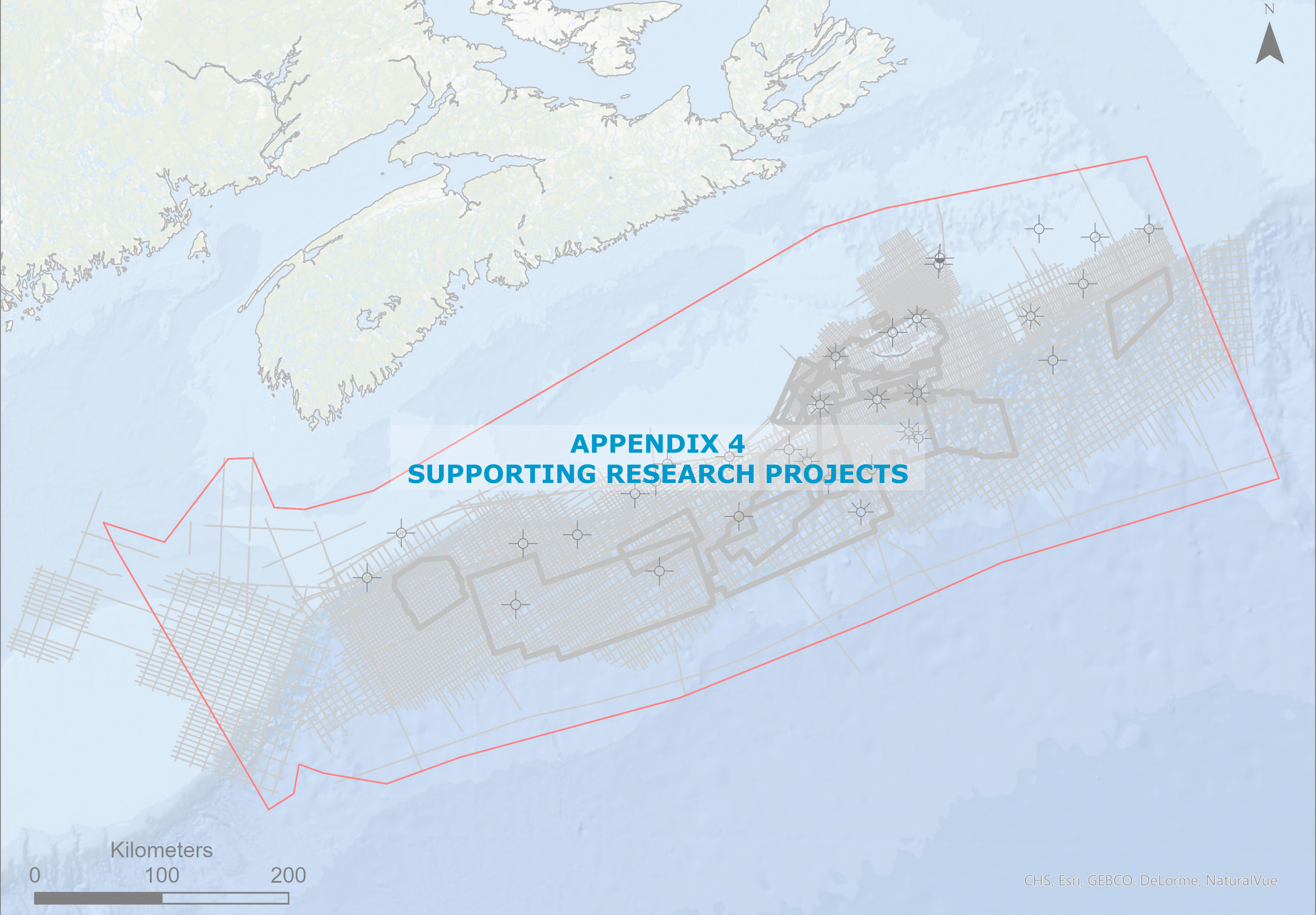
APPENDIX 4
SUPPORTING RESEARCH PROJECTS



CHS, Esri, GEBCO, DeLorme, NaturalVue

HYDROCARBON MIGRATION MAPPING

Natasha MacAdam

Shallow migration pathway indicators and seismic anomalies can provide support for hydrocarbon migration from candidate source kitchens through deepwater stratigraphy into potential shallow traps and seafloor seeps. New seismic analysis from 3D surveys along the Scotian Slope show clear indications of acoustic anomalies including bright spots and gas chimneys which can be linked to salt structures, faults, and fluid migration pathways. In some cases, the interpreted seismic anomalies are associated with areas where geochemical analysis of piston cores has shown evidence for thermogenic hydrocarbons. The mapping of these potential pathways aimed to provide corroborating evidence of Lower Jurassic source rock presence in offshore Nova Scotia.

Project Summary

Task 1 of this project examined nine 3D seismic surveys along the Scotian Slope to attempt to identify seafloor hydrocarbon pipes, gas chimneys, and other notable seismic acoustic anomalies. The interpretation focused primarily on shallow, Cenozoic sediments. Please note the Stonehouse 3D survey was considered however deemed to be outside the range of maturity for a potential Lower Jurassic Source Rock. Surveys included in this study were:

Database

Seismic Database

1. NS24-P003-004E - Barrington 3D
2. NS24-B071-001E – Tangier 3D
3. NS24-S006-003E- Shelburne 3D
4. NS24-G005-008P – Mamou 3D
5. NS24-P003-002E - Torbrook 3D
6. NS24-P003-004E - Weymouth 3D
7. NS24-S006-001E,002E - Thrumcap 3D
8. NS24-V003-002P,003P,004P - Veritas 3D
9. NS24-M055-001E, NS24-V003-002P,003P,004P – Marathon 3D

Well data

- Hydrocarbon Shows
- Geochemical studies

Seabed Coring Geochemistry (drop coring, piston coring, push coring)

- 2015 – 25 piston cores tested
- 2016 – 42 piston cores tested
- 2018 – 10 gravity cores tested
- 2021 – 89 push cores tested

AUV Sensor Data

- Multibeam Bathymetry (MBES)
- Side Scan Sonar
- Backscatter Imagery
- Sub-bottom Profile Shallow Seismic

Genomic Evidence

- Thermospore, dipicolinic acid, archaeal, etc.

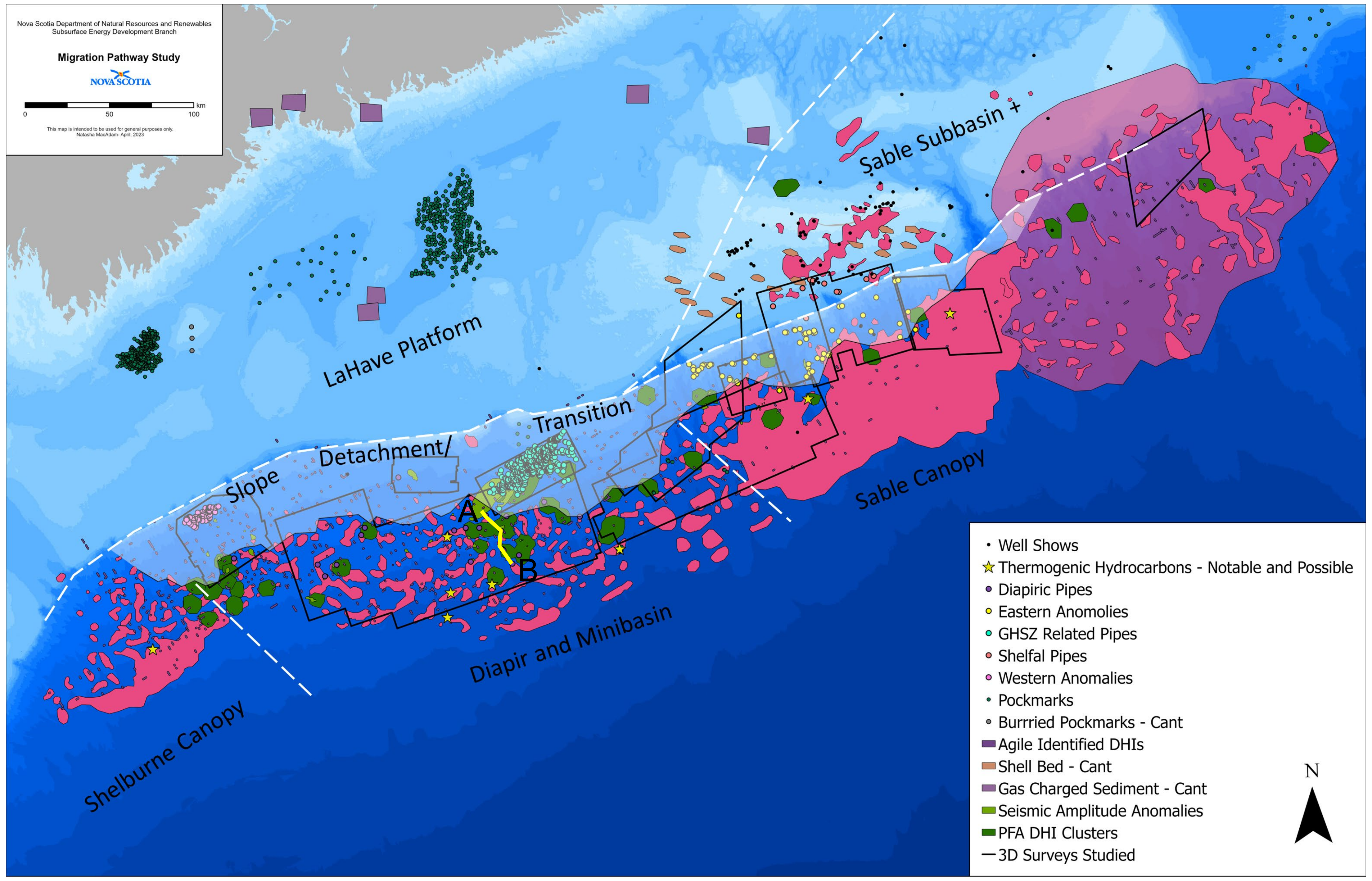
ROV Imagery

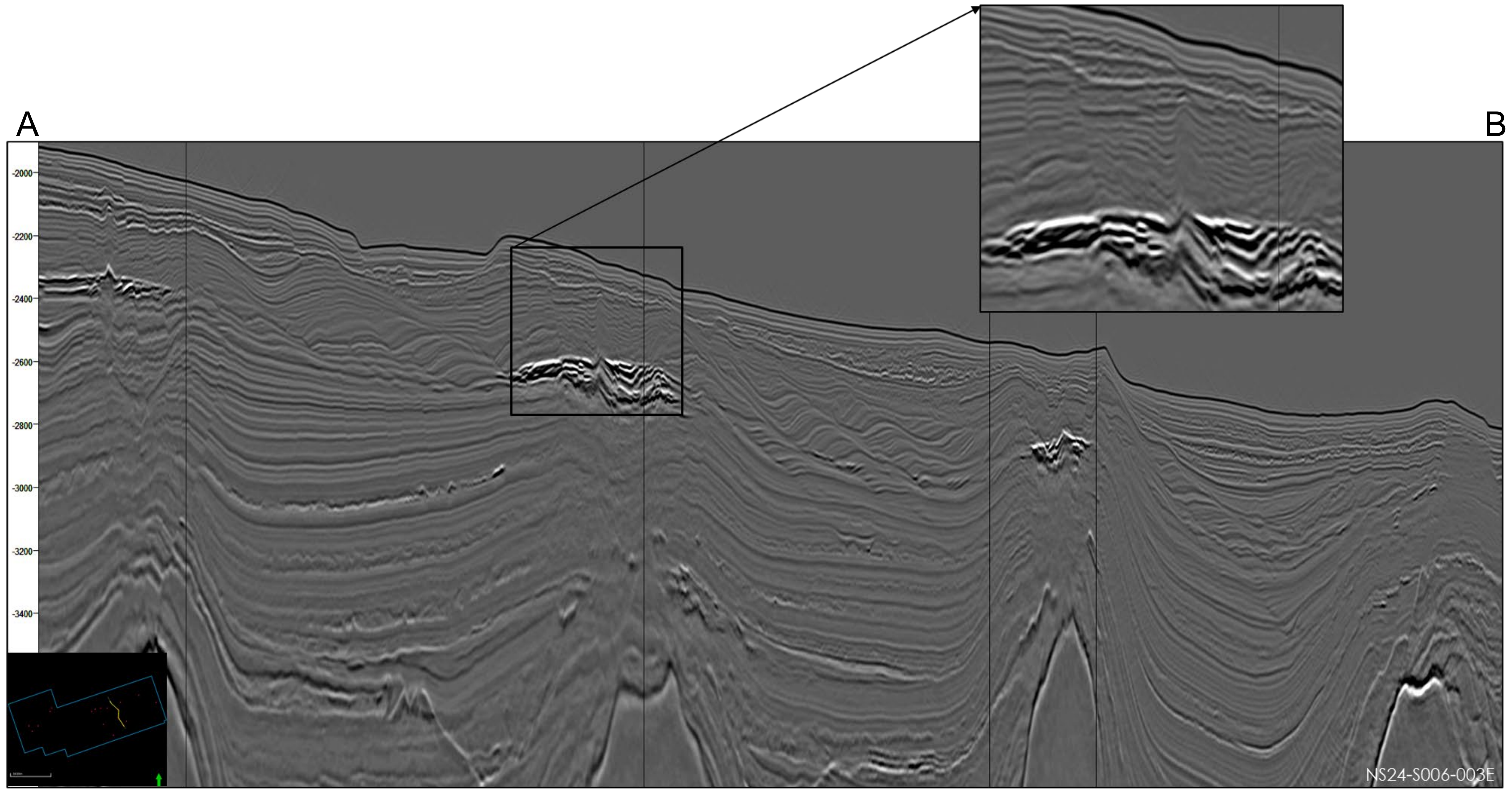
- HD Video, SD Video, Stills

This new seismic analysis was then integrated with complementary legacy datasets along the margin. This includes a multi-year, Nova Scotia Department of Natural Resources and Renewables (NSNRR) dataset acquired by piston coring, AUV multibeam surveying, and ROV direct sampling methods through a collaborative partnership with Saint Mary's University, University of Calgary, Genome Atlantic/Genome Alberta, Applied Petroleum Technology, Natural Resources Canada, and additional researchers. Documented geochemical signatures from samples collected are consistent with the presence of thermogenic oil, gas, and light hydrocarbons along the Scotian Slope. New bioassays based on sediment microbial genomics also support this interpretation.

Additional evidence from Hall and Bianco's (2016) direct hydrocarbon indicator (DHI) mapping of 2D seismic data in offshore Nova Scotia provided further deeper evidence to support new findings. Other legacy datasets such as mapped pockmarks and shallow hydrocarbon indicators, DHI clusters, and seafloor lithologies were digitized and also incorporated into the findings (e.g. King and MacLean, 1970; Cant, 1991; Beicip-Franlab, 2011).

Task 2 examined deeper seated migration pathway mapping in key areas identified during Task 1. This task has two main components; (1) examining the key areas seismically with the use of opacity controls to visualize potential pathways, and (2) integrating results of Task 1 with legacy drainage maps created in the 2011 Play Fairway Analysis (Beicip-Franlab, 2011).





Regional Reservoir-Aquifer Mapping

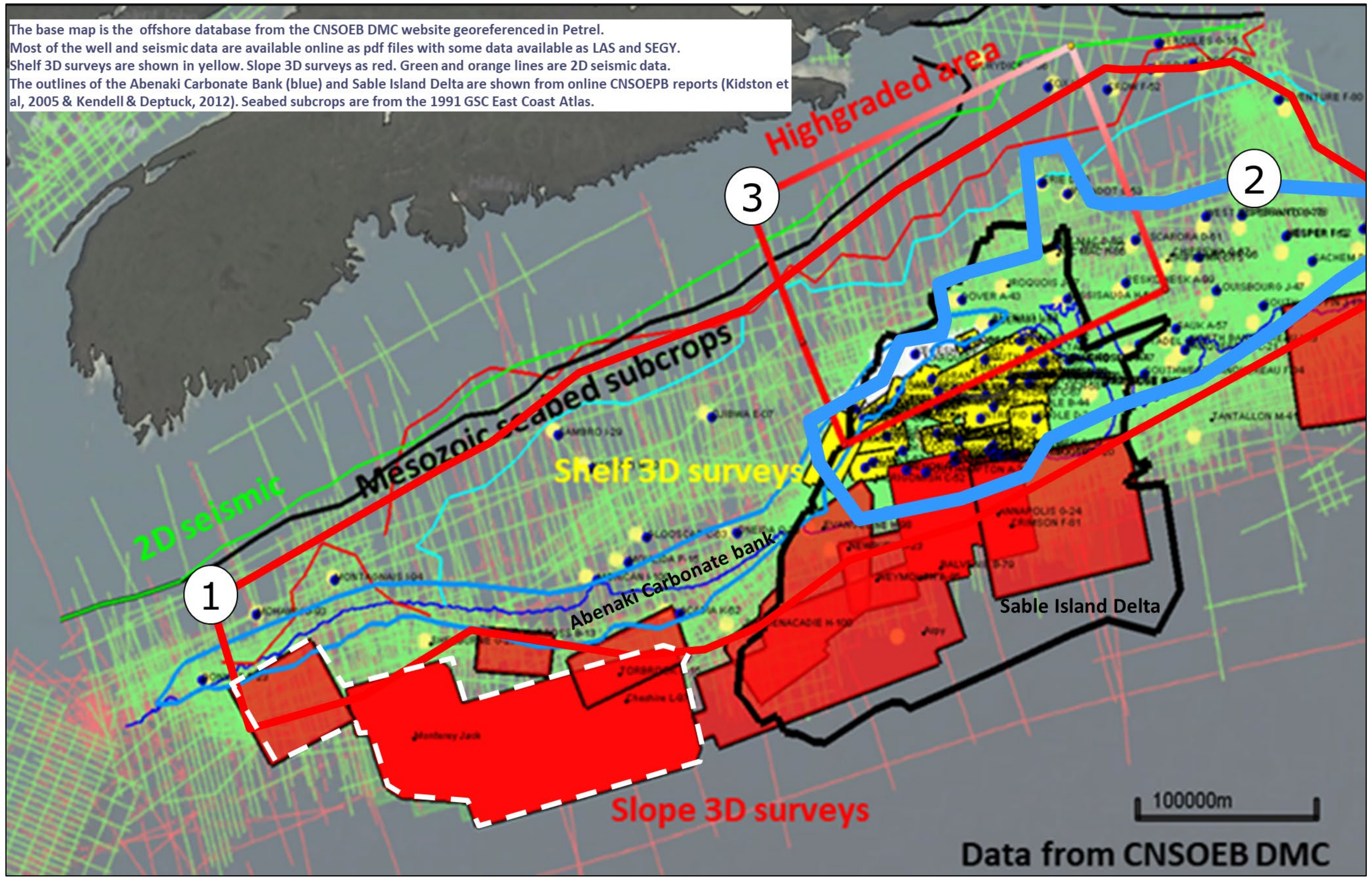
Xiochun Cen and Bill Richards

A summary of results of three projects at the NS DNRR, all of which involve quantitative evaluation of reservoir - aquifer quality on the Scotian Shelf, are presented here.

