DALHOUSIE UNIVERSITY

PRELIMINARY 1D MODELLING APPROACH TO THE INVESTIGATION OF MESOZOIC SOURCE ROCKS IN SEVERAL OFFSHORE NEWFOUNDLAND BASINS

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Abstract

The current understanding of the petroleum systems offshore Newfoundland rely on one source rock interval, the prolific Egret Member of the Rankin Formation. To reduce exploration risk, further investigation of the distribution, potential, and maturation of other possible source rocks is needed. Lower Jurassic source rocks are observed in outcrop at Portugal (the conjugate margin to Newfoundland) and, considering the similarity of the sedimentological record from these two sides of the Atlantic, we hypothesize that a similar source rock occurs offshore Newfoundland.

This preliminary study focuses on the 1D modelling (PetroMod™) of the Lower Jurassic interval offshore Newfoundland using previously published and newly acquired geochemistry datasets, i.e. Total Organic Carbon (TOC) and Rock-Eval pyrolysis (kerogen characterization) from five wells (Bittern M-62, Coot K-56, Cormorant N-83, Golconda C-64 and Murre G-67). Three additional wells, without new geochemical data (Osprey H-84, Skua E-41, and Spoonbill C-30) are also assessed. Boundary conditions such as paleo-water depth (PWD), surface-water interface temperature (SWIT), and basal heat flow are vital controls of the model. PWD and SWIT are inputted based on the modeler's interpretation of the dataset; basal heat flow is calibrated using vitrinite reflectance and well temperature data. These are used in conjunction with the main lithology, biostratigraphy, and geochemical inputs (available at NRCan's BASIN database) to create models that characterize the targeted intervals and to determine their potential as a hydrocarbon source rock.

The obtained geochemical results suggest that the investigated interval in the studied wells is dominated by type III-IV kerogens and have low TOC values (< 1 %). Regarding thermal maturity, while considering the poor reliability of the dataset, T_{max} values suggest that these intervals are within the oil generation window. Our 1D models advise that the Lower Jurassic reaches temperatures related to this early maturity window around the Late Jurassic. Further studies are needed to verify and extend our conclusions to other areas offshore Newfoundland.

Keywords: Lower Jurassic, offshore Newfoundland, source rock, petroleum system modelling, conjugate margin

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Thank you!

Chapter 1: Introduction

Petroleum exploration offshore Newfoundland commenced in the early 1960's. As of February 28, 2017, there are 436 wells drilled offshore Newfoundland and Labrador, and of these, there are 167 exploration, 56 delineation, and 213 development (production) wells (CNLOPB, 2017). The majority of wells were drilled in the Jeanne d'Arc basin where there are four active production fields: Hibernia, Terra Nova, White Rose, and North Amethyst (Nalcor Energy and Department of Natural Resources 2015).

Offshore Newfoundland is part of the Eastern North American rift system (Withjack 2012), creating a present-day passive margin that stretches from Florida to Labrador. Thick successions of Upper Triassic synrift continental redbeds and evaporites were followed by early postrift peritidal to shallow marine dolomitic carbonates and siliciclastics. Proximal fluvial-deltaic and shallow marine sands and distal marine shales were deposited throughout the Jurassic and Cretaceous (McAlpine 1990; Withjack et al. 2012; Enachescu et al. 2013). These successions, typical of a passive margin, contain the essential elements of working petroleum systems.

The exploration for these successful petroleum systems have led to hydrocarbon discoveries in shallow water areas. As exploration moves further offshore and into other relatively unexplored basins, a better understanding of the petroleum systems are needed to reduce risk and increase chances of success (Saeed and Peters 1994; Nalcor Energy and Department of Natural Resources 2015).

A petroleum system is defined by essential elements and processes that result in the accumulation of oil and gas. Elements of a petroleum system include i) source rock, ii) reservoir rock, iii) seal rock and iv) overburden rock. Trap formation as well as generation and migration of hydrocarbons are crucial processes for the accumulation of hydrocarbons. Elements must be in place in the correct sequence and correct timing of processes to determine if the system works. Uncertainty in any element of a petroleum system increases risk (Saeed and Peters 1994; Magoon and Beaumont 1999).

1.1 Problem Statement

The current understanding of the petroleum systems offshore Newfoundland rely on one source rock interval, the Egret Member of the Rankin Formation of Late Jurassic age (Figure 1). This prolific, and effective source rock is a restricted marine shale deposited during the Kimmeridgian (Nalcor Energy and Department of Natural Resources 2015). The reliance on this one source interval heightens exploration risk in the offshore regions of Newfoundland.

Figure 1. A core photo of the Egret Member of the Rankin Formation as seen in Panther P-52. Photo by Ricardo Silva.

The geology offshore Newfoundland has been studied by academic and industry researchers for decades. However, most studies focus on a single basin, and look to analyze the thermal maturity of the Egret Member. For example, Baur (2010) detailed the heat flow of the Jeanne d'Arc basin and demonstrated the importance of the initial rifting event in the Triassic. Nalcor's resource assessment (2015) showed that there was variable maturity of the Egret Member throughout the Flemish Pass area.

Nalcor's study also demonstrated that there are areas offshore Newfoundland where the sedimentary successions of pre-Late Jurassic age reached temperatures corresponding to catagenesis. Catagenesis is one of three stages of evolution of a source rock. It involves heating in the range of 50° to 150°C. At these temperatures, chemical bonds break down in kerogen (and clays) within shale, generating hydrocarbons (Tissot and Welte, 1984) (Figure 2). However, the intervals of pre-Late Jurassic sediments have not been analyzed in detail regrading their source rock potential.

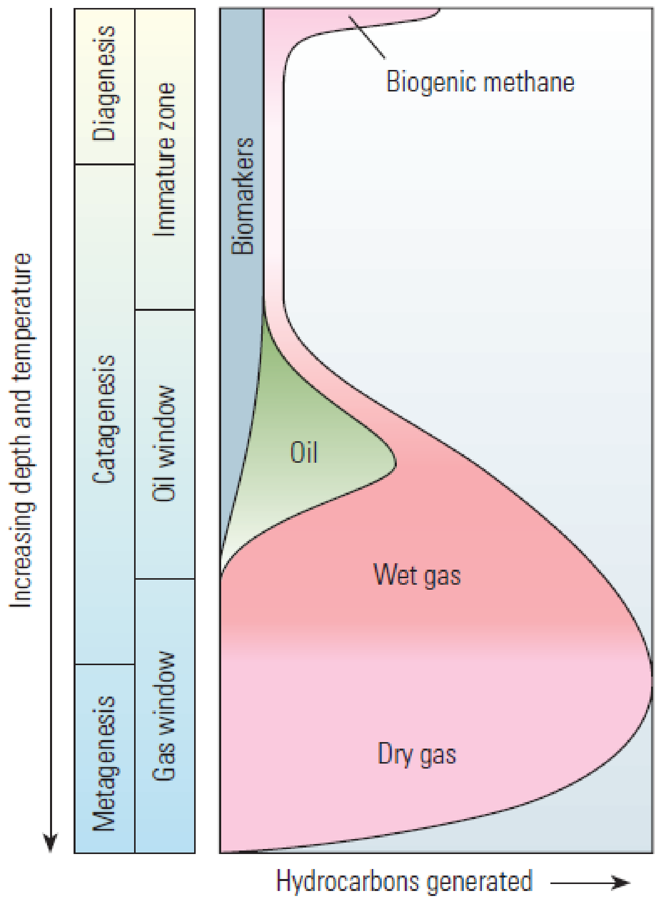


Figure 2. Transformation of kerogen (and products that are generated) with depth of burial and associated increase in temperature. Taken from McCarthy et al. (2011).

1.2 Source rocks in the Conjugate Margins

Lower Jurassic and Middle Jurassic source rocks are present globally in rift basins associated with the break-up of Pangea (Figure 3). Sedimentary basins associated with this rifting are found on both conjugate margins of the North Atlantic Ocean (Alves et al. 2002; Silva et al. 2015). They share similar stratigraphic records which may have led to deposition of similar source rock intervals. The Iberian margin has several Lower Jurassic source rocks that are found in the Lusitanian Basin of Portugal. Sinemurian – Pliensbachian source rocks within this basin are composed of varying amounts of limestones, marls and shales with differing amounts of organic matter (eg. Duarte et al. 2010; Silva et al. 2011; Duarte and Silva 2012; Silva and Duarte 2015)

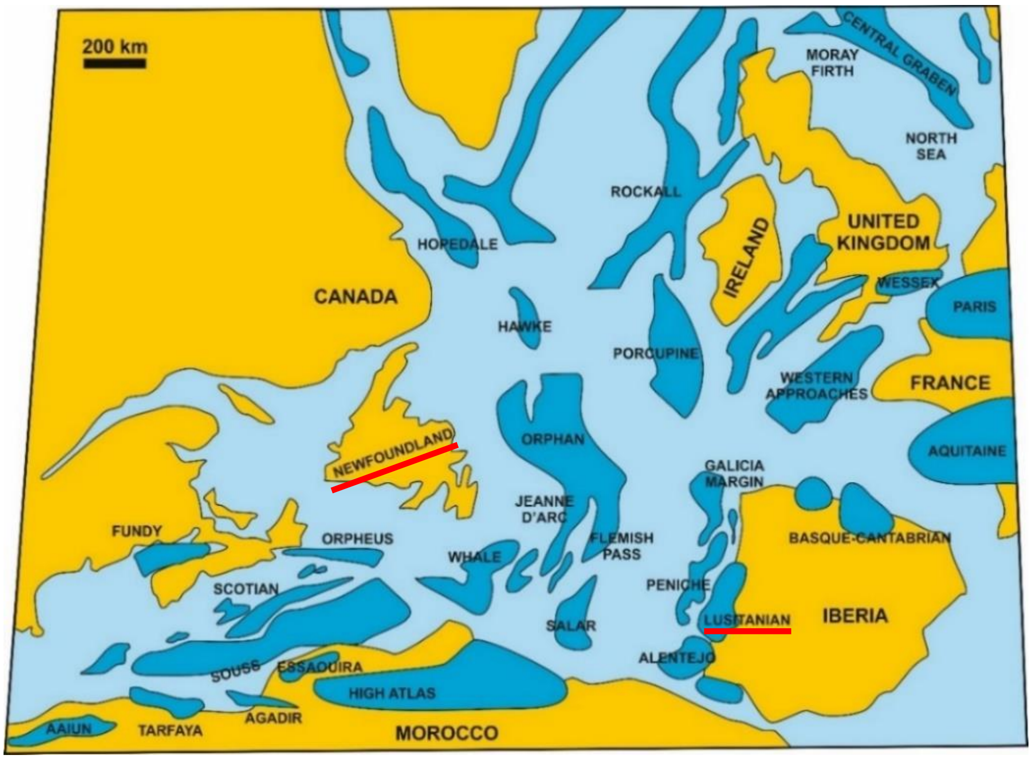


Figure 3. Location of sedimentary basins formed during rifting and seafloor spreading that began in the Late Triassic, leading to the opening of the Atlantic Ocean (modified from Tankard and Balkwill, 1989, among others).

The Lusitanian Basin is a small Mesozoic basin located in western Portugal and extends into the Atlantic Ocean (Figure 3). This north-south elongated basin was formed during the opening of the Atlantic Ocean during the same rifting period as offshore Newfoundland. The rocks deposited in this basin are exposed onshore and thus are accessible for detailed study that has been ongoing for decades. Most studies relate to sedimentology and paleogeography, biostratigraphy, and lithostratigraphy (Duarte et al. 2010; Silva et al. 2011; Duarte and Silva 2012; Silva and Duarte 2015). The Lusitanian Basin, having formed on the conjugate margin to Atlantic Canada, and more specifically, Newfoundland, is used by industry as an analogue for the reconstruction of possible petroleum systems in less studied regions offshore eastern North America (e.g. Wach et al., 2014; Silva et al., 2015).

The extensive Jurassic organic-rich intervals observable on the Western European and African conjugate margins suggest that exploration for hydrocarbons in Atlantic Canada can test new and alternative play concepts with a potential Lower Jurassic source rock interval, thus improving chances of success (e.g. Silva et al., 2015).

1.3 Hypothesis

Lower Jurassic source rocks are observed in outcrop at Portugal (the conjugate margin to Newfoundland) and, considering the similarity of the sedimentological record from these two sides of the Atlantic, we hypothesize that a similar source rock occurs offshore Newfoundland.

Our hypothesis of a Lower Jurassic source rock will be tested using publicly available borehole data (Natural Resource Canada), new geochemical data (TOC and pyrolysis RockEval), and 1D geological modelling (i.e. Petroleum Systems Modelling or PSM). Our study is limited to the number of wells that penetrate the Lower Jurassic and had data available, although these criteria led to a widespread approach across five basins.

1.4 But, what are Source Rocks?

Source rocks are a critical element of a petroleum system. They form in several depositional environments and must contain sufficient organic matter of suitable chemical composition to generate and expel hydrocarbons through biogenic or thermal processes (Miles, 1994). This definition is applied regardless of the thermal maturity of the organic matter (Belaid et al., 2010; Potter et al., 1993; Tissot & Welte, 1984).

Source rocks are divided into four main categories: potential, effective, relic effective, and spent. Potential source rocks have sufficient organic matter of suitable composition but are not thermally mature. Effective source rocks have sufficient quantity and quality of organic matter that is thermally mature and generating hydrocarbons. Relic effective source rocks were at one point producing but have since cooled. Finally, spent source rocks have expelled all hydrocarbons and are over mature (Law, 1999).

Understanding the depositional history and various geochemical properties of a source rock is required to determine its potential to produce hydrocarbons. To characterize the potential of a source rock, an assessment of the i) quantity, ii) quality and iii) maturity of organic matter is required.

The quantity of organic matter is defined by the Total Organic Carbon (TOC). This is a measurement of the amount of kerogen and bitumen in a sample relative to the total weight of the sample. Shale type source rocks typically have 2% TOC (Figure 4). The amount of organic matter depends on the depositional environment, preservation potential and amount of other material deposited (Jarvie, 1991).

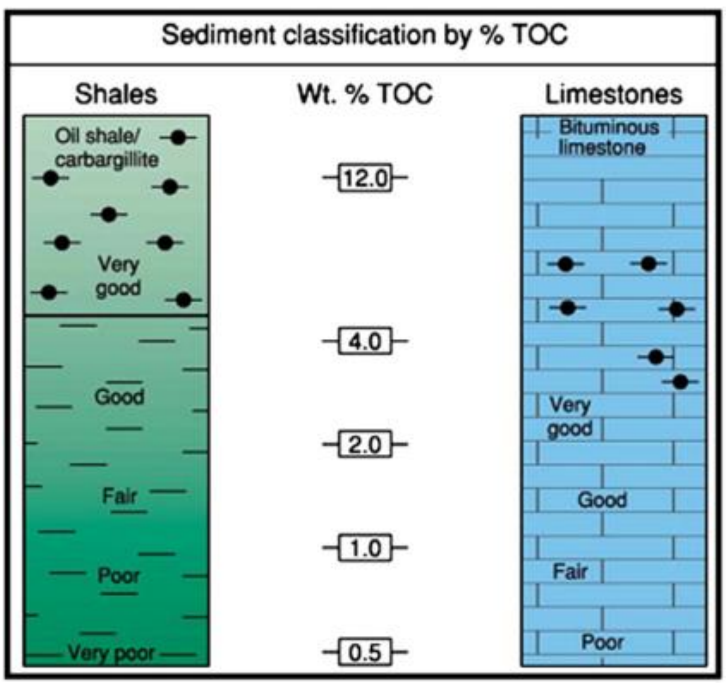


Figure 4. Classification of wt% TOC in both shale and limestone source rocks (Tissot and Welte, 1984).

The “quality” of a source rock is defined by the type of organic matter contained in the rock. Determining the type of organic matter is important as different types of organic matter have varying degrees of hydrocarbon potential. Kerogen is the fraction of organic matter that remains after the rock sample is treated with organic solvents. Bitumen is the portion of organic matter that is soluble in organic solvents and is usually formed from kerogen during petroleum generation (Forsman & Hunt, 1958). The type of hydrocarbons generated relies on the type of kerogen present in the source rock. One of the most widely used techniques to investigate source rock quality is Rock-Eval pyrolysis. Pyrolysis is the decomposition of organic matter by heating in the absence of oxygen (Law, 1999).

Vitrinite Reflectance (VR), is used to measure the maturity level of a source rock. Vitrinite is a type of maceral; an organic component of coal, or organic-rich sediments analogous to the minerals of rocks (ICCP, 1994). VR is a measurement of the reflectance of the vitrinite maceral at 500x magnification, under strictly controlled conditions. VR measurements are given in units of reflectance (% Ro), and is the measured percentage of reflected light from a sample with values typically ranging from 0-3% (Tissot and Welte, 1984).

PetroMod™ Petroleum Systems Modelling (PSM) software is used throughout academia and the petroleum industry to better understand the development of a petroleum system. PSM is a relatively new process in which well data is incorporated into a model to simulate the evolution of a basin through time. These simulations can provide insight into the development of petroleum system elements, including formation, burial and subsequent maturity of source rock (Saeed and Peters, 1994).

1.5 Significance

Demonstrating the presence and maturity of Lower Jurassic source rocks offshore Newfoundland, beyond the currently known petroleum systems, has scientific, commercial, and political significance. Scientifically, this investigation will test the hypothesis that Lower Jurassic source rocks, seen globally in rift basins associated with the break-up of Pangea, were deposited, preserved, and matured in Newfoundland offshore basins. Commercially, it lessens the uncertainty associated with the petroleum systems. Politically, it can increase the rate of success, thus reducing the need and number of exploration wells.

Chapter 2: General Geological Background

2.1 Geological Setting

The Grand Banks of offshore eastern Newfoundland include the Mesozoic Carson-Bonnition, Flemish Pass, Horseshoe, Jeanne d'Arc, and Whale basins (Figure 5).

This complex network of basins is part of the Eastern North American rift system that developed during the break up of Pangea (Withjack, 2012). The northern and central segments are separated by the Minas fault zone and the adjacent Newfoundland fracture zone, both defining the southern edge of the Newfoundland offshore basins. These NWN – ENE trending zones follow the northern extent of the Fundy and Orpheus basins (Driscoll et al. 1995, Withjack et al. 2012). To the north, the Grand Banks are bounded by the Flemish Cap, a basement high (Driscoll et al. 1995). Some basins extend further offshore to the ocean-continent boundary, providing deep water exploration opportunities (Enachescu et al. 2013). Extension direction and reactivation of pre-existing fabrics in the basement governed the development of basins in the Grand Banks area (Driscoll and Hogg 1995). Throughout periods of rifting and subsidence, thick successions of sediment, up to 14 km, were deposited in the basins (Driscoll and Hogg 1995).

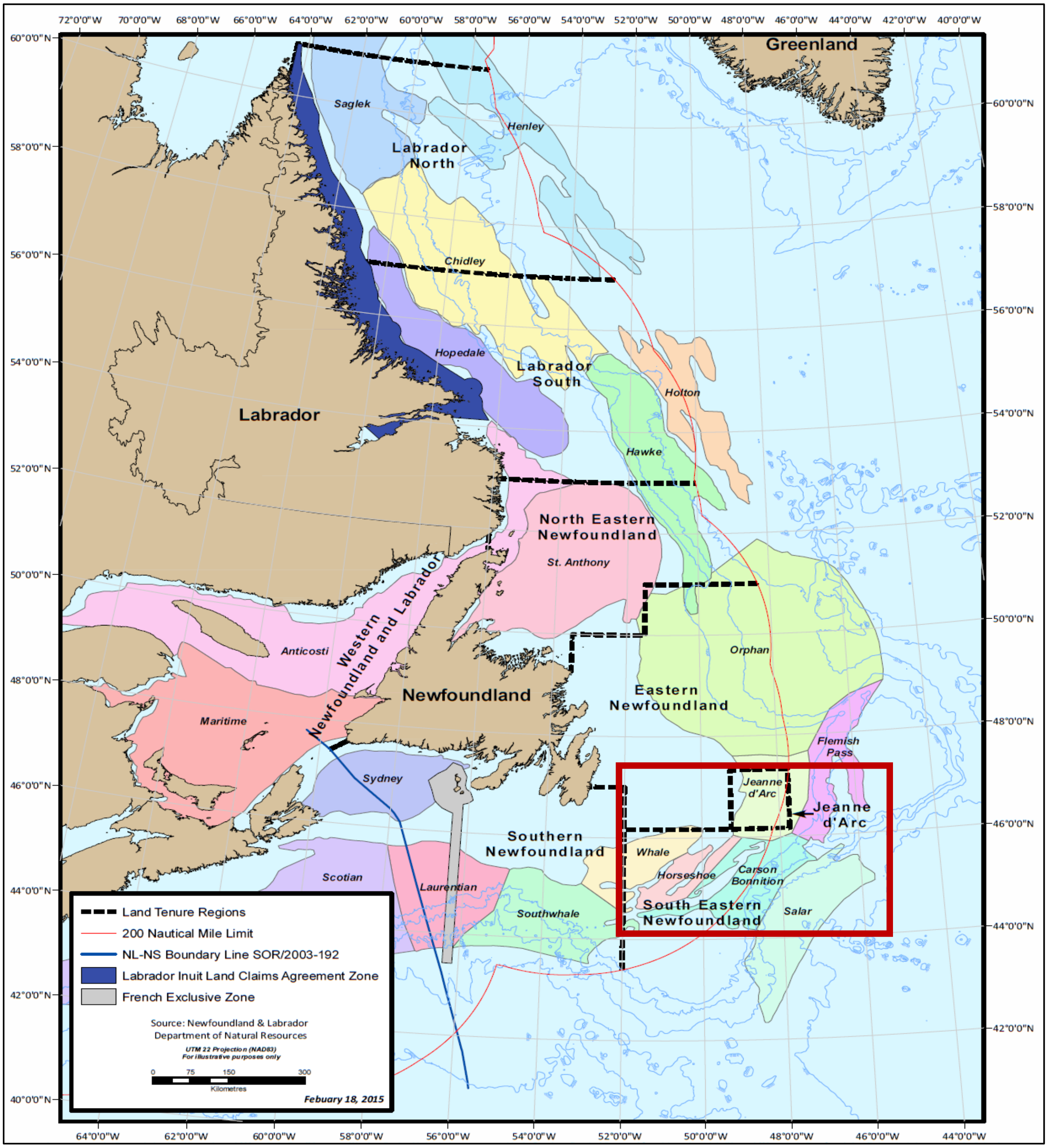


Figure 5. The offshore basins of Atlantic Canada. This study looks at the Carson-Bonnition, Flemish Pass, Horseshoe, Jeanne d'Arc, and Whale basins (Newfoundland and Labrador DNR, 2015). Wells are located within the red box.

2.2 Rifting Stages

Offshore Newfoundland basins developed through three main rifting stages. Each episode was followed by thermal subsidence and the subsequent deposition of thick sequences of sediment (Enachescu et al. 2013).

The first stage, beginning in the Late Triassic and continuing into the Early Jurassic, initiated the formation of multiple NE-SW trending intracratonic basins (Balkwill and Tankard 1988; Sinclair 1995; Withjack et al. 2012; Enachescu et al. 2013). The timing of this extension is identified through the presence of coarse sediments that accumulated in the basin. These coarse sediments are also evidence for elevated relief existing near border faults, which developed during active rifting. Additionally, the analysis of well, seismic and core data show the thickening of Late Triassic sediments towards the boarder faults (Withjack et al. 2012). Once this stage of rifting ended, post-rift thermal subsidence followed, deepening the basins and facilitating the formation of carbonate platforms around the uplifted margins and associated deeper water carbonates (Enachescu et al. 2013). From the Early Jurassic to Late Jurassic, there is evidence of both thermal subsidence and possible rifting. Broad sediment distribution, few thickness variations and limited structure development supports thermal subsidence. However, syn-rift sediments are still seen near the border faults, suggesting rifting was still occurring throughout the Jurassic, although at a much slower rate (Sinclair et al., 1999).

