Additional "sedimentological" work to contribute to the PFA programme in the Upper Jurassic–Lower Cretaceous clastic systems, Scotian Basin

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1. Summary

This project was intended to provide critical information for the Play Fairway Analysis on the Upper Jurassic–Lower Cretaceous clastic reservoir rocks of the Scotian Basin. Although the scientific objectives were varied, most of the studies involved work that could only be done reliably on conventional core. The objectives and first year deliverables of the study were:

Workpackage 1A. Sand provenance and diagenesis: sources and delivery of sand to the basin. OBJECTIVE: sub-basin and member scale understanding of sources and delivery of sands to the basin, characterized chemically and mineralogically. YEAR 1 DELIVERABLES: sub-basin and member scale overview of sources and delivery of sands to the basin.

Workpackage 1B. Sand Provenance and diagenesis: impact of detrital petrology on reservoir quality. OBJECTIVE: sub-basin and member scale understanding of impact of detrital petrology on diagenesis. YEAR 1 DELIVERABLES: general understanding of impact of detrital petrology on diagenesis at a sub-basin and member scale.

Workpackage 2. Diagenetic processes and fluid flow in the basin. OBJECTIVE: Relate the record of fluid flow that is preserved in fluid inclusions to the diagenetic evolution of the basin. YEAR 1 DELIVERABLES: Interpretation of fluid inclusion data (in collaboration with Hanley contract).

Workpackage 3. Cretaceous volcanism and heat flow. OBJECTIVE: compile and understand the various lines of evidence for a thermal effect related to Early Cretaceous volcanism and its precise timing and extent. YEAR 1 DELIVERABLES: Synthesis of evidence for the distribution and timing of volcanism and other evidence of high heat flow in the Early Cretaceous of the Scotian Basin.

Workpackage 4. Depositional systems. OBJECTIVE: understand nature of lithofacies in conventional core based on new ideas relating to delta-front turbidites. Provide advice and interaction with consultant doing seismic correlation and log interpretation. YEAR 1 DELIVERABLES: Available good quality conventional core from the Upper Jurassic–Lower Cretaceous conventional rocks has been logged and interpreted in terms of facies.

We have met these deliverables and our data have provided the following critical information for the Play Fairway Analysis. (1) Detailed lithofacies interpretation from conventional core to validate interpretations of depositional environments made from well logs. (2) A stage-by-stage interpretation of the changing sources on input to the Scotian Basin, contributing to basin modeling. (3) A predictive understanding of major features of diagenetic cements and thus reservoir quality. (4) Data on the entrapment temperature, salinity and hydrocarbon content of fluid inclusions in diagenetic cements, which indicate a mid-Cretaceous thermal event, and provide ground truth for validating models of thermal evolution of the basin. (5) A reinterpretation of the Lower Cretaceous volcanism and related basement tectonics that provides regional context for the development of Lower Cretaceous reservoir rocks.

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3. Introduction

This project was intended to provide critical information for the Play Fairway Analysis on the Upper Jurassic–Lower Cretaceous clastic reservoir rocks of the Scotian Basin. Although the scientific objectives were varied, all the studies involved work that could only be done reliably on conventional core. The availability of conventional core and its distribution in the basin thus presents a limit to the work. One major work package was to log those conventional cores in the appropriate intervals that had not been described during our previous work. Samples taken during this logging for further analysis were thus well positioned within a consistent lithofacies scheme. These lithofacies interpretations have constrained the well log interpretations of lithofacies by BEICIP.

New and previous samples have been used for three main objectives:

(a) to constrain the sediment sources and pathways to the basin and the variation in composition of the sediment deposited.
(b) to describe and interpret the regional variability in diagenetic cements and hence reservoir quality.
(c) to track thermal and fluid history in the basin from fluid inclusions in diagenetic cements.

A new study of the volcanic rocks of the basin and other evidence for thermal events in the Early Cretaceous was completed. Interpretation of the volcanic history is closely tied to basement tectonics, which in turn influenced detrital sediment supply and perhaps the location of thermal anomalies in the basin along major NE-trending faults.

Our work has been iteratively integrated with the BEICIP seismic and well interpretation and the new RPS biostratigraphy. Some key results have only become available in the last month and interpretation of the data summarized here will continue during the second year of this project. Nevertheless, we are confident that most of the summary presented here is robust and we have indicated where uncertainty remains. As OETR and RPS have not yet taken the decision on the final format for summary reports to accompany the PFA atlas, and as our synthesis work is continuing in year 2 of the project, we have provided brief summaries of the results in each part of this project. More lengthy accounts are available in present and forthcoming journal papers, open file reports and theses.

