Offshore Newfoundland & Labrador Resource Assessment
Orphan Basin Area NL20-CFB01

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

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INTRODUCTION

Nalcor Energy – Oil and Gas Inc., working with the Newfoundland and Labrador Department of Industry, Energy and Technology, engaged Beicip-Franlab to conduct an independent resource assessment of the Orphan basin area following the resource assessments of the Flemish Pass (NL15_O1EN), Orphan basin area (NL16-CFB01), East Jeanne d’Arc (NL18-CFB02) and Orphan basins (NL18-CFB01) and Carson-Bonnition-Salar area (NL19-CFB01) in 2015, 2016, 2018 and 2019. The Orphan Basin is in an early exploration phase and has recently demonstrated material potential after new regional 2D and 3D 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 interpretation, basin analysis, play risk analysis, and resource assessment for the area subject to the upcoming license round (NL20-CFB01 November 2020) based on available geological and geophysical data. The final deliverables of this project includes a detailed Beicip-Franlab internal report for Nalcor Energy – Oil and Gas and the Department of Industry, Energy and Technology and this Public Atlas which summarizes the main methodologies and key results of the resource assessment project.

WORKFLOW

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

MAIN RESULTS

The Beicip-Franlab petroleum system resource assessment of the Orphan basin area demonstrates a prolific petroleum system with syn and post rift potential reservoirs sourced by regionally known source rocks. The timing of burial with respect to trap formation enable hydrocarbons to be trapped and sealed regionally through Jurassic blocks and associated structural traps, as well as stratigraphic traps in the Early Cretaceous and Cenozoic. Several geological scenarios have been tested, all being calibrated on well data and seismic features. They show the likelihood of an efficient petroleum system in the NL20-CFB01 area.
STUDY 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 – Oil and Gas Inc. and Beicip-Franlab began the resource assessment of the entire Orphan area. In order to account for recent 3D seismic datasets, the focus in 2020 was placed on an area of interest (AOI) which included the blocks to be offered in the next bidding round NL20-CFB01.

On June 11, 2020 the Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) announced the Call for Bids NL20-CFB01. The block definition includes 17 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/nl2001doc.pdf

Interested parties have until 12:00 p.m. NST on November 4th, 2020 to submit bids for the parcels offered in Call for Bids NL20-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. Regional wells (Baie Verte J-57, Bonavista C-99, Sheridan J-87, Cumberland B-55, Linnet E-63, Mizzen O-16, Harpoon O-85, Fitzroya A-12 and Baccalieu I-78) were used for the study. Each well contains a set of petrophysical logs, stratigraphic markers, and geochemical report. **5 wells within the modeled area served as direct calibration points:**
   - Blue H-28
   - Great Barasway F-66
   - Lona O-55
   - Margaree A-49
   - Cupids E-33

2. **2D seismic surveys** (regional, 10x10km and 5x5km grids) interpreted by Nalcor Energy – Oil and Gas and covering an area of 39,000 km² within the Orphan/Flemish Pass basins (2012-2019 – Nalcor invested TGS/PGS broadband long offset multi-client project).

3. **3D Seismic surveys** interpreted by Nalcor Energy – Oil and Gas and covering an area of 22462 km² within the Orphan Basin (2017 - 2019 Nalcor invested TGS/PGS broadband long offset multi-client project).

4. **A set of eleven (11) horizons** were interpreted using both 3D and 2D surveys and 10 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
   - K114, Top Mid Aptian unconformity, 114 Ma
   - Top Tithonian/Base Cretaceous, 145 Ma
   - J151, Top Kimmeridgian, 151 Ma
   - Base Oxfordian/Top Callovian, 165 Ma
   - Base Mesozoic/Economic Basement, 251 Ma

5. **Fault sets** picked for structural evolution and 3D modelling

The 2020 Orphan Basin Resource Assessment study area shares its boundary with previous resource assessments. Nalcor Energy – Oil and Gas and Beicip-Franlab extended the main structural trends, seismic horizons, and paleogeography interpretations from these Area of interests to ensure regional consistency.
DATA SET REVIEW AND RELEVANCY

Regional seismic interpretation - The seismic interpretation of the sector covers the entire Mesozoic 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 and 3D volumes is adapted to the play study scale. It identifies the main traps, the main structural features (depo-centres, 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.

Well geological data - The study also uses the comprehensive well information of five (5) wells within the study area and others in its vicinity. It includes: well logs, paleo-environment data, temperature, pressure, and hydrocarbon 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 is only recorded in Great Barasway well (Ro, Tmax, TOC measurements). The existence of a proven and efficient petroleum system in the neighboring basins (Jeanne d'Arc and Flemish Pass), with similar geological characteristics, provides a useful analogue for the Kimmeridgian source rock characterization.

Reliability and accuracy of the resources assessment - The data quality ensures that reliable and reasonably well-constrained 3D geological models of the area can be built. Several scenarios have been considered. All scenarios have to be calibrated against sand shale ratio, thicknesses and TOC observed at well data. Some scenarios have been discarded for not honoring well data, interpreted seismic features and hydrocarbon occurrence forecasts. The corresponding oil and gas resource assessment can be undertaken with greater accuracy covered through the low and high cases of the different calibrated scenarios.

Experimental design: scenario tree

Early geodynamical change (153 Ma) against eustasy
- Riffed basins are recording a significant sea level rise while opening further, recording OM in oxic open basin
- Sand limited
- Sand rich

Late geodynamical change (151 Ma) against eustacy
- Riffed basins widely open while eustacy remains stable, recording OM in isolated highly anoxic basin
- Sand limited
- Sand rich

Sensitivity testing (impact on Source rock & maturity)

Source Rock
- Use only proven SR
- DionisosFlow simulated SR / Add hypothetical SR

Rifting scenario
- Change the onset of the Jurassic rifting to test timing of maturity

Maturity calibration
- Scenarios calibrating the lowest or highest vitrinite value range

Erosion
- Scenarios based on amount and timing of main erosion to test impact on maturity

Hypothesis on the age of the main geodynamical setting affecting the transition from continental to marine rifting against the late Kimmeridgian eustacy high this impacts the open marine (OM) deposition and preservation.

Sediments sourced from the northern area (Knoll) can be sand rich or limited.

Sensitivity runs are made to evaluate the impact of given parameters on trapped resources. Sensible parameters can be hypothetical source rocks, timing of rifting events, maturity levels or amount and timing of main erosion.
Unrisked Volumes (Alternative calibrated models approach)

- The unrisked volumes of hydrocarbons correspond to the amount of oil (Bbl), gas (Tcf) and oil+gas (in Bboe) present in the plays according to several calibrated geological scenarios.
- The hydrocarbon volumes of each scenario have been computed using a 3D integrated Darcy model of hydrocarbon migration and entrapment and post processed using the Trap Charge Assessment (TCA) module applied to the various plays. Each scenario includes a low, best and high hydrocarbon volume estimate, which is given by cutoff values applied to the hydrocarbon mass in place / km² and saturation in the reservoir layers of the 3D model. The TCA module has been used to test the impact of the seal efficiency for a given hydrocarbon charge in a reservoir play.
- Different scenarios have been tested and are presented on page 7 and discussed on page 27.
- The scenarios and their outcomes using the cutoff values on hydrocarbon concentrations have been compared to the observations made at wells (dry wells in the Study Area), TOC values and AVO anomalies. Some outcomes were rejected as they contradicted the observations.
- The remaining outcomes were considered as equiprobable and were used to obtain an unrisked volume distribution.