The second rifting stage, from the Late Jurassic to the Early Cretaceous, is responsible for the opening of the Atlantic Ocean and further development of the basins (Balkwill and Tankard 1988; Sinclair 1995; Withjack et al. 2012; Enachescu et al. 2013). During this rifting event, there was an enlargement of the basins and faulting oblique to the first extensional stage. After the main rifting event, stretching and crustal thinning continued to the east of the Grand Banks, extending the breakup of North America and Europe (Enachescu et al. 2013). According to magnetic, seismic reflection and refraction data seafloor spreading and separation of the Grand Banks and Iberia began in the Early Aptian (Driscoll et al. 1995). At this time, Newfoundland's Carson basin and Portugal's Lusitanian basin were divided by attenuated transitional crust. Ultra-slow extension in the Early Berrasian to Late Valangian – Early

Hautervian and slow extension from the Early Hautevian to Late Aptian formed the distal continental margins and transitional zones (Enachescu et al. 2013).

The third stage represents Early Cretaceous to mid-Cretaceous rifting of the North Atlantic (Balkwill and Tankard 1988; McAlpine 1990; Withjack et al. 2012; Enachescu et al. 2013). This rifting stage mostly affected the Orphan basin and the basins of offshore Labrador. The structure of the Grand Banks basins were weakly influenced by this rifting stage, but still contributed to the overall subsidence of the basins. Sea floor spreading and separation of Newfoundland and Iberia continued to their present day positions (Balkwill and Tankard 1988; McAlpine 1990; Enachescu et al. 2013).

2.3 Stratigraphy

The stratigraphic record is quite similar within basins of the Grand Banks (Figure 6). Widespread deposits of Upper Triassic salt, Jurassic carbonate platforms and Upper Jurassic source rock demonstrate "connectivity" of the basins at certain points in the past. The appearance of these similarly aged sediments that share the same lithology support a similar rifting history for the Grand Banks basins (Enachescu et al. 2013).

The basement is made up of pre-Mesozoic metasediments that are representative of the Avalon Terrane. During the initial extension in the Late Triassic, continental sands and muds of the Eurydice formation were deposited within grabens formed on the rifted basement. The Osprey and Argo formations are made up of evaporite deposits that formed under arid conditions in numerous restricted basins. The Jeanne d'Arc basin includes subaerial basalt flows between the Osprey and Argo formations (Jansa and Pe-Piper, 1989). These are evidence of the short-lived but widespread magmatic period marking the first stage of North American rifting known as the CAMP event - Central Atlantic Magmatic Province (Withjack et al. 2012). Marine incursion is recorded by continually deeper depositional environments that show flooding of the basin by the Tethys Sea (McAlpine 1990; Withjack et al. 2012; Enachescu et al. 2013). With continued transgression, helped by thermal subsidence, Iroquois formation was deposited. These anhydrite-rich dolomites, along with oolitic and skeletal limestones, were deposited in warm shallow seas, coastal sabkhas and restricted lagoonal environments (McAlpine 1990; Withjack et al. 2012; Enachescu et al. 2013).

Post-rift subsidence continually deepened the basins, allowing for thick deposits of fine clastics, the development of marginal carbonate platforms and deeper water carbonates (Withjack et al. 2012; Enachescu et al. 2013). The Downing formation is made up of intercontinental marine shales and limestones. The Voyager formation is representative of a near-shore marine environment that is made up of sands, shales, coal and limestones. Shallow water limestones and fine grained sandstones make up part of the Rankin formation to the south. In the north, there was deposition of deeper marine, fine grained siliciclastics. The known, prolific source rock of the Rankin Formation, the Egret Member, was deposited during the Kimmeridgian in restricted basins. This implies various separated depocentres that allowed for deposition of these organic-rich shales (McAlpine 1990; Withjack et al. 2012; Enachescu et al. 2013).

During the second stage of rifting, coarse clastics of the Jeanne d'Arc and Hibernia formations were deposited in alluvial, deltaic and shoreline settings. Sedimentation rates appear to have nearly doubled at the beginning of the stage, indicating the increased rate of rifting. The Fortune Bay and Whiterose shales members differentiate the sandstone units. The elevated areas created by the Avalon uplift, Bonavista Platfom and Outer Ridge Complex were the source of these sediments and may include eroded Jurassic and Triassic rocks. Post-rift subsidence in the Grand Banks region led to further basin wide limestone deposition (McAlpine 1990; Withjack et al. 2012; Enachescu et al. 2013).

In the Early Cretaceous to the Mid-Cretaceous sediments eroded from the rift margins and intra-basin ridges were deposited. These sandstones include the Avalon, Ben Nevis and similar reservoirs. Shales and sandstones, including the Dawson Canyon and Banquereau formations were deposited from the Late Cretaceous to present day (Fowler et al. 1990; Withjack et al. 2012; Enachescu et al. 2013).

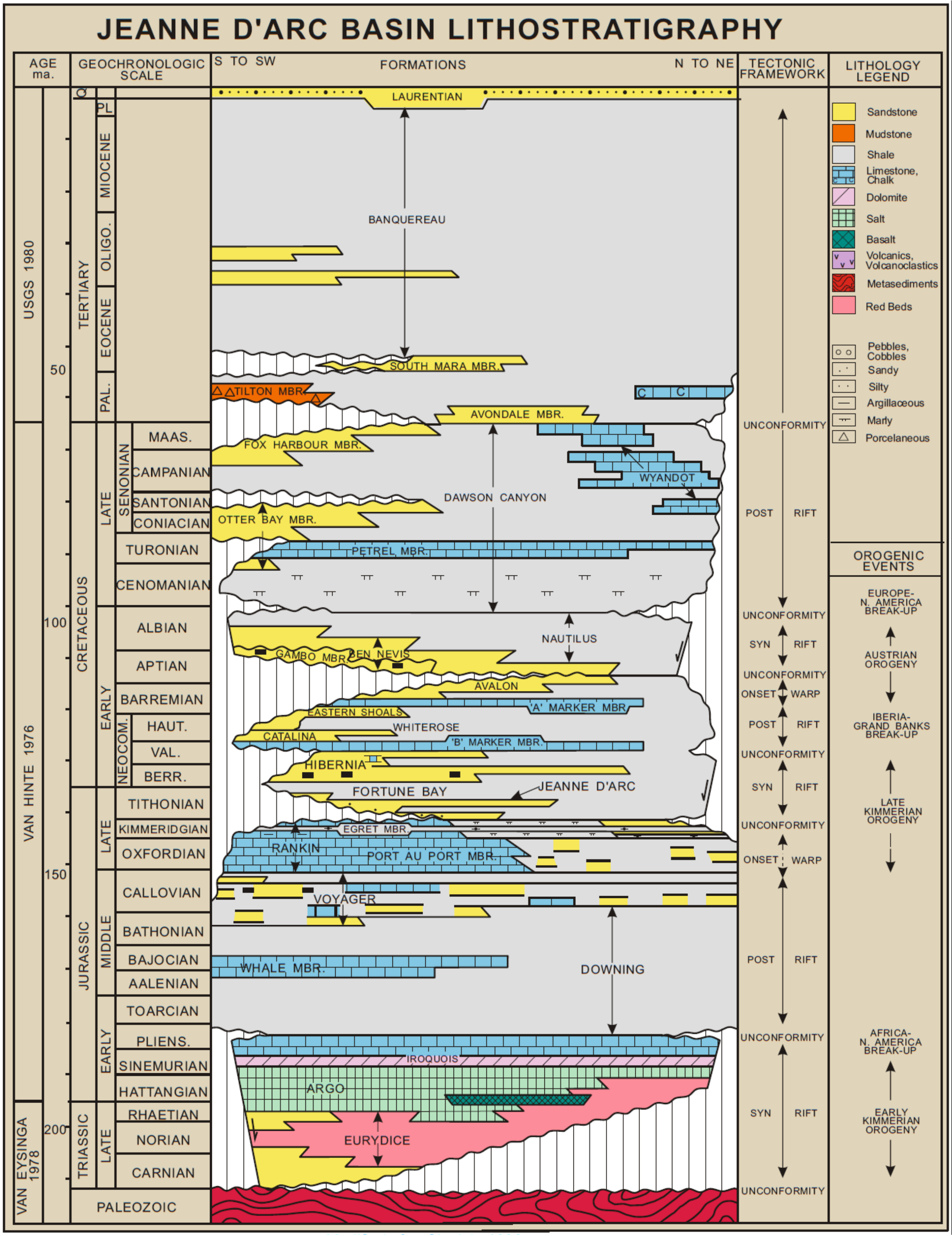


Figure 6. Stratigraphy of the Jeanne d'Arc Basin, offshore Newfoundland modified after Cohen, 2013.

2.4 Unconformities

In the Newfoundland margin, uplift and subsequent erosion occurred in the Late Jurassic to the early Cretaceous. Depicted in Figure 6, there are at least five major erosional and non deposition events that created the regionally extensive unconformities (Withjack et al. 2012). In relation to deposition rates, the southern portion of the Grand Banks had more erosion than the northern portion. This imbalance produced a northern tilt of the basement, increasing subsidence and sedimentation rate in the northern portion. A second unconformity, formed in the Lower Tertiary after active rifting ceased, mostly affected the northern region of offshore Newfoundland (Louden 2002).

The Cretaceous unconformities are related to basin inversion and regional uplift. They are related to the break-up of Grand Banks from Iberia (Louden 2002). Two possible reasons for this uplift and inversion are that there were compressional forces caused by varying rates of extension as well as rotation of the extension axis from NE to NE (Karner et al. 1993). Another possible reason is due to underplating of the margin which would add buoyancy (White and Lovell 1997).

Chapter 3: Materials and Methods

3.1 Well data and BASIN Database

This study examines the potential for a Lower Jurassic source rock located offshore Newfoundland using data from wells spread over five sedimentary basins (Figure 7). The chosen wells were interpreted to have penetrated the Lower Jurassic based on the available BASIN database biostratigraphy data analysis. Sixteen wells matched these criteria, and eight were selected for further evaluation: two wells were used from the Carson basin, one from the Horseshoe basin, four from the Jeanne d'Arc basin, one from the Flemish Pass Basin, and one from the Whale basin. Table 1 outlines the list of wells and how many data points were used.

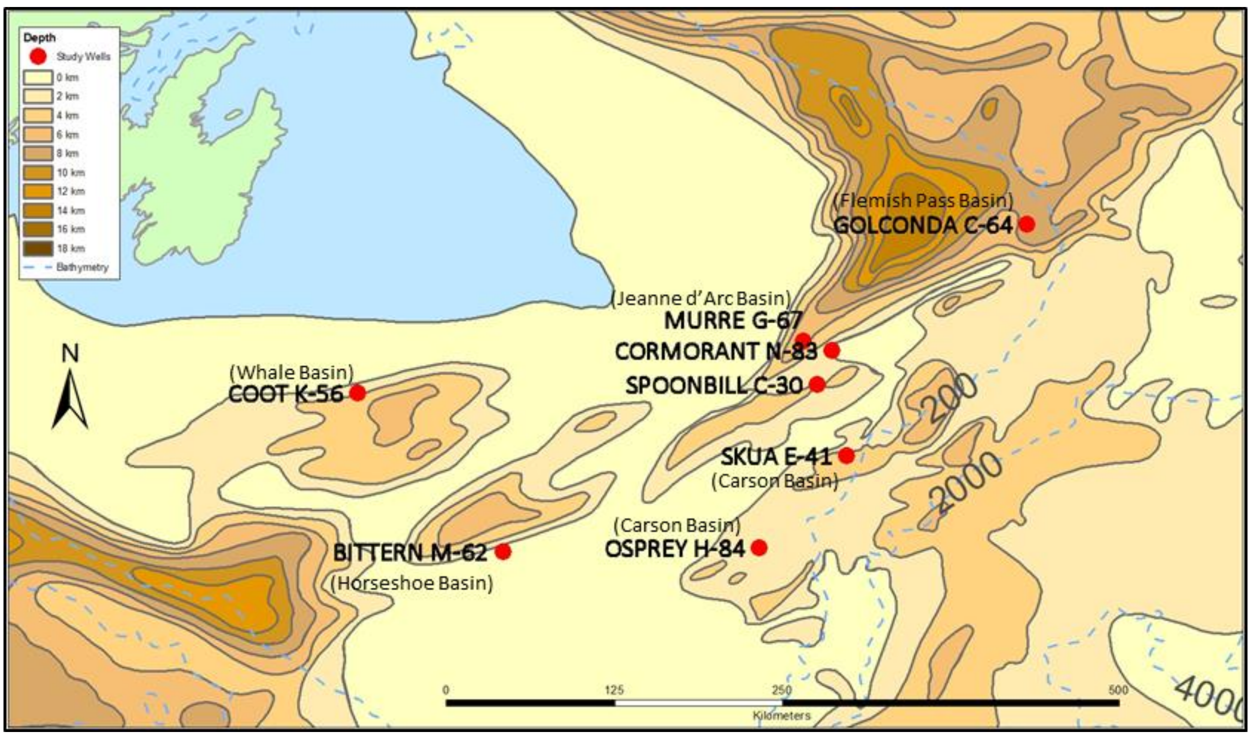


Figure 7. Location of the eight study wells located offshore Newfoundland overlain on a sediment thickness map. The most easterly potion of Newfoundland is located in the top left of the figure.

Well data is needed to generate 1D models for each well. The data used in this study was collected through publicly available data, and additional sample analysis. The publicly available data was obtained from Natural Resources Canada's (NRCan) BASIN database (http://basin.gdr.nrcan.gc.ca/index_e.php). If available, lithostratigraphy, biostratigraphy, geochemical and maturity data was sourced from the database and used in this study (Table 1).

The BASIN database is a website that contains raw and interpreted petroleum well data. The raw data is sourced from well reports whereas interpreted data is gathered from academia, industry and government research studies (Appendix A) and archived by the Canada-Newfoundland & Labrador Offshore Petroleum Board (CNLOPB) in St. John's, Newfoundland. Rock lithology's were sourced from Canadian Stratigraphic Services Ltd. - Canstrat, a company located in Calgary, Alberta that has generated lithology logs for each well through detailed cuttings and core sample analysis.

When retrieving well data from the BASIN database, there are multiple sources available for use for each type of data (Appendix A). During the creation of 1-D models, the number of sources that can be inputted depends on the data type. For example, maturity data can be inputted separately from multiple sources into the model, and compared to each other. Other types of data, such as lithology and biostratigraphy can only have one source for the data, as a model can only have a single input for the age and depth of a single horizon. Geochemical data is unique in that multiple sources should be considered when inputting data into the model, however only a single value can be inputted. For this reason, the TOC and HI values sourced from the various BASIN database sources have been compared and then averaged to provide a general value for the potential source horizons.

Sampling of each well was performed at the CNLOPB's core storage facility located in St. John's, Newfoundland. Sample selection was preceded by the visual inspection of the in-house stored washed drilled cuttings (not available for sampling). 121 samples from unwashed wet drill cuttings, corresponding to limestones and organic-rich marls and mudstones, were collected and shipped to the Basin and Reservoir Lab, Dalhousie University (Halifax, Canada) where they were cleaned to remove drill fluids and other visible contaminants (e.g. paint chips, lignite). Sample references correspond to the sample cutting interval depth in feet and meters. The samples were thoroughly rinsed with warm water and then dried in an oven at 30°C. From each sample, about 10 g were further inspected for final contaminant removal, separated, crushed, and sent to GeoMark Research Ltd. (USA) for TOC and carbonate content determination and Rock-Eval pyrolysis.

Table 1. The type of data gathered from the BASIN database and the number of data points used in this study for each well. Sources are listed in Appendix A.

BASIN & Well	Biostratigraphy		Lithostratigraphy		Geochemistry		Maturity
	Age Data	Paleo -environment	Unit Divisions	Unconformities	Total Organic Carbon (% TOC)	Hydrogen Index (% HI)	Vitrinite Reflectance (% Ro)
CARSON							
Osprey H-84	19	11	8	3	111	111	1
Skua E-41	29	29	12	4	320	320	42
FLEMISH PASS							
Golconda C-64	12	7	7	1	345	345	22
HORSESHOE							
Bittern M-62	24	15	11	2	409	409	33
JEANNE D'ARC							
Cormorant N-83	23	17	11	5	135	135	35
Murre G-67	19	13	10	5	104	104	40
Spoonbill C-30	15	13	11	3	5	5	2
WHALE							
Coot K-56	12	4	8	2	19	19	3
Total Number of Data Points	153	109	78	25	1448	1448	178

3.2 TOC and Rock Eval pyrolysis

TOC and Rock-Eval pyrolysis analyses were performed by GeoMark. TOC was measured using a LECO C230 instrument, calibrated with standards having known carbon contents. After weighing and decarbonation with concentrated HCl for at least two hours, the samples were rinsed with water and flushed through a filtration apparatus to remove the acid. The filter was then removed, the sample is weighed, and placed into a LECO crucible and dried in an oven (110 °C) for a minimum of four hours. Carbonate content (wt%) is calculated from the sample weight loss after decarbonation. The LECO C230 uses an induction furnace to combust samples and standards to a temperature of about 1200 ˚C in an oxygen-rich atmosphere. Both CO and CO_2 are generated; CO is converted to CO_2 by a catalyst. CO_2 is then measured by an infrared cell and converted to TOC wt%. GeoMark Standards were analyzed as unknowns every 10 samples to check precision and accuracy. Laboratory acceptable standard deviation for the sample's analytically-determined TOC value is 3%.

For Rock-Eval pyrolysis determinations (Rock-Eval II) about 100 mg of crushed sample were heated (in a pyrolysis oven) in an inert atmosphere (helium) to 550 ºC, per the analytical procedures outlined by Espitalié et al. (1977, 1986) and Peters (1986). Standards were analyzed as unknowns every 10 samples to check precision and accuracy. In addition to TOC, direct measurements obtained by this procedure include S_1 (free hydrocarbons; mg HC/g rock), S_2 (residual hydrocarbon potential; mg HC/g rock), S_3 (CO_2 produced from kerogen pyrolysis; mg CO_2/g rock), and T_{max} (peak generation temperature; ºC) (e.g. Tissot and Welte, 1984). The acceptable standard deviation for T_{max} is ± 2 °C, 10% for S_1 and S_2, and 20% for S_3. The pyrolysis oven was programed as follows: for five minutes, the oven is kept isothermally at 300 °C and the S_1 free hydrocarbons are volatilized and measured as the S_1 peak (detected by Flame Ionization Detector - FID). The temperature is then increased from 300° to 550 °C (at 25 °C/min). The released hydrocarbons from kerogen are measured as the S_2 peak. The temperature at which S_2 reaches its maximum is called T_{max} (°C) and depends on the nature and maturity of the kerogen. The CO_2 released from kerogen cracking is trapped between 300-390 °C. The trap is heated; CO_2 is released and detected on a Thermal Conductivity Detector during cooling (S_3 peak). Others parameters (derived measurements) such as Hydrogen Index (HI = S_2/TOCx100, mg HC/g TOC) and Oxygen Index (OI = S_3/TOCx100, mg CO_2/g TOC) were calculated (e.g. Espitalié et al., 1977, 1986; Peters, 1986).

3.3 Petroleum Systems Modelling - PetroMod™ Workflow

PetroMod™ Petroleum Systems Modelling (PSM) software is used throughout academia and the petroleum industry to better understand the development of a petroleum system. PSM is a method of dynamic forward modelling, demonstrating how different geological processes affect sedimentary basins (Cathles et al. 2003; Hantschel and Kauerauf 2009; Hermanrud 1993; Wach et al. 1997). PetroMod™ workflow (Figure 8) involves defining input parameters such as depositional environments, burial rates, organic matter accumulation and heat flow analysis. These processes are determined through the examination of well data and literature. Calibration of the model using vitrinite reflectance and temperature data is needed to refine the model. A complete model will take these processes and calibration data into account and provide a detailed analysis of the hydrocarbon generation potential. 1-D modelling uses data from a point location, a single drilled borehole, and offers an analysis of the burial history.

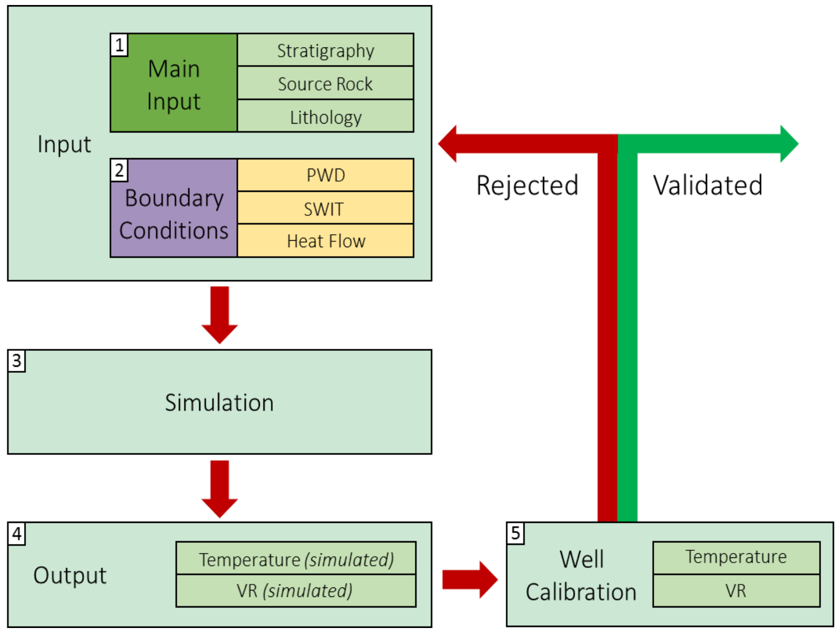


Figure 8. PetroMod™d workflow. The main input (1- Stratigraphy, Source Rock Properties, and Lithology) is followed by the input of boundary conditions (2- Paleo-water depth, Surface-water Interface Temperatures, and Heat Flow). The simulation phase (3) and Output phase (4- Simulated Temperature and Vitrinite Reflectance) are then completed. Well calibration (5) is required in order to validate the inputs. Based on the calibration quality, a decision is made to re-evaluate the parameters or proceed.

3.3.1 Main Inputs

3.3.1.1 Stratigraphy

The stratigraphic input for each well includes lithostratigraphy and biostratigraphy data. These inputs are used to define the basin depositional history and provide lithological data that is important for heat flow analysis. Each lithology has a thermal conductivity that controls the heat flow through the sediments, impacting the maturity of the source rock. The BASIN database lithostratigraphy data included formation names and depths for each well.

Biostratigraphy data includes interpreted ages and qualitative water depth for a range of depths. These were determined through palynofacies analysis. Biostratigraphy data is combined with the formation depths to assign ages to the stratigraphic divisions. They are linked based on the depths associated with the age assignments and the lithostratigraphy data. The start of deposition age and end of deposition age for each division is calculated by taking a percentage of the total thickness and then assigning that percentage to the age range associated with the division. The ages assigned to the chronostratigraphic stages are from the International Chronostratigraphy Chart (Cohen et al. 2013; updated).