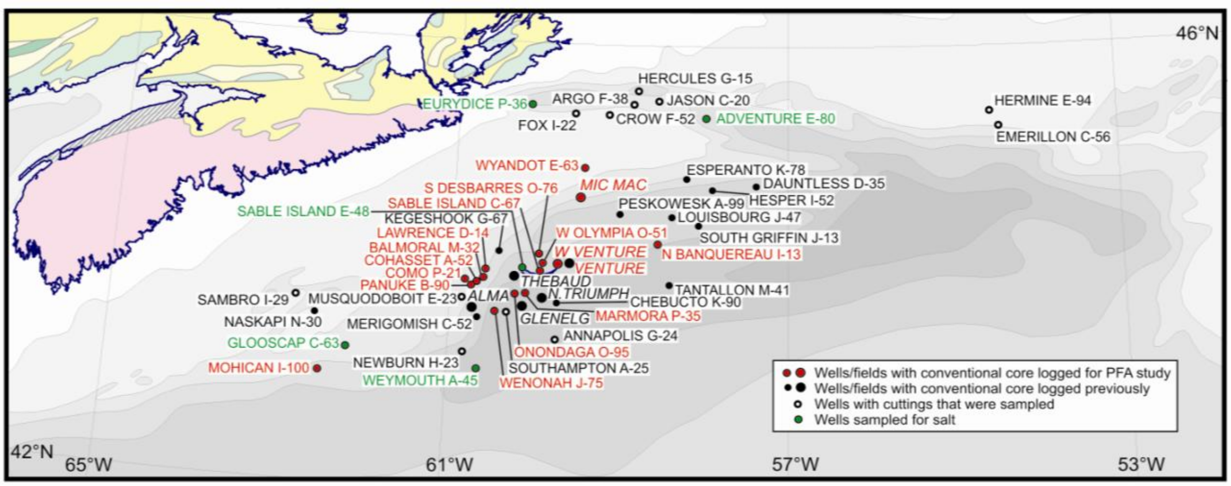

Figure 1. Map with the studied wells including the conventional cores logged as part of this project (in red).

4. Objectives, Methodology and Results

4.1 Objectives

The objectives of the study run over two years, generally with a deliverable in Year 1 of immediately necessary results and interpretations, followed by a more considered and thorough interpretation in Year 2. The objectives are summarized in this section. In subsequent sections, we present for each major objective the activities completed, a summary of existing documentation, and a summary of the results.

Workpackage 1A. Sand provenance and diagenesis: sources and delivery of sand to the basin. OBJECTIVE: sub-basin and member scale understanding of sources and delivery of sands to the basin, characterized chemically and mineralogically. YEAR 1 DELIVERABLES: sub-basin and member scale overview of sources and delivery of sands to the basin.

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Workpackage 4. Depositional systems. OBJECTIVE: understand nature of lithofacies in conventional core based on new ideas relating to delta-front turbidites. Provide advice and interaction with consultant doing seismic correlation and log interpretation. YEAR 1 DELIVERABLES: Available good quality Upper Jurassic–Lower Cretaceous conventional core logged and interpreted in terms of lithofacies.

4.2 - Sources and delivery of sand to the basin

4.2.1 Activities

Detrital muscovite currently underway with Peter Reynolds (Dalhousie); sampling completed, all but one date received, and preliminary interpretations made. Methodology as in Reynolds et al. (2009).

U-Pb zircon dates. Additional dating work on zircon almost completed, awaiting one final date. Data have been used to assess the role of polycyclic sediment supply from the Carboniferous (see Pe-Piper and Piper, 2010a), with implications for reworked vitrinite reflectance data. Methodology in Piper et al. (in prep.).

Additional Sm/Nd isotopes. Additional samples collected, submitted to lab and data received March 2011, and preliminary interpretation have been made.

Sub-basin and member scale understanding of sources and delivery of sand to the basin. New microprobe work done on Louisbourg, Esperanto, Kegeshook, MicMac, Mohican and Wyandot; and preliminary interpretations have been made. Methodology for using detrital minerals and geochronology is summarized in the Pe-Piper August 2010 final report to OETR; also in Pe-Piper et al. (2009), Triantaphyllidis et al. (2010) and Tsikouras et al. (2011).

4.2.2 - Analytical method for detrital minerals

Analytical method for detrital minerals

Core sample preparation

Subsamples were cut from the outside of conventional core. Loosely cemented samples were broken up by hand; well cemented samples were crushed until all particles passed through a 250 mm sieve. A few sandstone samples from the Scotian Basin were only loosely cemented (Table 1) and were disaggregated by rubbing between the fingertips. More lithified sandstones were cleaned of any drilling contaminants, cut into cm sized chips, and gently crushed with a pestle and mortar with crushing rather than a grinding action. A 0.5 mm sieve was used to remove the material that did not need 188 further crushing and the > 0.5 mm material was further crushed. After everything had passed through the 0.5 mm sieve, the 63–177 μm fraction was separated.