HYDROCARBON PLAY RESOURCE ASSESSMENT METHODOLOGY

- The hydrocarbon (hydrocarbon) play resource assessment methodology follows the Petroleum Resources Management System (PRMS) SPE Guidelines (2018) 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 simulations include 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, page 24) and TemisFlow™ 3D / KronosFlow™ 2D (for petroleum system, page 36).
- Several geological scenarios were computed, being considered as calibrated against data on reservoir and seal presence, source rock presence and maturity, hydrocarbon shows (sea bottom seeps, AVO anomalies) and well post-mortem analyses.
- 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%).

PRMS Guidelines 2018:
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, over 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 1.8 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.

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 et al. spudded Mizzen O-16 and on April 8, 2009 the company announced an oil discovery. The well tested oil from Late Jurassic sandstones, 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 F-89 and Bay de Verde F-67, and in June 2018 filed their project description with the Federal Regulator for the Bay du Nord Project.

More recently, in October 2019, Exxon Mobil et al. spudded Harp L-42A in EL 1135. In April 2020 Equinor and BP spudded Cappahayden K-67 and in July 2020 spudded Cambriol G-92 in EL 1156. All three wells are currently under confidentiality status.

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 – Oil and Gas, 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 Energy – Oil and Gas 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, 2016 and 2018 Call for Bids. These land sales resulted in work commitments of $1.2 billion, $514 million and $1.3 billion respectively.

Continuing the investment with TGS and PGS, additional 10 x 10km 2D infill programs have been completed. Also, four 3D surveys were acquired pre-bid over portions of the 2016, 2018 and 2020 Call-for-Bids respectively. These recent investments have resulted in over 90% of the six new parcels for this license round being covered by high quality long offset broadband 3D data.
REGIONAL GEODYNAMIC AND STRUCTURAL ELEMENTS

The Northeast edge of Newfoundland was subject to two consecutive rifting episodes. The first one, NW-SE-oriented, occurred in the Late Jurassic – Early Cretaceous and is related to the continental dislocation between North America and Iberia Plates. The second, NE-SW-oriented, rift phase occurred during the Early Cretaceous and is related to the separation between the North America and Eurasia Plates. Mesozoic basins lying at the Northeast edge of Newfoundland (Grand Banks) are recording this complex geodynamic evolution. The Charlie-Gibbs Fracture Zone and the Orphan Knoll, west of the Continent Ocean Transition (COT), mark the northern limit of the Orphan Basin. The Flemish Cap, an unstretched continental block, and the Bonavista platform bound are the Eastern and Western limits of the Orphan Basin. A strong positive free air gravimetry anomaly (the Cumberland Transfer Zone) forms the limit between Jeanne d'Arc, Carson, Bonnition and Salar basins with Orphan and Flemish Pass basins.
PLATE KINEMATICS

The eastern margin of Canada experienced successive rift episodes since Late Triassic times, propagating northward eventually leading to the rifting between Newfoundland and Iberia margins and then Newfoundland and Irish margins.

A diachronous NW-SE-oriented extension characterized the Newfoundland – Iberia rifting phase. The Early Jurassic extension reaches the southern Newfoundland, South Whale, Whale and Horseshoe basins (Welsink and Tankard, 2012).

Rifting between Central Newfoundland and Iberia started in the Late Callovian. The final separation between Flemish Cap and Iberia (Galicia Bank) occurred in the mid-Cretaceous.

Continental extension eventually propagates further north leading to the rifting between the Newfoundland and Irish margins with a drastic change of the maximum horizontal stress from NW-SE to NE-SW. Generalized rifting occurs between the Flemish Cap-Goban Spur conjugate margins in the Early Barremian (128-126 Ma; De Graciansky et al., 1985). Post-rift sediments indicate a final breakup at 100 Ma.

The final phase of extension in the Orphan basin is marked by the Aptian-Albian Unconformity (Dafoe et al., 2017). The rifting continues toward the north in the Labrador Sea where extension began in the early Aptian and ended with the continental breakup in the late Maastrichtian (Dickie et al., 2011).

Tectono-thermal domains and margin segmentation history. Modified after Pichot et al, 2018; Welsink & Tankard, 2012; Welford et al, 2010. PH: Porcupine High; OK: Orphan Knoll; GbS: Goban Spur; FC: Flemish Cap; GB: Galicia Bank; RB: Rockall basin; PrcB: Porcupine basin; OB: Orphan basin; GbB: Goban Spur basin; FB: Flemish Pass basin; JdAB: Jeanne d’Arc basin; BB: Bonnition basin; SB: Salar basin; CB: Carson basin; WB: Whale basin; HB: Horseshoe basin; GbB: Galicia Interior basin; PrtB: Porto basin; PnB: Peniche basin; LB: Lusitania Basin; AB: Alentejo basin.
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. An extraction at the 3 well positions of cumulated accommodation gives some clues on rift opening tectonic subsidence.

**Cumulative accommodation space history at Great Barasway, Lona (2020 Resources Assessment) and Margaree (2018 Resources Assessment)**

**ACCOMMODATION SPACE HISTORY**

1. Phase III rifting: Flemish Cap – Galicia opening
2. Phase III rifting
3. Phase IV-V rifting: Orphan Knoll – Goban Spur opening
4. Phase IV-V rifting and post rift
5. Passive margin
Throughout the study area there are structures that could be interpreted as gravity-related antiforms. These structures, which are mostly located on the flanks of depocenters in the area, are linked to extension or transtension tectonics. The primary decollement level of these structures is considered to be shaly Jurassic sediments interpreted to be Kimmeridgian in age.

Syn-tectonic thickening of the Upper Jurassic sediments against the SSW ridge, followed by the deposition of even thicker Cretaceous sediments. The thick Cretaceous sequence indicates the acceleration of extension in a broadly NNE-SSW direction.

Areas having undergone oblique movements due to major strike-slip fault zones show evidence of transpression and transtension affecting primarily the Jurassic and Cretaceous sediments. The series of three parallel seismic sections above (A to C) illustrates an example of the evolution of a transpressional zone (A, B) into a transtentional one (C) in a distance of less than 30 kilometers – moving from West to East.
Thirteen depth maps were picked from the depth-converted 2D and 3D 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 regions.