3.3.1.2 Unconformities

Unconformities are present within each well. Due to the lack of available erosional thickness data, erosion has not been considered in these thermal models. The unconformities are treated as hiatuses in these models, reflecting non-deposition. Trial runs with significant amounts of erosion (i.e. >500 m) were used to determine the sensitivity of erosion on the modelled vitrinite reflectance. No major changes were observed.

3.3.1.3 Lithology

The lithology of each interval is determined by combining well log data and Canstrat lithology logs. Each interval is created by the combination of biostratigraphy and lithostratigraphy well data and has been assigned multiple lithology's of varying thicknesses. The percentage of each lithology that makes up the interval is determined through Techlog™, a Schlumberger well log data visualization software. These lithology's and percentages were then placed into PetroMod™'s Lithology Editor for each well.

3.3.1.4 Source Rock Properties

The source rock properties include the TOC and HI values for each interval. These values are sourced from the BASIN database sources and then assigned to the respective defined intervals. The values are then averaged and placed into the model. From our analysis, we determined that the source interval would have type III-IV kerogen, which needed to be considered for the source rock kinetics. The kerogen type was resolved using both the hydrogen index and oxygen index values seen in chapter five. The kinetics for the Lower Jurassic interval were assigned to the Burnham (1989)- TIII grouping. This is a general type III kinetics group used for unknown generation kinetics in PetroMod™.

3.3.2 Boundary Conditions

3.3.2.1 Paleo-water Depth (PWD)

The paleo-water depth (PWD) represents the depth of the water column during deposition. This is interpreted from the biostratigraphy depositional environment data. These depths are used to calculate and recreate the burial history of the model, which will be a reconstruction of the subsidence history of a basin, which controls the sediment thicknesses that can accumulate (Allen and Allen, 2005), and their compaction. Paleo-water depth is prone to a large uncertainty because an interpretation of the paleo-water depth is based on interpreted depositional environments.

3.3.2.2 Surface-Water Interface Temperature (SWIT)

The Surface-water interface temperature (SWIT) is the upper boundary condition for heat flow. It is calculated using the paleo-water depth and estimated mean surface temperatures. PetroMod™ calculates SWIT based on a model by Wygrala (1989), to get a historical mean air surface temperature, which is affected by latitudes that change throughout geological history (Hantschel and Kauerauf 2009).

3.3.2.3 Heat flow

The basal heat flow is a critical input for basin modeling, as it influences the amount of paleo-heat flow that the source rock will experience, which influences a potential source rock's ability to generate hydrocarbons. This input allows the simulation to calculate when the source rock starts transforming organic matter into hydrocarbons. The most commonly used heat flow model in PSM is the McKenzie model (McKenzie 1978; Hantschel and Kauerauf 2009), a model of uniform stretching where the lithosphere deforms as a single layer, and has been selected for use in this study. For this study, we will use a heat flow model based on the McKenzie model. The McKenzie model assumes that all heat passing through the lithosphere originates below the lithosphere. It also predicts an instantaneous increase in heat flow during rifting (Hantschel and Kauerauf 2009).

The heat flow is calibrated based on vitrinite reflectance data gathered from the BASIN database sources. The maximum and present day heat flow were determined by adjusting the values over geological time to fit the simulated maturity data to the measured data (Figure 9). The McKenzie model was followed by ensuring there was a 10 Ma instantaneous rifting event, in which the heat flow increased dramatically to its maximum value. After this rifting, a gradual decline in heat flow to the present-day value was assumed. This method is useful when trying to simplify the modelling process when there is a lack of heat flow data available.

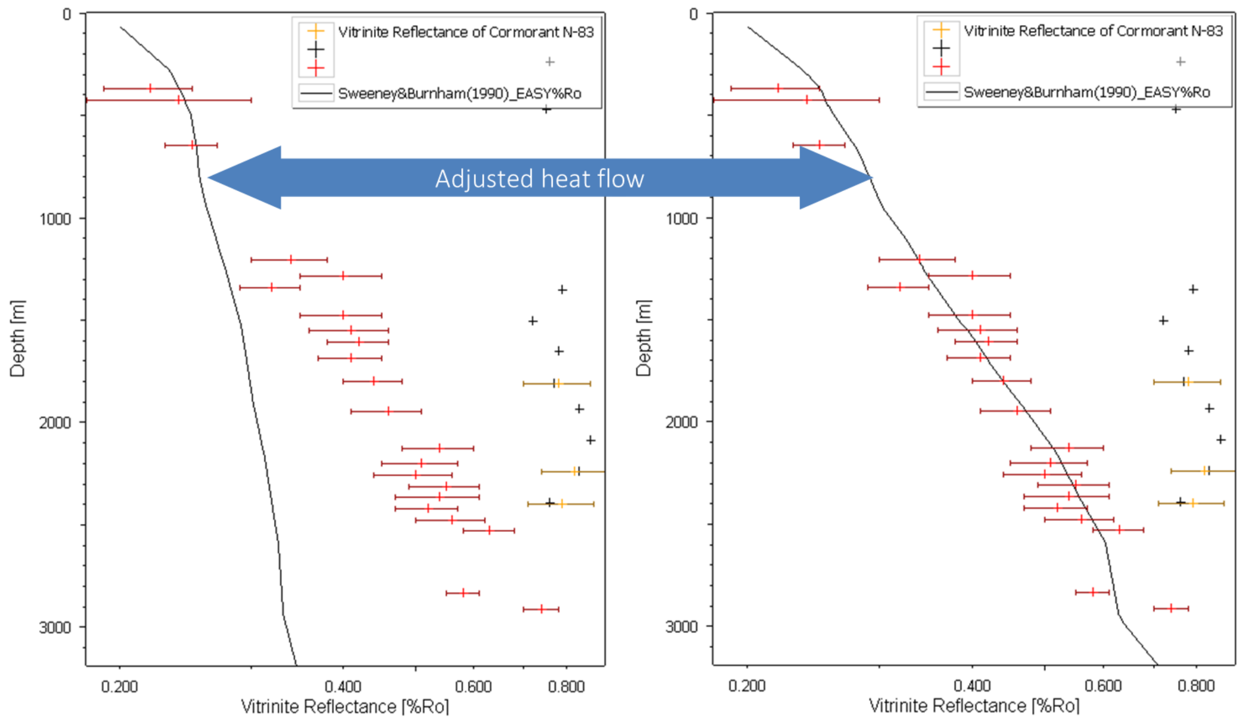


Figure 9. Calibration of heat flow using vitrinite reflectance data. To the left is a simulated vitrinite reflectance curve that does not match the measured data. After adjusting only heat flow, the simulated curve to the right matches the measured data. This heat flow has been validated and can be used to assess the maturity of the organic matter.

3.3.3 Simulation, Output and Well Calibration

To run a simulation in PetroMod™, the appropriate boundary conditions are required (Figure 8). These conditions are necessary, as they define how the model interacts with the paleo-water depth (PWD), sediment-water interface temperature (SWIT) and heat flow. The simulation process starts by restoring the original thickness for each lithostratigraphic unit in the model, using the back-stripping, or decompaction, method by Watts and Ryan (1976). The back-stripping method quantitatively estimates the basement subsidence and uplift history in the absence of sediment and water loading. Once the original thickness for each layer is calculated, PetroMod™ will start simulating the basin subsidence by applying compaction, PWD, fluid dynamics or Darcy flow, and thermal properties such as SWIT and heat flow, through geological time. The simulation process will also calculate the source rock geochemical properties by using built-in petroleum generation kinetics through geological time. These petroleum generation kinetics schemes are based on mass balances and distributed reactivity kinetics. These schemes include sequential and parallel reactions that are approximated as first order of the Arrhenius type reaction (Hantschel and Kauerauf 2009). These kinetics are different for each type of kerogen (Type I-IV), and the type of investigation, or calculation output of the source rock, such as bulk, oil-gas, or compositional kinetics used from this process gives us the calculated temperature and vitrinite reflectance used in the model.

The output generated by PetroMod™ includes the burial history, thermal maturation history, timing of hydrocarbon generation, and timing of hydrocarbon expulsion. Although each model run has solutions from the simulation, each must be validated with well-calibrated data (Figure 9). This is done by comparing calculated and measured data available for the well, such as vitrinite reflectance and temperature. If the calculated data are not within the appropriate range of the measured data, the model inputs or boundary conditions must be changed, and the simulation run again. This process cannot be done automatically since there are many uncertain input parameters, such as PWD, SWIT, and paleo-heat flow, that can affect the result of the model (Hantschel and Kauerauf 2009).

It must be emphasized that petroleum systems models are predictive tools subject to the variations and accuracy of the input parameters and available datasets, however, using them in a realistic and intelligent manner can provide important insights into a basin's petroleum systems and reduce exploration risk. Once a satisfactory result is obtained from the simulation of a well's burial and thermal history, it is then possible to determine the potential for the existence of source rocks in the respective Newfoundland offshore basins and hydrocarbon generative potential.

Chapter 4: Results

This chapter summarizes the new TOC and Rock Eval pyrolysis data, and 1D modelling results completed with PetroMod™ PSM software from this study. A summary of the well datasets provided in the BASIN online database and used in this study is presented in Table 1, with full citations of the individual subject data sources detailed in Appendix A.

4.1 TOC

Samples sent to GeoMark were accessed for their geochemical properties and the results were returned upon completion of the analysis (Table 2). The TOC of each sample was listed along with various other values associated with its hydrocarbon generative potential. The TOC wt% and carbonate % values are presented in Table 2 and Figures 10 – 14. TOC values are separated by the dashed lines into four categories: Poor (0 – 1 wt% TOC), Fair (1 – 2 wt% TOC), Good (2 – 4 wt% TOC), and Excellent (>4 wt% TOC) following Tissot and Welte (1984).

Overall, the analysis shows low TOC amounts for the Lower Jurassic intervals (Figures 10 – 14). They plot within the upper margin of the "poor" zone of the graph, indicating low amounts of organic matter in the samples. The amount of carbonate in the samples was variable and revealed no distinct pattern. The sample with the highest TOC amount was in the Flemish Pass basin's Golconda C-64 (Flemish Pass Basin) well with a value of 1.22 wt%. The average TOC for all samples was 0.56 wt%.

4.2 Rock-Eval pyrolysis

As presented in Table 2, the Bittern M-62 (Horseshoe Basin) well has low HI values that range from 5.00 – 10.53 mg HC/g TOC and non-valid T_{max}. Coot K-56 (Whale Basin) has three samples with low HI values that range from 43.33 – 67.86 mg HC/g TOC A fourth sample has a value of 239.39 mg HC/g TOC. In this well, T_{max} ranges from 428 – 438 ^{o}C. The sample with the lowest TOC did not yield a valid T_{max}. Cormorant N-83 (Jeanne d'Arc Basin) has low HI values that range from 19.05 – 44.93 mg HC/g TOC. T_{max} ranges from 433 – 437 ^{o}C. Two samples did not yield a valid T_{max}. Golconda C-64 (Flemish Pass Basin) has low HI values that range from 54.10 – 94.12 mg HC/g TOC. T_{max} ranges from 353 – 403 ^{o}C. Murre G-67 (Jeanne d'Arc Basin) has low HI values that range from 30.00 – 63.46 mg HC/g TOC. T_{max} ranges from 431 – 438 ^{o}C. All samples are classified as type III – IV kerogens (Van Krevelan, 1950) (Figure 15).

4.3 Petroleum Systems Modeling - Maturity

4.3.1 Heat Flow

Heat flow was calibrated using the vitrinite reflectance data available for each well (Figure 16 and 17). Three wells (Coot K-56, Osprey H-84, and Spoonbill C-30) have limited maturity data and extremely high modelled heat flows (maximum >100 mW/m^2 and present day values near 100 mW/m^2). These limited datasets, in addition to their high values at relatively shallow depths made modeling these heat flows difficult. These limitations need to be considered when analyzing these wells.

Bittern M-62 (Horseshoe Basin), Cormorant N-83 (Jeanne d'Arc Basin), Golconda C-64 (Flemish Pass Basin), Murre G-67 (Jeanne d'Arc Basin), and Skua E-41 (Carson Basin) have thermal histories modelled from 220 Ma until present day (Figures 18 and 19). Heat flow begins at 50 mW/m^2 and increases to a maximum at 210 Ma. The exponential curve is based on the McKenzie model for instantaneous heat flow. Following this peak, the heat flow gradually decreases to present day values at 70 Ma. An instantaneous rifting event, with a gradual decline to present day values created simulated vitrinite reflectance curves that match the measured data. Increases in heat flow from later rifting events so not need to be considered for the modeling of these vitrinite reflectance values. Figures 18 and 19 show the heat flow curves for each well and the calibration with the vitrinite reflectance data.

Figures 20 – 23 show modelled vitrinite reflectance (%Ro) overlays on the burial history plots for the Lower Jurassic interval of each well. The Lower Jurassic has a wide range of maturity values that lie within the immature to dry gas range. Bittern M-62 (Horseshoe Basin), Coot K-56 (Whale Basin) and Golconda C-64 (Flemish Pass Basin) have Lower Jurassic intervals with %Ro values that reach the gas generation zones. The other five wells (Cormorant N-83, Murre G-67, Osprey H-84, Skua E-41 and Spoonbill C-30) have maximum Lower Jurassic %Ro values that fall in the oil generation zones (0.55-1.3 %Ro). The timing of maturity and the depth of maturity vary for each well. In general, temperatures corresponding to the oil generation window occurs at some time in the Jurassic or the Late Cretaceous. The depth of oil generation window ranges from about 900 m in Spoonbill C-30 (Jeanne d'Arc Basin) to about 2300m in Cormorant N-83 (Jeanne d'Arc Basin). Although, Spoonbill C-30 (Jeanne d'Arc Basin) has a compromised heat flow due to limited maturity data, so the onset of maturity occurring at 900 m depth is most likely shallower than expected.

4.3.2 Transformation Ratio

The transformation ratios, overlain on the burial history plots in Figures 24 – 27, show the generation of hydrocarbons with the maturation of organic matter. Bittern M-62 (Horseshoe Basin) and Golconda C-64 (Flemish Pass Basin) show the highest amounts of generation in the selected source rock intervals, with values ranging from 50% to 95% in the Lower Jurassic. The other six wells have Lower Jurassic transformation ratios that range from 0% to a maximum of 50%.

Table 2. Rock Eval Pyrolysis data for samples in five wells used in this study. The analysis was completed by GeoMark Laboratories Ltd. Drilling mud type and mud additives are listed below.

Well Name	Depth	TOC (wt %)	% Carbonate	Hydrogen Index (mg HC/g TOC)	Oxygen Index (mg CO_2/g TOC)	Tmax (°C)
Bittern M-62	3721.6	0.2	95.26	5.00	40.00	-
(Horseshoe Basin)	3800.9	0.19	95.66	5.26	47.37	-
	3837.4	0.19	92.96	10.53	57.89	-
	3956.3	0.36	88.10	8.33	19.44	-
Coot K-56	2551.2	0.66	23.15	239.39	145.45	428
(Whale Basin)	2557.3	0.56	27.44	67.86	114.29	436
	2798.1	0.3	16.98	43.33	96.67	-
	2831.6	0.47	24.05	57.45	61.70	438
Cormorant N-83	2072.6	0.64	32.11	32.81	65.63	437
(Jeanne d'Arc Basin)	2103.1	0.69	36.91	44.93	46.38	433
	2136.7	0.55	48.37	36.36	81.82	435
	2170.2	0.65	29.77	21.54	95.38	-
	2188.5	0.21	85.06	19.05	104.76	-
Golconda C-64	4130.0	0.51	53.20	94.12	113.73	402
(Flemish Pass Basin)	4230.0	1.22	26.64	54.10	56.56	403
	4445.0	0.68	16.98	57.35	83.82	353
Murre G-67	2465.8	0.9	29.67	46.67	103.33	438
(Jeanne d'Arc Basin)	2523.7	1.04	27.47	63.46	25.96	431
	2551.2	0.7	39.03	30.00	17.14	438
	2581.7	0.75	37.67	38.67	22.67	432

Bittern M-62 (Horseshoe Basin) – mud: seawater with additives (CROMEX, KWIKSEAL, NUTPLUG); Coot K-56 (Whale Basin) – mud: dispersed seawater with additives (CROMEX, KWIKSEAL, NUTPLUG); Cormorant N-83 (Jeanne d'Arc Basin) - mud: dispersed seawater with additives (CROMEX); Golconda C-64 (Flemish Pass Basin) – mud: KCL - Pre-Hydrated Gel; Murre G-67 (Jeanne d'Arc Basin) - mud: seawater with additives (CROMEX, KWIKSEAL)

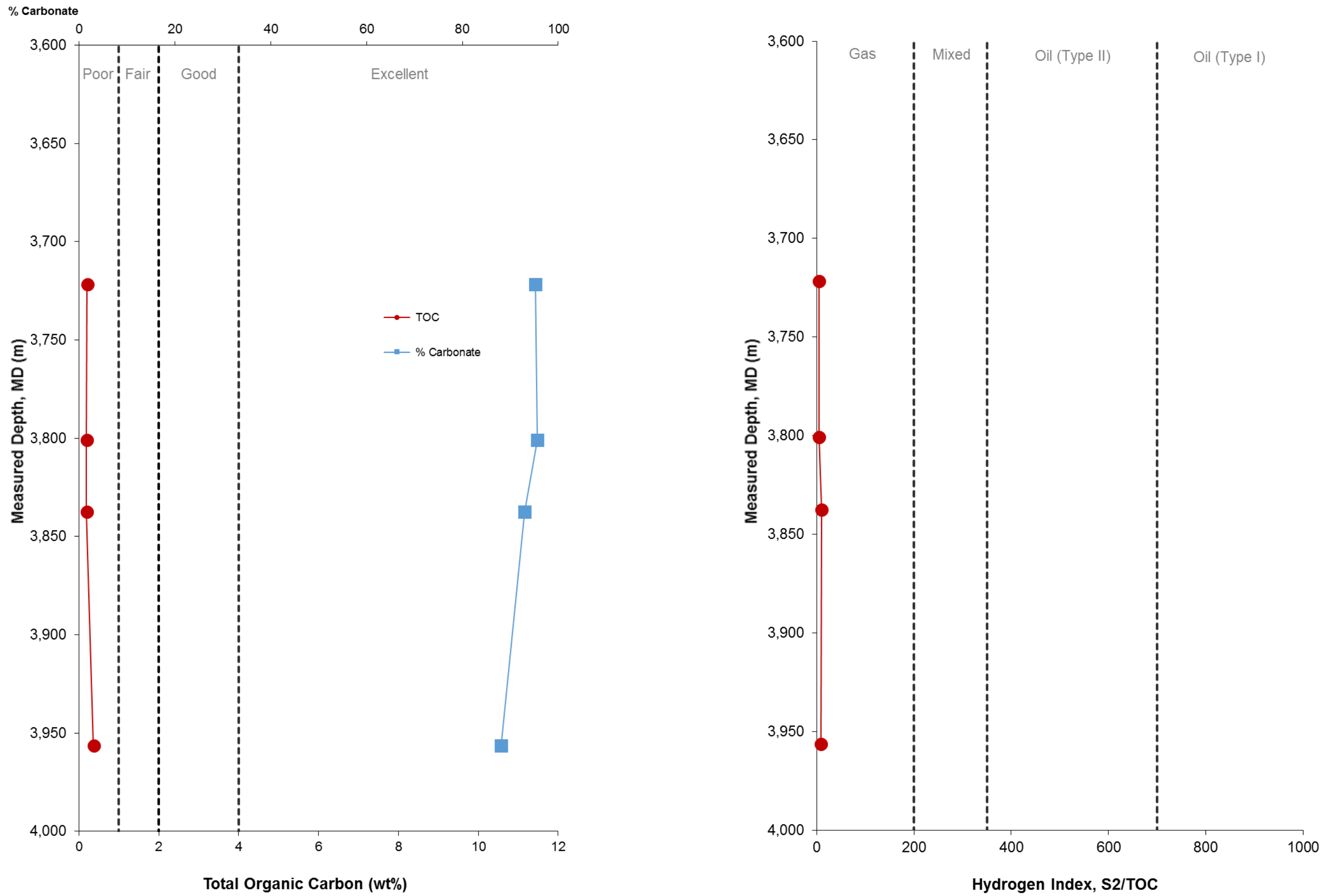


Figure 10. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) results from GeoMark Laboratories Ltd. for Bittern M-62 (Horseshoe Basin).

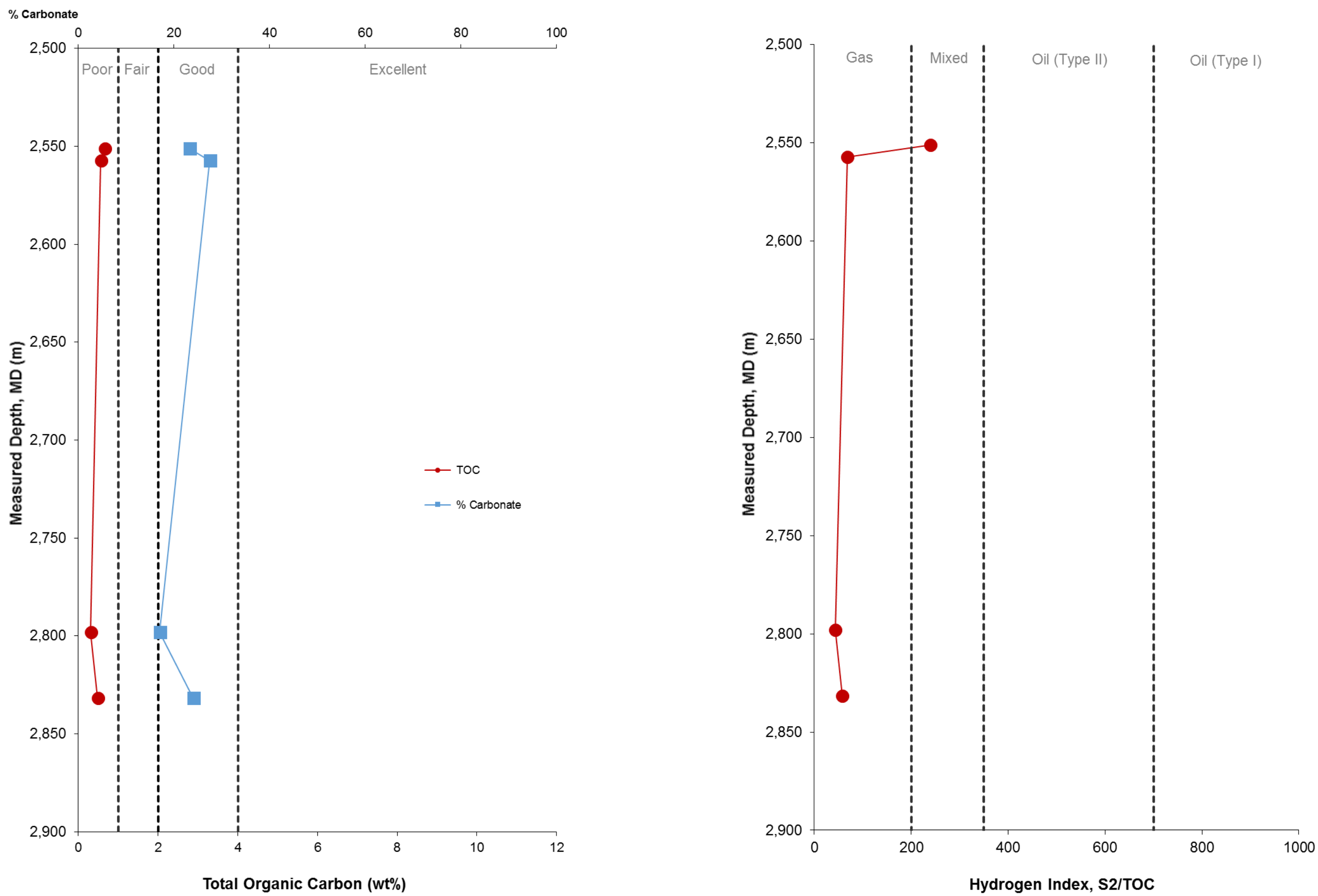


Figure 11. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) results from GeoMark Laboratories Ltd. for Coot K-56 (Whale Basin).