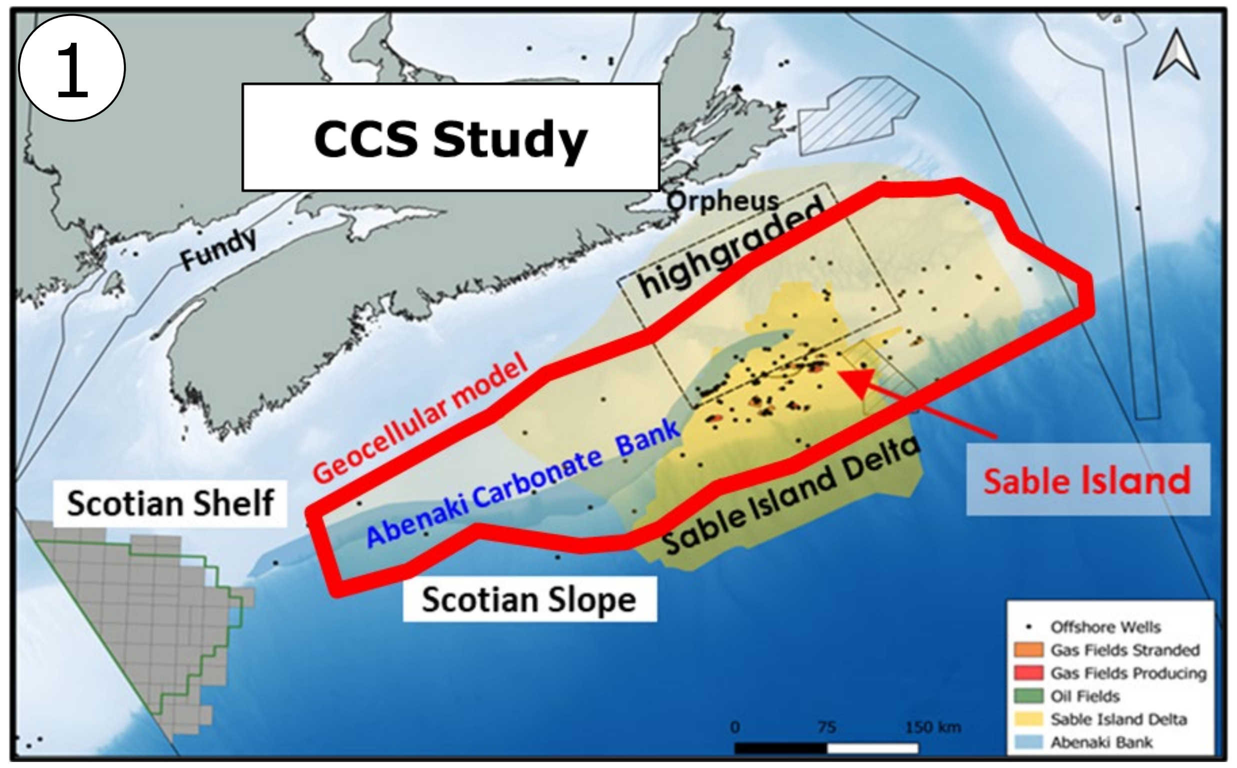
1. **Regional mapping of Carbon storage potential in deep saline aquifers (Richards & Cen, 2021; NS DNRR)**
    - The regional framework for this project was built using seismic horizons from the 2011 Play Fairway Analysis augmented with updip structure (approaching Mesozoic near-seabed sub-crops) from the 1991 GSC East Coast atlas. Faults were not necessary for regional-scale static assessment of CCS potential.
    - Sonic porosities with Vshale cutoffs were calculated in ~ 80 wells (of the 210 on the margin) and propagated shelf-wide using several algorithms in Petrel.
    - Three regional porosity-meter maps are presented here, reflecting sediment supply, principally via the Sable Island Delta.
    - A key issue in this project (and the second project) was deciding on how the stratigraphic section should be divided for quantitative purposes. For CCS, we used 2011 PFA seismic horizons – which are only precisely tied to a small number of wells – adjusted to our best estimates of well-to-well correlations: K94-K125-J150-J163.
    - The results of this project – a world-class storage resource, with the groundwork for a state-of-the-art CCS atlas – were presented at the April 19-20 2023 Carbon Neutrality Forum at Dalhousie University.
    - They also formed the basis for the 2021 EAGE Minus CO2 Student Challenge and are documented in the April, 2022 edition of First Break magazine.

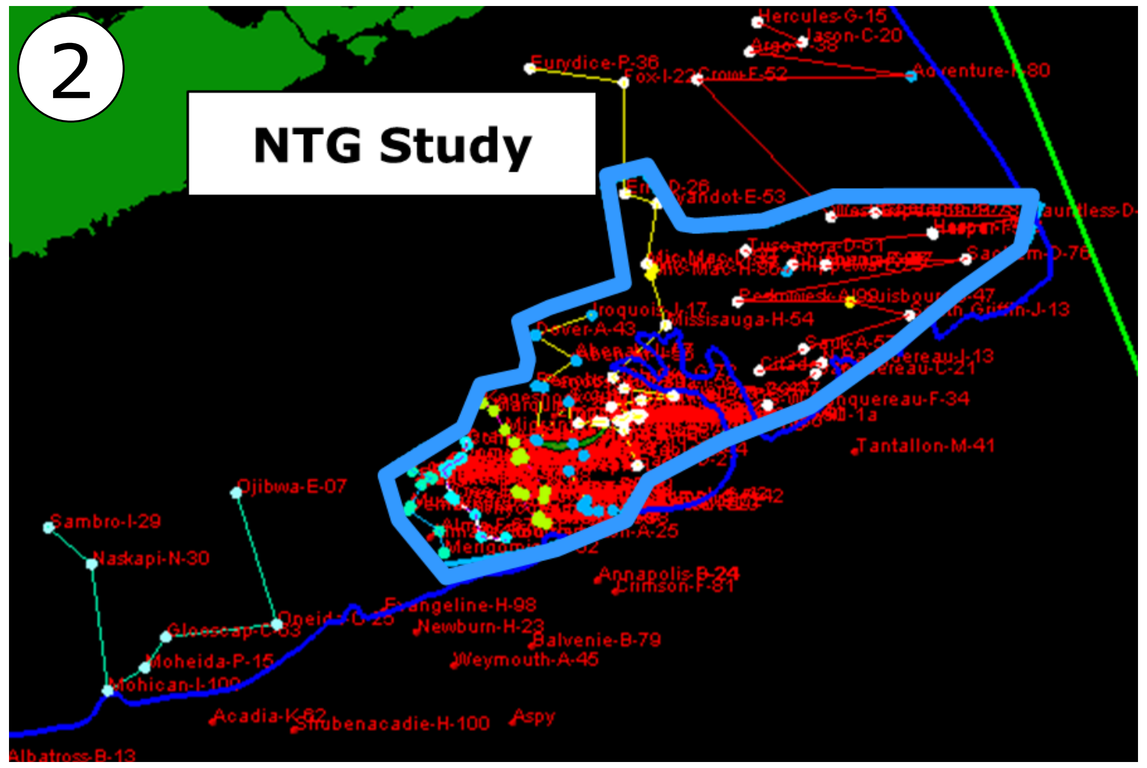
2. **NTG estimation and mapping in the Sable Island Delta core commercial area (Richards & Cen, 2022; NS DNRR)**
    - This project was proposed as extension of the CCS project. The objective was to systematically generate an Excel spreadsheet of NTG ratios (Appendix X) at many of the Scotian Shelf wells.
    - We established a workflow using the well log calculator in Petrel that can be iterated for differing stratigraphic picks, porosity calculations or Vshale cutoffs – and could be extended to more wells as digits become available or as required.
    - Again, a key consideration was stratigraphic picks, with thousands of interpretations in the GSC BASIN DATA BASE.
    - We used a consistent suite of litho-stratigraphic picks by Rob Fensome from the 2011 PFA with our best estimates of further correlations and minor adjustments.

3. **Besides mapping and quantification of reservoirs/ aquifers in the core commercial area on the Scotian Shelf, these studies also highlight an area updip on the regional monocline suitable for further study.**
    - This area includes and is updip of the optimum locations for Carbon storage but is data poor (sparse wells and old 2D seismic) and is also light oil-prone (oil at Panuke-Cohasset, Penobscot and West Sable).
    - These fields are probably Tithonian sourced but there is evidence of a deeper HC system in the underlying Abenaki subbasin.
    - It is suggested here that this high-graded area should be considered for further study: for potential monitoring of CCS plumes approaching the regional subcrop, and for small but potentially abundant stratigraphic oil traps: analogous to Mannville channels in Alberta; or even possibly a large biogenic subcrop trap reminiscent of the Athabasca anticline or Kern River Field in California.



The base map is the offshore database from the CNSOEB DMC website georeferenced in Petrel. Most of the well and seismic data are available online as pdf files with some data available as LAS and SEGY. Shelf 3D surveys are shown in yellow. Slope 3D surveys as red. Green and orange lines are 2D seismic data. The outlines of the Abenaki Carbonate Bank (blue) and Sable Island Delta are shown from online CNSOEPB reports (Kidston et al, 2005 & Kendell & Deptuck, 2012). Seabed subcrop are from the 1991 GSC East Coast Atlas.



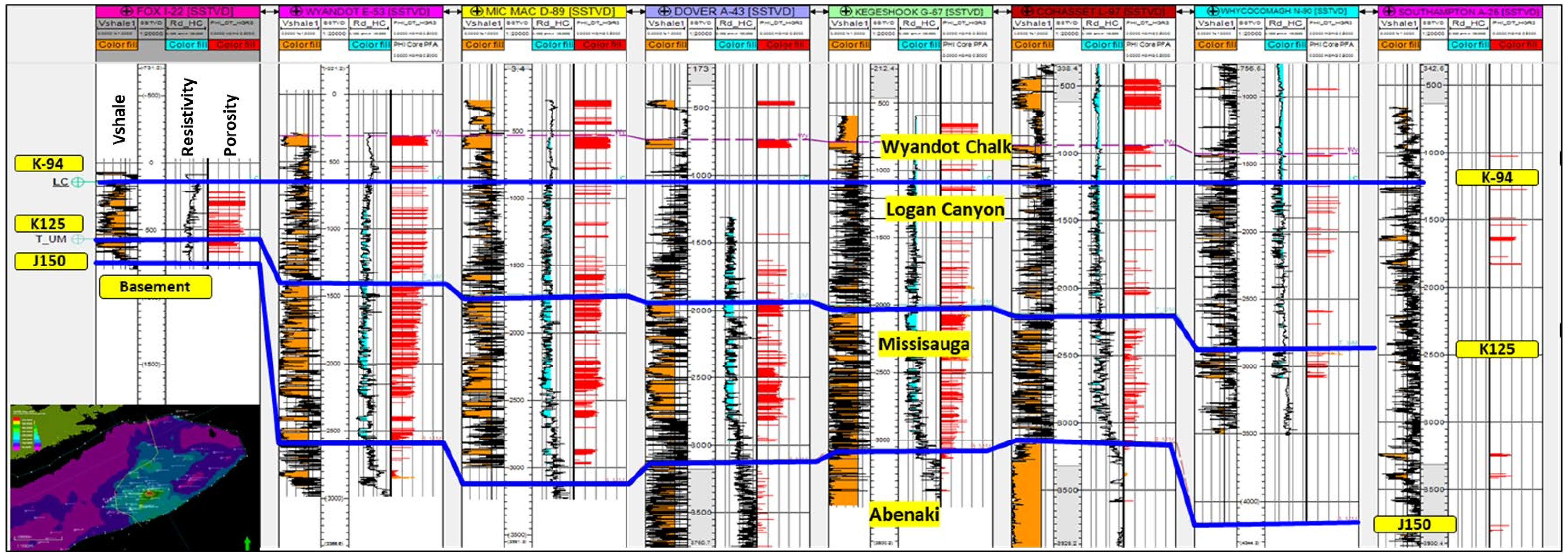


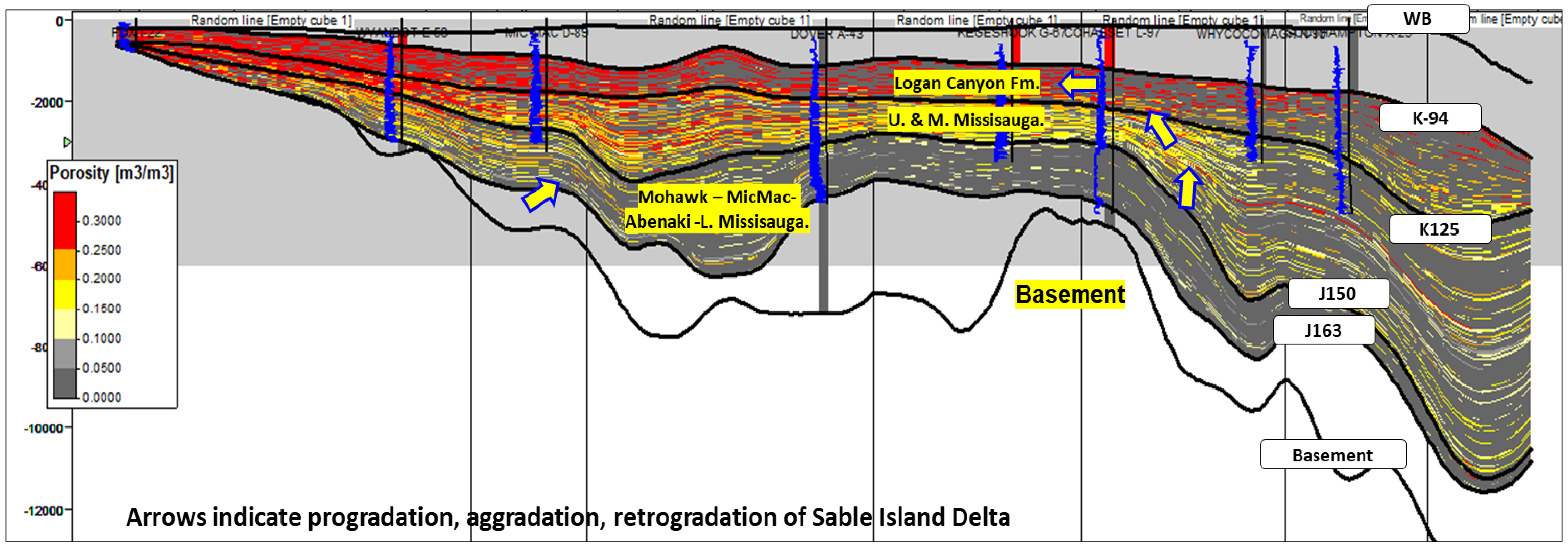
Regional Reservoir-Aquifer Quality Mapping on the Scotian Shelf – NTG Study

Appendix 4

Carbon Capture and Storage Study

These images represent porosity-meter maps produced in the 2020 Carbon Capture and Storage Project. Intervals were based on 2011 PFA horizons online & 1991 GSC East Coast Atlas. The carbon storage capacity was then calculated using a range of sonic porosities, Vshale cutoffs and storage efficiency factors from published CCS atlases in North America and Europe. The result was that the Deep Saline Aquifers on the Scotian Shelf have world-class storage potential as identified in the 2005 IPCC Special Report.