**Base Mesozoic/Economic Basement**

**Dominant Petroleum System Element**
- Conglomerate Alluvial
- Silty Marine
- Sandy Shoreface
- Sandy Marine
- Organic rich Mud
- Picked Seismic horizons

**Structural Maps**

Twelve depth maps were picked from the depth-converted 2D and 3D 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 regions.
GEOLOGY & STRATIGRAPHIC FRAMEWORK: STRATIGRAPHIC CORRELATION

The stratigraphic framework has been updated to tie to well stratigraphic correlations and seismic interpretation. Main time markers (Base Mesozoic, J_165, J_151, J_145, K_140, K_114, K_100, C_65, C_54, C_45, C_34 and C_24) were picked using biostratigraphic interpretation as a guide. Well penetrations largely sample the Cenozoic, Cretaceous and Jurassic levels. Aptian and top Cretaceous erosive events locally remove part of the stratigraphic records.

Blue H-28

Great Barasway F-66

Lona O-55

Margaree A-49

Cupids A-33

Depositional env.
- Continental
- Littoral
- Inner neritic
- Middle neritic
- Outer neretic
- Bathyal

Well lithologies
- Sandstone
- Siltstones
- Shale
- Claystone
- Carbonate

Horizons
- Water bottom C_0
- Top Miocene C_10
- Top Oligocene C_24
- Top Eocene C_34
- Intra Eocene C_45
- Top Paleocene C_54
- Top Cretaceous C_65
- Top Albian K_100
- Top Aptian K_114
- Top Berriasian K_140
- Top Tithonian J_145
- Top Kimmeridgian J_151
The interpretation, in terms of seismic stratigraphy, aims at identifying sedimentary bodies from seismic data. A regional seismic cross-section was chosen in the northern part of the AOI to define the key stratigraphic features of the margin.

This NW-SE section highlights the infill of the depocenter located in the northern part of the Central Orphan Basin.

Specifically, this section displays:

a) Thick Jurassic synrift continental to marginal marine deposits in the central portion of the section.

b) Cretaceous thick post rift deposits to the East (Orphan trough), whereas synrift sedimentation prevails in the Western grabens.

c) Cenozoic deep marine sedimentation toward the whole section.
The interpretation, in terms of seismic stratigraphy, aims at identifying sedimentary bodies from seismic data. A regional seismic cross-sections is chosen, in the southern part of the AOI to define the key stratigraphic features of the margin.

This NW-SE section highlights the infill of the depocenter located between the Central Orphan Basin. Specifically, this section displays:

a) Thick Jurassic synrift continental to marginal marine deposits in the Eastern portion of the section.
b) Cretaceous post rift deposits to the East, whereas synrift sedimentation prevails in the Western grabens.
c) Cenozoic deep marine sedimentation toward the whole section.
The initial phase of rift opening and associated sedimentary filling occurs during the mid-upper Jurassic. The active tectonic subsidence, which is linked with crustal thinning in the Eastern area of the AOI, 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 areas, along fault escarpment. Those sediments are deposited in continental (disconnected grabens) to marine conditions with early oceanic connection to the southeast, while the western part remains continental.
During Tithonian, the rift opening continues propagating to the northwest. Marine conditions prevailed toward the central and eastern region, with the exception of horst structures remaining above sea level in the northwestern part. The central rift grabens are connecting and wider basinal areas are observed eastward.
The stress regime drastically changes during early Cretaceous, when the main extension direction is shifted to NE-SW in a shallow to open marine context. The connection with the 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. However, turbiditic sand rich systems developed during lowstand intervals.
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 have been described around Margaree A-49 (local incisions/pathways and slope fans) and in the northeastern part of the study area.
During the Tertiary, passive margin conditions 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 currents during Paleocene. Turbiditic systems are successively oriented from the SE to the NW (Paleocene) and from west to east (Eocene/Oligocene) with topographic constrain due to Cumberland ridge paleohigh.
Within the NL20-CFB01 license area, there are multiple Stacked plays. These 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 within the license round area shows a classical structural play of Jurassic and Cretaceous age with escape features indicative of migration into a Tertiary fan system and an increase in amplitude strength in the far angle stack.
Within the NL20-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 round area shows an increase in amplitude strength in the far angle stack.
Within the NL20-CFB01 license area, there are multiple Cretaceous structural and stratigraphic plays. These 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 these play types 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 Cretaceous stratigraphic play within the license round area shows an increase in amplitude strength in the far angle stack.
FORWARD STRATIGRAPHIC MODELLING: OBJECTIVES AND WORKFLOW

A forward stratigraphic simulation was performed using DionisosFlow™ (an IFPEN software) 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 Late Callovian up to waterbottom. 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. Carbonate production is the in-situ production function of ecological parameters (mainly bathymetry, substratum, wave energy, and 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 kilometers.

Sedimentation or erosion were 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 Jurassic to Cenozoic. This implies (a) a calibration of tectono-stratigraphic sequences with existing structural maps, (b) a reproduction of internal geometries observed on seismic profiles, and (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 System Modelling.

The stratigraphic model extends over 37 500 km² (250 x 150 km) in the Mesozoic and 525 x 415 Km in the Cenozoic. It spans from economic basement to waterbottom. Time step resolution is 0.2 My for the Cenozoic interval, for 325 layers and 0.1 My in the Mesozoic (1000 layers). The spatial resolution is 4km in the Mesozoic and 5 km in the Cenozoic. Model calibration is performed based on 11 structural maps (seismic horizons), three (3) wells in the Mesozoic and fifteen wells in the Cenozoic.

In order to encompass sediment sources from the continent, the Cenozoic model area is larger than the Mesozoic. The model was later cropped to merge with the Mesozoic AOI.
FORWARD STRATIGRAPHIC MODELLING: INPUT PARAMETERS

SILICI-CLASTIC SEDIMENT SUPPLY

The main sources of sediment interpreted to feed this area was 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 Jurassic until the Late Cretaceous originating from the Orphan Knoll and the southern area. 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.

ORGANIC MATTER

The simulation of the original organic matter deposition and preservation (an example is presented page 25) takes into account:
- The primary productivity, in m/Myrs. It is adjusted in order to fit the observed TOC at wells (page 28).
- The sedimentation rate.
- The possible dilution due to the depositional energy.
- The preservation condition at bottom, expressed through an anoxicity coefficient for stagnant or open marine model.

CARBONATE PRODUCTION

The Orphan Basin is largely dominated by silici-clastic sediments but several carbonate levels exist.

DionisosFlow™ simulations take into account carbonate production rate as a function of bathymetry, wave energy, substratum nature, and fluvial discharge.

![Graph showing carbonate production rate vs. wave energy and bathymetry](image-url)
Well geochemical analysis demonstrate several organic-rich layers potentially acting as major source rock (page 38). Their distribution within the basin, away from drilled locations was assessed. Organic matter simulation using DionisosFlow™ is used to predict, delineate and derisk the source rock potential (see method page 25).