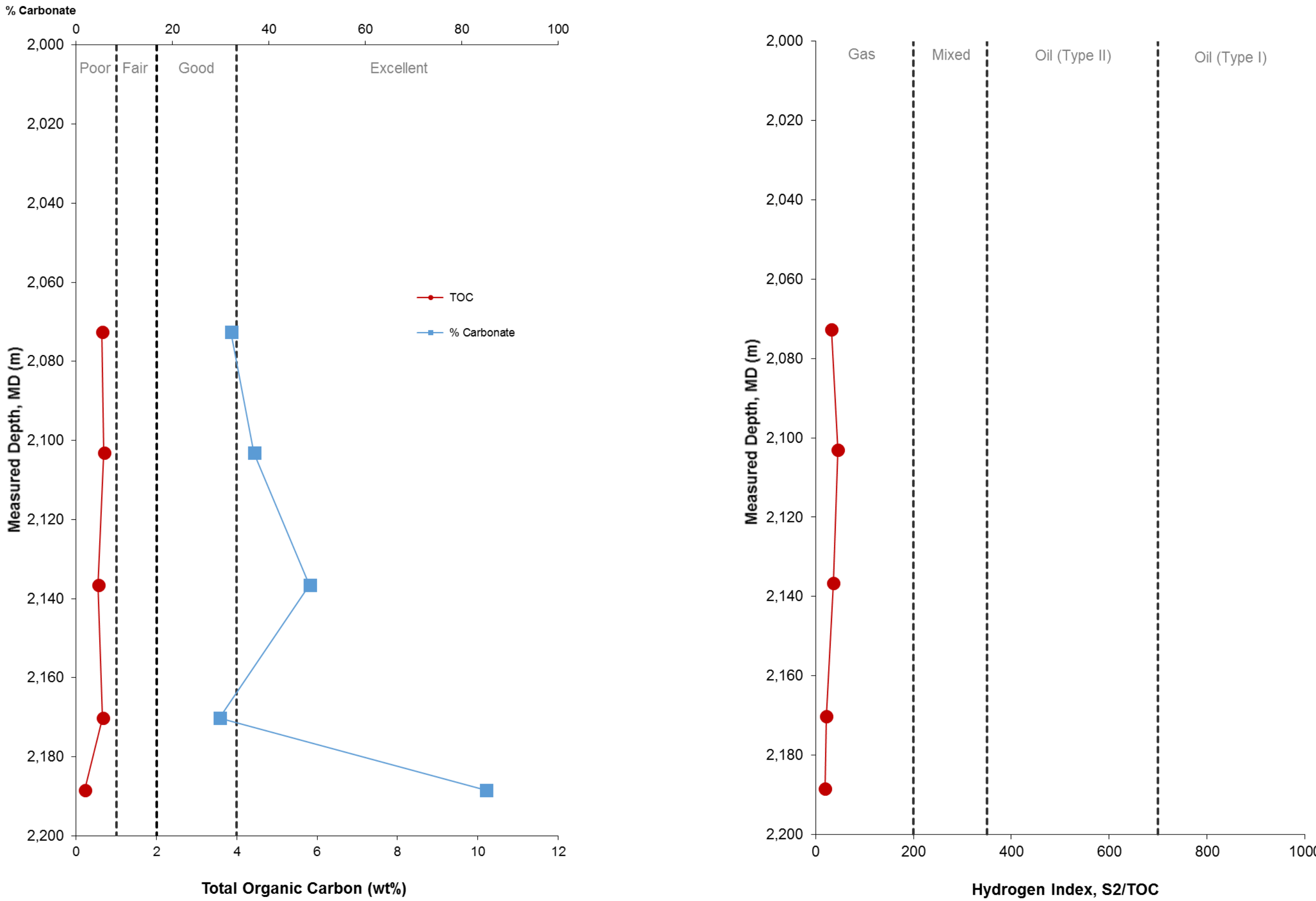


Figure 12. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) results from GeoMark Laboratories Ltd. for Cormorant N-83 (Jeanne d'Arc Basin).

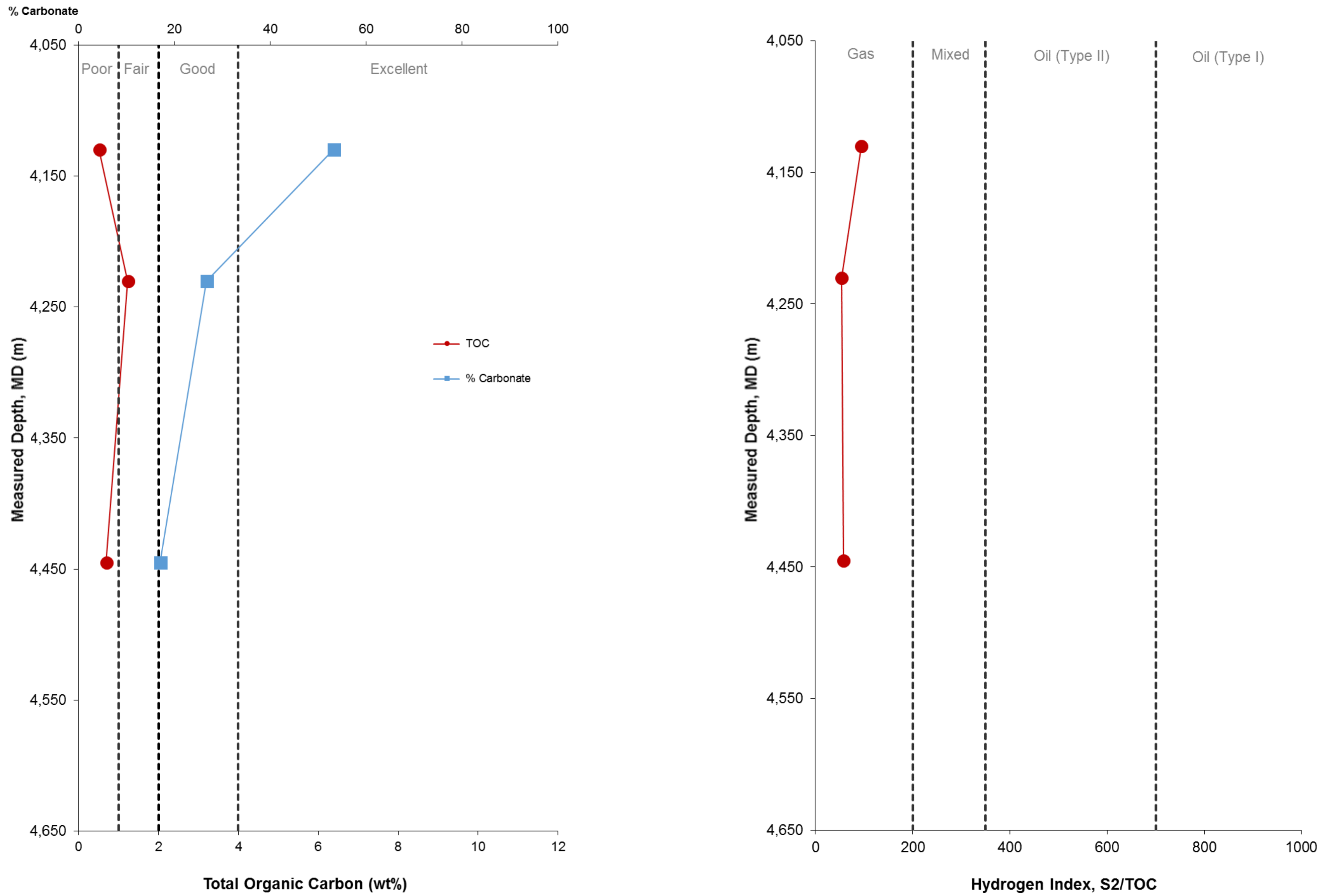
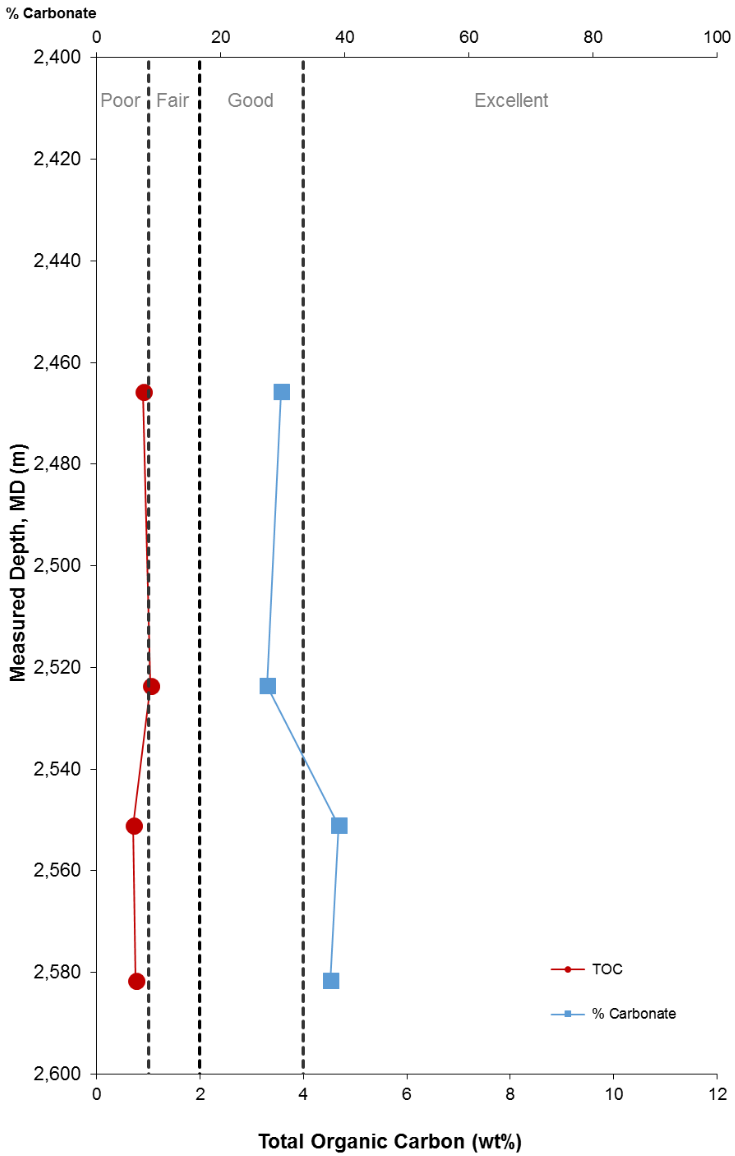


Figure 13. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) results from GeoMark Laboratories Ltd. for Golconda C-64 (Flemish Pass Basin).



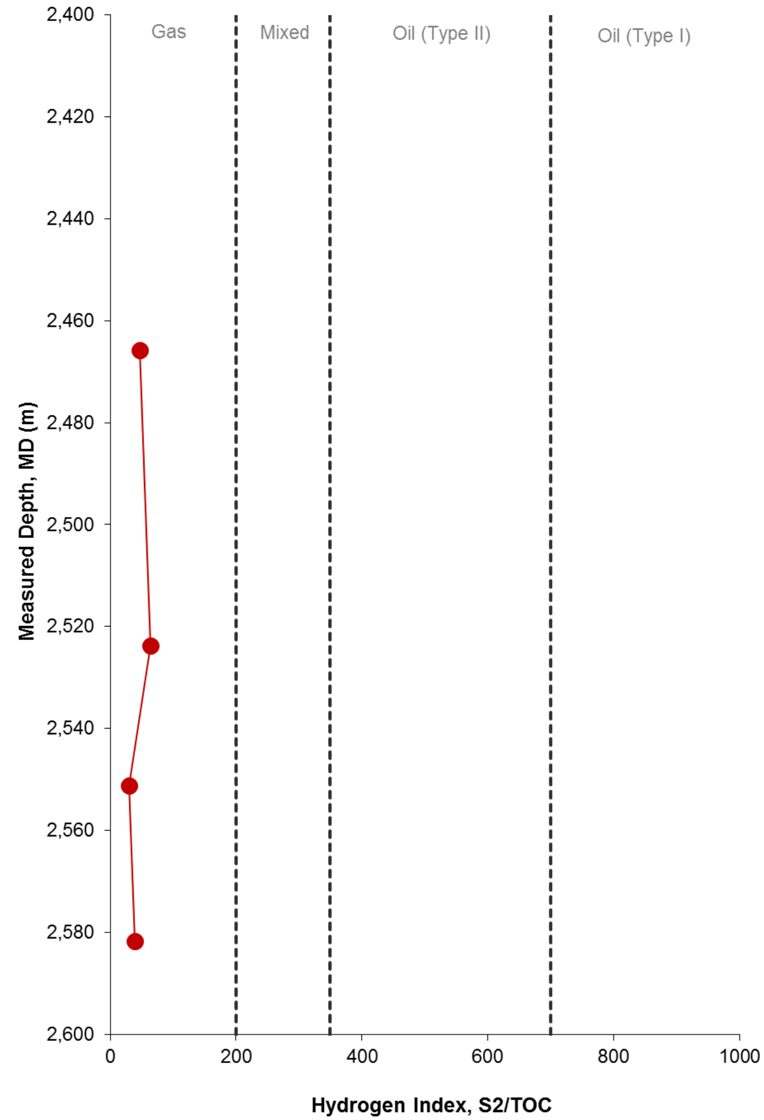


Figure 14. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) results from GeoMark Laboratories Ltd. for Murre G-67 (Jeanne d'Arc Basin).

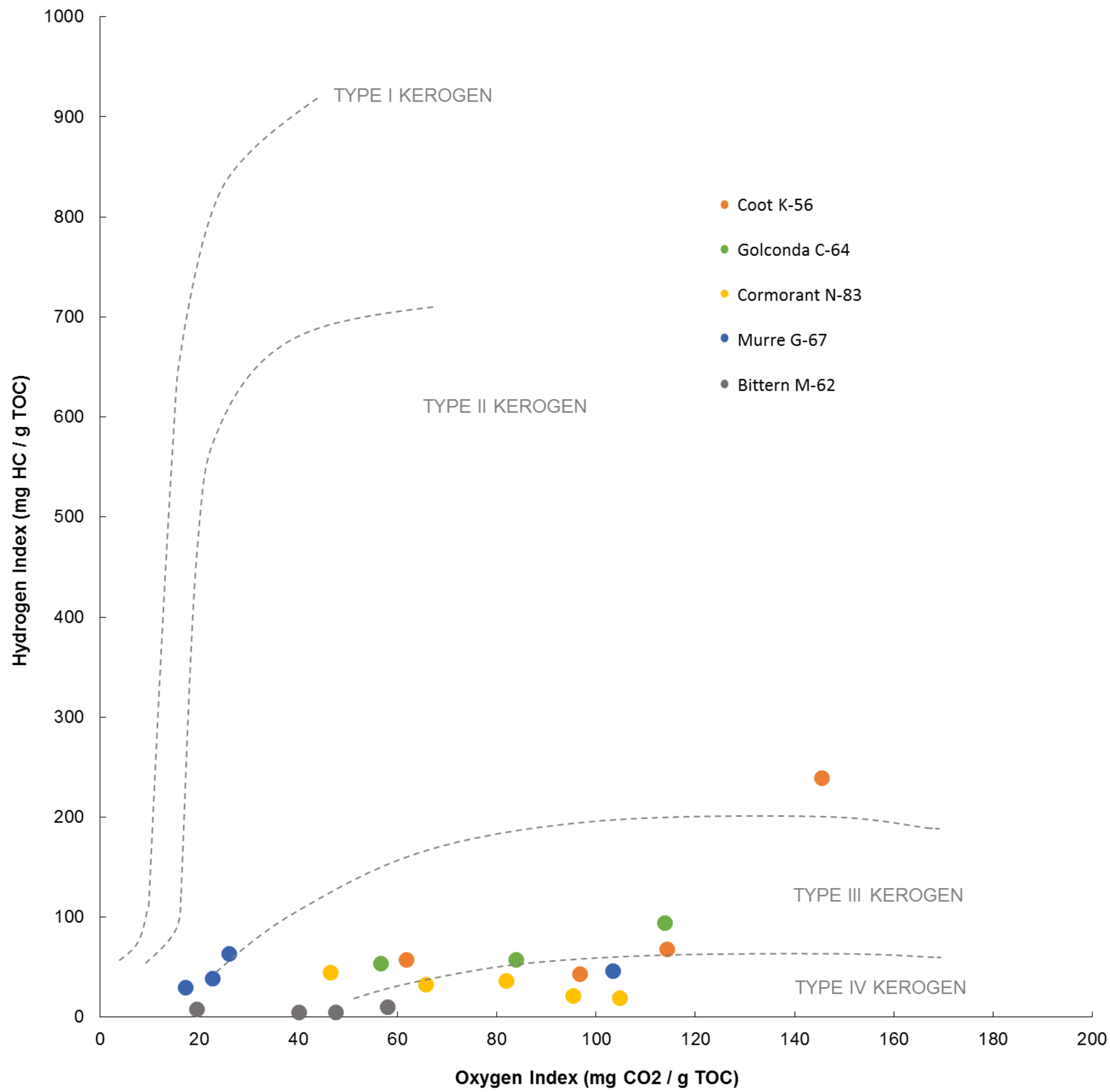


Figure 15. A Van Krevelen plot is used to determine the type of kerogen present in the studied interval. The newly acquired dataset lies within Type III - IV kerogen.

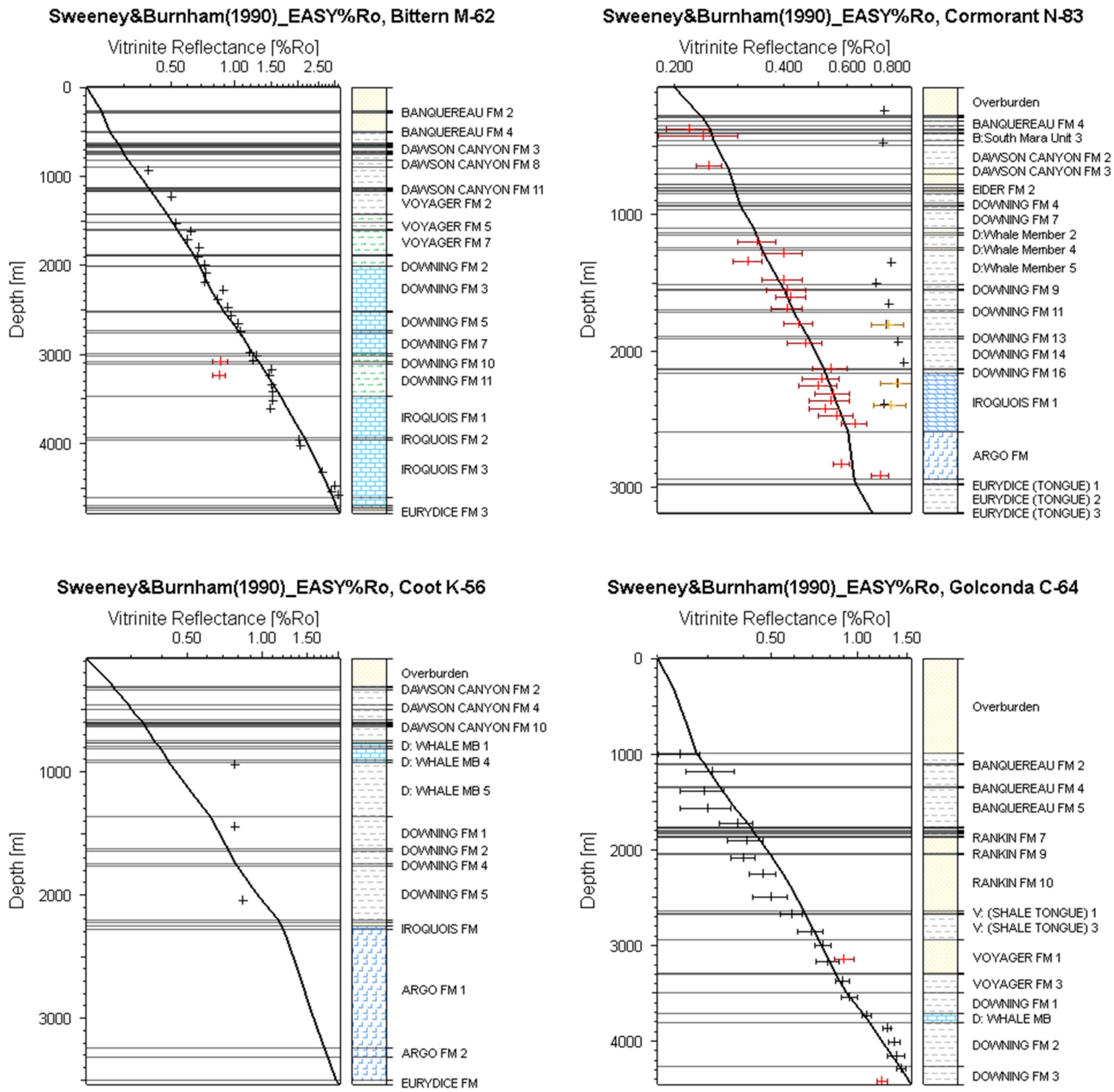


Figure 16. Calibration of 1-D modelling using vitrinite reflectance values.