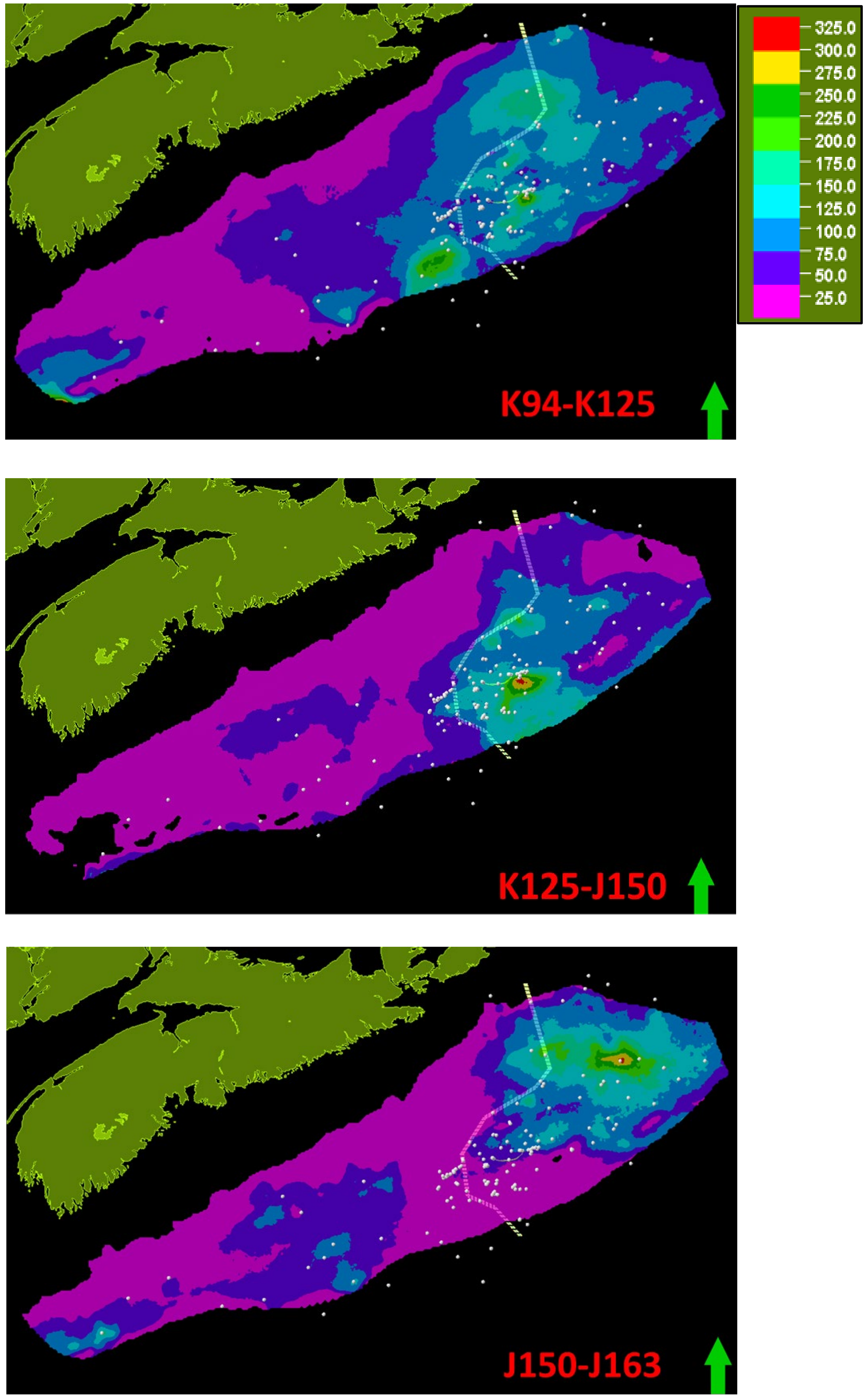


Arrows indicate progradation, aggradation, retrogradation of Sable Island Delta

Algorithm	Storage Efficiency	Low Vsh<30%	Med Vsh<50%	High Vsh< 70%
Moving Average	E=5%	77	250	588
	E=3%	46	150	353
	E=1%	15	50	118
SGS	E=5%	125	257	483
100km, 200km, 10m	E=3%	75	154	290
72 degrees	E=1%	25	51	97
SGS	E=5%	187	353	618
640km, 400km, 30m	E=3%	112	212	371
72 degrees	E=1%	37	71	124

Storage Capacity (Gt) with a range of algorithms, storage efficiencies & Vshale parameters

Depth Range 800-4000m subsea; Phi cut off 10% ; Density 700kg/m^3



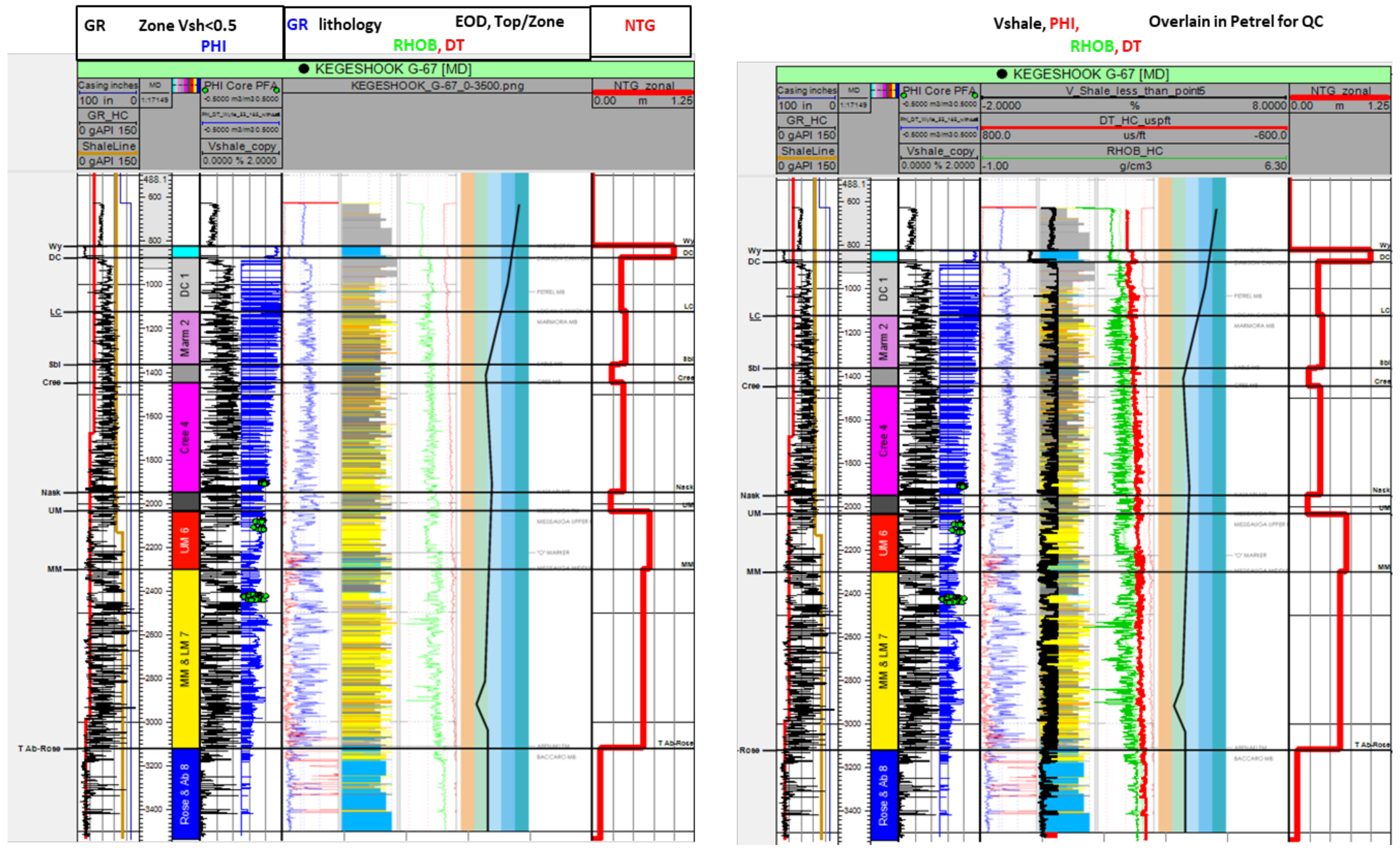
Porosity Thickness (Phi-m) Maps of each of the intervals studied.

Appendix 4

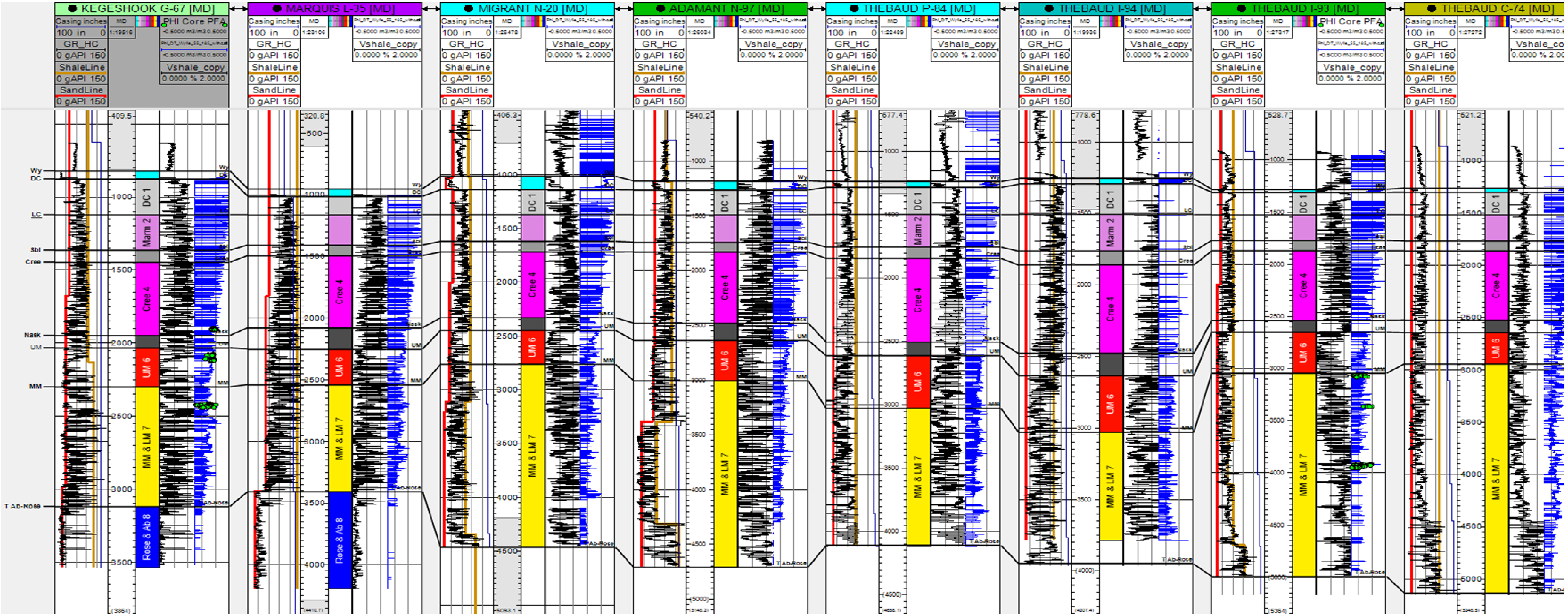
Net to Gross Study

Below is the methodology of NTG calculations in the Sable Island Delta area that were achieved by developing a workflow in Petrel and using legacy litho-stratigraphic intervals based on Fensome, 2011.

- Built cross-sections in Petrel covering the Scotian Margin (210 wells on margin: excluded 15 slope wells and 61 deviated development wells).
- Imported & georeferenced 63 (of 85) "Fensome" composite logs from the 2011 PFA.
- Adjusted legacy NRR picks to Fensome's & extended to additional wells - using many GSC BASIN picks imported to Petrel via spreadsheets produced by Rob Lake at GSC.
- Identified wells for NTG calculations in core area (light blue) based on log availability, depth of penetration and thickness of section. Wells with several thin / absent intervals to the west & on the rift shoulder of Orpheus Graben were left out for now.
- Drew sand & shale lines & calculated Vshale. Used a 50% Vshale cutoff.
- Calculated Sonic porosity (Wylie: DT matrix=185 us/ft; DT fluid=55.5 us/ft).
- Plotted PFA 2011 core porosities on cross sections for visual calibration.
- Built a Petrel depth model using well tops to "make horizons" and establish zones in a 3D depth grid: Wyandot (Wy), Dawson Canyon (DC), Marmora (LC), Sable Shale (Sbl), Cree, Naskapi (Nask.), Upper Missisauga (UM), Middle & Lower Missisauga (MM), Roseway / Abenaki (T Ab-Rose).
- Imported zone property to input pane as a log (RC on Wells – Settings – Select property – Make logs) and used these with "logical IF" & "@sum" functions in well log calculator to calculate zonal NTG ratios at each well.
- Imported these zonal NTGs as zonal properties to grid and used "quality assurance" to generate a NTG spreadsheet, by zone and well.



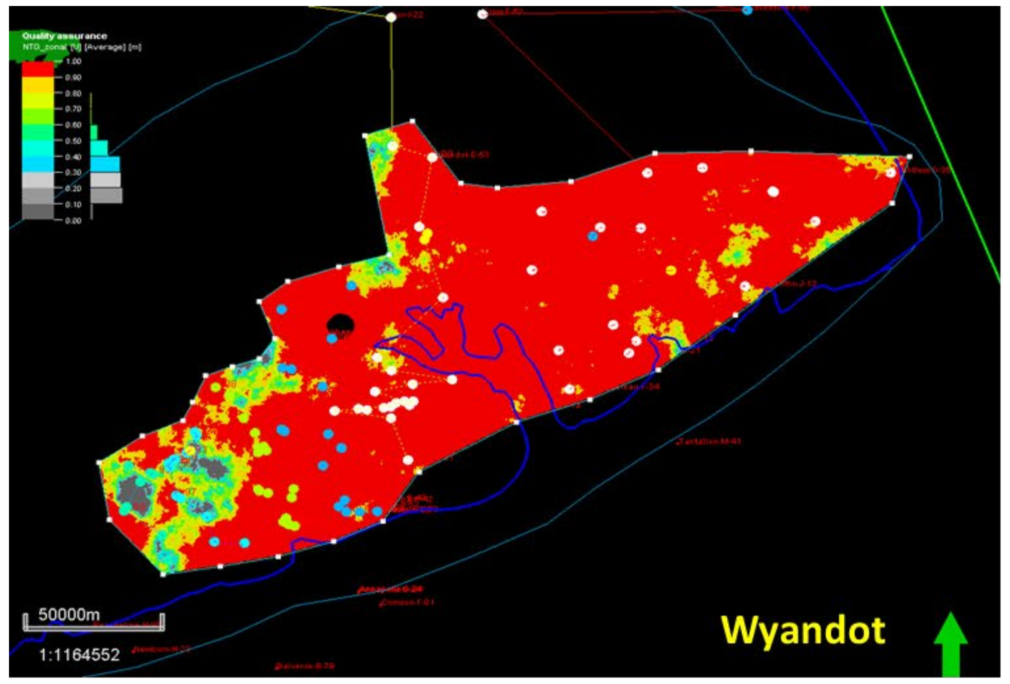
Well log cross section with georeferenced Fensome composite and calculated NTG

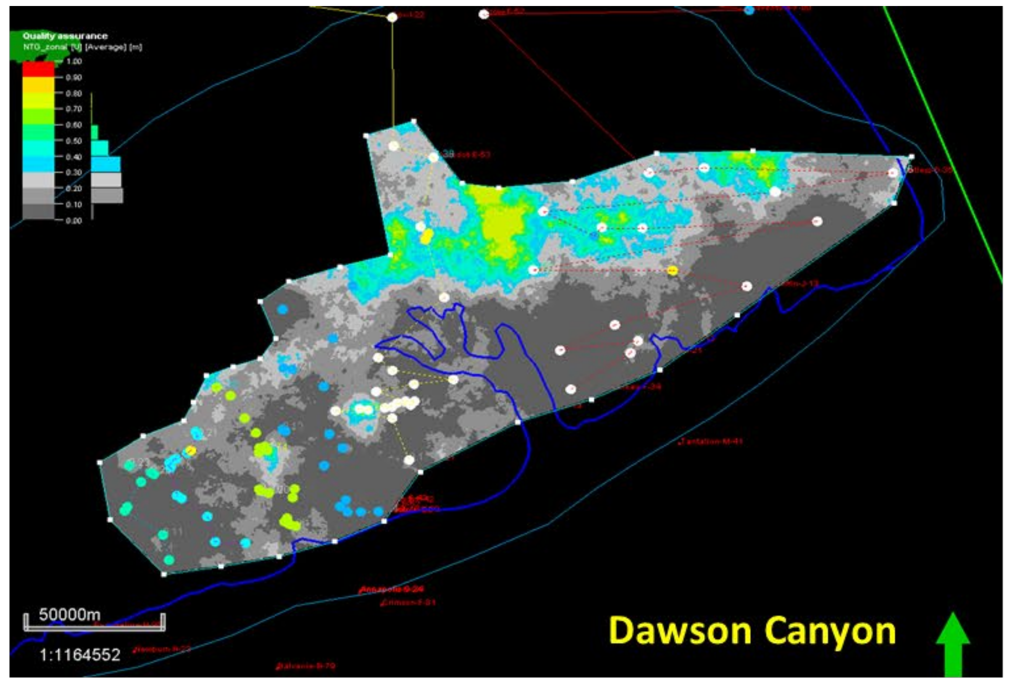


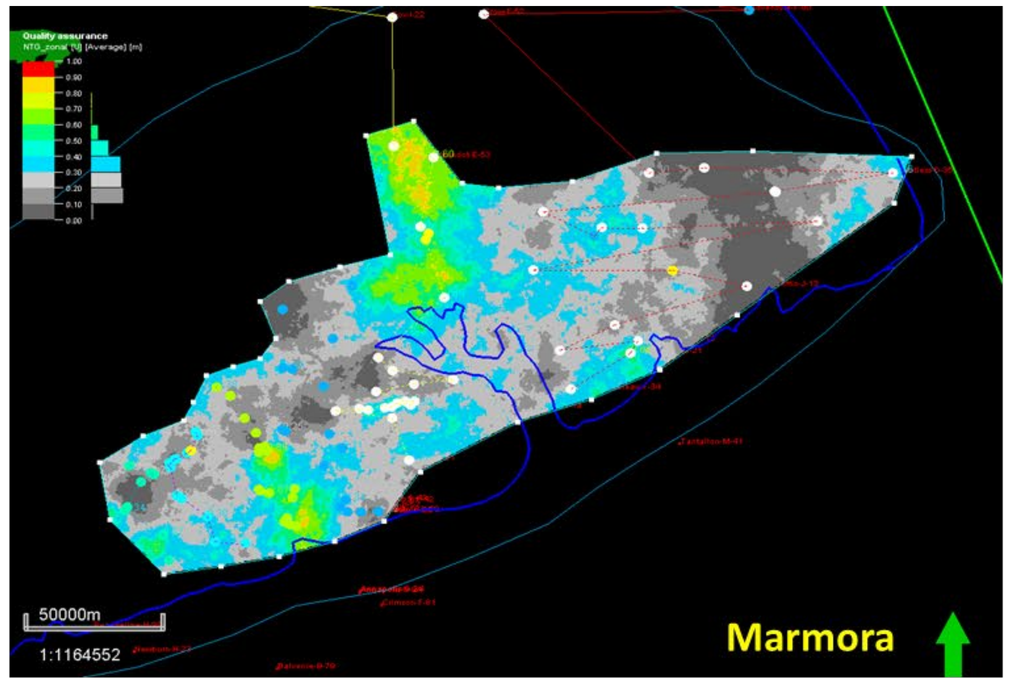
Representative Well log Cross Section with (1)Track 1: GR (Black), Sand (Red) and Shale (Brown) Lines (0-150); Casing (Blue) (100-0 inches), (2) Track 2: MD (m), (3)Track 3: Zones, and (4)Track 4: Vshale<0.5 (Black, 0-2); Porosity (Blue, -0.5-0.5); Green dots are core porosities (PFA 2011). Tops used include the Wyandot, Dawson Canyon, Logan Canyon, Upper & Middle/Lower Missisauga and Abenaki Track Formations. Marmora, Sable, Cree, Naskapi and Roseway Members. Zone codes are 0-8.

