Predictive modelling of sandstone reservoir quality in the Scotian Basin

Final Report

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2. Summary

Reservoir Quality is an OERA Geoscience Research Priority. We have collaborated with Beicip-Franlab in improving regional prediction of reservoir quality by a modelling approach using their forward stratigraphic model *DionisosFlow*. This has been accomplished by a Nova Scotian M.Sc. student, Chris Sangster, who has taking our existing knowledge of inferred drainage basin areas (from provenance information) and paleoclimate (based on geochemical indicators) to model multiple river inputs to the central Scotian Basin. The modelled sedimentary succession is compared with actual sediment thicknesses and facies in the basin, already compiled for the PFA. The input sediment load provided by rivers is based on global relationships of load to drainage basin parameters, further constrained by (a) present distribution of bedrock in the paleo-drainage basins, for availability of coarse and fine sand, (b) our detrital mineralogy and geochemistry data that indicate specific source rocks, and (c) paleoclimate information. The objective was to develop a model that would accurately simulate regional thickness variations of sedimentary units and lithofacies distribution in reference wells. This model was then used to test various hypotheses related to sand dispersion in parts of the basin lacking lithofacies calibration, with particular emphasis on the distribution of deep-water sands. Mass-balance calculations derived from modelling results confirms that the shaly nature of the Naskapi Member is the result of tectonic diversion of the Sable river and suggests additional episodic diversion during the Cree Member. Sand is dominantly trapped on the shelf in all units, with transport into the basin along salt corridors and as a result of turbidity current flows in the Upper Missisauga Formation and Cree Member. This led to sand accumulation in minibasins, with the largest deposit seaward of the Tantallon M-41 well. Sand by-passes the modelled area of the basin via salt corridors, suggesting the presence of some ultra-deep sandstone reservoirs. Modelling has provided baseline estimates of rates of sediment supply from known river catchment areas under Early Cretaceous climatic conditions that can be applied to modelling other areas, such as the Shelburne sub-basin, in which much fewer calibration data are available.

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4. Introduction

Reservoir Quality was the third priority in the list of OERA Geoscience Research Priorities in 2016, when this project was proposed. We had been approached by Beicip-Franlab to collaborate in improving regional prediction of reservoir quality, particularly in undrilled areas, by a modelling approach using their forward stratigraphic model *DionisosFlow*. Peer reviews of the PFA and follow-up studies have consistently raised questions about sediment sources and resulting reservoir quality prediction. These are also questions being asked in other basins. We supervised a Nova Scotian M.Sc. student, Chris Sangster, to carry out this modelling study.

The provenance of deltaic sediment in the clastic reservoir intervals of the Scotian Basin is exceptionally well known in comparison to most other petroleum basins, and comparable to the North Sea, as a result in investments by OERA and its predecessors (as summarized by Zhang et al, 2014). Nevertheless, calibration of models required some additional provenance data from under-represented stratigraphic intervals.

The objective of the modelling study was to develop a model that would accurately simulate regional thickness variations of sedimentary units (known from seismic mapping for the

PFA) and lithofacies distribution in reference wells (Fig. 1). This model was then used to test various hypotheses related to sand dispersion in the basin, with particular emphasis on the distribution of deep-water sands.

In order to have a model of manageable size and adequate resolution, the study was restricted to the Sable sub-basin and its deep-water continuation. The modelled grid had a spatial resolution of 5 x 5 km, extending from Newburn H-23 in the west to Tantallon M-41 in the east. The model was run from 130 Ma to 101 Ma (Upper Missisauga Fm to Cree Member) at 0.5 Ma time steps.

The results of this study were anticipated to (1) improve prediction of regional reservoir quality risk in the deep-water Scotian Basin and (2) improve modelling protocols and input parameters so that reservoir quality can be predicted in undrilled frontier basins, such as the southwestern part of the deep-water Shelburne sub-basin. Methodological improvements in reservoir quality prediction were expected to be of interest to both the academic community and to petroleum E&P and service companies.