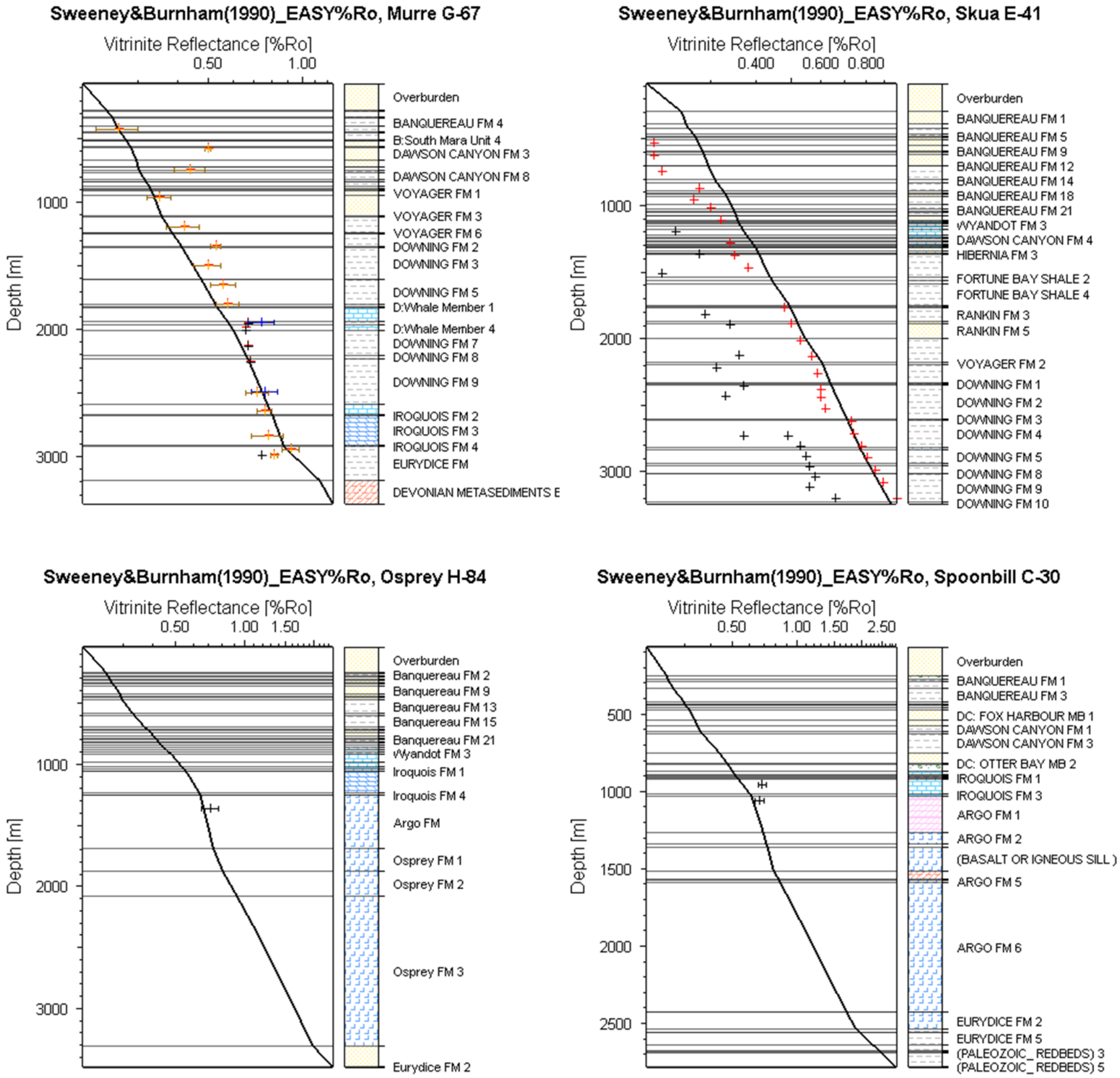


Figure 17. Calibration of 1-D modelling using vitrinite reflectance values.

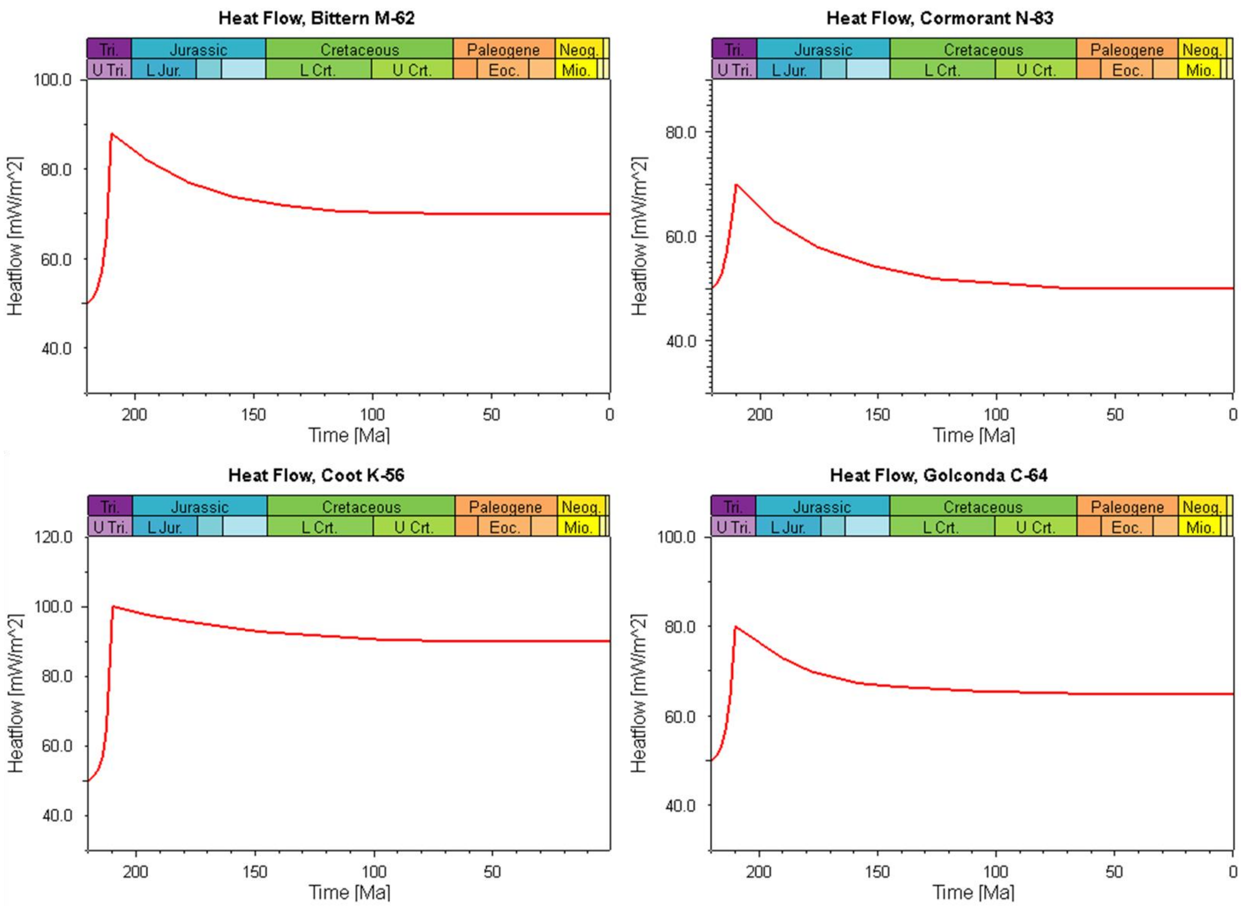


Figure 18. Modelled heat flow curves over geological time.

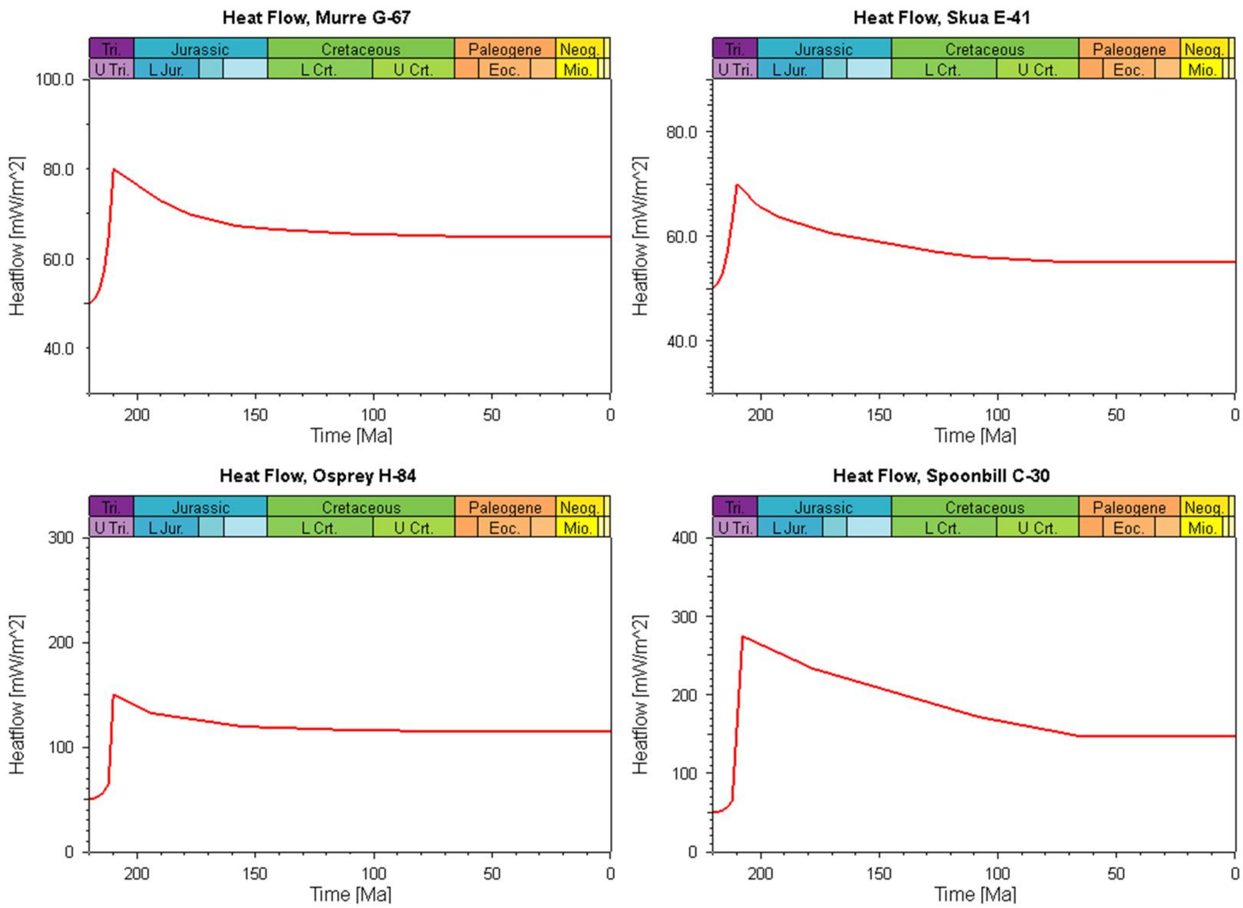


Figure 19. Modelled heat flow curves over geological time.

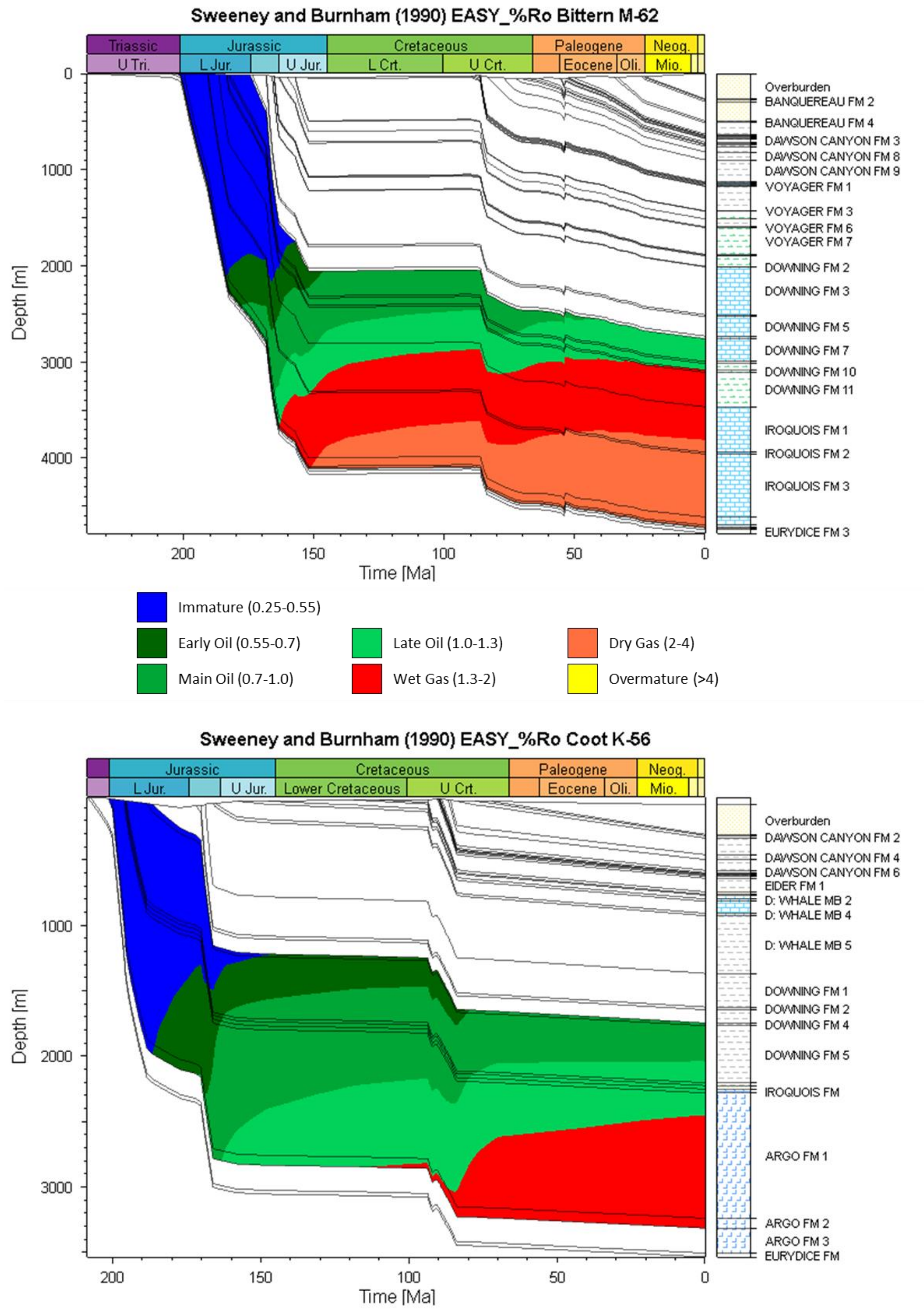
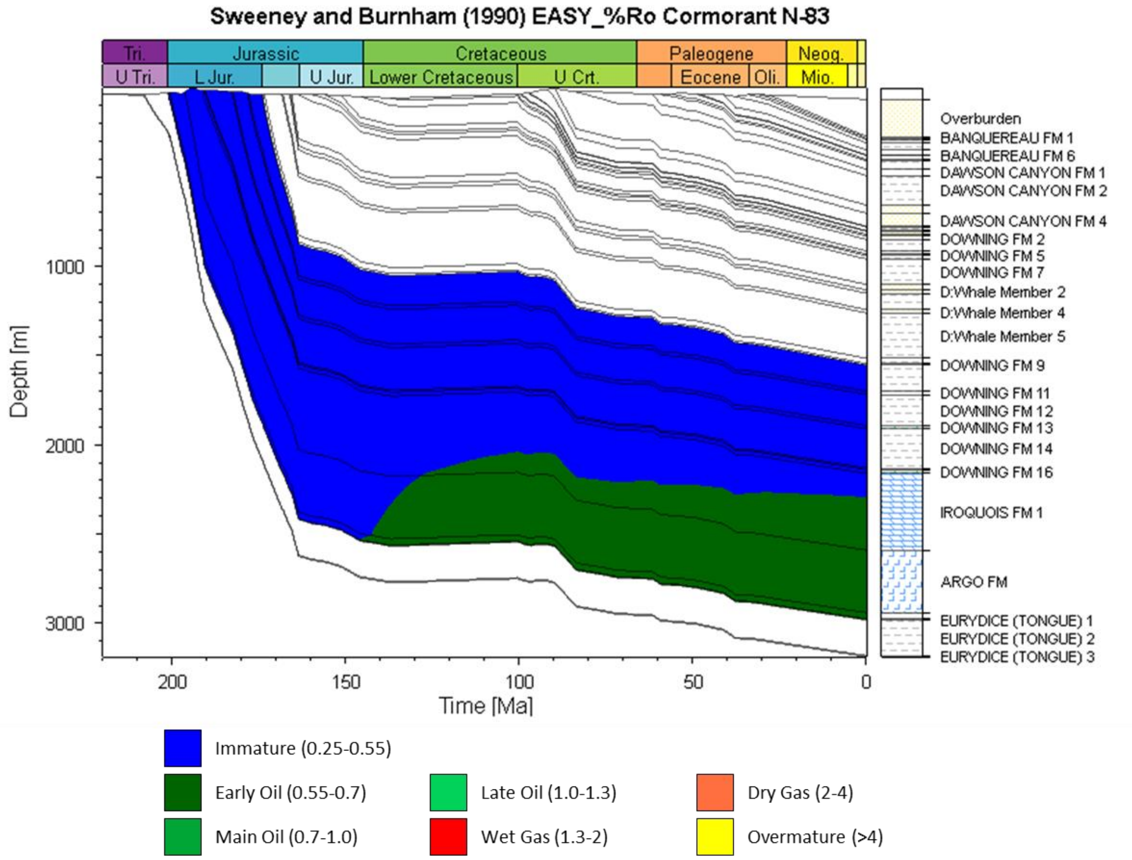


Figure 20. Burial-history curve of the Bittern M-62 (Horseshoe Basin) (top) and Coot K-56 (Whale Basin) (bottom) wells, with a maturity overlay of the Lower Jurassic interval.



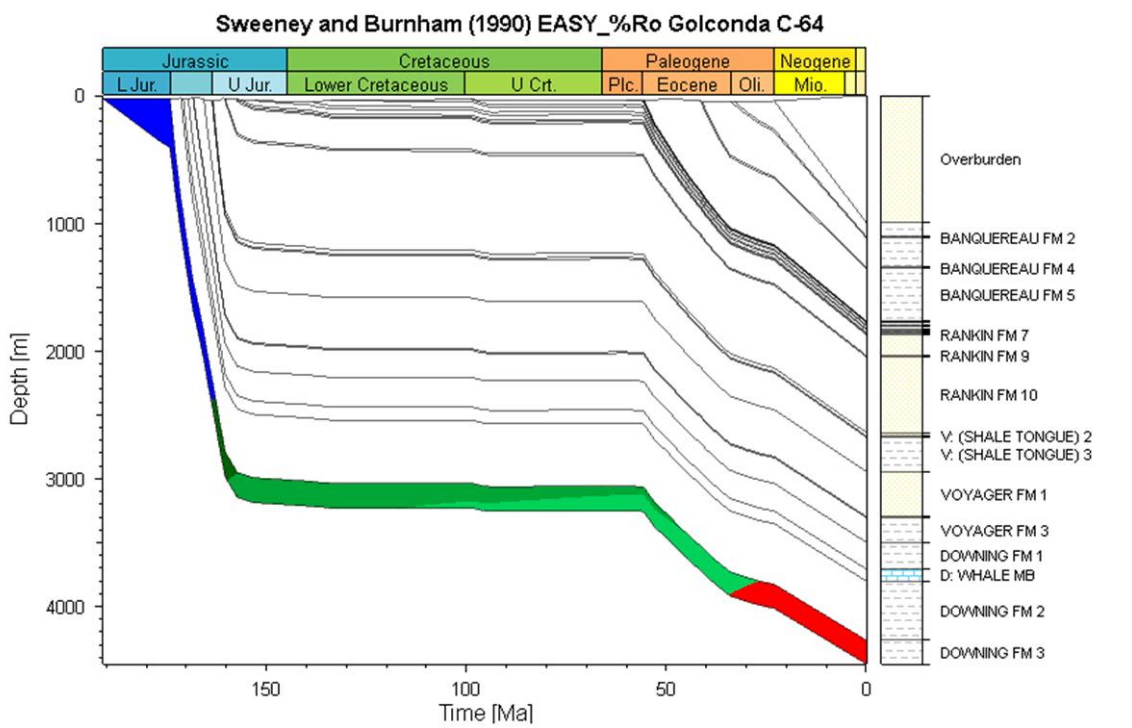


Figure 21. Burial-history curve of the Cormorant N-83 (top) and Golconda C-64 (bottom) wells, with a maturity overlay of the Lower Jurassic interval.

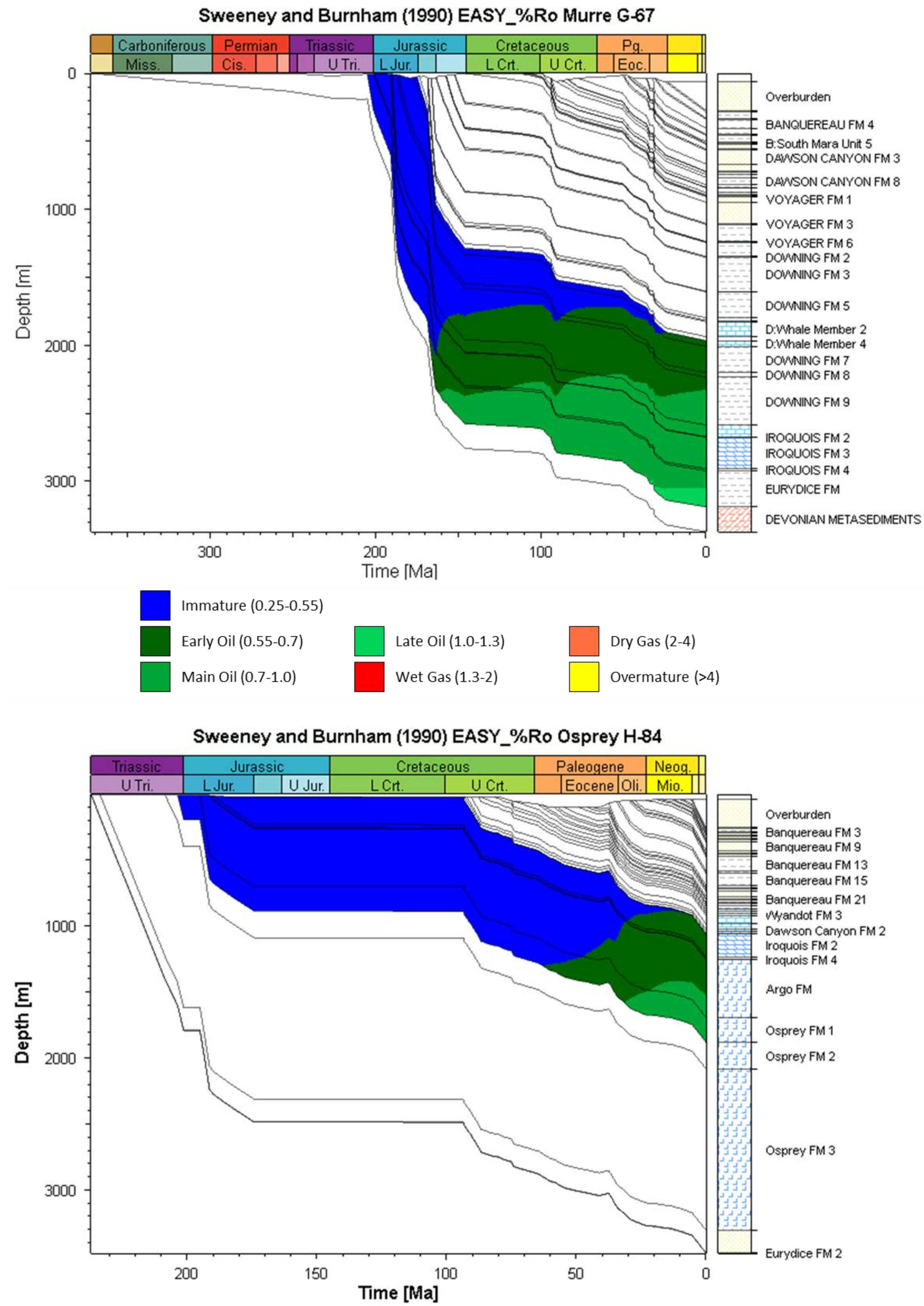


Figure 22. Burial-history curve of the Murre G-67 (Jeanne d'Arc Basin) (top) and Osprey H-84 (Carson Basin) (bottom) wells, with a maturity overlay of the Lower Jurassic interval.