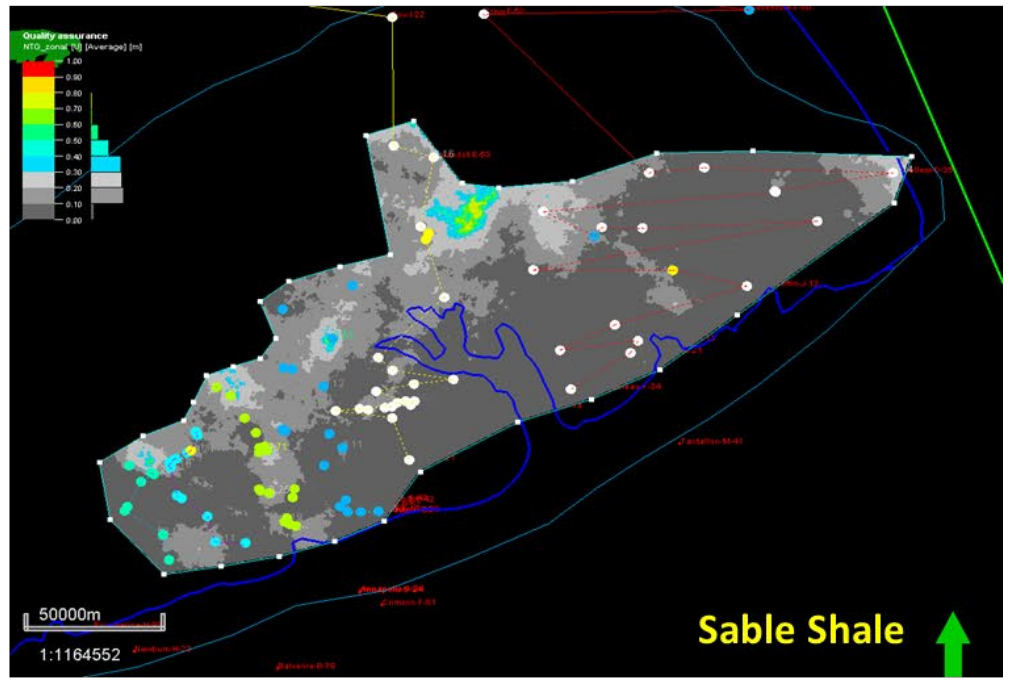
Appendix 4

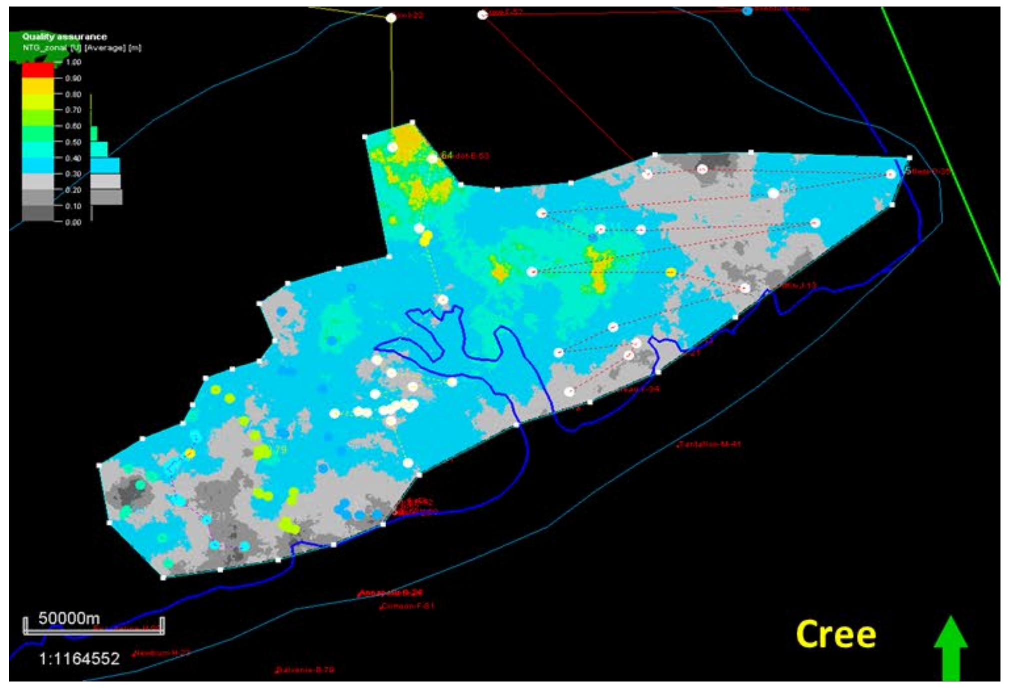
Below are the results of NTG calculations in the Sable Island Delta area that were achieved by developing a workflow in Petrel and using legacy litho-stratigraphic intervals based on Fensome, 2011.

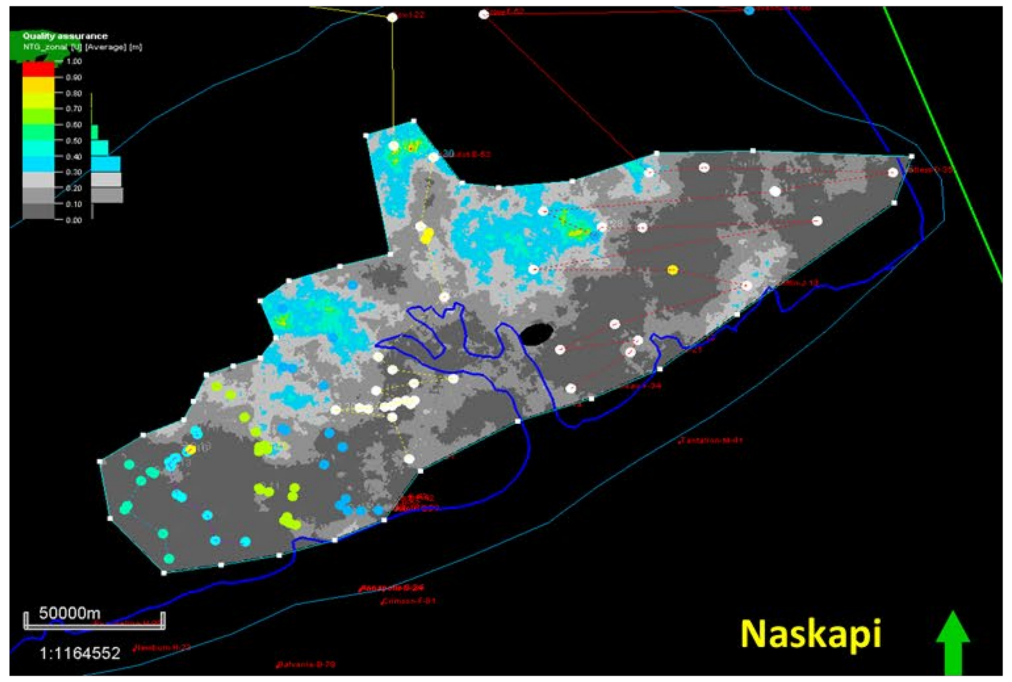


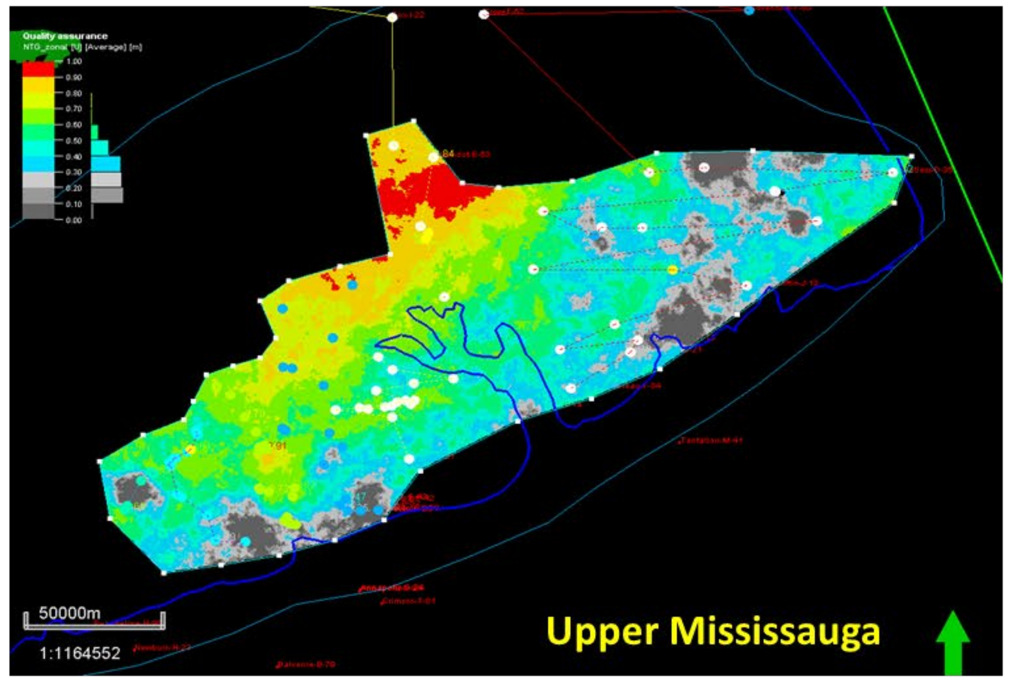


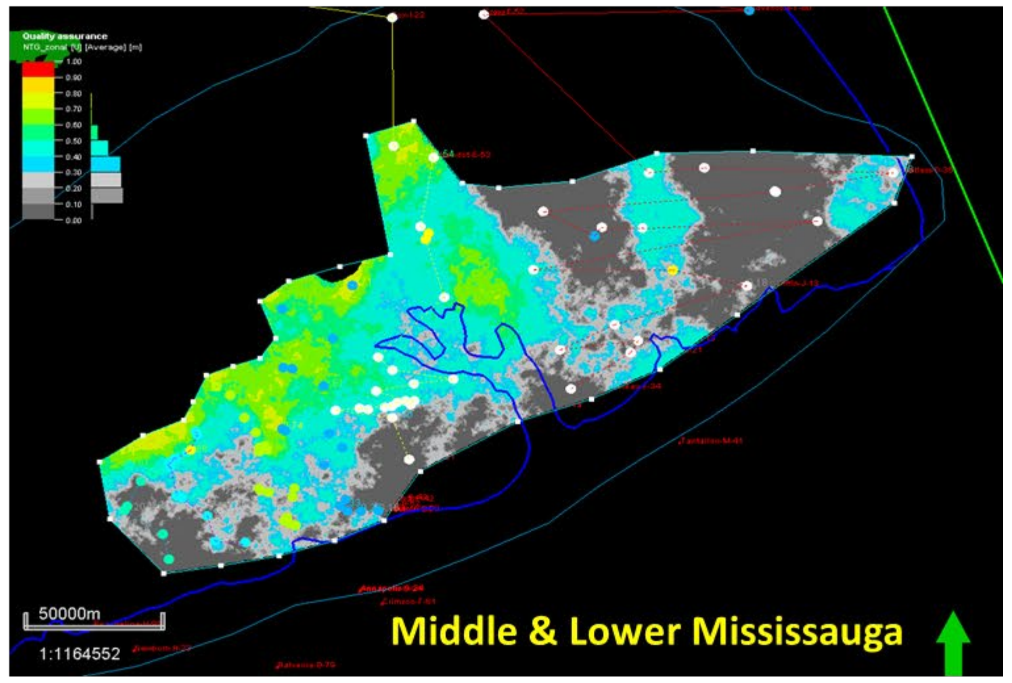


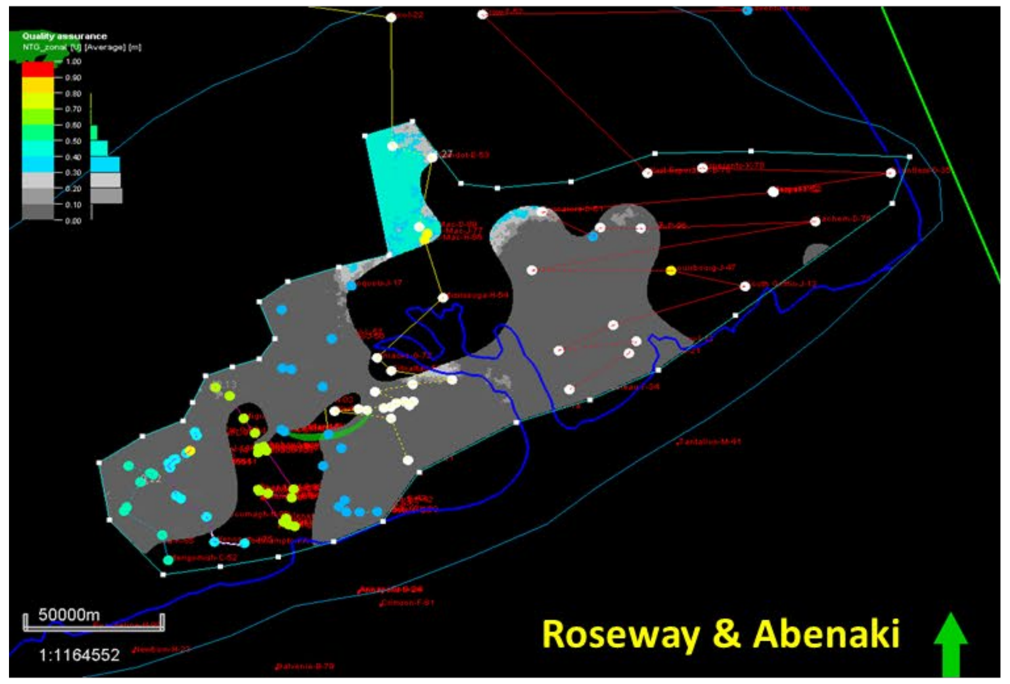


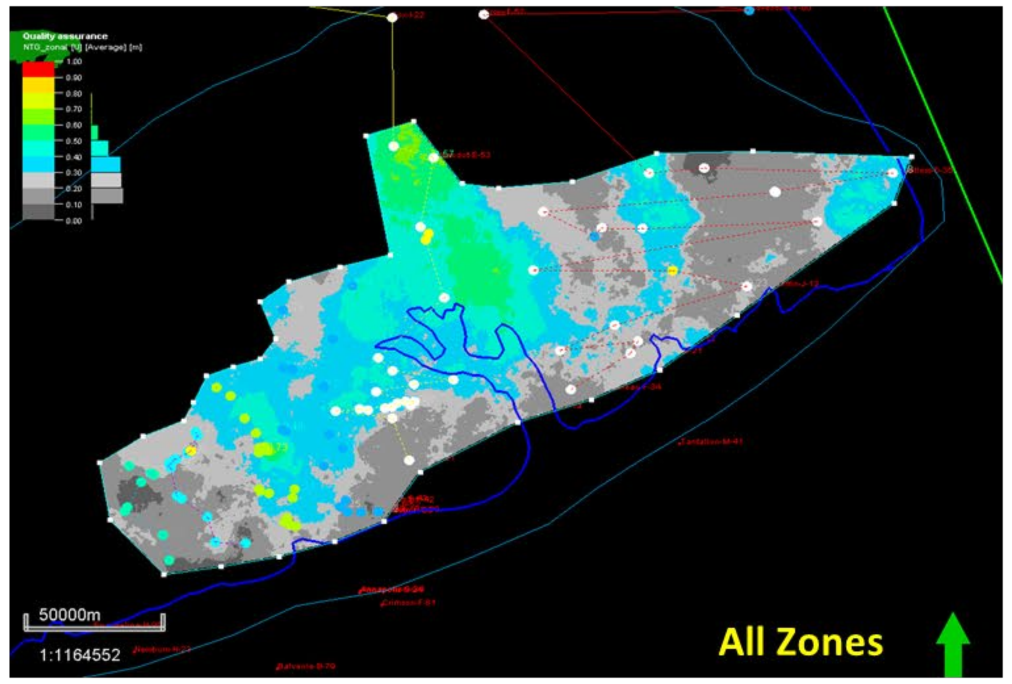


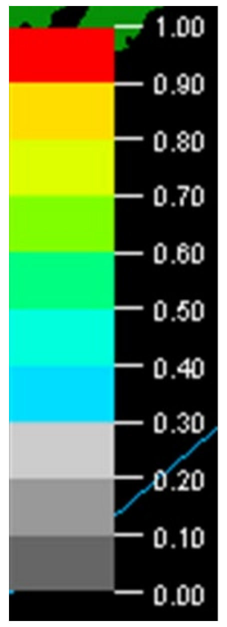












Appendix 4

BARRINGTON REPROCESSING AND INVERSION

Reprocessing

Raj, A., Dutcher, E., and Evans, C. 2021. Barrington 3D Reprocessing: Final Processing Report

The Barrington reprocessing project, as outlined in Chapter 2. 4, was executed by Schlumberger WesternGeco. The Barrington prospect is located offshore Nova Scotia, on the continental shelf of the north Atlantic Ocean. The figure below displays the survey polygon and map location alongside a map of water depth. The input data for the reprocessing consists of narrow azimuth streamer data, with a nominal fold of 50, acquired from May to June of 2001 using a dual source / six streamer configuration.
The project input area is comprised of roughly 1800 sq. km. The reprocessing effort began in September 2020 and completed in May 2021. The input fold of coverage map on a 12.5x37.5m grid oriented to a 56.499° azimuth.