5. Discussion of Methodology, Objectives and Results

Methodology:

In this study, stratigraphic modeling was conducted using *DionisosFlow*™, a diffusion based, deterministic 4D multi-lithology forward stratigraphic modeling software, which simulates basin infilling over geological time scales by tracking particles with differing diffusion coefficients during the evolution of the basin (Granjeon 2014). Using this information, the net product of sediment supply, transport, uplift, subsidence, and sea level fluctuation in large scale sedimentary systems is recreated. Produced models are then analysed using *CougarFlow*™, a statistical software which uses Response Surface Modeling (RSM) and Monte-Carlo statistical analysis to analyse multiple *DionisosFlow* models to asses the impact of various simulation parameters, and determine areas of increased sensitivity (Agrawal et al. 2015; Hawie et al. 2015).

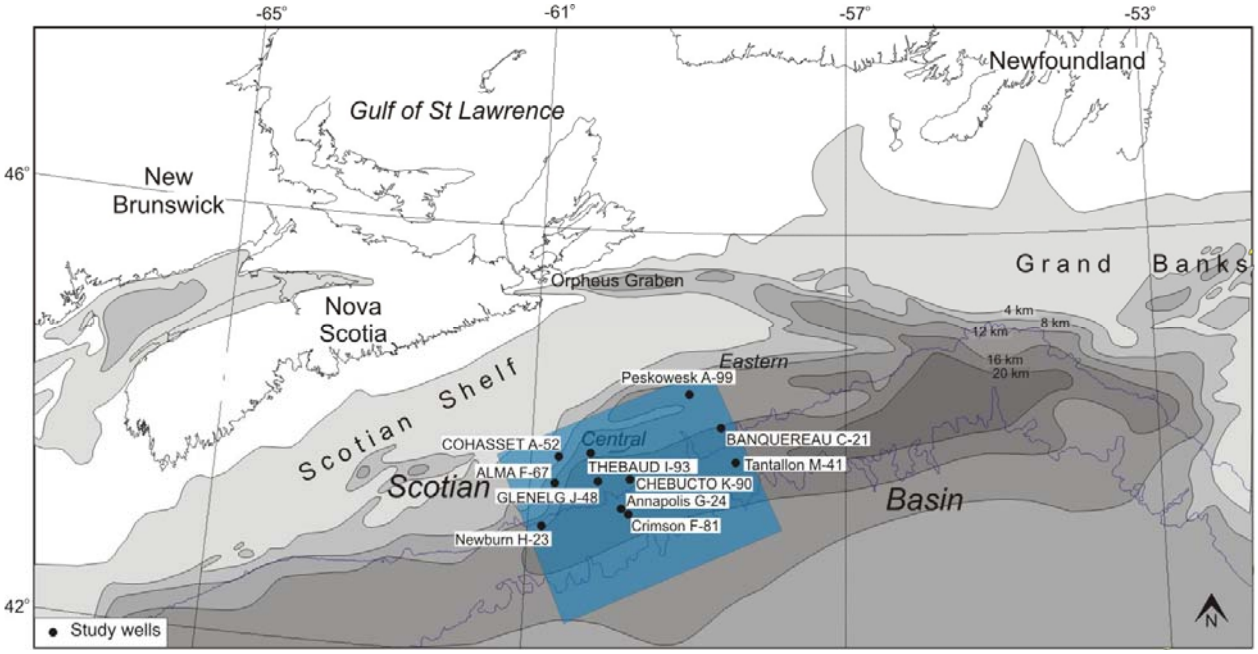

Figure 1. Map of Scotian Basin showing study area (blue).

The study area is a 185 km x 215 km region of the central Scotian Basin (Fig. 1). This area has the highest density of deep-water wells in the Scotian Basin, and covers a range of salt-tectonic domains (Kendell 2012). This study focuses on the Early Cretaceous reservoir sandstone units from the base of the Barremian (130 Ma) to the top of the Albian (101 Ma). This age span, which includes the Upper Missisauga Formation and the Naskapi and Cree members of the Logan Canyon Formation (Fig. 2), is the interval of producing reservoirs in which basin-scale correlation of seismic markers is possible. Modelling was carried out on a 5x5 km grid at 0.5 Ma time steps.