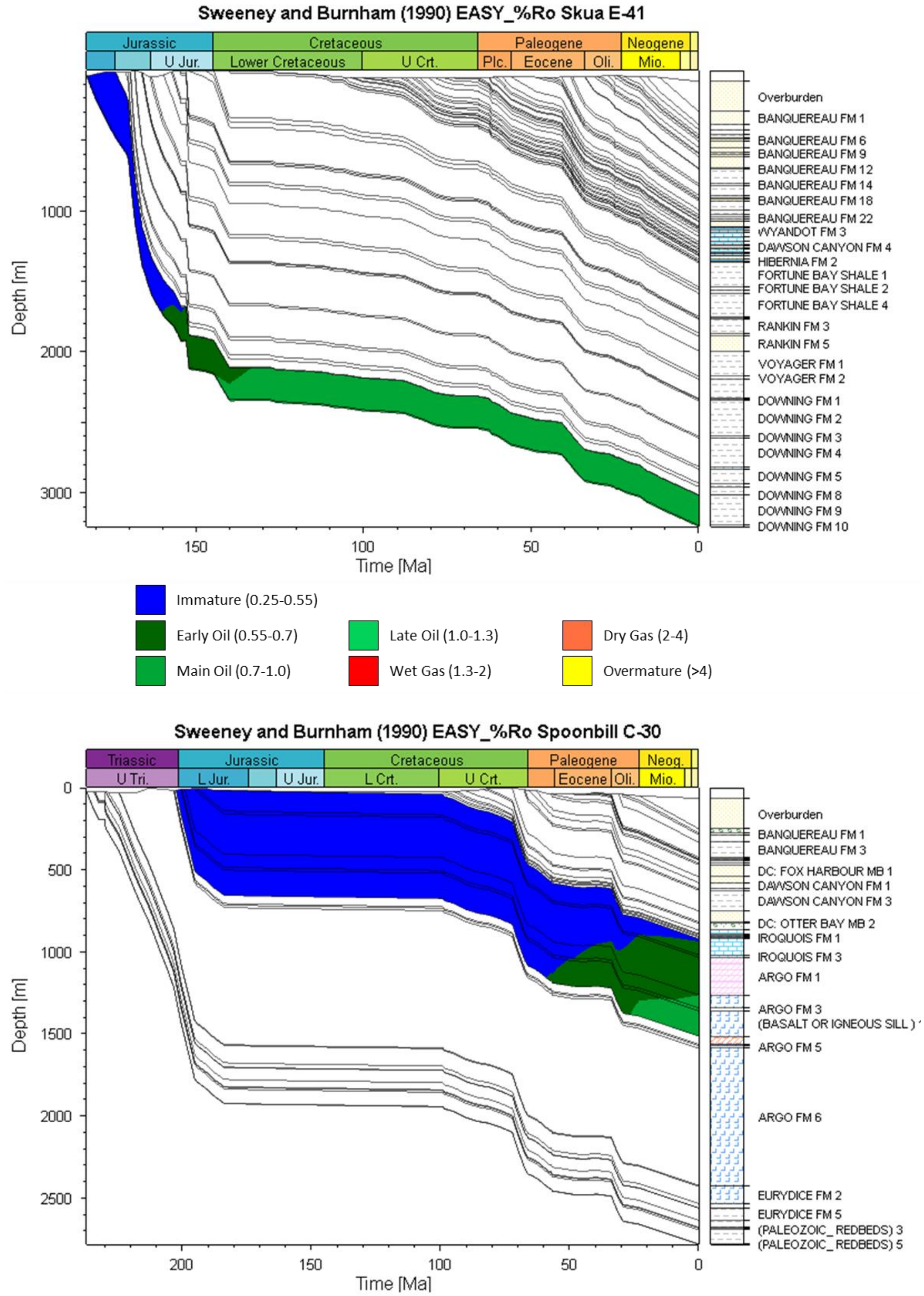


Figure 23. Burial-history curve of the Skua E-41 (top) and Spoonbill C-30 (Jeanne d'Arc Basin) (bottom) wells, with a maturity overlay of the Lower Jurassic interval

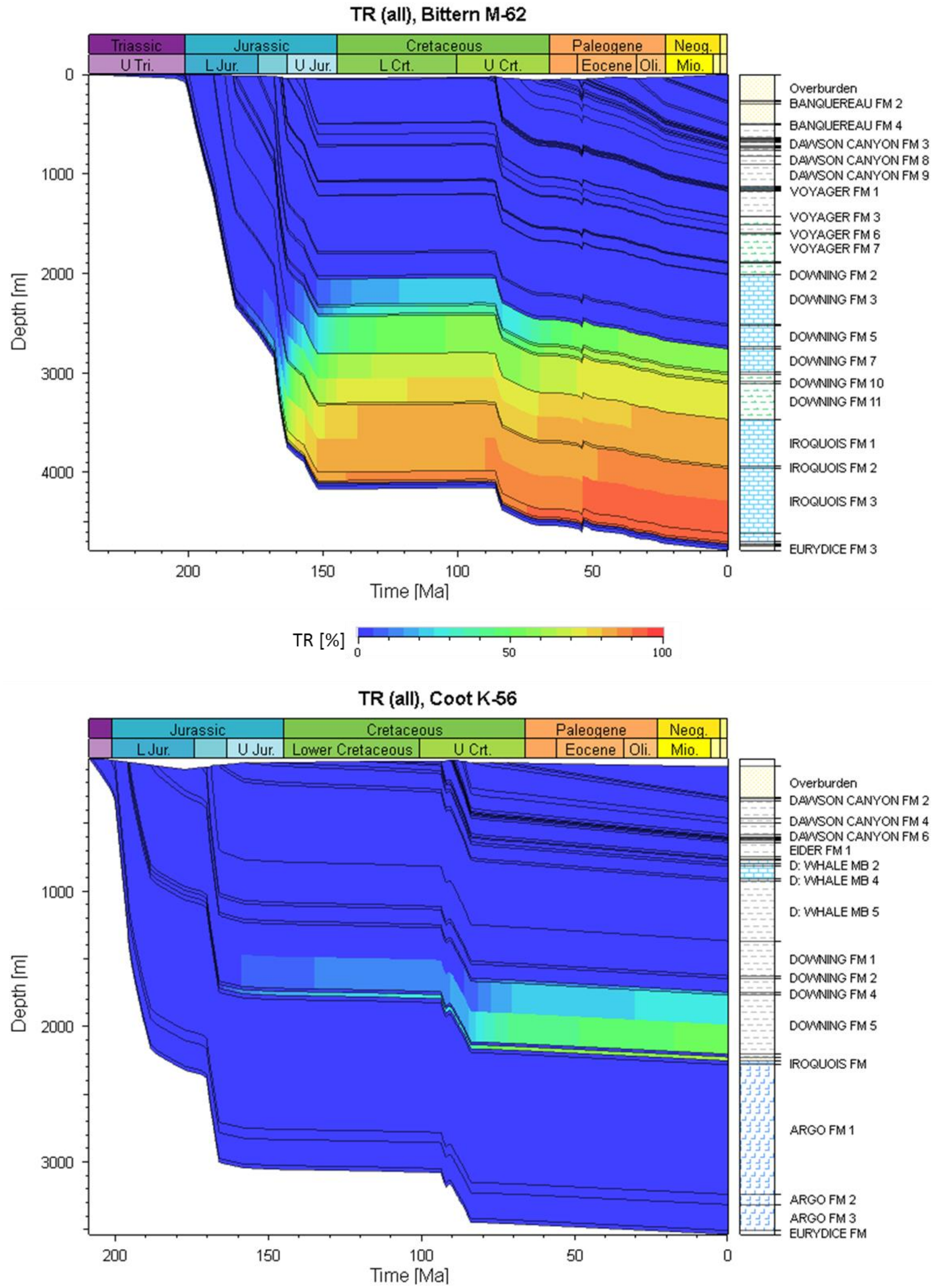
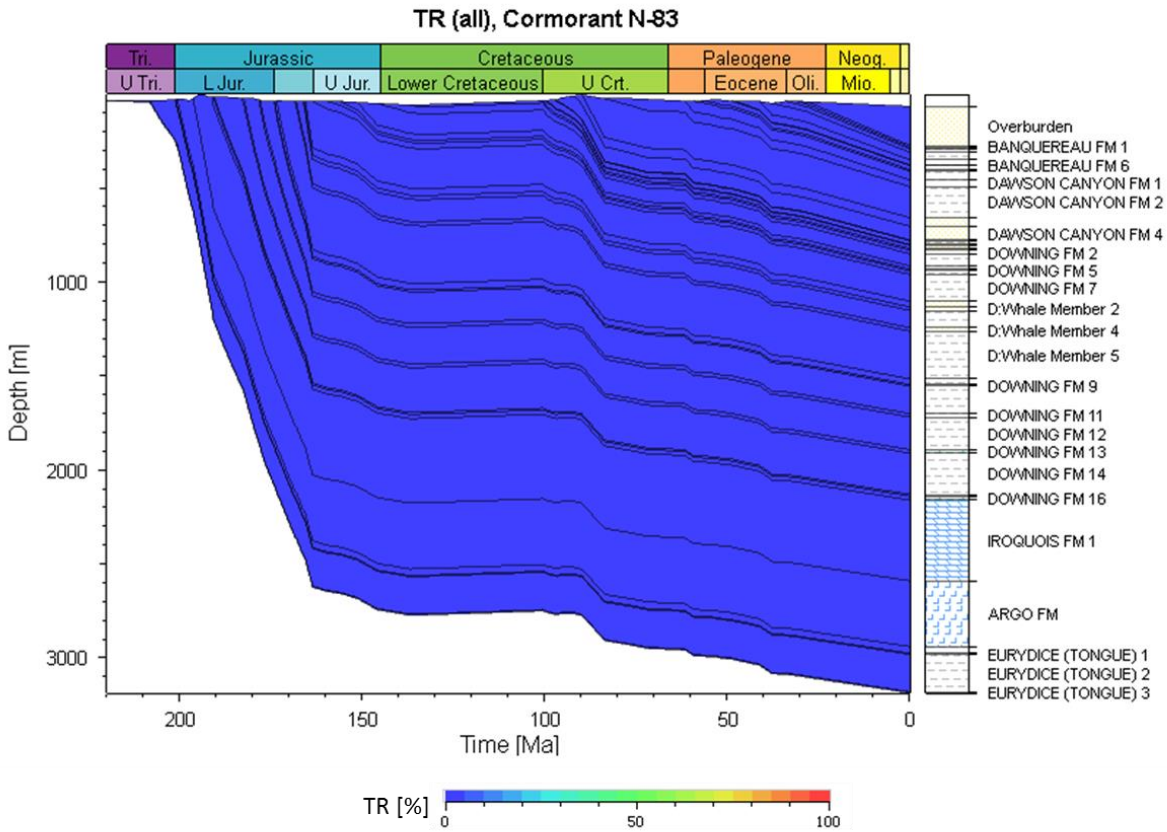


Figure 24. Burial-history curve of the Bittern M-62 (Horseshoe Basin) (top) and Coot K-56 (Whale Basin) (bottom) wells, with a transformation ratio overlay.



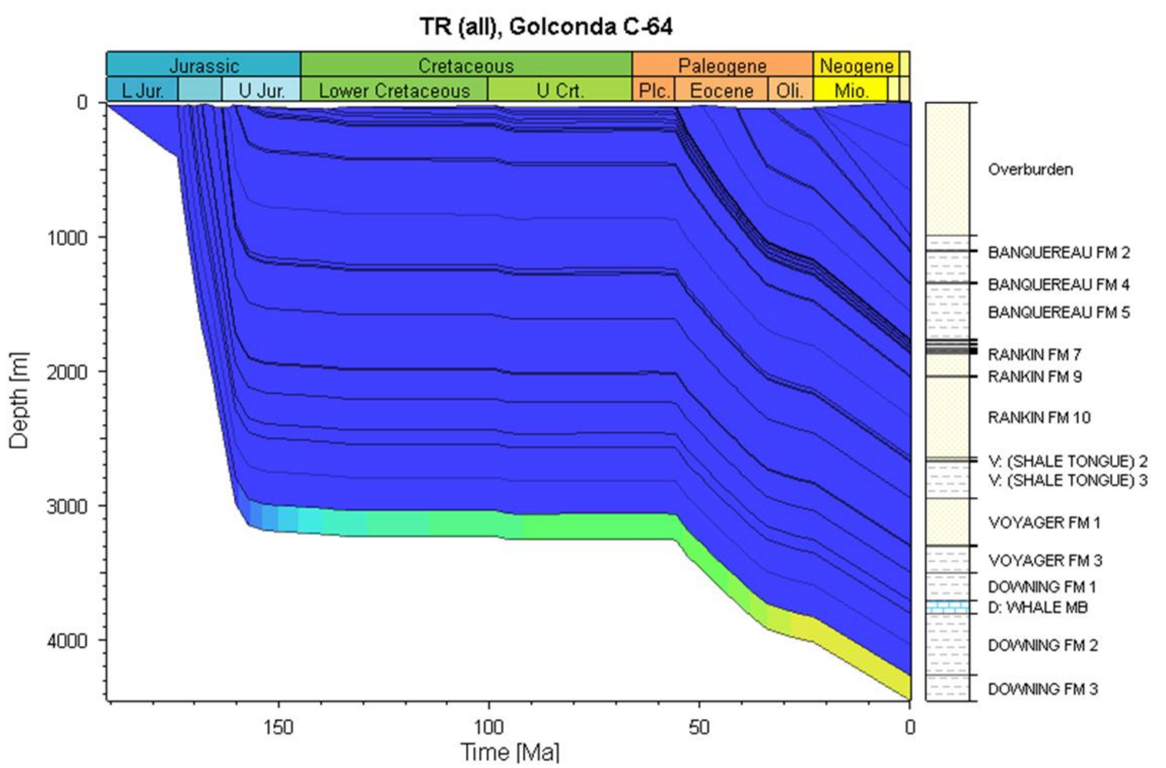


Figure 25. Burial-history curve of the Cormorant N-83 (top) and Golconda C-64 (bottom) wells, with a transformation ratio overlay.

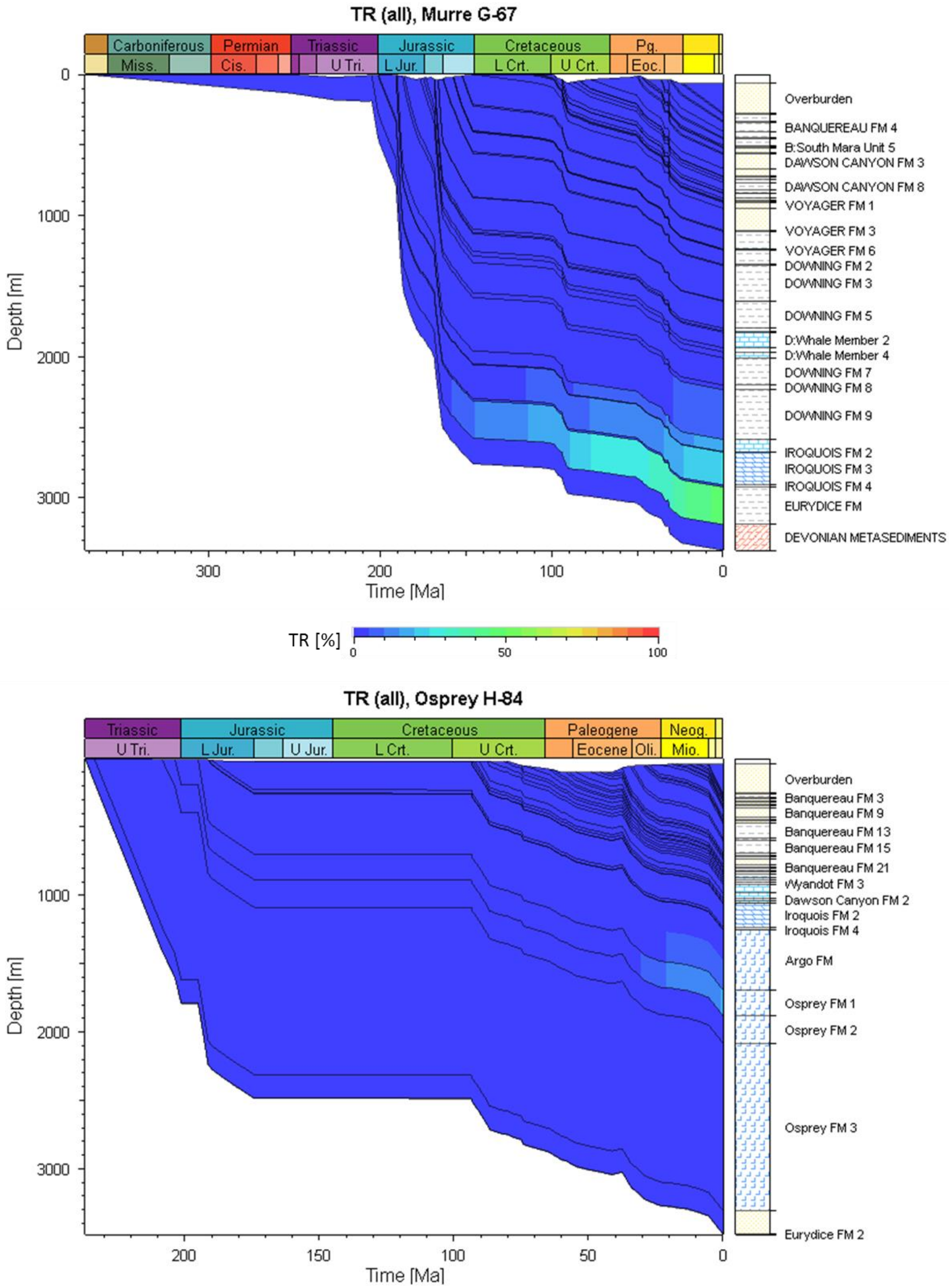


Figure 26. Burial-history curve of the Murre G-67 (Jeanne d'Arc Basin) (top) and Osprey H-84 (Carson Basin) (bottom) wells, with a transformation ratio overlay.

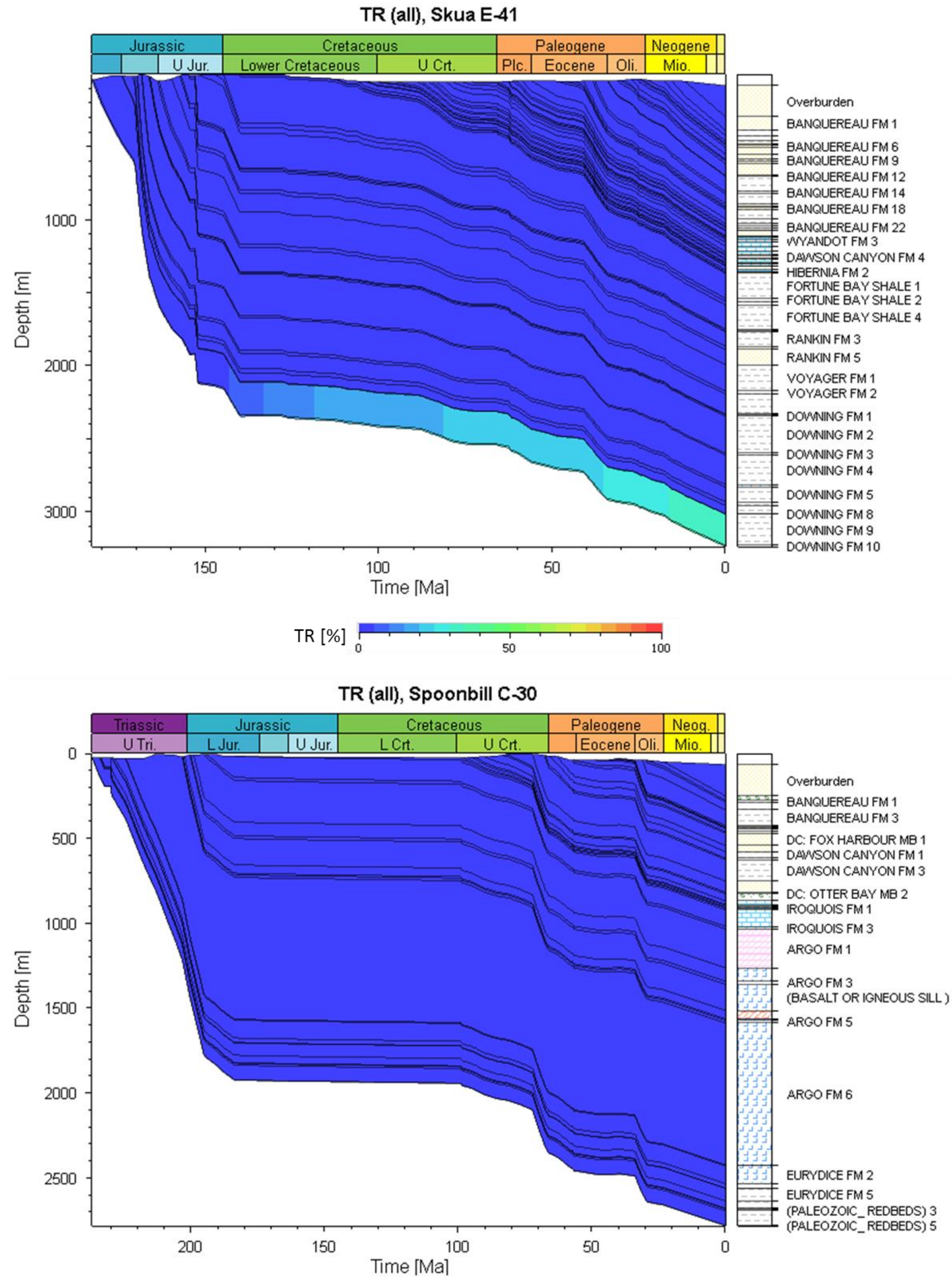


Figure 27. Burial-history curve of the Skua E-41 (top) and Spoonbill C-30 (Jeanne d'Arc Basin) (bottom) wells, with a transformation ratio overlay.

Chapter 5: Discussion

This study uses TOC values (organic matter quantity), HI data (organic matter quality), and 1D modelling (maturity assessment using burial history plots, vitrinite reflectance, and transformation ratios) to test the hypothesis for a possible Lower Jurassic source rock interval offshore Newfoundland.

5.1 Source Rock Potential – Quantity and Quality of Organic Matter

There are at least four critical considerations to detect poor-quality data in source rock studies: Flame Ion detector (FID) saturation by extraordinarily rich samples, low TOC samples, samples impacted by oil-based mud contamination (OBM), and anomalous T_{max} and %Ro estimates (e.g. Carvajal-Ortiz and Gentzis 2015).

The low TOC and the non-valid T_{max} values clearly highlight the difficulty in interpreting the obtained dataset. Due to the low TOC of the analyzed samples and the probability of contamination by minute mud drilling residues escaping the washing process (Table 2), caution is advised when interpreting these data results in absolute terms. However, the analyzed samples do not show source-rock potential (overall low TOC) for the Lower Jurassic interval with kerogen types probably corresponding to gas-prone type III – IV.

The newly obtained dataset agrees with the datasets in the BASIN Database and their geochemical reports. TOC vs Depth, and HI vs Depth plots were used to assess the source rock's quantity and quality of organic matter. Eight wells were used in this study, with five having new geochemical data from GeoMark and data sourced from the BASIN database (Figures 28 – 35). There are some wells with intervals that have fair to good TOC values (Bittern M-62, Coot K-56, Golconda C-64, and Murre G-67).