Geologic Setting

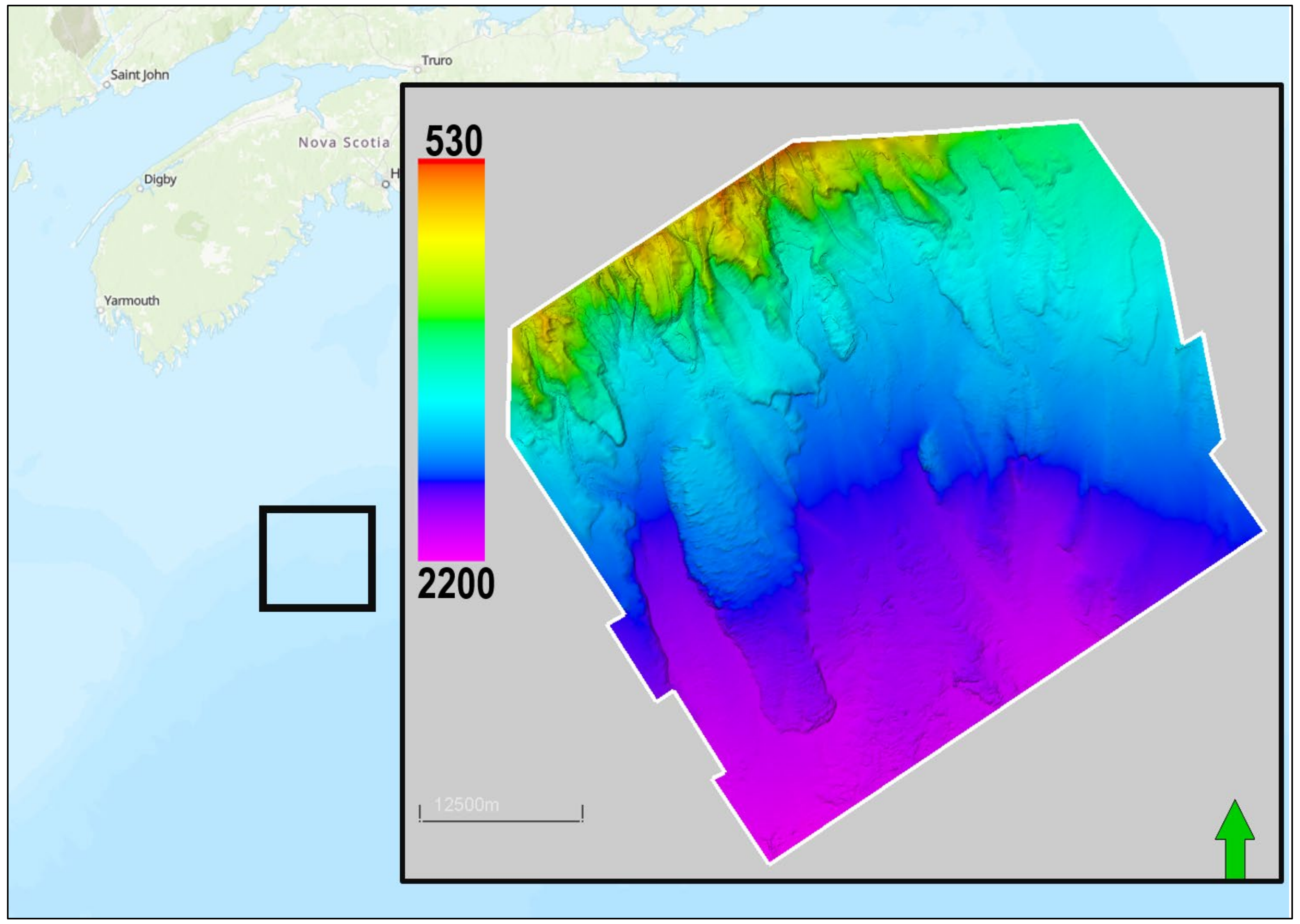
The Barrington seismic was acquired on the outer shelf and slope in the southwestern portion of the Scotian Basin. It is situated to the east of the Yarmouth arch, a basement feature consisting of a horst block, separating the Georges Bank Basin from the Shelburne Subbasin (see Fig. 1.3). The region is bounded by two salt basins, one to the west and one to the east of the Yarmouth arch. Barrington is located over the eastern basin with salt features including pillows, rollers, and diapirs.

The area of interest is located directly on the Yarmouth transform, which is a northwest-southeast trending strike-slip margin. Amplitude anomalies have been seen in the deep cretaceous and tertiary turbidite channels with up-slope onlap. The overlying angular unconformity and regional seal reduces the risk of up-slope leakage along the channels. These amplitude anomalies have been theorized to be analogous to the late jurassic Buzzard field in the North Sea or the Turonian stacked turbidities of the Jubilee discovery in Ghana (Deptuck et al, 2015).

Water depths range from approximately 530 to 2200 meters, giving seabed two-way traveltimes of 800 to 2800 ms.

Project Objectives

The primary objective of this project was to create high quality prestack depth migrated images to improve structural and stratigraphic definition and to generate input volumes for AVO analysis and inversion. The workflow was tailored from WesternGeco's extensive experience in Atlantic Canada, where the following were critical to the successful imaging project: maximizing signal to noise ratio, increased bandwidth through deghosting techniques, attenuation of multiples, and accurate velocity model building. These objectives were attained while preserving amplitude balances across all offsets to allow for an accurate subsequent AVO analysis.



Inversion

Dasgupta, S., Gofer, E., and Bachrach, R. (2021) Final Inversion Report: Barrington 3D Reprocessing.

Seismic reservoir characterization (SRC) was carried out on Barrington 3D reprocessed PSDM seismic data. The objective was to assist the interpretation of potential hydrocarbon exploration prospects by performing amplitude versus angle (AVA) inversion and deriving elastic rock properties and lithologies form seismic amplitude. In This project the SRC workflow is based on the Litho-Petro-Elastic (LPE) technology. Conventional seismic inversion relies heavily on accurate elastic parameters prior model derived from measured well logs to fill the low-frequency end of the spectrum, not covered by the input seismic. In areas where building a prior model is challenging, such as frontier exploration where building the low-frequency model (LFM) based on very few wells that may be located away from the area will bias the predictions. To overcome the limitation associated with conventional seismic inversion, a single-loop approach and characterization was developed. LPE inversion provides a single-loop approach to reservoir characterization based on rock model and compaction trends, reducing the dependency on a detailed prior low frequency model. LPE inversion incorporates rock physics modeling and lithology classification directly with the seismic AVA inversion or optimal estimation of lithofacies and elastic properties. LPE technology integrates basin modeling estimates of effective stress and temperature to generate a geologically consistent, elastic and lithology estimates.

The three main parts of the project were: rock physics modeling, AVA analysis, and LPE inversion.

Rock physics allows the relationship between the petrophysical properties (such as lithology, porosity and saturation) and the elastic properties (Acoustic Impedance, VP/VS ratio (or Poisson’s Ratio), Density, Lambda-Rho, Mu-Rho) to be examined, understood and modelled. The rock physics analysis is used to determine the likely separation of different lithologies (shale, water-saturated reservoir rock and hydrocarbon-bearing reservoir rock) based on their elastic properties. Rock physics models link seismic data to reservoir properties and provide valuable insight to the interpretation of seismic amplitudes. The rock physics analysis and workflow can be summarized as exploratory data analysis, deterministic rock physics modeling, and stochastic rock physics modeling.

AVA analysis ties between the elastic parameters derived from the rock physics modeling and the seismic amplitude response. The AVA response across an interface is a function of key reservoir properties and understanding the relationship can assist in interpreting the seismic data and the seismic inversion results. Modeled AVA can be related to contrast between different rock types at different reservoir conditions.

Conclusions

LPE inversion results are meant to assist with the interpretation of the Barrington 3D seismic data with identifying potential hydrocarbon prospects. The inversion provides several property volumes that can be incorporated with other data to reduce uncertainty. The estimated lithoclass volume can be used to see where HC Sands were predicted, and the lithology probability volumes give information of the confidence level. It should still be noted that there were no wells with geophysical logs within the survey area, only three lithologies were observed from wells in surrounding the area, and we assumed equiprobability prior of finding any of the lithoclasses in anywhere in the area covered by the seismic data.

Having a well with geophysical logs can assist with the wavelet estimation process and allow a more accurate estimation of the amplitude, phase, and bandwidth. A well within the survey area can provide a location for inversion results validation. The recommendation is that when a well is drilled within the area, to log sonic and bulk density. The well not only can be used to check the current inversion but also used for updating the estimated model.

The elastic property compaction trends and the input LithoBrain are all based on pre-defined lithoclasses. The pre-defined lithologies are based either on log measurements or other prior information. In such a case only observed lithologies will have compaction trends calibrated to measurements. Other lithofacies will have trends with values that are based on general rock physics models and given general rock and fluid properties taken from literature or from specific measurement from the Basin. Similarity of geological processes at different basins gives confidence that rock physics modeling can give good approximation of compaction trends and can be used even in locations where measure data is absent. We may also have a case where other lithologies apart from those defined are present. This may cause a bias in the absolute values of the elastic properties and a wrong lithology is predicted where the undefined facies are present. One way to resolve this is to include the new facies in a new run of LPE inversion. Other ways to mitigate the issue is to compare the elastic properties of the undefined lithoclass to the other lithofacies and to carry out AVA forward modeling to understand the impact on identifying hydrocarbon prospects.

Equiprobable lithofacies prior means that the presence of no specific lithoclass is preferred over other lithologies. As a result, the LithoBrain PDFs are not weighted and are only a function of the stochastic rock physics modeling. Therefore, the probabilities related to any of the lithofacies are only driven by the P-impedance and the VP/VS ratio estimated from the AVA inversion. Adding a lithofacies probability prior may increase or decrease the AVA driven results. When possible, it is always preferred to apply the prior before generating the LithoBrain, but the prior can also be incorporated after the inversion with prior posterior multiplications. The results are such that when the prior suggests there is greater possibility of presence of one lithoclass over another, the LPE’s estimated probability for one class will increase and for others may decrease in a proportional manner. In this project as the LPE inversion results are being used along other available data such as interpreted horizons, calculated intercept and gradient, and elastic properties among other types of data, an equiprobable prior may be sufficient.

Barrington Reprocessing and Inversion

Appendix 4

Synthesis and Critique of Lower Jurassic Hydrocarbon Charge Evidence, Offshore Nova Scotia

Dr. Andrew Bishop, 2022

Executive Summary

Over the past decade, OERA on behalf of the Nova Scotia Department of Natural Resources and Renewables, has commissioned numerous studies to help constrain Lower Jurassic source rock risk offshore Nova Scotia. The objective of this study has been to review those past works, and highlight those observations of particular importance, both positive and negative. Though direct evidence for the presence of a Lower Jurassic source rock offshore Nova Scotia is lacking, there are numerous lines of evidence which strongly suggest that such a horizon is present. However, there are several key risks which might preclude material hydrocarbons.

Proven Lower Jurassic well calibration, in particular with regards to post-salt marine facies, are currently lacking in the Scotian Basin. It is likely that the basal Lower Jurassic is present in many of the shelf wells, occurring as a series of sabkha related dolomites and anhydrites. However, the biostratigraphy on this section is challenged given the depositional environment, so exact age calibration within the Lower Jurassic is yet to be definitively assigned. Above this section, the Middle or Upper Jurassic typically rests uncomformably, reflecting the effect of the break-up unconformity. Whereas the wells on the slope rarely penetrate any deeper than the Middle Jurassic. Thus, the Lower Jurassic is still largely uncalibrated in the area of interest. Notably, some of the southern Grand Banks wells include thick Lower Jurassic sections, including post-salt marine facies.

Marginal Lower Jurassic source rock facies, i.e. with modest organic enrichment, is observed in several wells around the immediate Central Atlantic region, including the Morocco wells MZ-1 and DSDP-547b, and the southern Grand Banks Heron H-73 well. Though none of these wells contain evidence for an economic source rock, the occurrence of subtle organic enrichment in the Sinemurian and Pliensbachian may relate to the accumulation of true source rocks in basinal areas. Molecular geochemistry data from DSDP-547b, where Pliensbachian extracts contain significant concentrations of the extended 17□,21□-hopanes (up to C35), attest to marine, anoxic conditions.

Widespread hydrocarbon occurrence data across the slope, in terms of shows, surface hydrocarbons (piston core data) and DHIs are most readily accounted for on a maturity basis by charging from the Lower Jurassic. Given late Paleozoic tectonic and igneous activity, the charge potential of the pre-rift is considered unlikely. Of particular note is an anomalous oil family recorded from a DST sample at Mic Mac J-77, which is also found in shows from neighboring wells. The signature of this oil is that of an anoxic marine carbonate, exhibiting Lower Jurassic character in terms of the extended tricyclic terpanes. It is expected that any Lower Jurassic marine source rock is most likely to be carbonate given the climatic conditions at that time. There are other anomalous signatures which are not readily accounted for by the proven Upper Jurassic Verrill Canyon source rock, though are too ambiguous to relate to any other potential source horizon, typically due to the high maturity of the samples.

Modeling studies have also been conducted to help constrain source potential in the Lower Jurassic. There are considerable uncertainties when it comes to understanding the paleoclimate of the Lower Jurassic and the timing of both connections to the Tethys and Pacific realms for the Hispanic Corridor. However, modeling results indicate that good conditions of restriction and upwelling, focused primarily on the Morocco side, were probable during the Lower Jurassic. The conditions in the Scotian Basin would not have been too different to that of the Lusitanian Basin, where Pliensbachian source rocks are known and associated with modest hydrocarbon accumulations.

Notable significant risks associated with remaining uncertainties include: the paleobathymetry of the basin (was it deep enough for source rock preservation); the potential negative consequences of the breakup unconformity; arid conditions inhibiting water column anoxia via negative water balance; and, potential localization of source rock distribution due to early salt tectonics.

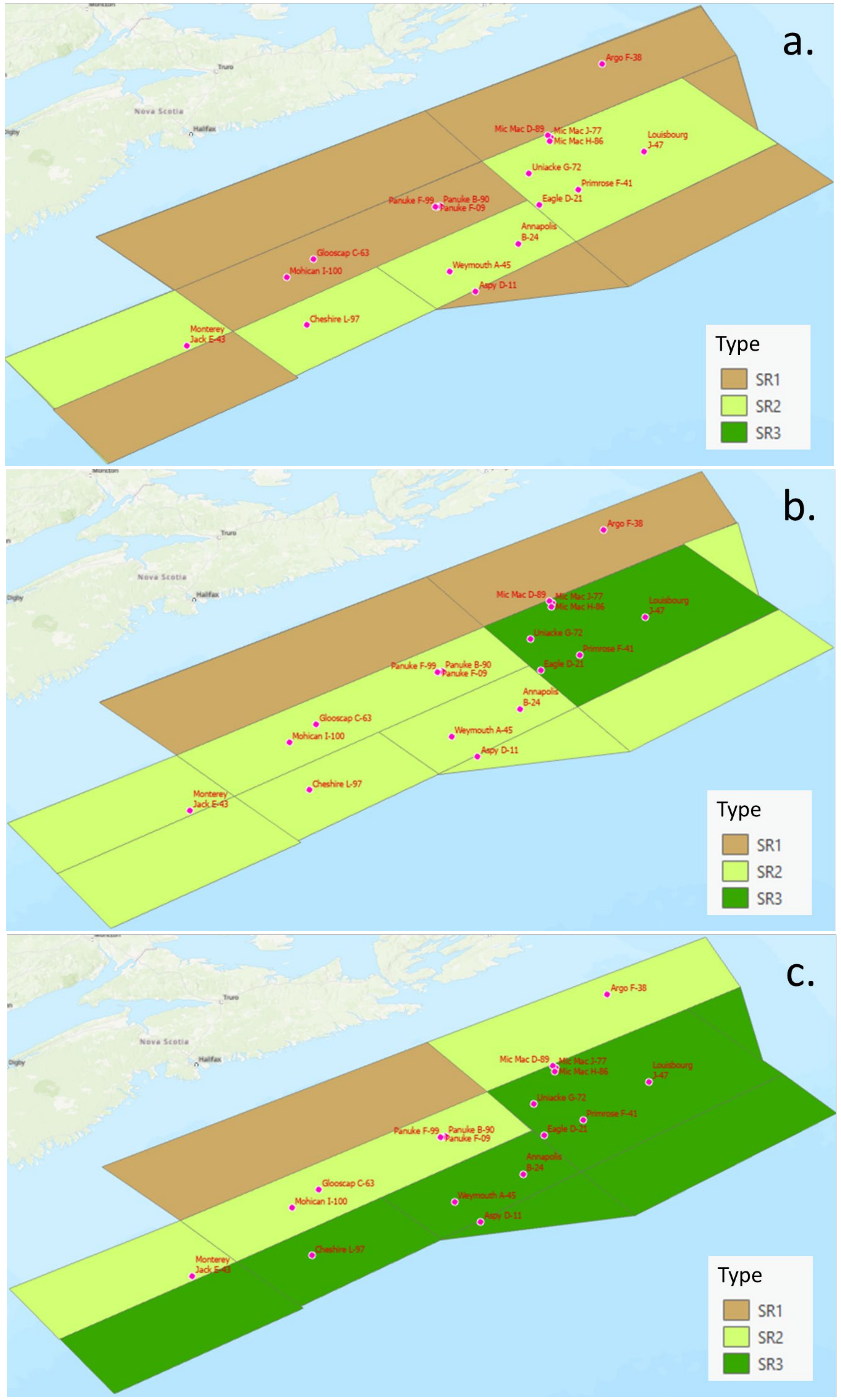
One of the most important uncertainties is the subsidence history of the basin. Several lines of evidence suggest that subsidence was much less than would be expected for a typical McKenzie rift model. One possible explanation is mantle uplift resulting from magma-poor hyperextension. However, this hypothesis requires further consideration before any predictions can be made in terms of bathymetry evolution.

The observations derived in this study have been used to define three possible source rock scenarios, representing P10, P50 and P90 risk. Ultimately, however, additional well control comprising penetrations of the Lower Jurassic on the slope is needed to answer the question once and for all as to whether or not there is a Lias source rock offshore Nova Scotia.

Conclusions

Direct evidence for a Lower Jurassic source rock offshore Nova Scotia is lacking. However, there is a considerable amount of circumstantial evidence which suggests that such a source rock may exist. Hydrocarbon occurrences on the slope are difficult to account for unless a Lower Jurassic source rock is inferred. Several anomalous geochemical signatures are found in oils from the Scotian Shelf, which are inconsistent with the terrigenous Upper Jurassic Verrill Canyon source rock, including the intriguing Mic Mac J-77 carbonate signature oil.

The presence of a Lower Jurassic marine facies offshore Nova Scotia is also yet to be definitively proven. It is likely that much of the indeterminate age, sabkha facies strata below definitive Middle Jurassic strata represent Lower Jurassic sequences. These lack sufficient fossil evidence for dating, though unpublished data by MacRae (pers comm) suggests that this is possible in some wells, with the confirmation of a Lower Jurassic age for the post-salt 'indeterminate' section. The presence of reworked Lower Jurassic flora proves that this was an area of active Lower Jurassic sedimentation, and a significant Lower Jurassic section is routinely implied on seismic. Considerable thicknesses of Lower Jurassic are known from wells on the southern Grand Banks, such as Heron H-73 and Bittern M-62 (Figure 7), which contain evidence of marginal source facies, which may correlate with true source rock horizons in distal basin areas. Similar evidence is found on the Moroccan conjugate margin, especially DSDP 547b. This well penetrated thin, marine anoxic mudstones with high TOC values. None of these peripheral observations constitute definitive demonstrations of a source rock in the Sea of Acadia, but they are consistent with the occurrence of basin conditions favorable to source rock deposition at times during the Lower Jurassic. Optimum source rock conditions would naturally be expected in distal basin locations, for which data is currently unavailable.