Information regarding the catchment areas (size and relief), sediment properties (grain size and density), and basin properties (bathymetry) during the study time are of particular importance as system inputs (Hawie et al. 2017). The use of these properties allows for the creation of models which are predictive within a known degree of uncertainty, and can be used to better understand the evolution of sediment sources through time, the impact of changes in source composition, improve our knowledge of sediment transport pathways within the basin, and also predict the distribution of potential reservoir units in the study area. This modeling is used to test; 1) if provenance pathways based on sandstone petrology (Pe-Piper et al., 2014; Zhang et al. 2014) are validated by observed sediment distribution and sediment supply; 2) what proportion of sands were trapped on the slope or bypassed to the deep ocean floor; and 3) what external factors (e.g. climate, salt tectonics, changing sediment supply from river catchments) control the distribution of sands within the study area.

A number of methodological problems were encountered with the modelling. (1) This is the first modelling of its type to be carried out in an area of active salt tectonics, and various work-arounds were developed to deal with salt movement. (2) Lateral facies variation in coastal depositional environments is on a length scale much smaller than the model grid size. For this reason, calibration of the model to some individual wells was poorer than desirable. (3) The goal of modelling feldspar dispersion was complicated by circular reasoning relating to the extent to which observed feldspar grain size and abundance was a consequence of diagenetic breakdown and dissolution. The degree of success in predicting reservoir quality based on susceptibility to feldspar diagenesis is still being assessed. On the other hand, the modelling has been successful in providing predictions on the distribution of reservoir sands in the basin and estimating how much sediment has bypassed the study area into ultra-deep water (>3000 m).

Because of the importance of feldspar in this study, as a guide to the influence of diagenesis on reservoir quality, additional petrographic data was required on feldspar distribution in the basin. Existing data was based on point counting of petrographic thin sections from widely spaced conventional core (Pe-Piper, 2016). Any use of feldspar abundance as an input parameter to modelling required a continuous stratigraphic record of feldspar abundance. We considered, but rejected, analysis of cuttings either by pXRF because of the lack of a distinctive chemical signature in mixed shales and sandstones, or by physical separation of sand because of extreme dilution by rock chips. Eventually, we negotiated with the CNSOPB sample repository to sample friable loose sand that had accumulated in the vials that contained sidewall cores. Some 54 samples of this type, from 12 different wells, were analysed in this way. Polished thin sections were made from these sands and a work-flow was developed to make X-ray maps on the scanning electron microscope (SEM) and analyse abundance and grain size of feldspar using MultiSpec software, building on the earlier procedures of Zhang et al. (2015).

Objectives:

The overall goal of the project was to obtain a predictive model for reservoir quality risk at a regional scale in the central Scotian Basin. The modelling was originally set up to test the hypothesis that sediment provenance influence on reservoir quality in the Scotian Basin can be modelled using variation through time in supply from three principal sources: (a) an immature Meguma terrane source that has been recognised as contributing to Panuke and Alma and is dominant at Mohican and Mohawk; (b) a texturally more mature source from the Carboniferous Maritimes Basin (circum-Gulf of St Lawrence) and southern Labrador, with abundant polycyclic quartz and pluton-derived quartz, that is the principal source to the Sable sub-basin; and (c) a source with a higher proportion of metamorphic quartz and K-feldspar derived from a discrete Banquereau River draining through the Humber Valley of western Newfoundland and probably other smaller rivers from central Newfoundland (Tsikouras et al., 2011; Pe-Piper et al., 2014; Zhang et al., 2014).

As the study evolved, the greatest emphasis was placed on: (a) predicting the grain size and distribution of sand in the deep water basin; (b) evaluating what input parameters have greatest impact on the sensitivity of the model; and (c) understanding the distribution of feldspar in the basin at the scale used for modelling.

Results:

The principal results will be publicly available in an M.Sc. thesis by Chris Sangster, that will be completed and defended early in 2019. The principal findings are presented in a paper to be published in the journal Basin Research once very minor corrections have been made. The abstracts for this paper is given below:

Forward stratigraphic modeling of sediment pathways and depocentres in a basin dominated by salt tectonics: Lower Cretaceous, central Scotian Basin.