Overall, it is apparent that the studied samples do not support the hypothesis of an Early Jurassic source rock. The data from both this study and BASIN database show low TOCs and HI values that lie within the gas prone range. There are some exceptions that plot in the mixed zone. Uncertainty in the accuracy of the geochemical data, due to low TOC values, is noted by the BASIN database geochemistry references (Appendix A). The HI values and OI values, used to determine the organic matter quality, are therefore uncertain.

5.2 Maturity

5.2.1 Burial History

The burial history plots (Figures 20 – 23) offer insight into basin development offshore Newfoundland and aid in determining causes for maturation of source rock and the subsequent generation of hydrocarbons. During the Jurassic, increased subsidence rates, from both rifting and sedimentation buried sediments quickly and to great depths. Following this, most wells show a period of little to no subsidence. This is seen on the burial history plots as a near-horizontal line from the Jurassic through to the Cretaceous. This lack of subsidence indicates limited rifting and correlates to a period of slow extension in the rifting history. Understanding the subsidence history, along with geochemical analysis, allows for insight into the maturation of a potential Lower Jurassic source rock interval.

5.2.2 Heat Flow

Heat flow was modelled for eight wells and calibrated using the vitrinite reflectance values determined in multiple studies sourced from the BASIN database (Figures 20 – 23 and Figures 16 -17 respectively). The present-day heat flow values, remaining the same since 70 Ma, are lower than those found by Reiter et al. (1985). Limitations in 1-D modelling may be the cause of this underestimation of the heat flow. The vertical heat flow through the well can be modelled using 1-D modelling techniques but this method does not take the lateral heat flow into account. There are two wells with geochemistry analysis, that do not have vitrinite reflectance values to calibrate the heat flow. These wells were not modelled, as there is too much uncertainty in calibrating with another wells VR data.

Basing the general shape of the heat flow curve after the McKenzie model heat flow was successful in matching the simulated vitrinite reflectance with the measured vitrinite reflectance values. Three of the eight wells (Coot K-56, Osprey H-84, and Spoonbill C-30) have compromised vitrinite reflectance curves, as they only contain one, two and three vitrinite reflectance data points, respectively. These wells all have significant amounts of salt underlying them which may cause the high values from increased heat flow through the conductive salt.

5.2.3 Transformation Ratio

Understanding the possible generation of hydrocarbons from a modelled source rock is done using kinetics to determine the transformation ratio. When transformation ratio is higher than 20%, it is assumed that the threshold for hydrocarbons expulsion was reached (e.g. Tissot and Welte 1984). Using this criterion, Bittern M-62 (Horseshoe Basin), Golconda C-64 (Flemish Pass Basin), Murre G-67 (Jeanne d'Arc Basin) and Skua E-41 (Carson Basin) all show the possibility of generation and expulsion of hydrocarbons. Regarding the other wells, they do not reach maturity.

The determined transformation ratios and burial histories (Figures 24 – 27) indicate that the Lower Jurassic in some areas reach temperatures allowing for the generation and expulsion of hydrocarbons. This observation supports the recent modeling efforts from Nalcor Energy (2015).

5.3 Uncertainties

5.3.1 Ages

The ages of deposition in the model were determined by a method developed by trial and error. Once the biostratigraphy data and the lithostratigraphy data are combined, there are intervals with dates from the biostratigraphy analysis and there are intervals that have not been assigned an age. To determine the age of the unassigned intervals, a thickness percentage method was used. Each interval with the same age assignment was given a percentage of that age interval. From there, the percentage was multiplied by the thickness of the specific intervals to assign the percentage of the age. This was calculated and added to the previous age to build consecutive deposition ages. This method uses the biostratigraphy from the BASIN database sources, so like all the data from there, uncertainty is always present depending on the process of determining the age. The BASIN database biostratigraphy analysis references used palynology for the determination of ages. The uncertainty lies in the fact that there could have been cavings or mixing of sediment that would provide an inaccurate age. The other uncertainty in this method is that (or assumption) is that all sediments in an age range are accumulating at the same rate. Whether it is a salt or a sand, the sedimentation rate for that age interval is the same. This assumption has its flaws but it is also a simple way to estimate the ages for each interval while using the data at hand. Many studies rely on age estimations from the stratigraphic chart, meaning they are not using direct well analysis data for the ages.

5.3.2 Vitrinite Reflectance

Vitrinite reflectance has uncertainties related to both the measurement process as well as using these measurements as a control for the heat flow. Using vitrinite for the heat flow calibration results in heat flows values that only relate to the times of deposition as well as where the wells have penetrated (Baur et al. 2010). For this preliminary study, this is sufficient, as it is a good approximation of the heat flow. Using these approximations to understand the maturity of possible source rocks needs refinement for proper quantification, but acts as a starting point to understand the maturity. Vitrinite reflectance values have an error associated with them that is indicated on the plots. These accounts for minor deviations in the measurement process. During the measurement of vitrinite reflectance, the number of vitrinite particles measured can affect the value determined for a sample (Corcoran and Doré 2005).

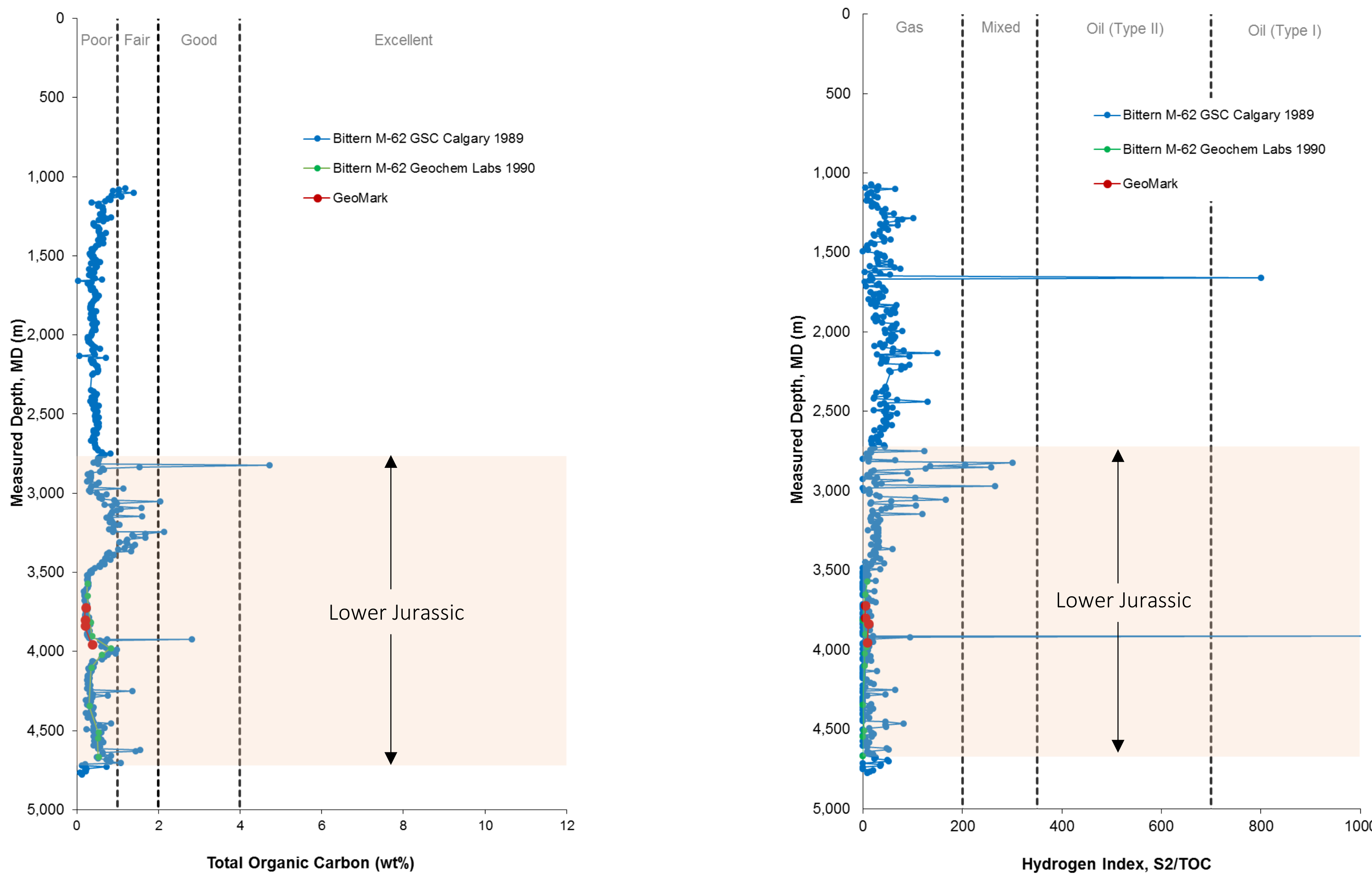


Figure 28. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Bittern M-62 (Horseshoe Basin).

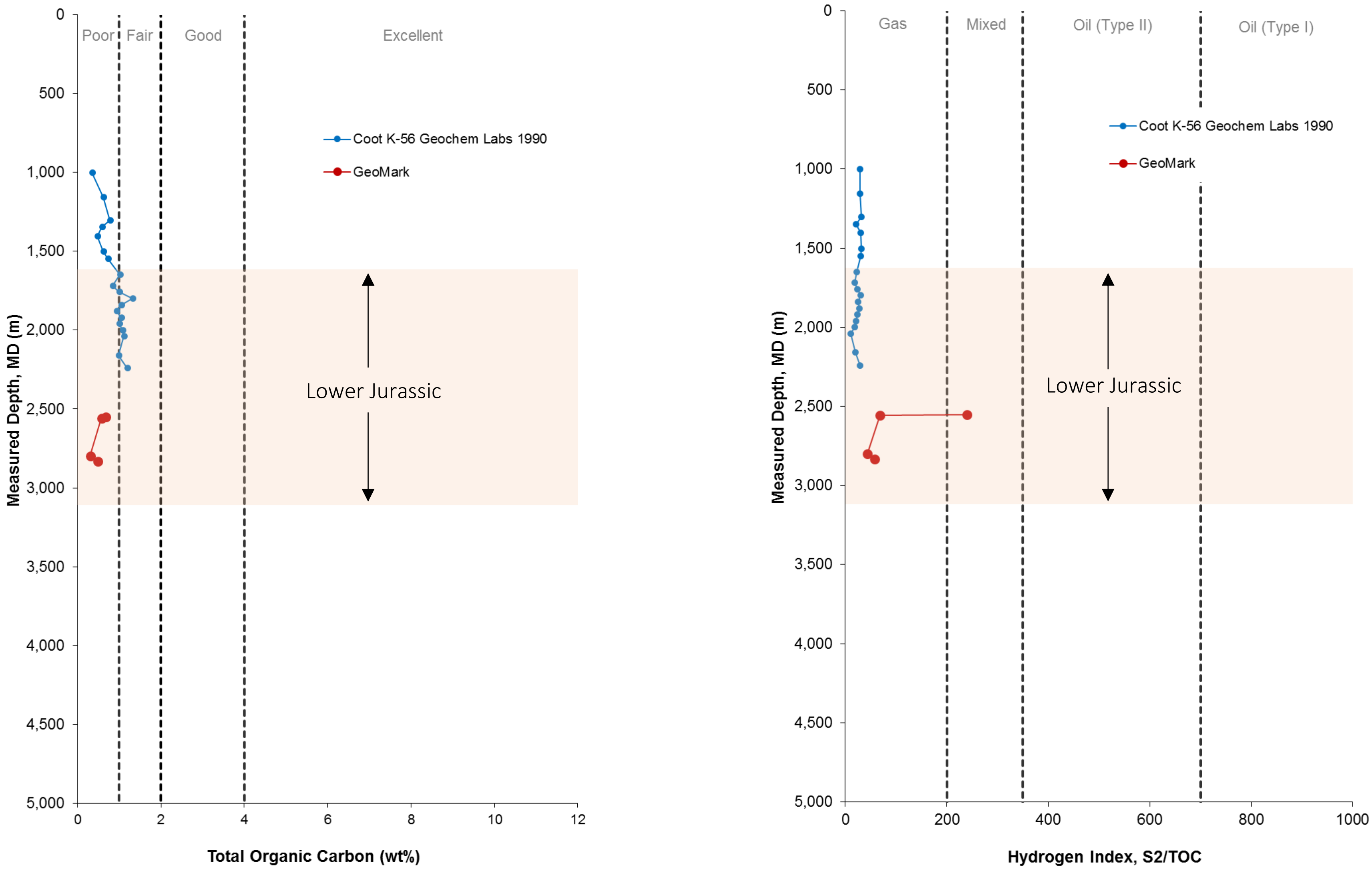


Figure 29. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Coot K-56 (Whale Basin).

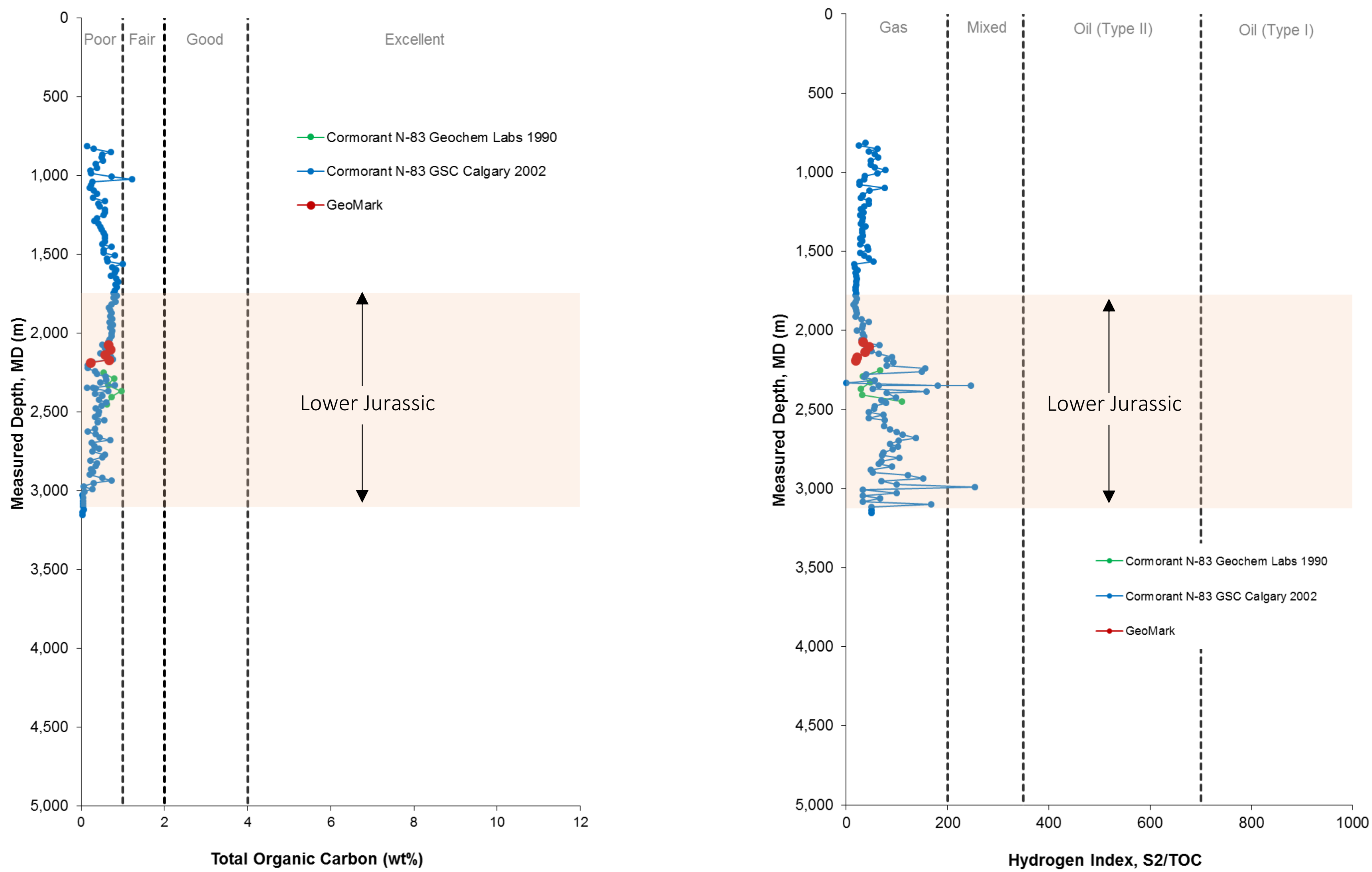


Figure 30. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Cormorant N-83 (Jeanne d'Arc Basin).

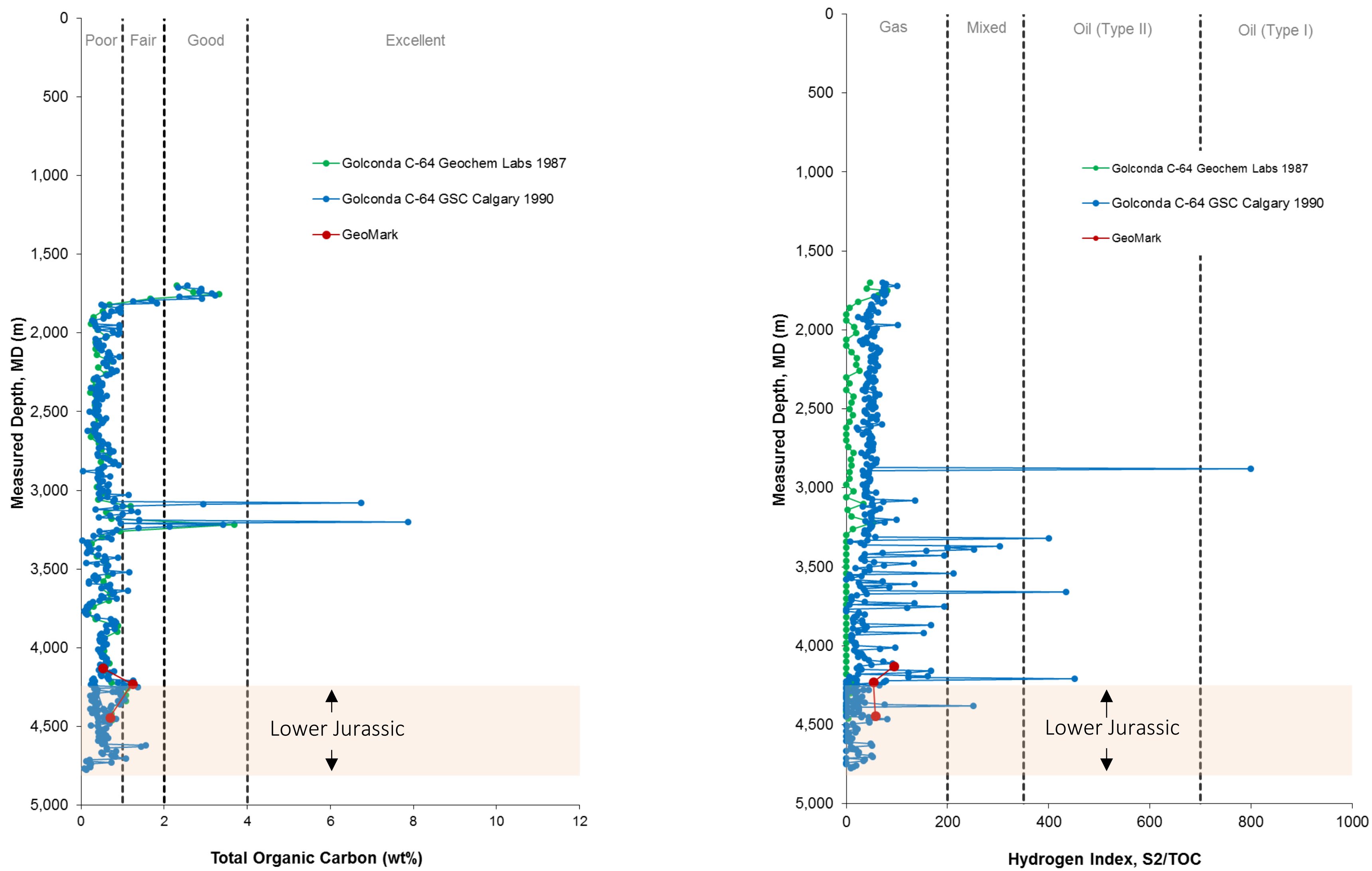


Figure 31. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Golconda C-64 (Flemish Pass Basin).

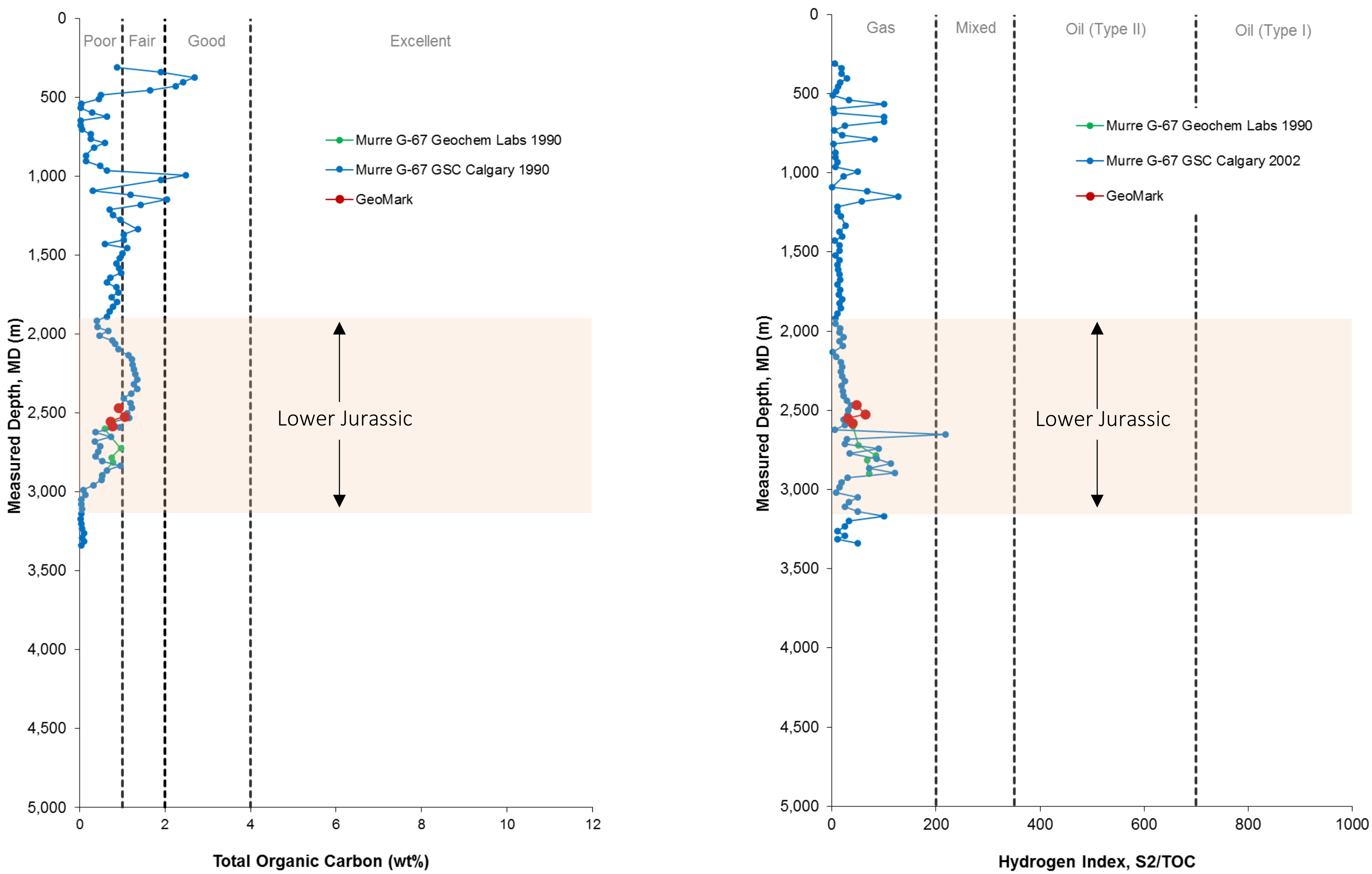


Figure 32. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Murre G-67 (Jeanne d'Arc Basin).