Simulations of organic matter deposition (marine and terrestrial) were performed using the different model (Open Marine / restricted) and presented below based on data observed at Great Barasway F-66 for one scenario.

The cross section, presented below, is an extraction of the model for one scenario showing a distribution of Bulk oTOC (%). It highlights the stratigraphic position of the richer organic matter layers. Two thick and rich Tithonian source rocks are clearly identified. Kimmeridgian and Aptian source rock potential, although not proven at well, are also simulated within depocenters.

The maps, presented below, are result for a given source rock level. It shows the simulated original TOC distribution (average %) and simulated Hydrogen Index used for petroleum system analysis.

Simulated original TOC (oTOC) corresponds to the total amount of deposited and preserved organic matter at sea bottom. Approximately 30% to 40% gets lost during early diagenesis under shallow (<1000m) burial (hydrolysable fraction). The remaining amount (refractory fraction), may be directly compared to the observed TOC near the top of oil window. The oTOC computed by the model reproduces the relative variations of TOC, as well as the measured TOC (approximately 60% to 70% of the computed oTOC).
FORWARD STRATIGRAPHIC SIMULATION: EXPERIMENTAL DESIGN

Given the uncertainty on source rock distribution (only Great Barasway presents RockEval measurements, page 38), alternative realistic scenarios testing the match between the basin geodynamical opening against the main Tithonian sea level rise are proposed to provide equiprobable calibrated scenarios (see calibration Page 28). For these two main scenarios, the tested uncertainty parameter is the age of the marine connection/onset of the Tithonian flooding. Alternative scenarios a and b consider the sand-shale ratio shaded in the model, especially from the Orphan Knoll. All proposed scenarios are calibrated against the well data.

1. Early geodynamical change (153 Ma) against eustasy

- Geodynamic settings: Rifted basins are recording a significant sea level rise while opening further, recording marine OM in oxic open basin.

2. Late geodynamical change (151 Ma) against eustasy

- Geodynamic settings: Rifted basins widely open while eustacy remains stable, recording OM in isolated highly anoxic basin

Organic Matter

- Absolute Sea level

   - Wheeler Diagram

   - Geodynamic settings

   - Bathymetry (m)

   - Net Thickness

   - TOC (%)

Lithological content

- Sand limited

- Savnd rich

Hypothesis on the lithological content of sources outside the model (Orphan Knoll and southern source) and sources within the AOI (erosion of emerged areas).

Examples shown are of one layer extracted from the calibrated volume.
FORWARD STRATIGRAPHIC SIMULATION: WELL CALIBRATION

Some calibration results are presented here following the hypotheses as defined in the scenario tree on page 7 below.

Experimental design: scenario tree

Calibrations are performed on lithologies at the two wells simultaneously (scenario 1 and 2). The dominant lithology is represented per cell in the model. They all provide a good match. The four (1a, 1b, 2a and 2b) models are considered calibrated and represent possible equiprobable end members.

Calibrations are also performed on simulated original TOC (%oTOC) content accounting for its deposition and preservation (see page 27 and 28). Good match (absolute values and trends) exist for most time units. Matching scenarios (1 and 2) were used to define a sound source rock model.

All calibrated scenarios at both wells provide a wide range of TOC richness and effective thickness in areas away from well control.

Following basin modelling, simulations are taking into account all the matching end member scenarios to propose an alternative vision in terms of petroleum system behavior.
The calibration phase consists of testing various scenarios to calibrate both geometry/thickness maps and respective lithologies recorded at well locations. The main input parameters used for calibration are source location, fluxes, sand/shale/carbonate/organic matter ratio, erosion and timing.

The sample maps shown compare interpreted thickness maps (between picked seismic horizons) and simulated sediment thickness. All the alternative models show a good consistency.
FORWARD STRATIGRAPHIC MODELLING: METHODOLOGY FOR MAPPING GROSS LITHOLOGY DISTRIBUTIONS

The grid above illustrates the simulated stratigraphic model with lithology properties (or dominant lithology). For each layer, a set of output properties can be extracted (on the right). They include paleoenvironment conditions, such as bathymetry, water flow, and paleoslope gradient; and lithologies such as sand, detritic shale, pelagic mud, carbonate, and organic matter.

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

The depositional environment maps are built by combining the previous properties for each sequence.
Simulated environmental properties, such as the paleobathymetries and lithological content (clastics, carbonate, organic matter), are used to define the paleoenvironments.
SOURCE ROCK AND RESERVOIR DISTRIBUTION ALTERNATIVE SCENARIOS

Net sandstone thickness and distribution varies per scenario depending on the position and lithological composition of the sedimentary sources (see Experimental Design in page 27). A sample layer is given for three key time horizons with alternative equiprobable scenarios, all calibrated in terms of thickness (well markers and seismic isopachs) and the lithologies at the wells (see Page 28).

Early geodynamical change (153 Ma) against eustasy

Late geodynamical change (151 Ma) against eustacy

Early Cretaceous
One sample layer

Jurassic
One sample layer

Wheeler Diagram
The Wheeler diagram reflects the paleo environment setting as a function of geological time. The environments within the Jurassic change from continental/alluvial deposits toward the western grabens, to shallow marine depocenters on the eastern rift basins. The Late Jurassic sandy deposits are related with adjacent horst erosion and consists in interfingering stringers of shale and sand with locally organic rich deposits. Post rift to passive sedimentation prevailed during Late Cretaceous and Cenozoic with progressive drowning of the central Orphan basin, and alternate detrital shale and sandy turbidites. For this stratigraphic interval, most of reservoirs are located to the east of the studied area and they are considered as the product of erosion of the Northern Knoll paleohigh and supply from the South Orphan basin.
According to the PRMS Guidelines defined by the Society of Petroleum Engineers (SPE), a "play or petroleum play" is a model of how a petroleum system (hydrocarbon 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). Six plays have been defined. Two plays (late Jurassic and early Cretaceous) display effective reservoirs in the neighboring Jeanne d'Arc and Flemish Pass basins. The mid-Jurassic play remains hypothetical. Because of hydrocarbon trapping proficiency, plays have been grouped in Syn-Rift and Post-Rift in order to present volumes.

**PETROLEUM PLAY DEFINITION**

**Plays** | **Source Rock** | **Reservoir** | **Seal**
---|---|---|---
**Paleogene** | Egret eq. / Upper Tithonian Aptian Paleocene | Avondale/ Banquereau Eqv. | Eocene / Oligocene
**Upper Cretaceous** | Egret eq. / Upper Tithonian Aptian | Otter Bay Dawson Canyon | Dawson Canyon
**Lower Cretaceous** | Egret eq. / Upper Tithonian | Ben Nevis | Upper K
**Tithonian** | Egret eq. / Upper Tithonian | Jeanne d'Arc Hibernia | Cretaceous intra Jurassic
**Kimmeridgian** | Lower Kimmeridgian | Jeanne d'Arc | Egret
**Mid Jurassic** | Callovo-Oxfordian | Voyager | Intra Jurassic
FROM SEDIMENTOLOGY / STRATIGRAPHY TO MODELLING

Initial Seismic and Stratigraphic Interpretation
Seismic interpretation & GDE mapping

3D Forward Stratigraphic Model
Lithofacies Distribution
1325 layers in 4x4km grid

3D Petroleum System Model
29 to 33 upscaled layers
1x1km grid
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 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 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 lithofacies maps extracted from the DionisosFlow™ results.