Appendix 4

Organic Facies Prediction and Risking of Jurassic Source Rocks, Offshore Nova Scotia

GETECH, Scougal et al, 2021

Available from https://oera.ca/research/Analysis-Palaeoenvironment-Palaeoclimate-Palaeooceanographic-Models

Executive Summary

This report presents the results of the Jurassic source rock prediction study undertaken by Getech Group plc on behalf of OERA.

Lower Jurassic source rock horizons recognised across the North Atlantic, along with inconclusive well observations within the Scotian Basin, have led to considerable supposition on the occurrence of more oil-prone lower Jurassic source rocks contributing to hydrocarbons in the Scotian Basin. These are in addition to the more widely recognised Tithonian source that has charged the gas and condensate discoveries found on the Scotian Shelf.

The aim and objective of this study was to predict the distribution of Tithonian and Early Jurassic (Toarcian, Pliensbachian, Sinemurian, Hettangian) source rocks offshore Nova Scotia, based on biogeographic principles derived from modern environments, and palaeoenvironmental interpretations derived from palaeogeographic mapping and Getech's proprietary organic facies prediction (OFP) modelling. In order to ground-truth the model predictions against true data values, the wider region of the European Tethys was initially used to predict (pre-maturation) Total Organic Carbon (TOC) content and Hydrogen Index (HI) of sediments deposited. Subsequent higher resolution modelling was undertaken for the Hispanic Corridor. Source rock risk maps were constructed by taking into account the palaeogeographic, palaeogeological and palaeoocean boundary conditions that would have influenced source rock deposition. The resulting maps will provide a spatial understanding of both the how and where favourable conditions existed for source rock development at the time of deposition.

To provide both the inputs and calibration data for the gross depositional environment mapping (GDE) and the OFP models, extensive data was provided by OERA, and used alongside Getech's internal databases (Globe, Regional Reports) and public domain data.

Gross Depositional Environment (GDE) maps were generated for each of the five proposed source intervals to provide a spatial understanding of coastlines, bathymetry and depositional environments. These maps, have incorporated the tectonic and structural morphology of the depositional basin to identify potential depocentres that would have been favourable for fine-grained source rock deposition, as well as those areas such as intra-basinal highs where fine-grained accumulation would have been less likely.

The Hettangian, Sinemurian and Pliensbachian intervals were deposited during the late synrift to early post-rift stage, prior to the first occurrence of oceanic crust in the Central Atlantic, and portray a gradual encroachment of the Tethys Sea. The seaway separating Nova Scotia from Morocco was relatively narrow (~250 km at its widest) and was relatively shallow. Due to the hot and dry climate, the shallow seaway was repeatedly evaporated, resulting in the precipitation of extensive salt and minor anhydrite deposits in the Hettangian. Continued restricted shallow marine conditions established mixed clasticcarbonate sedimentation in the Sinemurian and Pliensbachian. Getech's Multi-Sat gravity data (2019) has enabled us to visualise a series of gravity lows, which may represent former Triassic-Lower Jurassic grabens inboard of the Naskapi, Mohican and Oneida Grabens. These inboard co-eval fluvial-lacustrine continental rift basins stood above the level of the invading Tethys Sea and were subsequently eroded during the break-up unconformity.

The Toarcian represents deposition during the early thermal subsidence stage, immediately after the break-up unconformity and creation of the oceanic crust at the onset of the opening of the Atlantic Ocean. Transgressive shallow water to tidally influenced dolomites and clastics were deposited in a shallow, warm, agitated and extensive ramp system that extended across the Scotian Basin.

The Tithonian interval represents the pinnacle of a Jurassic carbonate reef, bank and platform environments that had formed in the Middle Jurassic and thrived along the basin hinge line on the Lahave Platform. Concurrent with carbonate deposition, increased Late Jurassic clastic input led to the establishment of the Sable and Shelburne delta complexes.

Organic Facies Prediction (OFP) was carried out for the wider Tethys region, utilizing Getech's palaeographical and bathymetric reconstitutions as boundary conditions for the modelling. A suitable oxygen minimum zone scenario was defined to capture the widespread anoxia that was evident in the Lower Jurassic epicontinental basins of the Tethys. Initial results showed a good agreement with the data collected for constraining the models, with the modelled TOC values correlating well with the range of published values for the region.

Although this initial Tethys modelling provided favourable correlations, the relatively long, narrow seaway of the Hispanic Corridor within which the Nova Scotia region was located during the Lower Jurassic, is likely to have experienced very different oceanographic conditions to the adjacent Tethyan epicontinental shelf area. As a result of these environmental differences, as well as the lack of data to constrain the oceanographic conditions at the time, it was necessary to refer to modern analogues to define the oceanographical conditions on which to base the higher resolution models for the Hispanic Corridor, with focus on Nova Scotia. Four analogues were identified: Red Sea, Gulf of California, Saanich and the Black Sea. All four scenarios were modelled for each time interval and the most appropriate identified.

Due to the shallow water depths of the Hispanic Corridor Basin at the time of deposition, the water depths of the Red Sea, Gulf of California and Saanich were deemed too deep to be the most accurate analogue for the Lias Hispanic corridor. Therefore, the Black Sea model was considered most appropriate in terms of oceanographic conditions and has been subsequently applied to the source rock risk maps.

The construction of the source rock risk maps involved the stacking of the gross depositional environment maps, with the organic content (TOC), richness (HIA) and oxygen levels derived from the Black Sea OFP model runs.

For each risk map, three conceptual categories of favourable, less favourable and unfavourable were used to classify the source rock parameters. The assignment of each category were based purely on the results of the OFP modelling and GDE mapping results.

The results of the source rock risk mapping for the five Jurassic intervals are shown in Figure 1. The risk maps show the extent of favourable to unfavourable conditions for source rock deposition. However, the risk maps have not taken into account:

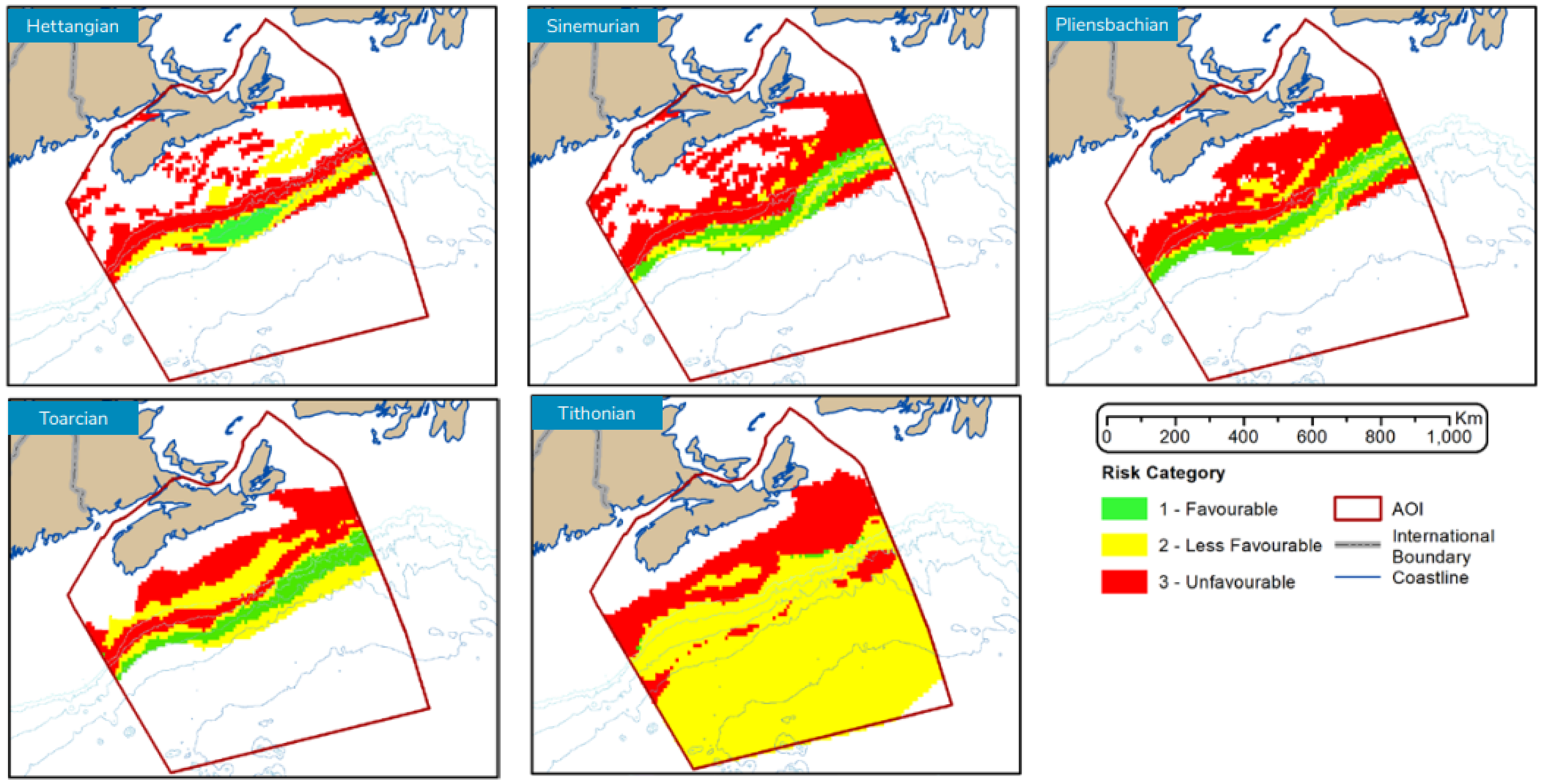
- if there was sufficient accommodation space for sediment accumulation;
- potential thickness;
- any post-depositional process that may have perversely(or conversely) affected source rock development and preservation, or;
- maturity of each source interval.

When these extra factors are added, the extent of a productive (and effective) source horizon is likely to be smaller.

Despite being a recognized source rock interval in the Sable Island area, the risk map for the Tithonian interval shows "less favourable" conditions for source rock development when compared with the four Lower Jurassic horizons (Figure 1). This is due to relatively low predicted TOC and HIA (in the modelling results), which are a result of the geometry of the offshore region during deposition. The inboard region consists of a very shallow carbonate platform, bounded by a steep foreslope, where water depth dramatically increased. As a result, the OFP models a significant reduction in sedimentation rate and Carbon Delivery Flux (CDF) with consequently reduced TOC and HI. Additionally, in the Tithonian, the geography and oceanography has changed from a restricted narrow seaway to a fully open marine setting. Therefore, using the Black Sea modelling results will not be as appropriate for this scenario. However, it is important to consider that "less favourable" areas on the risk maps (shown on Figure 1) do not necessarily preclude the possibility of source rock development, only that the prevailing depositional conditions (defined by the palaeogeographical reconstruction) result in moderate to low modelled TOC and HI values; these lower values can still equate to moderate to good source rock potential, but are not as favourable as the very good-excellent potential shown in the "favourable" classification. An example of this is the Annapolis discovery, which lies withing the "less favourable" mapped area for the Tithonian, but there is indirect evidence of a Tithonian source horizon (albeit overmature).

"Less Favourable" to "Unfavourable" conditions were mapped across the palaeo-onshore regions for all five Jurassic horizons. This is due to the lack of direct or modelled data to support a favourable classification. The Abenaki, Sable and Huron Sub-basins playa facies that formed part of the Hettangian salt basin, along with Sinemurian and Toarcian low energy, high salinity coastal areas away from the clastic input, are considered to provide limited favourable conditions for source rock development. This is highlighted by analysis of oil stains from the Mic Mac J-77 and D-89 wells that demonstrates some evidence of a Lower Jurassic source. Elsewhere, the GDE mapping for the palaeo-onshore areas generally show high energy, coarse clastic deposition. These environments typically lower the preservation of organic matter and are likely to have been unfavourable for source rock deposition.

In summary, all four lower Jurassic intervals show favourable conditions for source rock development. Due to the shallow low oxygen conditions, coupled with the high CDF and sedimentations rates predicted, the margins of the marine basin show widespread favourable conditions for organic rich sediments to have been deposited. The Hettangian has the smallest area of favourable conditions, as the water depths were too shallow and mainly within the oxic zone as a result of it being in the early development of the Hispanic corridor. As the Hispanic corridor widened and deepened during the Sinemurian to Toarcian, a greater area of the offshore region fell within the optimum PZE depositional conditions for organic rich sedimentation, therefore the spatial extent of favourable source rock development increases during the later stages of the Lower Jurassic.



Final source rock risk maps for the Lower Jurassic and Tithonian intervals.

Appendix 4

Tracking Mesozoic paleoclimate events on the Nova Scotia Margin

TNO, Houben and Verreussel, 2022

Available from https://oera.ca/research/Tracking-Mesozoic-Paleoclimate-Events-NovaScotia-Margin

Executive Summary

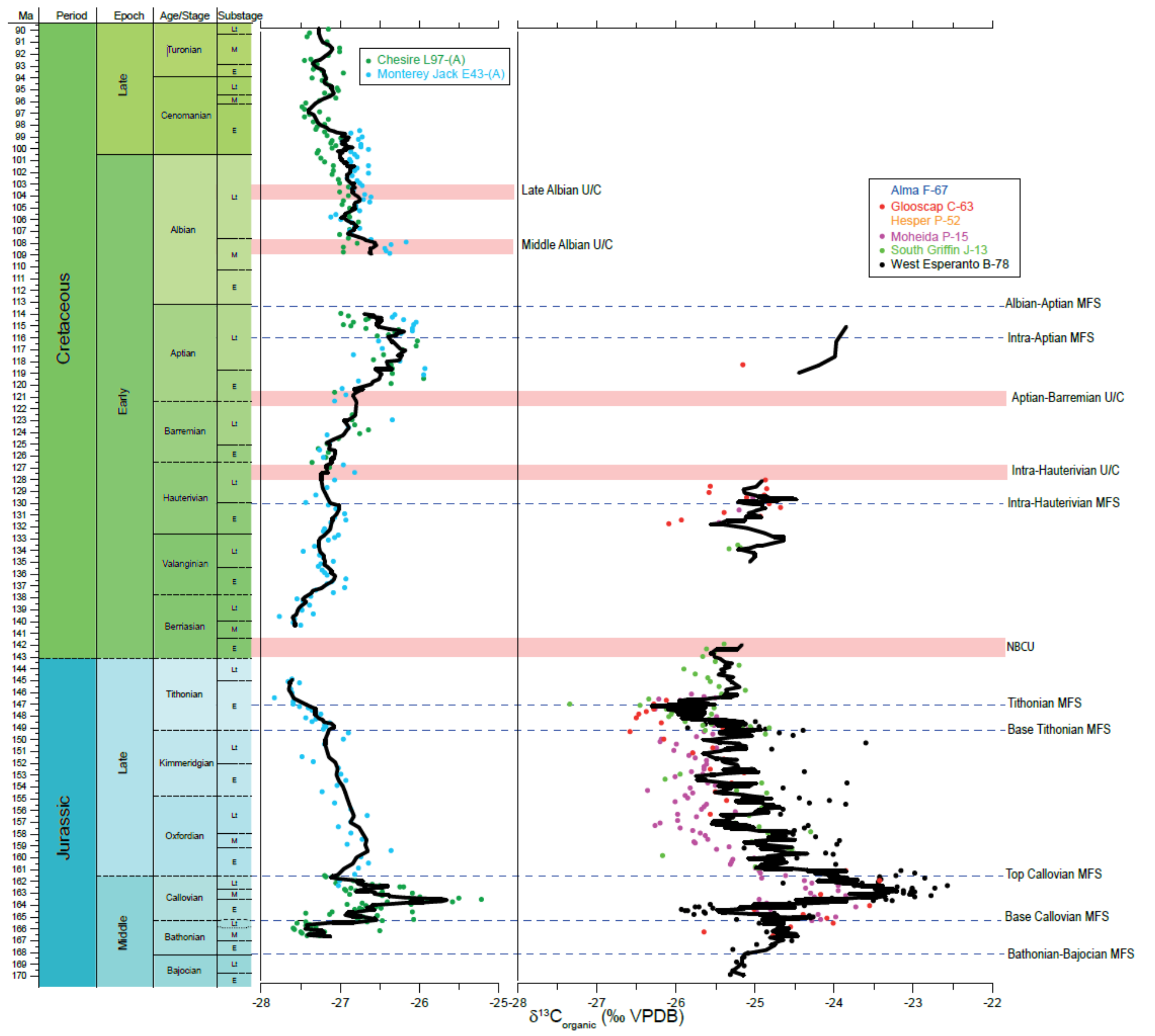
This project entitled “Tracking Mesozoic paleoclimate events on the Nova Scotia Margin” is a research project carried out by TNO-Geological Survey of the Netherlands (TNO-GSN) as part of the Paleogeography-to-Petroleum Systems: Research Innovations for Offshore Nova Scotia (PaGeo2) Program of the The Offshore Energy Research Association of Nova Scotia (OERA).

The primary aim of this study is to evaluate whether and if so, what carbon-cycle perturbations (and consequent phases of paleoclimate change) can be recorded within Jurassic and Cretaceous sedimentary successions from the Nova Scotia Margin and the adjacent Grand Banks Basin of Newfoundland. This is of importance because these phases of climate change may have led to the development hydrocarbon source rock accumulations. Since carbon-cycle perturbations can be represented by an array of fundamentally different depositional signatures, it is of great importance to independently assess the carbon cycle variations specifically. The current project focuses on reconstruction of a baseline for carbon cycle dynamics during the Jurassic and Cretaceous on the Nova Scotia Margin, by measuring the stable carbon isotopic composition of bulk organic-carbon (d13C_{org}), sampled from a selection of offshore exploration wells.