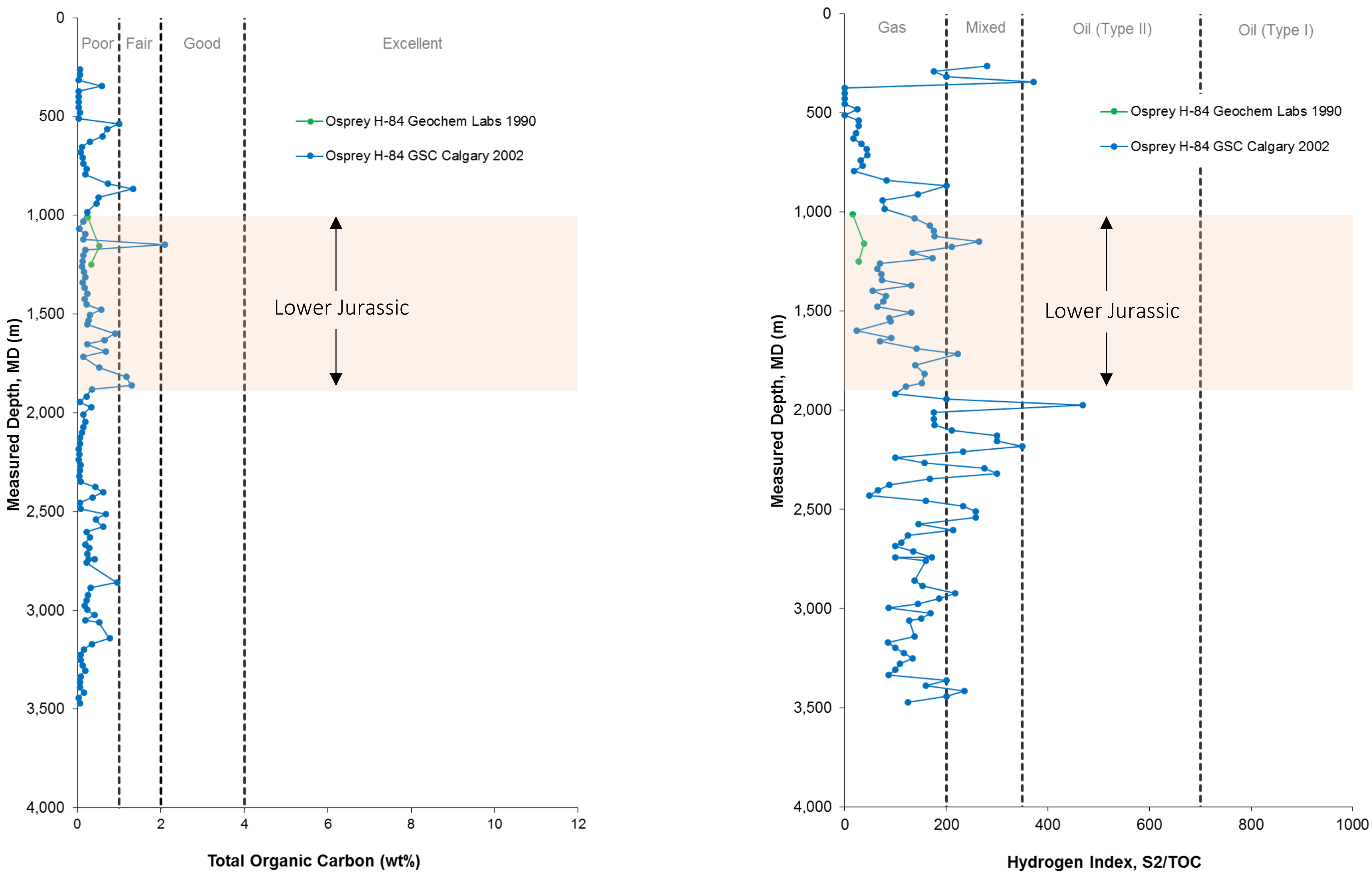
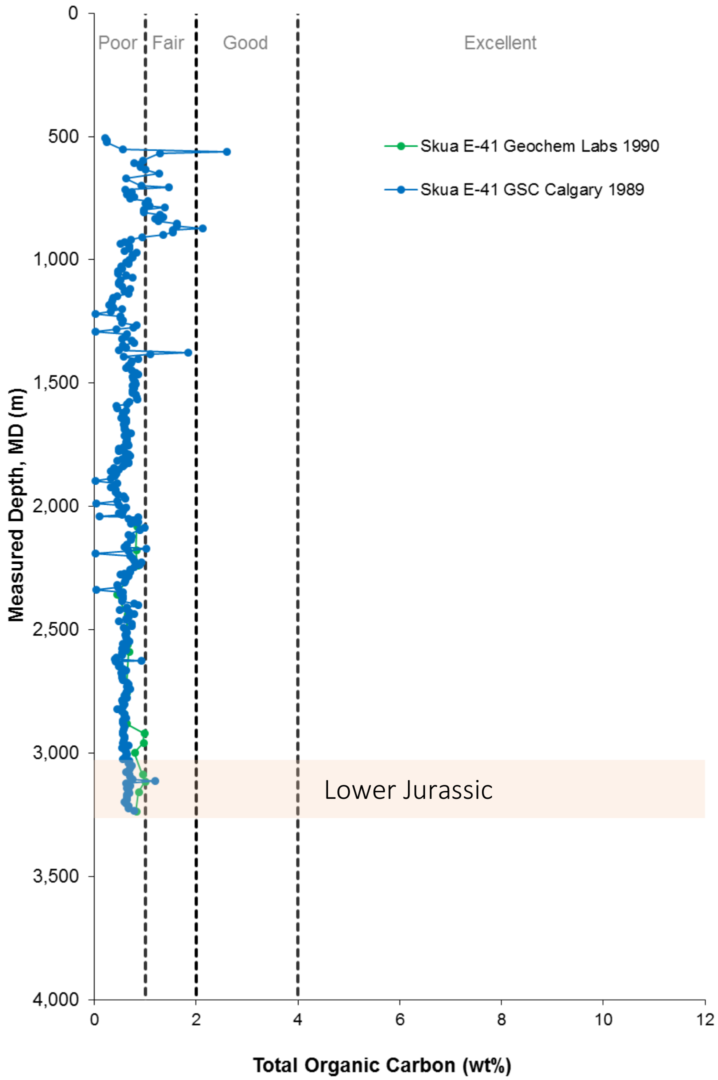


Figure 33. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Osprey H-84 (Carson Basin).



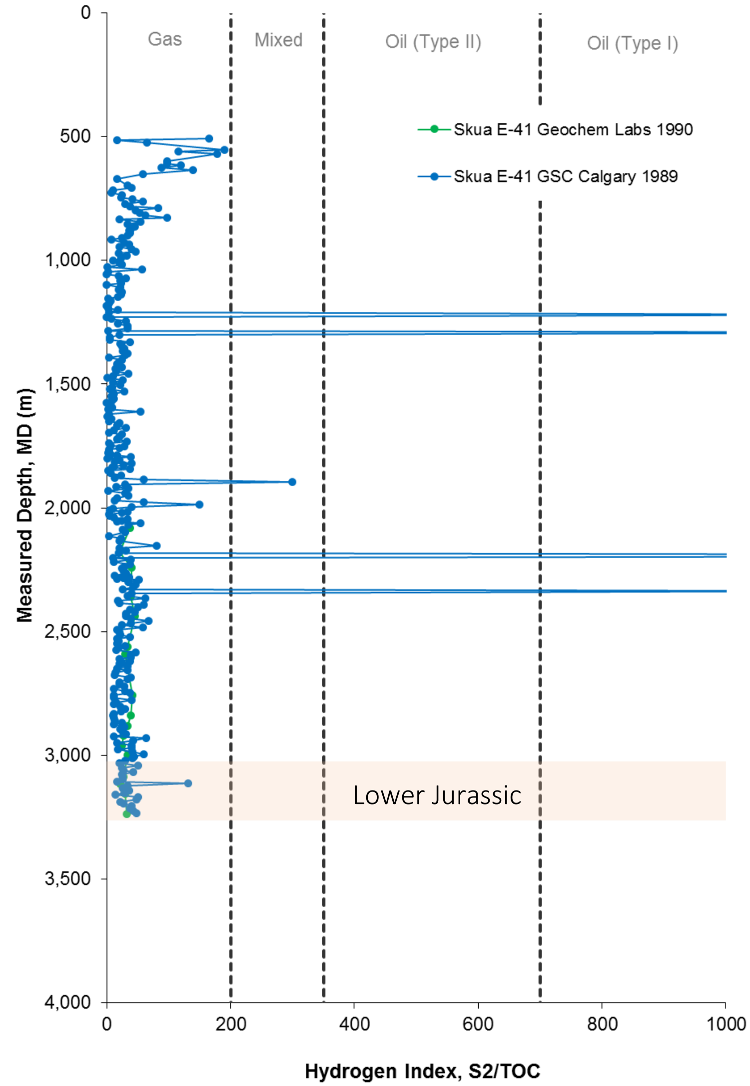


Figure 34. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Skua E-41 (Carson Basin).

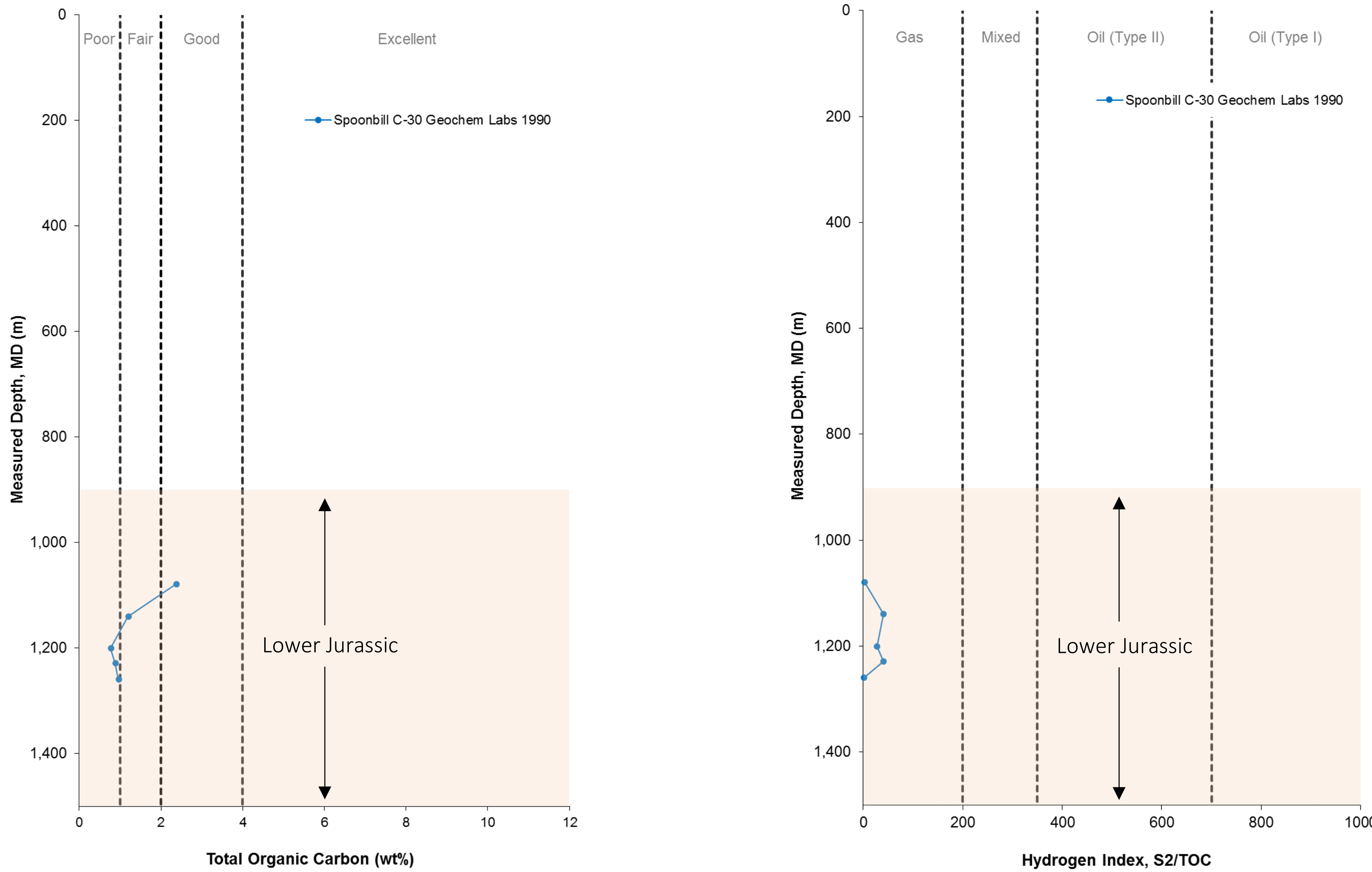


Figure 35. (Left) Total Organic Carbon (TOC wt%) and (Right) Hydrogen Index (mg HC/g TOC) values from both the BASIN database geochemistry analysis sources and results from GeoMark Laboratories Ltd. for Spoonbill C-30 (Jeanne d'Arc Basin).

Chapter 6: Conclusion

This study aimed to determine the potential of a possible Lower Jurassic source rock interval, offshore Newfoundland. A highly studied Lower Jurassic source rock interval exists onshore in the Lusitanian Basin of Portugal, which is the conjugate margin to Newfoundland. This connection, along with a highly similar stratigraphic record suggested the presence of a similar source rock interval offshore Newfoundland. Adding to the current understanding of the petroleum systems through the assessment of a source rock interval offshore Newfoundland leads to decreased exploration risk.

1-D petroleum systems modelling of eight wells was completed to determine the source rock potential of the Lower Jurassic interval offshore Newfoundland. This modelling was accompanied by additional geochemical analysis to understand the TOC and HI values of the interval. Paired with publicly available data, the source rock quantity, quality and thermal maturity was assessed.

The new geochemical dataset and our 1D models suggest that the Lower Jurassic interval in the studied wells offshore Newfoundland is not a viable and effective source rock. The thermal maturity of the Lower Jurassic interval is highly variable between basins. Further analysis is necessary to fully understand the maturation of the Lower Jurassic interval in a basin wide scale, as widely spaced well data limits the understanding of lateral maturity changes. Further investigation is needed to better understand the possibility of a Lower Jurassic source rock in offshore Newfoundland basins.

6.1 Future work

Further work is needed to fully understand the potential of a Lower Jurassic source interval offshore Newfoundland. 2-D seismic data can be used to determine the lateral maturity of a potential source rock, and is effective at connecting processes such as salt migration, and faulting with maturation. A better understanding of the heat flow, with further calibration parameters would be useful to ensure that the heat flow history is accurate through geological time. This can be done by determining pre- and post- rift crustal thicknesses. Determining erosion amounts would add to the understanding of source rock maturity, as potential uplift would affect the maturation of the source rocks.

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Appendix A

This Appendix provides the full citations of the original sources of the well, lithologic, biostratigraphic and geochemical data used in this study and presented in the BASIN database from government, industry and academic researchers and organizations: see http:///basin.dgr.nrcan.gc.ca/index_e.php.

Well Name	Data Category	Reference
Osprey H-84		
	Biostratigraphy	Williams G.L., 2006. Palynological analysis of Amoco-Imperial-Skelly Osprey H-84, Carson Basin, Grand Banks of Newfoundland. Geological Survey of Canada Open File Report 4974.
	Lithostratigraphy	McAlpine, K.D. (1988) (Data provided by author for NRC)
	Geochemistry	GSC Calgary (2002)- NO REFERENCE
		GEOCHEM Labratories, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
	Vitrinite Reflectance	GEOCHEM Labratories, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
	Well Temperature	MOIR (GSCA)
		AMOCO Canada Petroleum Company LTD
Skua E-41		
	Biostratigraphy	Williams, G.L., 2003. Palynological analysis of Amoco-Imperial-Skelly Skua E-41, Carson Basin, Grand Banks of Newfoundland. Geological Survey of Canada Open File Report 1658.
	Lithostratigraphy	McAlpine,K.D. (1988) (provided by author)
	Geochemistry	GEOCHEM Labratories, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
		Fowler, M.G., Snowdon, L.R., 1989. Rock Eval/TOC data from wells located in the southern Grand Banks and the Jeanne d'Arc Basin Offshore Newfoundland. GSC open file 2025, 20-25.
	Vitrinite Reflectance	Robertson Research (1982) Geochemical Evaluation Report. CNLOPB Reference Number: 10275
		Cooper B.S., Darlington C., Butterworth J.S., Morley R.J., Simpson W.B., Fisher M.J., 1976. A Maturation Study and Source Rock Evaluation of Four Wells Drilled on the Grand Banks, Offshore Newfoundland. Robertson Research International Limited, Report No. 2989.
	Well Temperature	MOIR (GSCA)
		AMOCO Canada Petroleum Company LTD
Bittern M-62		

	Biostratigraphy	Barss M.S., Bujak J.P., Williams G.L., 1979. Palynological zonation and correlation of sixty-seven wells, eastern Canada. Geological Survey of Canada, Paper 78-24, 47-50.
	Lithostratigraphy	CNLOPB, 2007. Schedule of Wells: Newfoundland and Labrador Offshore Area, Amoco Imperial Bittern M-62. March 14, 2007.
	Geochemistry	Fowler, M.G., Snowdon, L.R., 1989. Rock Eval/TOC data from wells located in the southern Grand Banks and the Jeanne d'Arc Basin Offshore Newfoundland. GSC open file 2025, 8-15.
		GEOCHEM Labratories, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
	Vitrinite Reflectance	Robertson Research (1982) Geochemical Evaluation Report. CNLOPB Reference Number: 10275
		GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
	Well Temperature	MOIR (GSCA)
		AMOCO Canada Petroleum Company LTD
Cormorant N-83		
	Biostratigraphy	Williams G.L., 2006. Palynological analysis of Amoco Imperial Cormorant N-83, Jeanne d'Arc Basin, Grand Banks of Newfoundland. Geological Survey of Canada. Open File Report 4973.
	Lithostratigraphy	Mcalpine K.D., 1989. Lithostratigraphy of Fifty-Nine Wells, Jeanne d'Arc Basin. Geological Survey of Canada, Open File 2201, p. 14.
	Geochemistry	GEOCHEM Labratories, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
		GSC Calgary (2002)
	Vitrinite Reflectance	Avery M.P., 2004. Vitrinite Reflectance (Ro) of Dispersed Organic Matter from Amoco-Imperial Cormorant N-83. Geological Survey of Canada Open File 4626.
		GEOCHEM Labratories, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
		Geochem Labratories, 1980. Hydrocarbon Source Facies Anlaysis. Amoco-Imperial Well History Reports.

	Well Temperature	MOIR (GSCA) AMOCO Canada Petroleum Company LTD
Murre G-67		
	Biostratigraphy	Barss, B.S., Bujak J.P., Williams G.L., 1979. Palynological zonation and correlation of sixty-seven wells, Eastern Canada. Geological Survey of Canada, Energy Mines and Resources Canada. Paper 78-24. 71-72.
	Lithostratigraphy	MCALPINE, K.D., 1990. Lithostratigraphy of fifty-nine wells, Jeanne d'Arc Basin. Geological Survey of Canada, Open File 2201. 36.
	Geochemistry	FOWLER, M.G., SNOWDON, L.R., STEWART, K.R., MCALPINE, K.D., 1990. Rock-Eval/TOC data from nine wells located offshore Newfoundland. Geological Survey of Canada, Open File 2271. 1. GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E)
	Vitrinite Reflectance	AVERY, M.P., BELL, J.S., MCALPINE, K.D., 1986. Vitrinite reflectance measurements and their implications for oil and gas exploration in the Jeanne d'Arc Basin, Grand Banks, eastern Canada. Geological Survey of Canada, Paper 86-1A, p. 489-498. GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E). HARRISON, P.H., 1984. Vitrinite reflectance (Ro) on the dispersed organics in the Amoco-IOE A-1 Murre G-67. Report No. EPGS-DOM.30-84PHH. ERVINE, W.B., 1984. Vitrinite reflectance (Ro) on the dispersed organics in Amoco A-1 Murre G-67. Report No. EPGS-DOM.13-84WBE.
	Well Temperature	MOIR (GSCA) AMOCO Canada Petroleum Company LTD
Spoonbill C-30		
	Biostratigraphy	Barss, B.S., Bujak J.P., Williams G.L. 1979. Palynological zonation and correlation of sixty-seven wells, Eastern Canada. Geological Survey of Canada, Energy Mines and Resources Canada. Paper 78-24. p. 82-84.
	Lithostratigraphy	CNLOPB, 2007. Newfoundland and Labrador Offshore Area. Schedule of Wells, Amoco Imperial Skelly, Spoonbill C-30. March 14, 2007.

	Geochemistry	GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E).
	Vitrinite Reflectance	GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E).
	Well Temperature	MOIR (GSCA)
		AMOCO Canada Petroleum Company LTD
Golconda C-64		
	Biostratigraphy	BUJAK DAVIES GROUP, 1987. Palynological Biostratigraphy of the Interval 995-4450 M, Golconda C-64, Grand Banks. GSC Open File Report 1871.
	Lithostratigraphy	CNLOPB, 2007. Newfoundland and Labrador Offshore Area. Schedule of Wells. Husky- Bow Valley et al. Golconda C-64. March 20, 2007.
	Geochemistry	FOWLER, M.G., SNOWDON, L.R., STEWART, K.R., MCALPINE, K.D., 1990. Rock-Eval/TOC data from nine wells located offshore Newfoundland. Geological Survey of Canada, Open File 2271. p. 4.
		Geochem Labratories, 1987. Husky Oil Operations Ltd.- Well History Report. Must retrieve from CNLOPB.
	Vitrinite Reflectance	AVERY, M.P., 2001. Vitrinite reflectance (Ro) of dispersed organic matter from Husky/Bow Valley et al. Golconda C-64. GSC Open File Report 4013.
		Geochem Labratories, 1987. Husky Oil Operations Ltd.- Well History Report. Must retrieve from CNLOPB.
	Well Temperature	MOIR (GSCA)
		HUSKY OIL OPERATIONS LTD
Coot K-56		
	Biostratigraphy	Barss, B.S., Bujak J.P., Williams G.L. 1979. Palynological zonation and correlation of sixty-seven wells, Eastern Canada. Geological Survey of Canada, Energy Mines and Resources Canada. Paper 78-24. p. 53-54.
	Lithostratigraphy	CNLOPB, 2007. Newfoundland and Labrador Offshore Area. Schedule of Wells. Amoco Imperial Skelly, Coot K-56. March 14, 2007.

Geochemistry	GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E).
Vitrinite Reflectance	GEOCHEM LABORATORIES, 1990. East Newfoundland Basin Regional Study. Geochem Laboratories Limited, Calgary. (C-NOPB File Number 8933-G018-001E).
Well Temperature	MOIR (GSCA)
	AMOCO Canada Petroleum Company LTD