2D kinematic Modelling: a section is built from Great Barasway to Lona using KronosFlow™, modelling tool to allow simulation of kinematic fault during the functioning petroleum system. KronosFlow output is a series of paleo-sections sharing a single mesh continuously deformed, adapted to sedimentation, erosion, and basin extension. The 2D model was populated from the 3D framework to perform the calibration of the thermal and pressure regimes. The 2D section allows to test basin structural history and fault behavior against source rock timing of maturity, expulsion and migration.

3D Hydrocarbon migration calibration: The hydrocarbon generation and migration simulation was performed using Full Darcy Compositional Migration in TemisFlow™. Source rock type and richness were also defined in the model derived from the DionisosFlow™. 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 hydrocarbon (dry gas, wet gas, condensate, light oil, intermediate, and heavy oil). The hydrocarbon chemical composition depends on the kerogen compositional kinetics and hydrocarbon product cracking.

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

The hydrocarbon fluid flow is computed through the multiphase Darcy Law flow. It simulates the pressure regime (hydrocarbon 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 toward 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) is subdivided into 32 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 1325 to 32 layers for the interval between base Jurassic and waterbottom while maintaining the regional geological context and keeping the highest degree of information.

- No reported hydrocarbon accumulation. Fluid inclusion work contracted by Oil and Gas Corporation of NL (2020) reveals the presence of mature hydrocarbons in Jurassic reservoirs (25-45°API).
- Good reservoirs in the Jurassic section.
- Rich organic matter layers of Type II and Type II/III, progressively passing to more terrestrial in the Upper Tithonian.
- SR level not mature at well location - based on vitrinites and Tmax (note that some reworked vitrinites have been discarded).
- The lowest Tithonian SR sampled here is assumed to be the lateral stratigraphic equivalent of the Egret SR in the Jeanne d’Arc basin.

Lona O-55 (2010)

- No reported hydrocarbon accumulation.
- Good reservoirs in the Jurassic section.
- Same source rock Kinetics as the Egret of the Jeanne d’Arc basin.
- Source rock level not mature at well location - based on present day temperature.
- Petroleum inclusions gives 31-34°API. No hydrocarbon accumulations (FIT Lona Report, 2010).
WELL DATA INFORMATION ON PETROLEUM SYSTEM ELEMENTS (II)

Blue H-26 (1979)
- No reported Hydrocarbon accumulation.
- Good reservoirs in the Cenozoic section.
- Mature oil window up to base the Cenozoic.
- Over-pressure below 5000m.

Margaree A-49 (2014)
- No reported Hydrocarbon accumulation.
- Good reservoirs in the Jurassic section.
- Rich organic matter layers evidenced with Carbolog.
- Early mature oil window based on present day temperature.
- Fluid inclusions: fluorescence around 30-35° API.
  Two fluids trapped (homogenization temperature is 115°C for (a) and 85°C for (b)).

Cupids A-33 (2017)
- Small hydrocarbon show.
- Good reservoirs in the Jurassic section.
- Rich organic matter layers evidenced by Carbolog.
- SR level probably not mature based on present day temperature.
Four source rocks have been considered and modeled with *DionisosFlow*™ for further use in the petroleum system modelling:

1. The lower Kimmeridgian source rock has not been encountered in wells within the study area. It has categorized as possible for this study. According to the organic matter deposition model, the TOC may reach locally high values (>3%) and would consist of mixed terrestrial/marine organic matter deposited in restricted mini-basins corresponding to low mixing environments.

2. Two Late Jurassic organic rich intervals were encountered in the Orphan basin wells. The lower source rock is assumed Lower Tithonian/Upper Kimmeridgian, depending on the stratigraphic interpretations. It shares geochemical similarities with the prolific Egret Fm. of the Jeanne d’Arc Basin (page 38). Both Upper and Lower Late Jurassic source rocks display TOC around 3% and marine Type II/I to II/III organic matter. According to the depositional model, the OM-rich layers appear more widespread than the possible lower Kimmeridgian source and may locally display high SPI (> 5 Tons HC/m²).

3. The Aptian source rock, although not encountered in the Orphan wells, is regionally known in the North Atlantic open marine environment (black shales). Its potential remains low to fair with SPI around 2 Tons HC/m².

4. Cenomanian/Turonian and Paleocene organic rich intervals are also proven in the ODP wells on the margin, but are not considered in the model because they are immature within the study area according to thermal modelling results (page 48).
The heat flow evolution in the Orphan basin results from the successive Jurassic and Cretaceous rifting phases leading to the late Cretaceous lithosphere cooling up to present day. The thermal model takes into account the heat transfer through evolving thinning continental crust and the synchronous deposition of sediments. The resulting heat flow varies through time and location in the basin and is controlled by the following factors:

- Thickness and type of crust leading to radiogenic heat production of continental crust.
- Depth of the Lithosphere-Asthenosphere Boundary LAB (isotherm 1333 °C).
- Heat advection across the LAB and conductive heat transfer across the lithosphere up to the top of sediments.
- Sedimentation rate.
- Bulk thermal conductivity of sediments controlled by compaction and type of lithology.
- Radiogenic heat production of sediments.

The heat advection during rifting is handled through an implicit 3D lithospheric model thinning factor of the continental crust calculated from an assumed prerift thickness of 34 km. The continental rifting also accounts for the uplift of the LAB (isotherm 1333 °C).

The successive Jurassic and Early Cretaceous rifting phases increase heat flow especially in the eastern part of the basin where the stretching factor is maximal – leading to a high geothermal gradient. Since the late Lower Cretaceous post-rift phase, the heat flow decreased progressively until equilibrium was reached. High sedimentation rate occurred during Neogene and contributed to the overall decrease of the heat flow.

Paleo-surface temperature reconstruction is based on paleo-climate, paleo-latitude, and meridional oceanic change in the Atlantic ocean. The sea bottom temperature results from paleo-surface temperature and paleo-bathymetry (computed by DionisosFlow) defining a boundary condition for the 3D thermal model.
THERMAL CALIBRATION

Temperature data

The temperature data from the Orphan basin wells are used to calibrate the present day thermal regime of the 3D basin model. The model indicates relatively low average deep thermal gradients in a range of 30 to 34 °C/km.

Vitrinite reflectance data

The Vitrinite Reflectance data are used to calibrate the paleo-thermal regime of the 3D basin model.

The Vitrinite Reflectance at Great Barasway F-66 allows to calibrate past thermal history. Data shows that maturity state was higher in the past than at present day.

