</td>
</tr>
<tr>
<td>P10 High scenario</td>
<td>1.7</td>
<td>7.1</td>
<td>4.5</td>
</tr>
</tbody>
</table>
The unrisked volumes are presented as high, most likely and low cases with sensitivity deriving from the geological reference model (previous page) for the charge of leads within the five main plays.

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

Probability of Geological Success POS = Pc x Ps x Pr x Pt

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

The probability of geological success is separated into four main independent terms

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 POS can be considered. It is defined as the product of Phc, Ps and Preservoir depending on the Risk level (low, best, high)

Risked volumes are the product of:
Ps x Pc x Pr x Pt x UNRISKED volumes at a given probability (e.g., P50)

In this approach, the risked volumes are lower than the Prospective Oil Initially In Place (OIIP) and 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.
Common Risk Segment (CRS) mapping was performed based on the reservoir and seal elements; it considered their presence and efficiencies. Using the full resolution, forward modelling stratigraphic 3D grid (one play example presented here) CRS maps took into account elements such as net sands and net shale and the thickness of vertically continuous beds.

For example 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. Resulting maps are not shown here but only a random example.

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).
INDIVIDUAL PROSPECT / LEAD AVERAGE SUCCESS RATE

For a given lead containing significant HC volumes (in the order of 1 Bboe best estimate per lead) the average success rate (individual Probability of success POS) may vary from 11% to 35% depending on the play (Upper Jurassic, Lower Cretaceous, etc.) and the trap type (faulted blocks, inverted horsts, 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 18% 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.
CONCLUSION: PETROLEUM SYSTEM CHART OF THE ORPHAN BASIN

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

The main and proven source rocks (Kimmeridgian and Tithonian) are generating oil since early stages during the Tithonian/Berriasian and are starting to expel oil a few million years later. The Cretaceous (Barremo-Aptian and Apto-Albian) source rocks are generating later in the tertiary and expulsion is still ongoing. The Turonian and Paleocene potential source rocks remain immature.

Since the inversion structure occurred during the second phase of rifting (Cretaceous), the Kimmeridgian and Tithonian reservoir sands were not always structurally trapped when maturation and expulsion occurred from Jurassic Source rock.

However, the Tithonian source rocks appears to yield the highest oil and gas volumes in place due to an efficient vertical migration from the source and significant amount of inverted structures with good timing of deformation.
REFERENCES