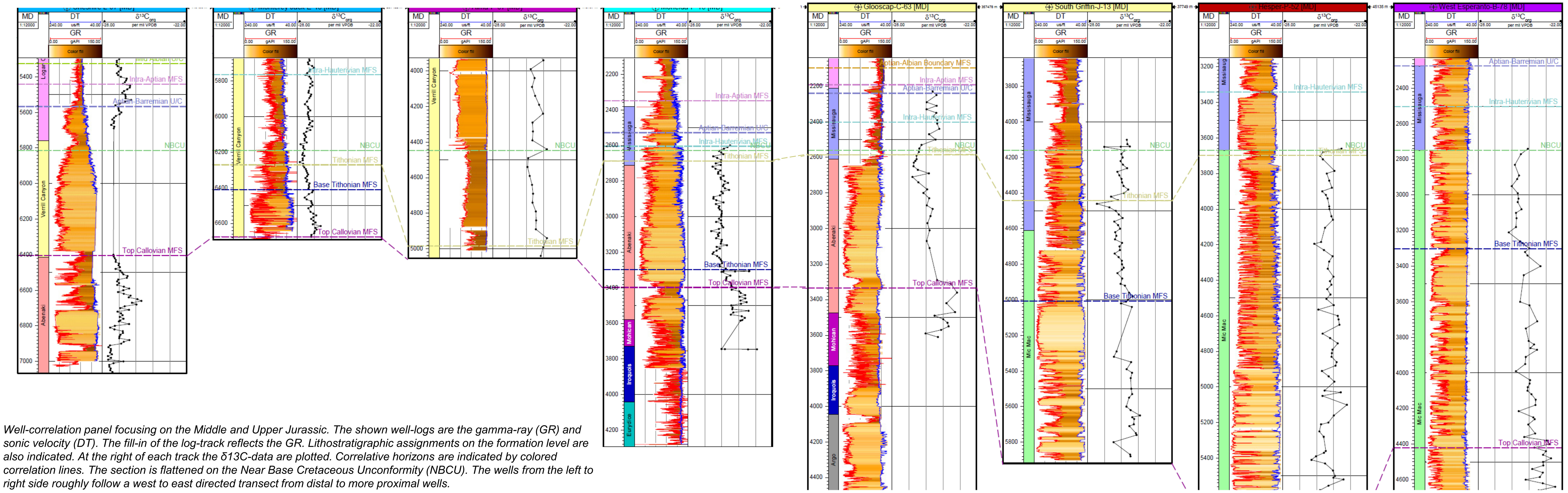
Thousand samples were analyzed for d13Corg and total organic carbon content (TOC). Of these 200 samples from three wells address the Lower Jurassic in the southern Grand Banks Basin, whereas 800 samples are taken from Middle Jurassic to mid-Cretaceous strata from 8 wells along the Scotian Margin. The analytical results were integrated with legacy data in order to arrive at a chronostratigraphically calibrated (age-dated) d13C_{org}-composite for the Middle Jurassic to mid-Cretaceous from the Scotian Margin and a new reference curve from well Bittern M-62 for the Lower Jurassic succession from the southern Grand Banks Basin. These deliverables are placed in context with regards to (1) improving stratigraphic correlations in the area, (2) paleoclimatic significance and (3) potential for hydrocarbon source rock presence.

Overall, the results from the different well-sections display consistent variation that bears stratigraphic and paleoclimatic significance, both on longer and shorter timescales. On longer time-scales (>10 Myrs) four distinct trends of increasing and decreasing signatures were recorded from Middle Jurassic to mid-Cretaceous times. These variations likely relate to long-term changes in net organic carbon burial within the developing Atlantic Ocean basin. In addition, we noted numerous shorter term ‘events’ (or carbon isotope excursions, CIEs) . The most prominent CIEs occur in the Early Jurassic. Unequivocal evidence for Triassic-Jurassic boundary CIE and the Toarcian CIE was found in well Bittern M-62. The records from the Scotian Margin indicate traces of a substantial excursions in the Callovian, Tithonian, Valanginian and Aptian. These can be correlated to records elsewhere. Based on a literature survey it is discussed that particularly the Toarcian CIE, the Callovian CIE and the Aptian CIEs correlate to phases of oceanic anoxia (OAEs), which correlate to substantial hydrocarbon source-rocks elsewhere.

In addition, the consistent trends among wells pose potential for refining conventional (bio)stratigraphic correlations. It is suggested that particularly the Middle Jurassic and the Jurassic-Cretaceous boundary intervals can benefit from isotope correlations, also because respective biostratigraphic correlations are typically compromised by poor preservation and scarce microfossil assemblages.



The chronostratigraphically calibrated composite curve for the Middle Jurassic to Turonian of the Scotian Slope and Scotian Shelf wells. Age models for each well were constructed through linear interpolation using the tie-points discussed in Section 2.4. The timescale is that of Gradstein et al. (2020). The primary tie-points (Maximum Flooding Services, MFSs and Unconformities U/Cs) are indicated. The black line represents the 5-point moving average through the δ13C-timeseries. The red line through the Scotian Shelf timeseries is the 5-point moving average after deletion of Alma F-67 and Hesper P-52, which are affected by drilling additives and highly variable facies respectively (see Section 3.1). It is clear that the resultant qualitative trends are not substantially affected by this deletion. The grey arrows indicate coeval long-term trends observed in both the Scotian Slope and Scotian Shelf. For a more detailed interpretation the reader is referred to Section 4.2.



Well-correlation panel focusing on the Middle and Upper Jurassic. The shown well-logs are the gamma-ray (GR) and sonic velocity (DT). The fill-in of the log-track reflects the GR. Lithostratigraphic assignments on the formation level are also indicated. At the right of each track the δ13C-data are plotted. Correlative horizons are indicated by colored correlation lines. The section is flattened on the Near Base Cretaceous Unconformity (NBCU). The wells from the left to right side roughly follow a west to east directed transect from distal to more proximal wells.

Appendix 4

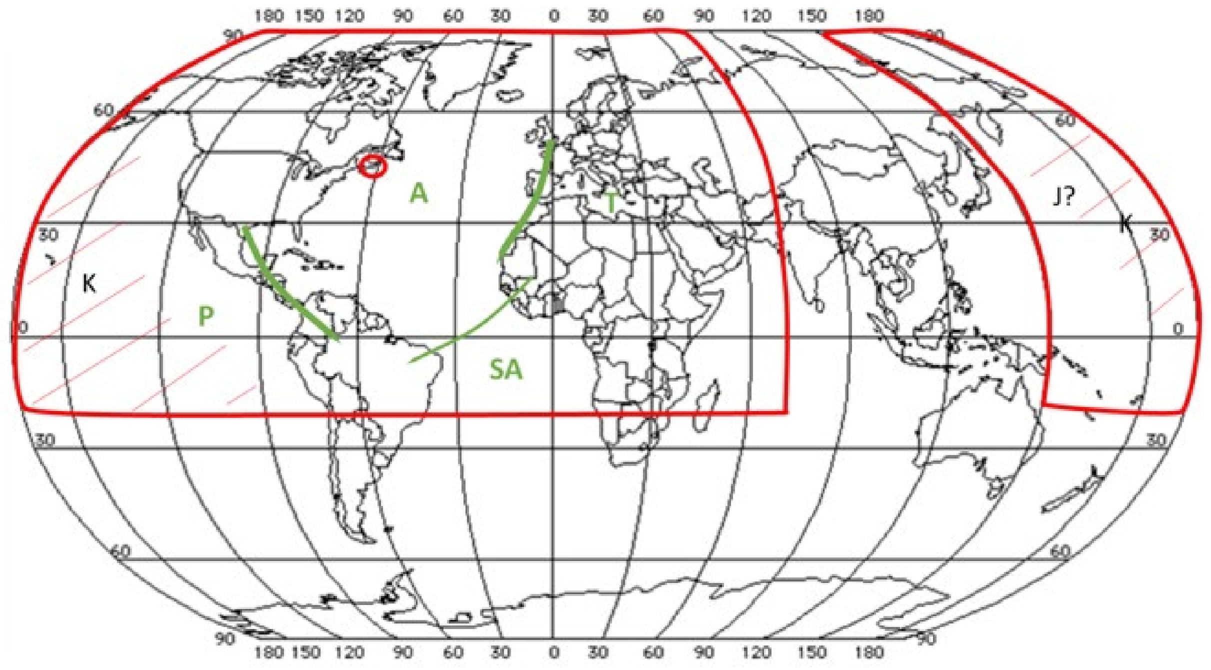
Paleogeography-to-Petroleum Systems: Research Innovations for Offshore Nova Scotia

Delgado et al. 2022

Available from: https://oera.ca/research/Spatiotemporal-Analysis-Paleobiogeographic-Data

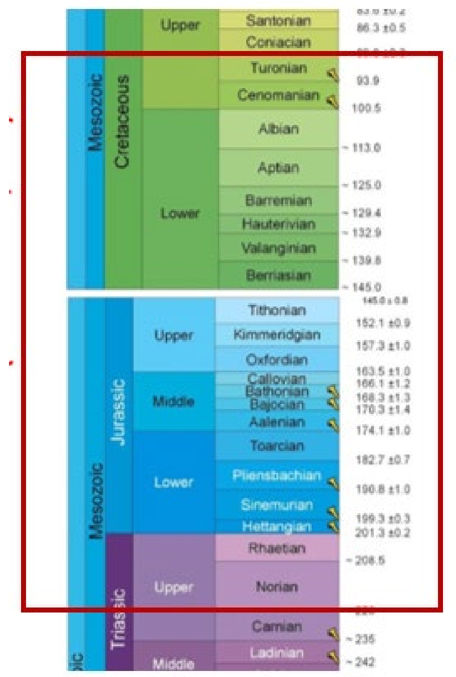
Collection scope (calcareous nannofossils)

GEOGRAPHICAL LIMITS



Latitude: 90°N to 20°S
Longitude: All, excluding 80°E to 150°E

CHRONOLOGICAL LIMITS



Norian to Turonian (~228 Ma – 89,8 Ma)

Data repository

Middle Jurassic to Early Cretaceous Calcareous Nannofossils from Onshore North Kuwait: A New Record

North Kuwait
ID: 356
Author(s): Adi Priyadi Kadar, Stephen Crittenden and Khalaf Abdulaziz Karam
Journal/ Publication: Fourth Arabian Plate Geology Workshop- Conference Paper
Year: 2012
IODP Report: 0
Scientific Paper: 0
Dissertations and Thesis: 0
Conferences: 1
Industry Report: 0
Institutional Report: 0

P2P Nova Scotia
Paleobiogeography to Petroleum Systems

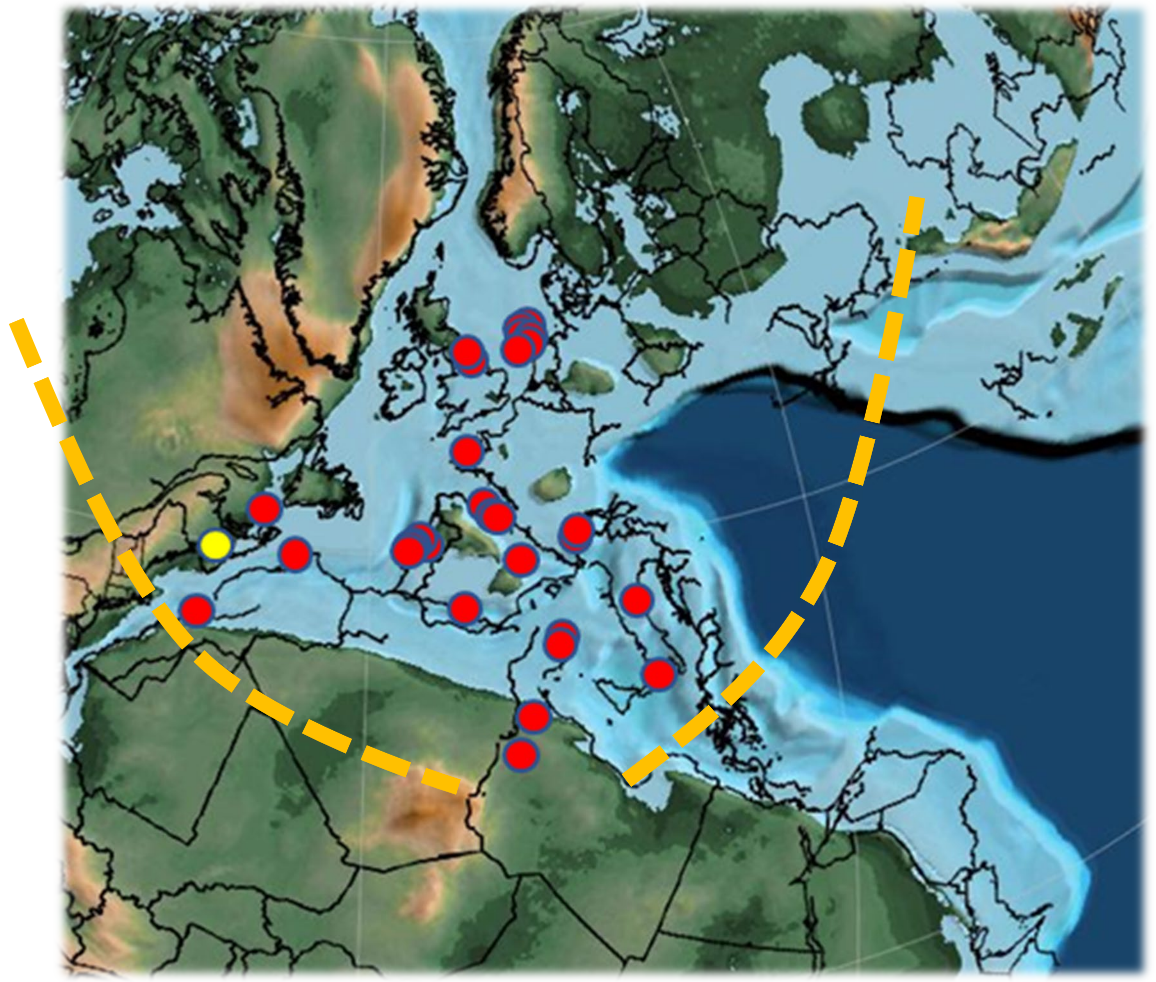
1195	940	648	254	67	12
TAXONS	SPECIES	LOCATIONS	DOCUMENTS	PUBLICATIONS	CONTRIBUTIONS

1178	416	1120	207	21	86	67	254
Location/ Stage	*Single Locations*	*Species/ Variants*	*Genus*	*Ages*	*Zones*	*Publications*	*Documents*

Main Goal

Use big data analytics and data science to zoom-in on best faunas, association and species-level proxies to model and date first water mass mix on two boundaries:

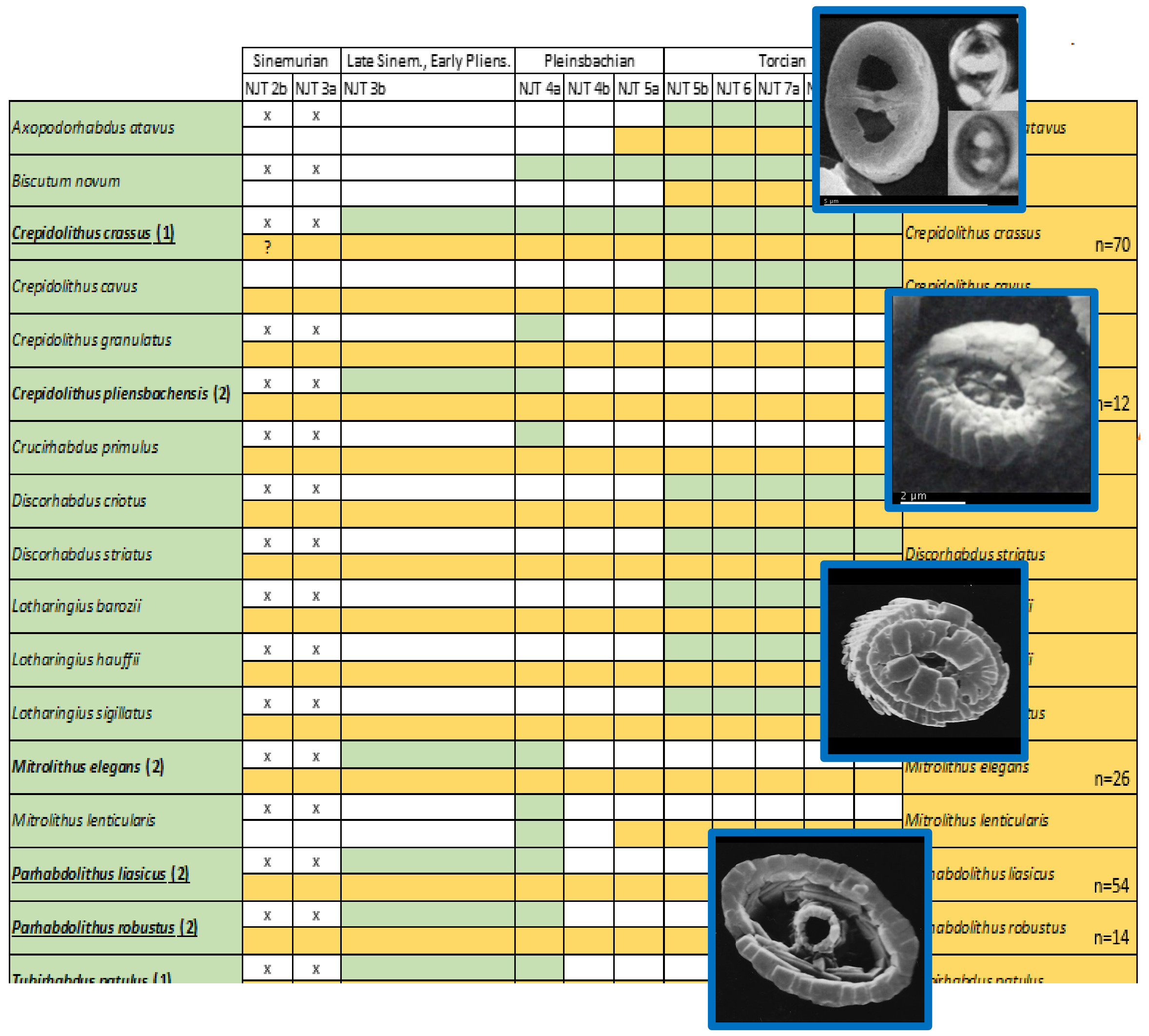
Tethys-Paleo Atlantic
Pacific-Paleo Atlantic



Main results

Best candidate proxies identified for each boundary. First water mass mixing between boundaries sooner than expected:

Tethys: 208.5 – 199.3 Ma
Pacific: (> ~189 Ma)