The Vitrinite Reflectance at Blue are in equilibrium with present day temperature and don’t provide additional elements for past thermal history. It validates present day thermal regime.

Note: vitrinite data have been screened for reworked vitrinite. The presence of reworked material especially in the Jurassic section has been described in several wells, including Blue and Great Barasway. Vitrinite data have been sorted using laboratory description reports and coherency with Tmax measurements.
LITHOFACIES

Lithofacies distribution of the 3D TemisFlow model results from DionisosFlow model through upscaling (page 35) highlighting main petroleum system elements. The deterministic approach of DionisosFlow provides a more realistic lithofacies distribution improving the migration modelling and entrapment reliability.

TEMPERATURE

Temperature at present day results from post-rift thermal cooling, deep water conditions, paleo-climate and Neogene sedimentation. Simulations point out an oil biodegradation risk around highs that are maintained in low temperature for several million years.

OVER-PRESSURE

Mild over-pressure within the study area can be expected except for the western region of the modeled AOI where sedimentation rates were higher. The over-pressures related with the western region can reach 15 to 20MPa in the deepest depo-centers.
VITRINITE Ro (%) - AT PRESENT DAY FOR SELECTED SOURCE ROCKS LEVEL

The present-day source rock maturity, expressed in Equivalent Vitrinite Reflectance Ro(%), displays Middle Jurassic source rocks within the oil and light oil condensate window over most of the depocentres within the study area. When present, the Kimmeridgian source shows a similar maturity pattern.

The Tithonian source rock remains in the oil window over the entire study area. The Aptian source rock remains marginally mature over the study area and is therefore unlikely to contribute significantly to the petroleum system.

The Paleocene source rock is discarded in this area as a potential contributor since if nether reached sufficient maturity.

SENSITIVITY

The uncertainty on the thermal regime during the Jurassic rifting only affects the Early Jurassic source rock. The Late Jurassic and Cretaceous maturities are not affected as they mature only during the Late Cretaceous-Cenozoic cooling stage.

1. Oxfordian - Kimmeridgian
   Vitrinite Ro (%) - at 0.0 Ma
2. Lower Tithonian layer
   Vitrinite Ro (%) - at 0.0 Ma
3. Upper Tithonian layer
   Vitrinite Ro (%) - at 0.0 Ma
4. Aptian layer
   Vitrinite Ro (%) - at 0.0 Ma
Maturity expressed in Vitrinite Reflectance was calculated for the Lower Kimmeridgian source rock layer through geological time. The oil window (VRo% > 0.6) is reached during the Latest Jurassic in the deepest part of the depocentres. The oil window (0.6 – 1.1 VRo%) is crossed in almost all the basin area early in the Cretaceous. The north west area develops less maturity in shallower basement conditions.
Maturity expressed in Vitrine Reflectance was calculated for the Lower Tithonian (Egret Eq.) source rock layer through geological time. The oil window (VRo% > 0.6) is reached during the Early Cretaceous in the deepest part of the depocentres. The oil window (0.6 – 1.1 VRo%) is crossed in almost all the basin area at the end of the latest Cretaceous. The north west area develops less maturity in shallower basement conditions.
Maturity expressed in Vitrine Reflectance was calculated for the Upper Tithonian source rock layer through geological time. The oil window (VRo% > 0.6) is reached during the Early Cretaceous in the deepest part of the depocentres. The oil window (0.6 – 1.1 VRo%) is crossed in almost all the basin area at the end of the latest Cretaceous. The north west area develops less maturity in shallower basement conditions.
Maturity expressed in Vitrine Reflectance was calculated for the Aptian source rock layer through geological time. The oil window (VRo% > 0.6) is reached at present day in the deepest part of the western depocentres. The oil window (0.6 – 1.1 VRo%) is crossed in periphery of the parcels.
HYDROCARBON GENERATION HISTORY

In the deeply buried depocentres, the kerogen Transformation Ratio of the late Jurassic source rock reaches near 100% during the Early Cretaceous. The Kimmeridgian rapidly reaches 90% and matures mostly during the Early Cretaceous. The Tithonian (Upper and lower) matures during the late cretaceous in the eastern areas while the west expulsion is slightly delayed until the Cenozoic.
HYDROCARBON SATURATION

The migration pathways include a lateral component along 20-30 km distance from the active depocentres toward the structural highs, usually associated with the crests of a Jurassic-tilded block. Not all traps are overfilled, and over-all hydrocarbons migrated to the highest points unless trapped against faults (see also page 52, 54 and 55).

At the crest of a tilted block, the buoyancy forces may overcome the capillary resistance of the seals, and a further charge can occur toward shallower reservoirs (Cretaceous and Cenozoic).

The generated hydrocarbons are generally in liquid phase, as they tend to originate from the active kitchens within the oil window.
A 3D Petroleum System Model is built on the basis of a calibrated lithofacies geocube derived from stratigraphic modelling (page 35). The sand-shale ratios and depositional environment facies obtained by the stratigraphic modelling have been used to define the main elements of the petroleum system in the Orphan Basin. This includes: reservoirs, carrier beds, overburden, seals, and source rocks.

The 3D view shows the top Kimmeridgian horizon and its maturity displayed as a background map in vitrinite reflectance equivalent. It shows the slope lines along the Kimmeridgian horizon, with the depocentres acting as kitchens and the distribution of potential significant traps (in blue/violet) associated with the different plays. These traps can be potentially charged according to the hydrocarbon migration modelling in certain scenarios. The lack of potential charge in some areas reflects the maturity levels, the source rock distribution or the reservoir and seal presence.

Hydrocarbon charge was compared to fluid escape features observed on the seismic dataset and AVO anomalies. Around the Great Barasway area, expelled hydrocarbon ¹⁰⁴ API do match values recorded in Great Barasway F-66 fluid inclusions within Jurassic reservoirs (around 40 ¹⁰⁴ API). For every selected scenario a good match exits validating their use in the final resource compilation.

All 3D models also demonstrate the importance of timing of hydrocarbon migration in regard to seal deposition and compaction. Also, some reservoirs remained for long periods of time in low temperature conditions allowing biodegradation to affect trapped hydrocarbons. These two phenomenon are simulated trough time in the various scenarios. The proposed resources take these scenarios into account.
2D KINEMATIC RESTORATION AND HYDROCARBON CHARGE MODELLING

In order to test fault behavior and kinematics settings against the petroleum system a 2D basin modelling tool (KronosFlow™) specifically designed to meet this objective is proposed. Starting from a present day section with balanced interpretations, 9 restoration steps were defined to account for petroleum system layers and detailed kinematic tectono-stratigraphic architecture (7 are presented here).

This kinematic restoration is then gridded, creating a mesh in which each cell deformation is tracked through time, preserving 2D mass balance. The section is calibrated similarly to the 3D modelling process (pressure, temperature and maturity). The same lithological distribution is used.