Sangster C., Piper D.J.W., Hawie N., Pe-Piper G., and Saint-Ange F., 2019. *Basin Research* (accepted pending very minor revisions)

Abstract: Source-to-sink studies and numerical modeling software are increasingly used to better understand sedimentary basins, and to predict sediment distributions. However, predictive modeling remains problematic in basins dominated by salt tectonics. The Lower Cretaceous delta system of the Scotian Basin is well suited for source to sink studies and provides an opportunity to apply this approach to a region experiencing active salt tectonism. This study uses forward stratigraphic modeling software and statistical analysis software to produce predictive stratigraphic models of the central Scotian Basin, test their sensitivity to different input parameters, test proposed provenance pathways, and determine the distribution of sands in the basin and the factors that control their distribution.

Models have been calibrated against reference wells and seismic surfaces, and implement a multidisciplinary approach to defining simulation parameters. Simulation results show that previously proposed provenance pathways for the Early Cretaceous can be used to generate predictive stratigraphic models, which simulate the overall sediment distribution for the central Scotian Basin. Modeling confirms that the shaly nature of the Naskapi Member is the result of tectonic diversion of the Sable and Banquereau rivers and suggests additional episodic diversion during the deposition of the Cree Member. Sand is dominantly trapped on the shelf in all units, with transport into the basin along salt corridors and as a result of turbidity current flows occurring in the Upper Missisauga Formation and Cree Member. This led to sand accumulation in minibasins with a large deposit seaward of the Tantallon M-41 well. Sand also appears to by-pass the basin via salt corridors which lead to the down-slope edge of the study area. Sensitivity analysis suggests that the grain size of source sediments to the system is the controlling factor of sand distribution. The methodology applied to this basin has applications to other regions complicated by salt tectonics, and where sediment distribution and transport from source-to-sink remain unclear.

Chris also did a lot of work on the distribution and character of feldspars in the Scotian Basin that is being written up in his thesis. Feldspar abundance shows stratigraphic variations that may be related to climate change in the hinterland, with more arid conditions favouring feldspar supply. Feldspars become finer grained and less abundant, presumably due to diagenetic effects, in more deeply buried strata. A full evaluation of the data will be available once his thesis is completed in March 2019.

In the first year of his M.Sc. work, Chris gained experience in scientific publishing and dissemination of results by helping write up a paper on some of the results of his B.Sc. honours thesis, on detrital petrology and diagenesis at the Newburn H-23 well. This was published in 2017 in the journal *American Mineralogist* (Pe-Piper et al. 2017).

6. Dissemination and Technology Transfer

Chris gave an oral presentation on this project at the Atlantic Geoscience Society meeting in February 2018. He presented to the CSPG core conference in Calgary in May 2018. He has also presented to the Canada-Nova Scotia Offshore Petroleum Board and to a Statoil representative (Ian Lunt), both of whom have been very helpful with advice. He won an award at the Conjugate Margins Conference in August 2018 for his talk on modelling sand distribution in the central Scotian Basin. Chris provided technical details for an OERA Webinar given by David J.W. Piper in December 2018. We have maintained informal communication with NSDoE. The results of his work will be widely disseminated in his journal publication.

Chris advised Dr Alex Normandeau of the Geological Survey of Canada (Atlantic) on the use of *DionisosFlow* for modelling response of late Pleistocene deltas to sea level change, and has also assisted new M.Sc. student Justin Nagle. Further dissemination of *DionisosFlow* technology is limited by the licencing conditions of the software at Saint Mary's University.

Chris applied his broad petroleum geology experience during a 4-month internship with ExxonMobil in St Johns in the fall of 2018.

7. Conclusions and Recommendations

Stratigraphic models of the Central Scotian Basin have been produced using *DionisosFlow*, forward stratigraphic modeling software, and analysed *CougarFlow*, statistical analysis software. These models were calibrated on the basis of reference wells and seismic surfaces, with parameters drawn from previously conducted sedimentological and geophysical studies. The generation of these models has been complicated by the high degree of facies variability present on a fine spatial scale in regions with complex depositional history, and the presence of salt tectonics in the region which are difficult to constrain and have been approximated in this study using unit thickness. Despite these complications, the reference case models have been calibrated to capture the major trends of sediment distribution for the Upper Missisauga Formation (Barremian), Naskapi Member (Aptian), and Cree Member (Albian). The simplified approach to modeling of salt bodies on the basis of preserved sediment thickness and subsidence has the potential to be applied to other basins where salt tectonics were actively controlling sediment distribution, but where the rate of withdrawal of salt bodies is not well known, such as in the Gulf of Mexico.