	NJT 2b	NJT 3a	
Axopodorhabdus atavus	x	x	*atavus*
Biscutum novum	x	x	
***Crepidolithus crassus* (1)**	x ?	x	*Crepidolithus crassus* n=70
Crepidolithus cavus			*Crepidolithus cavus*
Crepidolithus granulatus	x	x	
***Crepidolithus pliensbachensis* (2)**	x	x	n=12
Crucirhabdus primulus	x	x	
Discorhabdus criotus	x	x	
Discorhabdus striatus	x	x	*Discorhabdus striatus*
Lotharingius barozii	x	x	
Lotharingius hauffii	x	x	
Lotharingius sigillatus	x	x	
***Mitrolithus elegans* (2)**	x	x	*Mitrolithus elegans* n=26
Mitrolithus lenticularis	x	x	*Mitrolithus lenticularis*
***Parhabdolithus liasicus* (2)**	x	x	*abdolithus liasicus* n=54
***Parhabdolithus robustus* (2)**	x	x	*abdolithus robustus* n=14
***Tubirhabdus patulus* (1)**	x	x	*irhabdus patulus*

Paleogeography-to-Petroleum Systems: Research Innovations for Offshore Nova Scotia

Appendix 4

Palaeobathymetry and Tectonic Evolution of Lower Jurassic Source Rocks of the Conjugate Nova Scotia-Moroccan Margins

Geoffroy Mohn, Julie Tugend, and Nick Kusznir, 2023

Available from: https://oera.ca/research/Palaeobathymetry-Tectonic-Evolution-Lower-Jurassic-Source-Rocks

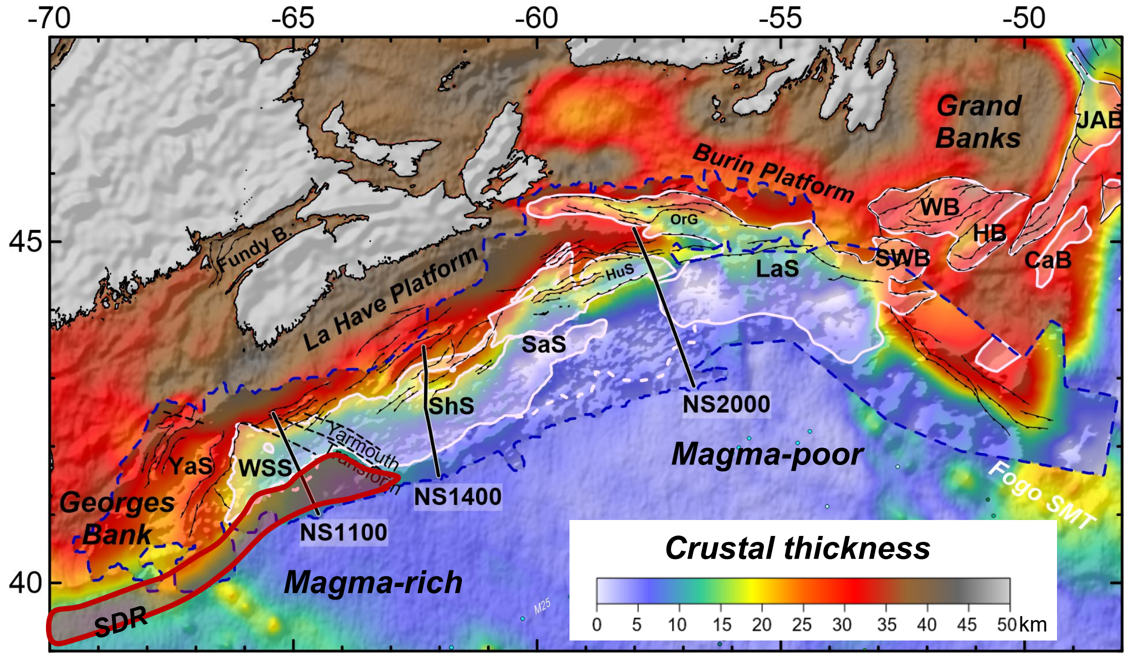
This project focused on investigating the formation processes and resulting structures, palaeobathymetry, subsidence history and segmentation of Lower Jurassic basins along the Scotian rifted margin and its Western Moroccan conjugate and the relationship to Western Tethys and southern North Atlantic.

This multidisciplinary project addressed three main objectives:

- Obj 1 - Constrain the crustal architecture of the conjugate Scotian and Western Morocco margins and the along strike variability in rifted margin magmatic type to investigate the distribution and connectivity of rift basins and their Lower to Middle Jurassic early post breakup subsidence history
- Obj 2 - Provide predictions of the palaeobathymetry and palaeostructure of the Scotian and Moroccan rifted margin and investigate the tectonic context related to the deposition of Upper Triassic evaporites and of the overlying Early to Late Jurassic sequences
- Obj 3 - Integrate the evolution of the Scotian rifted margin in the regional geodynamic context of the opening of the Central Atlantic, Western Tethys and southern North Atlantic

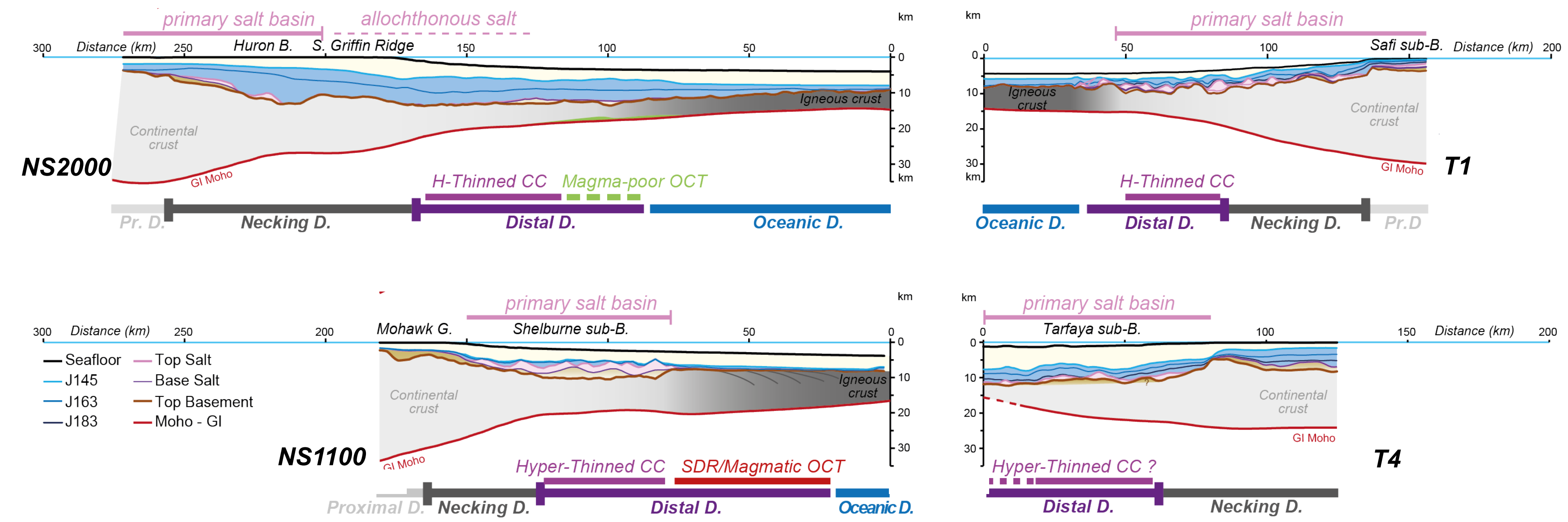
Objective 1 - Crustal structure of the conjugate Nova Scotian and Moroccan rifted margins

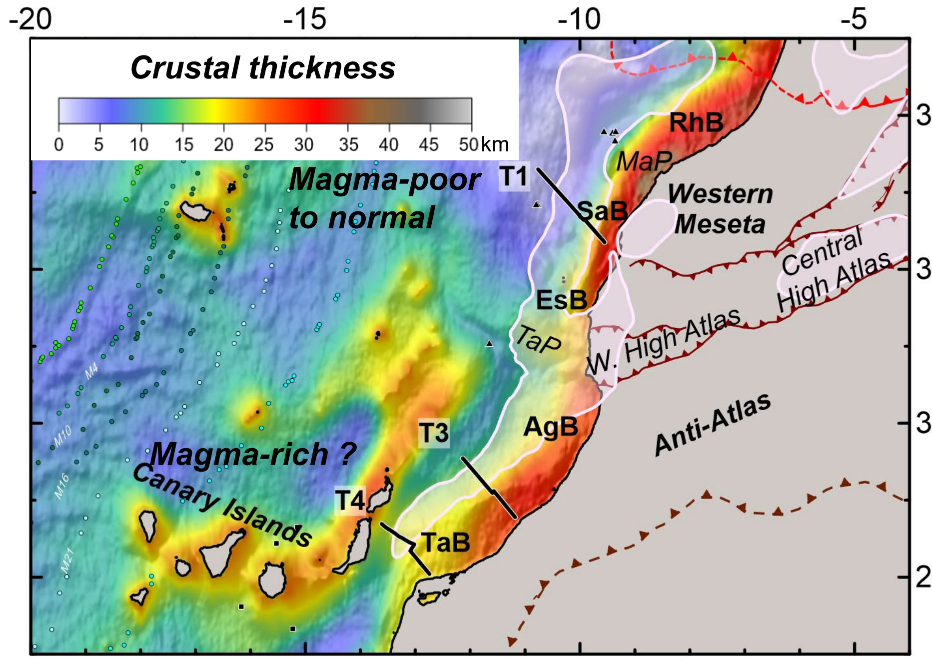
- Quantitative analysis of seismic reflection and gravity anomaly data together with residual depth anomaly analyses have been used to determine variations of crustal thickness and crustal type as well as volumes of magmatic addition emplaced during rifting and continental breakup.
- We show the magma-rich to magma-poor transition of the Nova Scotian margin, characterized by seaward dipping reflectors (SDRs) in the SW, while in the NE mantle is possibly exhumed.
- The northern Moroccan margin is magma-normal or possibly magma-poor. While the southern part might be expected to be magma-rich consistent with its Nova Scotia conjugate, the Neogene Canary Islands hotspot magmatism makes it difficult to confirm this.



Structures and salt province after: Deptuck & Kendell 2017

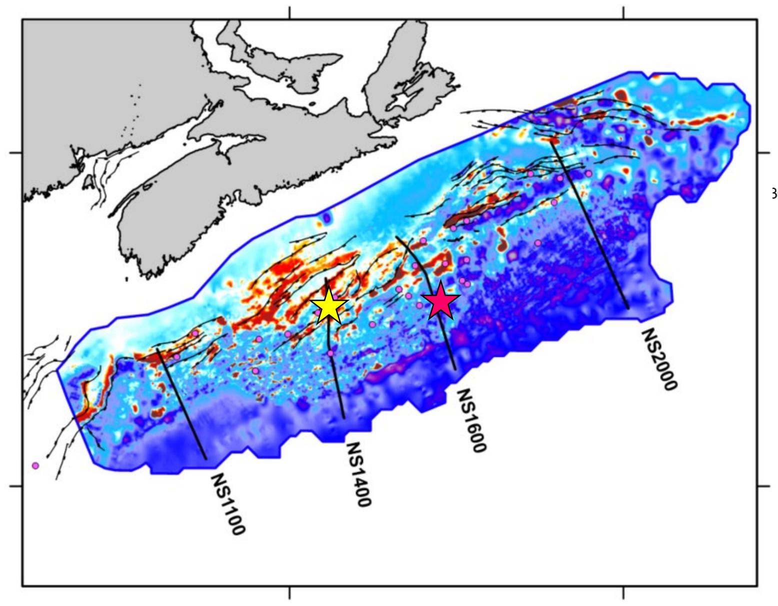
Nova Scotia margin ***Moroccan margin***



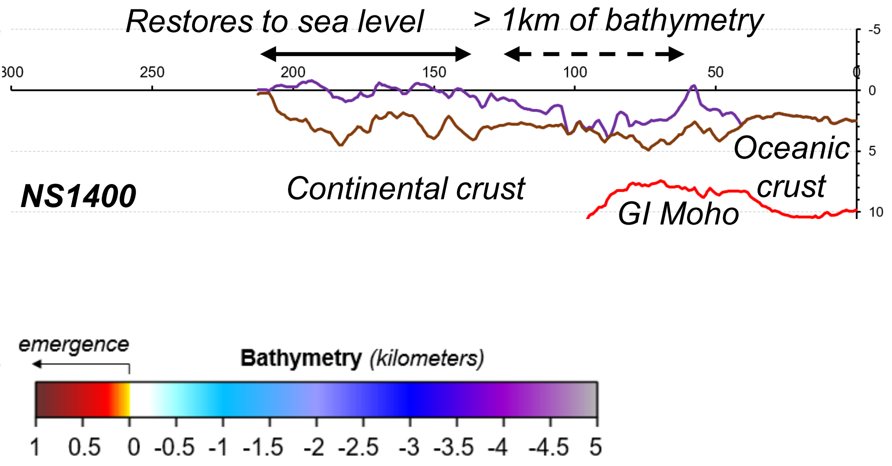


Salt province after Tari & Jabour 2013

Objective 2 – Palaeobathymetric predictions of the Scotian margin

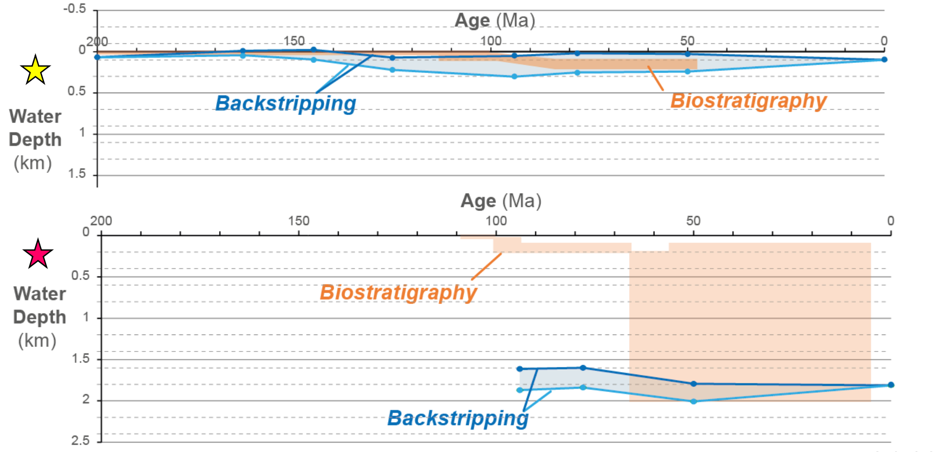


Palaeobathymetric predictions to base salt



- 3D flexural backstripping, which incorporates decompaction and post-breakup reverse thermal subsidence modelling has been applied to stratigraphic intervals through the Jurassic down to the Late Triassic base salt. Syn-tectonic subsidence is not restored.
- Comparison of our palaeobathymetric predictions with seismic observations and palaeoenvironments deduced from biostratigraphy of drilled samples agree over the continental shelf. As expected, discrepancies exist more distally related to salt withdrawal and sediment gravity-driven sliding.
- Palaeobathymetries predicted to base salt locally exceed 2 km in the distal parts of the margin. One possible explanation is that the distal salt was deposited during the latest stage of crustal thinning focused into the distal domain and underwent tectonic subsidence by crustal thinning in addition to post-rift thermal subsidence.

Comparison with drilling results



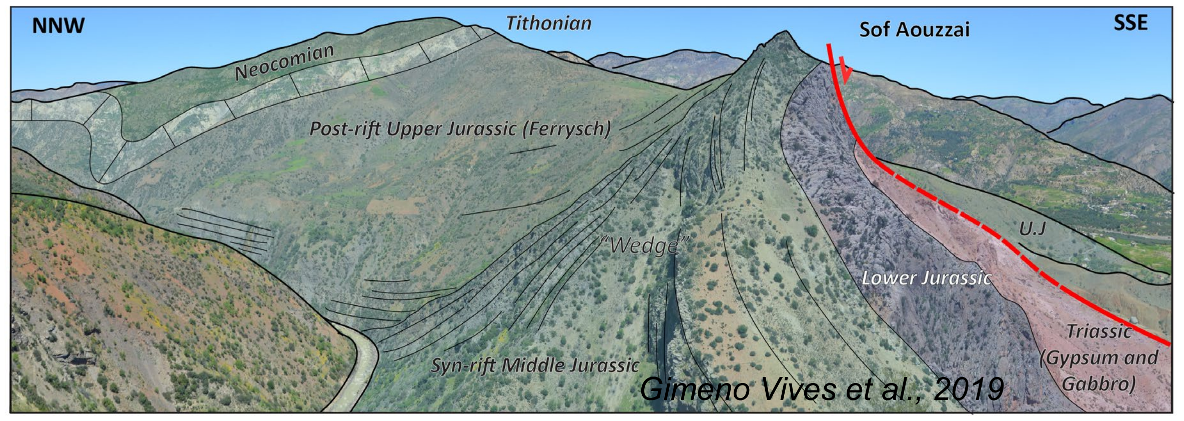
Biostratigraphic observations based on Weston et al., 2012

Objective 3 – The Scotian rifted margin in the context of the opening of the Central Atlantic, Western Tethys and southern North Atlantic

The Central Atlantic, Western Tethys and Southern North Atlantic oceans opened after a succession of Mesozoic rift events spanning from the Triassic to the Early Cretaceous that were recorded across North America, Africa, Iberia and Europe. We investigate the spatial and temporal interaction of the rift systems that preceded of the opening these three oceanic domains.

- Late Triassic-Earliest Jurassic rifting led to extreme lithospheric thinning and breakup between the Scotian and Western Moroccan margins. In the Central High Atlas, Middle Atlas, External Rif, Algarve and Alentejo Basins, Triassic extension only triggered minor crustal thinning.
- Early Jurassic (until the Pliensbachian) corresponds to a period of the tectonic quiescence.
- Late Early Jurassic-Middle Jurassic rifting is associated to a migration of extension towards the NE in the Western Tethys. The structural style of this episode is largely influenced by the Upper Triassic evaporitic sequence in the external Rif and in the Gulf of Cadiz. This rifting culminates in the Callovian associated with the exhumation of lithospheric mantle and continental breakup of the Western Tethys.
- Late Jurassic (Oxfordian?)-Early Cretaceous rifting focused north of the Central Atlantic between Eastern Canada (Newfoundland) and Western Iberia and lead to the opening of the southern North Atlantic.

Salt roller geometry in the fossil North African margin *(external Rif)*



Gimeno Vives et al., 2019