Forward basin modelling (heat transfer, pressure, hydrocarbon generation, migration and accumulation) is then run using this mesh, accounting for horizontal and vertical displacement, fault displacement and burial history. TOC content is adjusted to reflect expulsion timing and masses observed in 3D scenarios.

In this example (same section used throughout this report and presented in stratigraphic ages below), faults are set as transparent. All tested scenarios are presented page 53.
2D KINEMATIC HYDROCARBON CHARGE SENSITIVITY (FOUR SCENARIOS)

This original modelling approach allows the implementation of numerous fault objects in which gouge and damage zone properties are simulated through time. This realistic structural framework and kinematic restoration is used to test the impact of fault behavior and the hydrocarbon charge system, namely the hydrocarbon migration pathways.

Like in the 3D scenarios, cells with non-reservoir lithofacies are given permeability properties of alternating sand/shale, as observed in the wells. This non-reservoir lithofacies allows for lateral fluid migration and correspond to a carrier bed. Several scenarios are presented in order to test realistic hypotheses of fault behavior in the 2D modelling.

Faults are transparent. Only lithological juxtaposition of reservoir, seal and carrier beds control fluid migration across faults.

Faults are permeable (50% more permeable than nearby matrix), allowing fluids to flow efficiently trough the fault plane.

Faults are impermeable (high shale gouge ratio), not allowing any fluids to flow trough fault plane.

Faults are permeable during rift phases (up to 114 Ma) then impermeable when active tectonics is over (thermal subsidence).

Regardless of scenarios, the model indicates that hydrocarbons are not currently trapped at the Great Barasway well. Permeable faults tend to enhance hydrocarbon leakage through fault planes, while impermeable faults and fault offset tend to trap oil against faults before reaching Great Barasway. The low saturation within the lower section of the Great Barasway well corresponds to the mature source rock levels containing hydrocarbon.

In these 2D kinematic sections, the Lona well location appears to be localized at the apex of a structural high while in fact the highest point of the structure is a few kilometers north of the well (page 55). Based on the model at the Lona well location, hydrocarbons are not presently trapped. However, the model predicts accumulations are present in downdip traps.
ANALYSIS OF GREAT BARASWAY F-66 PETROLEUM SYSTEM COMPONENTS:

- **Trap**: Great Barasway F-66 roll over anticline (collapsed flanks) formed around the Lower Cretaceous (C145-135), see page 52.
- **Reservoir**: Great Barasway F-66 has identified many reservoir levels with good porosity within the Jurassic (page 38).
- **Seal**: The main regional seal is the Early Cretaceous, which thins out on top of the trap (page 38). The Cretaceous seal efficiency improves during the Cenozoic with burial.
- **Charge**: Source rock presence and quality is demonstrated at well and is largely mature on the flanks of the structure with efficient expulsion and migration since the Early Cretaceous onwards (from kitchen A).

**Great Barasway F-66 Through Time**

- Very efficient migration happened but fault activity may have acted as a barrier or leakage point for hydrocarbons on the pathway to the apex of the structure. 2D kinematic modelling (page 53) demonstrated in all scenarios that hydrocarbon should be trapped against faults in between the mature source areas and the well. The apex of the structure did not retained hydrocarbons due to lack of efficiency of the Cretaceous seal. During the Cenozoic, the migrated hydrocarbons were most probably trapped against down-dip faults.

**3D TemisFlow model** (with faults) transformation ratio and migration

**2D kinematic KronosFlow structural models**

- **Fault trapped HC**
- **Transparent faults**.
- **Permeable faults during syn-rift / impermeable during the sag.**

Note: residual saturation in the SR levels
ANALYSIS OF LONA O-55 PETROLEUM SYSTEM COMPONENTS:

- **Trap:** Lona O-55 tilted block formed around the late Jurassic, see page 52.
- **Reservoir:** Lona O-55 demonstrates many reservoir levels with good porosity within the Jurassic section (page 38).
- **Seal:** The main regional seal is the Early Cretaceous (page 38), which thins against the tilted block, and is absent at the well location. In time, latest Cretaceous sediments covered the regional high. Cretaceous seal efficiency is reached later in the Cenozoic with burial.
- **Charge:** Source rock presence and quality is demonstrated at the well (Carbolog at well location and by analogy with Great Barasway) and mature on the flank of the structure with efficient expulsion and migration up to the top of the regional structure (from the kitchen B and C, highlighted below).

**Lona O-55 Through Time**

- Lona is not located at the top of the tilted block structure. Hydrocarbons are potentially trapped higher up and probably bypassed Lona, as suggested by the scenarios tested in 3D modelling. The 2D Kinematic scenarios do not predict hydrocarbon charge at Lona location (page 53).
UNCERTAINTY IN HYDROCARBON MIGRATION AND CHARGE

Source Controlled HC Migration

- **High SR Potential**
  - Slow Drowning Anoxic Scenario
- **Low SR Potential**
  - Slow Drowning Oxic Scenario

Seal Controlled HC Migration

- **Low Seal Efficiency**
  - Sealed Leakage
    - HC Lost
- **High Seal Efficiency**
  - Trap not filled to spill point
    - Fill spill leakage
    - High seal efficiency
- **High SR Potential**
  - Slow Drowning Anoxic Scenario

Trap Charge Assessment

- **Scenario A**
  - Trap not filled to spill point
  - Fill spill leakage
  - High seal efficiency
- **Scenario B**

<table>
<thead>
<tr>
<th>Source Maturity</th>
<th>Source Controlled HC Migration</th>
<th>Seal Controlled HC Migration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>Oil Water</td>
<td>Fill &amp; Spill Chain</td>
</tr>
<tr>
<td>Early oil</td>
<td>Low Top capillary pressure</td>
<td>High SR Potential</td>
</tr>
<tr>
<td>Late oil</td>
<td>Low SR potential</td>
<td>Trap not filled to spill point</td>
</tr>
<tr>
<td>Containment gap</td>
<td>High SR potential</td>
<td>Slow Drowning Anoxic Scenario</td>
</tr>
<tr>
<td>Dry gas</td>
<td></td>
<td>Slow Drowning Oxic Scenario</td>
</tr>
</tbody>
</table>

Sensitivity analysis for 3D hydrocarbon migration modelling was taken into consideration to determine the main uncertainty parameters for hydrocarbon charge and therefore the unrisked in-place volumes estimation. Two main uncertainty parameters were considered:

- Initial Source Rock Potential: given by the different estimates on TOC between the forward stratigraphic models. The impact of hydrocarbon migration with source rock potential (source-controlled hydrocarbon migration).
- Seal Efficiency: given by the top capillary pressure calculated during hydrocarbon migration Darcy simulations.

Scenario A and B, illustrated in the 3D view, correspond to a mixture between a source-controlled hydrocarbon migration and a seal-controlled hydrocarbon migration. Both scenarios will give different hydrocarbon charge models with different in-place volumes.