The high degree of both thickness and facies calibration present on a basin wide scale, suggest that provenance pathways proposed in the literature for the Early Cretaceous are correct. Sediment supply suggests that the Naskapi Member likely formed as the result of tectonic diversion of the Sable River and Banquereau rivers, and the decrease in sediment supply to the Cree Member compared to the Upper Missisauga Formation, despite a lack in changes to the catchment areas, also suggest episodic diversion of these rivers during the Albian. The sediment budget methodology applied to this study can be used in other regions where sediment routing systems are ambiguous or where the origin of highstand shale units is contested.

Sand distribution maps and sensitivity analyses suggest that sand is distributed dominantly on the shelf, with transport to the basin occurring in salt withdrawal corridors by turbidity current flows. This study predicts that there likely are accumulations of sandy sediments seaward of the Alma F-67, Annapolis G-24, and Crimson F-81 wells, with a large deposit seaward of the Tantallon M-41 well in both the Upper Missisauga Formation and Cree Member. Extended area simulations show sand transport beyond the study area, suggesting that there is potential for exploration in the deep basin. This demonstrates how forward stratigraphic modeling can be applied where depositional settings are controlled by salt tectonism. Sensitivity analysis also shows that sand distribution is controlled by source composition, particularly the Sable River in the Barremian and Albian, and the Meguma Terrane source during the Aptian. Understanding the causes for variations in sediment delivery to the basin is therefore important in predicting the distribution of reservoir units.

Modelling of the central Scotian Basin has provided baseline information on rates of sediment supply from known catchment areas under climatic conditions prevailing in the Early Cretaceous. These estimates can be applied to modelling other areas, such as the Shelburne sub-basin, in which much fewer calibration data are available. The results also suggest that more sand is trapped in minibasins than has been interpreted from seismic west of the study area by Moscardelli et al. (2019): this apparent contrast will be followed up by further interaction with Statoil geologists. The mass-balance calculations derived from the *DionisosFlow* modelling of the central Scotian Basin have provided new impetus to assessing westward diversion of the Sable River to the Alberta oil sands deposits (Piper et al., 2018), which is being followed up with analysis of Pb-isotopes in detrital feldspar from the McMurray Formation.

8. Publications

Sangster, C.R, Hawie, N., Pe-Piper, G., Saint-Ange, F. and Piper, D.J.W., 2018. Application of Predictive Modeling to the Lower Cretaceous Sedimentary Sequences of the Central Scotian Basin. CSPG Annual Convention (extended abstract)

Sangster, C.R, Hawie, N., Pe-Piper, G., Saint-Ange, F. and Piper, D.J.W., 2018. Application of Predictive Modeling to the Lower Cretaceous Sedimentary Sequences of the Central Scotian Basin. Conjugate Margins Conference, Halifax, Aug. 2018 (abstract).

Sangster C., Piper D.J.W., Hawie N., Pe-Piper G., and Saint-Ange F., 2019. Forward stratigraphic modeling of sediment pathways and depocentres in a basin dominated by salt tectonics: Lower Cretaceous, central Scotian Basin. Basin Research (accepted pending very minor revisions)

Pe-Piper, G., Sangster, C. and Zhang, Y., 2017. Diagenetic F-rich ferroan calcite and zircon in the offshore Scotian Basin, eastern Canada: Significance for understanding thermal evolution of the basin. American Mineralogist, 102(7), 1542–1555.

Sangster, C., Pe-Piper, G., Saint-Ange, F., Piper, D.J.W. and Hawie, N., in prep. Significance of detrital feldspar for sandstone reservoir quality in the Scotian Basin.

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Tsikouras, B., Pe-Piper, G., Piper, D.J.W., & Schaffer, M. (2011) Varietal heavy mineral analysis of sediment provenance, Lower Cretaceous Scotian Basin, eastern Canada. Sedimentary Geology, 237, 150-165.

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