The hydrocarbon volume estimates (low, best and high) will be derived from the individual results of each outcome attached to a given scenario.
The distribution of unrisked volumes of hydrocarbons corresponds to the amount of oil (in Bbbl), gas (Tcf), and oil+gas (in Bboe) that can be present in the plays according to the equiprobable and calibrated petroleum system scenarios (see page 7). The unrisked volumes are presented as high, most likely, and low cases according to the various calibrated petroleum system scenarios. They have been computed from the outcome of calibrated runs (darcy runs) completed by TCA runs (see page 36) corresponding to:
- Low, medium , high cutoff on hydrocarbon concentrations (kg/m²) in reservoir cells
- Alternative lithological and source rock scenarios
- Sensitivity analysis

The obtained unrisked volume distribution corresponds to a near lognormal pattern.

The volumes described here are aggregate, summed volumes for the six license blocks only (parcels NL20-CFB01-06 to 11). Volumes within the study area but outside the license blocks are not considered.

Most volumes are trapped in the syn-rift plays and summed up in the following table:

<table>
<thead>
<tr>
<th>Total</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>6.7</td>
<td>15.3</td>
<td>9.2</td>
</tr>
<tr>
<td>P50 Most likely</td>
<td>11.1</td>
<td>24.5</td>
<td>15.2</td>
</tr>
<tr>
<td>P10 High case</td>
<td>20.9</td>
<td>49.5</td>
<td>29.7</td>
</tr>
</tbody>
</table>

The volumes described here are aggregate, summed volumes for the six parcels.
**RISK ANALYSIS**

Leads and prospects Probability of Success POS = Phc x Ps x Pr x Pt

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

- Phc = HC charge (source rock presence and HC expulsion/migration efficiency)
- Ps = Seal presence and efficiency (thickness/continuity/capillary resistance)
- Pr = Reservoir presence and quality (Porous thickness, permeability range)
- 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 POS in the case of success or failure will be higher or lower respectively compared to the independent POS.

The POS is attached to an unrisked volume (usually PIIP in MMBoe best estimate).

**RISK EVALUATION AND POS**

The risk analysis corresponds to semi-quantitative thresholds on the POS of the petroleum system components applicable over the studied area.

The hydrocarbon charge risk was defined by average amount of charge HC/km² (e.g., > 500 kg/m²) in the reservoir play toward and up to the traps. It is directly related to the presence of an active source rock in the drainage area of the traps.

The reservoir risk was defined by the 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 the 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 Gross Rock volumes (GRV) > 100, 500 or 1000 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 a Composite Common Risk Segment map (CCRS) and is obtained by superimposing the individual CRS maps. CCRS multiply maps may also be built to evaluate the global exploration risk.

**RISK SCALE – CHANCE OF SUCCESS**

The risk scale can be qualitative (low – medium – high) or quantitative (1 low probability to 5 highest probability). Grade and Probability can be associated as shown.

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**Global Play Grade**

The Global Play Grade is evaluated from the following components:

- The grade (1 to 5) of known plays (stratigraphic), as defined by the size of discoveries and petroleum system efficiency, known from available worldwide basin screening studies

The grade of potential plays (1 to 5), as defined by the likelihood of hydrocarbon accumulations within unproven plays according to the petroleum system grades of such plays (without discoveries/fields made to date).

**Risked volume** is the product for each sizeable (> 50 MMboe PIIP) lead/prospect of Ps x Phc x Pr x Pt x UNRISKED volume at a given probability (e.g., P50)

**FINAL RISK ESTIMATES (POGS) in the Study Area**

The final risk estimates (or POGS – Probability of geological success) are made using two approaches:

1. From the exploration potential = f (exploration well /10000 km² / success ratio) and Global Play risk
   - POGS = f(explo status/success rate; max{play grades})

1. From the individual lead P50 unrisked volumes and P50 risked volumes
   - POGS = Global Play grade (%) * Σ risked volumes / Σ unrisked volumes
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 (of which one play example is 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 hydrocarbon charge risk map was derived from the computed hydrocarbon 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 Energy – Oil and Gas/Department of Industry, Energy and Technology report and is not shown here. A random example is presented below.

For each play, HC Composite Common Risk Segment (CCRS) maps were obtained by combining the hydrocarbon 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 Energy – Oil and Gas/Department of Industry, Energy and Technology report).
INDIVIDUAL PROSPECT/LEAD POS

For a given lead containing significant hydrocarbon volumes (in the order of 0.5 – 1.5 Bboe best estimate per lead), the average probability of success (individual Probability of Success [POS]) may vary from 5% to 40% depending on the play (Cenozoic, Cretaceous, Upper Jurassic) and the trap type (faulted blocks, stratigraphic, etc.). The POS estimates are derived from the play component risk maps, and geophysical evidence.

GLOBAL PROBABILITY OF GEOLOGICAL SUCCESS for the NL20-CFB01

The Global Probability of Success POGS curve quantifies the chances of success to find at least a given hydrocarbon volume in the exploration blocks of NL20-CFB01 as a whole.

The Global Play grade estimate is 60% (as defined on Page 60) and corresponds to the Upper Jurassic play grade, which has the highest chances of success.

To date, the exploration status success is low (no discovery, three dry wells within the model).

The estimated POGS to find the P50 estimate (15.2 Bboe) is 22% and is consistent with the POGS estimate from the exploration potential and play grade as well as from the risked volumes weighted by play grade.

The POGS risk curve characterizes a medium to high risk exploration area.

EVolving POGS With ADDITIONAL DATA

The POGS is directly dependent on the amount and quality of data.
A synthetic petroleum chart illustrating the petroleum components and timing of generation, expulsion, migration and entrapment of hydrocarbons is proposed:

The 2 proven source rocks, Egret equivalent and upper Tithonian, are mature and provide hydrocarbon charge for a long period of time throughout the basin. Charge starts from the end of Jurassic until present day.

The Cretaceous (Barremian-Aptian) source rock is generating later during the Cenozoic and expulsion is still ongoing. Maturity is in relation with high sedimentation rate of the Neogene.

The hypothetical early syn-rift Oxfordian/Kimmeridgian source rock is mature to overmature and in some areas provide additional resource.

Kimmeridgian and Tithonian reservoirs are sealed by cretaceous shales onlapping on structural highs. Sealing is effective from mid-Cretaceous to Cenozoic depending on overall thickness.

Faults can create structures suitable for trapping hydrocarbons. However, understanding the migration history into these structures can be complex. Several mapped leads suggest trapping against rotated blocks closest to mature source rocks.

In places within the AOI, some shallow reservoirs remained in low temperature conditions for long periods of time - allowing biodegradation processes to occur. Such risk has been considered in the compiled resources.

The syn-rift play (Upper Jurassic) appears to yield the highest oil and gas volumes in place due to an efficient vertical migration from the source toward the reservoirs and favorable trapping and sealing conditions.
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