Heavy minerals were separated with an aqueous solution of sodium polytungstate prepared to a specific gravity of 2.9. The dry heavy minerals were mounted in epoxy resin and the mounts were subsequently polished.

Cutting sample preparation

Cutting samples were washed with warm water through a 63 mm sieve to remove any unwanted material (mud and oil from the drilling). Samples were then sieved at 2 mm, allowing the separation of the grains into two classes: >63 mm to <2 mm and >2 mm. “Heavy mineral” separation was performed on all sub-samples for the >63 mm to <2 mm fraction using the heavy liquid tetrabromoethane, which has density of 2.9 g/ml. The heavy separates of this fraction were then used to make polished thin sections. Polished thin sections of the heavy separates of the >63 mm to <2 mm grains were made for all available samples. For samples with bimodal sizes and enough heavy separates from both size classes, two polished thin sections were made, one for the finer fraction (F) and one for the coarser fraction (C). The grain size and preliminary identification of mineralogy/lithology of cutting grains was done using a polarized/reflected light petrographic microscope and subsequently refined with the use of an electron microprobe and/or scanning electron microscope.

Microprobe analysis

Polished thin sections were analysed at the Regional Electron Microprobe Centre located at Dalhousie University to find composition of both detrital and diagenetic minerals. The microprobe used is a JEOL-8200 electron microprobe with five wavelength spectrometers and aNoran 133 eV energy dispersion detector. The beam was operated at 15kV and 20nA, with an average beam diameter of 5 mm. Elements set up to be measured were Si, Al, Ti, Cr, Fe, Mn, Mg, Ca, Na, K, P, Zr, and Ba. The energy dispersive spectrometer (EDS) was used for fast and easy identification of minerals such as quartz, calcite, barite, rutile, and staurolite. It was also used to find elements not set up to be measured by the microprobe, such as S to identify pyrite, Zn and S to identify sphalerite, and Pb and S to identify galena. Cuttings and minerals (detrital or diagenetic) of interest were also documented as back-scattered electron (BSE) images.

Scanning electron microscopy

The Scanning Electron Microscope (SEM) at the Regional Analytical Centre at Saint Mary's University was used to locate grains of both detrital and diagenetic minerals for future analyses on the electron microprobe. It is a LEO 1450 VP SME with a maximum resolution up to 3.5 nm at 30 kV. Detection limit is >0.1 %. The SEM uses a tungsten filament to supply electrons to produce a back-scattered electron image of the grains on the polished thin section and return an atomic number. The SEM was also used to confirm the mineral identification of minerals that were not easily identified by petrographic microscope through the use of electron dispersion spectroscopy (EDS).

Whole rock chemical analyses

Both conventional core and cuttings samples were analysed for whole-rock geochemistry. The cuttings were brushed vigorously with a toothbrush, rinsed in deionized water and dried with Kimwipes. Both conventional core samples and dried cuttings were pulverized using a shatterbox with an iron bowl at the Minerals Engineering Centre of Dalhousie University. Major and trace elements were determined by Activation Laboratories according to their code 4Lithoresearch and Code 4B1 packages, combining lithium metaborate/tetraborate fusion ICP whole rock analysis with trace elements by ICP-MS (Activation Laboratories, 2006).

Analytical method for monazite

Introduction

Parrish (1990) was the first paper to draw attention to the use of monazite as a geochronometer. Since this paper, a number of other papers appeared in the literature, notably Suzuki and Adachi (1991), Suzuki et al. (1991), Montel et al. (1996), Williams et al. (1999), Zhu and O'Nions (1999a), Scherrer et al. (2000), Jercinovic and Williams (2002; 2005), Pyle et al. (2005), Crowley et al. (2008) and Spear et al. (2009).

Operating conditions

Chemical age dating of monazites was carried out at the Regional Electron Microprobe Centre, Dalhousie University, using a JEOL 8200 electron microprobe equipped with 5 wavelength spectrometers and a 131eV Noran Energy Dispersive Detector. For major elemental analysis, the probe was operated with an acceleration voltage of 15kV and probe current of 20nA. A counting time of 20 seconds on the peaks was used with a background time of 10 seconds. P10 gas was used for the flow counters. For trace element analysis, however, the probe was operated at 15kV and 200nA probe current. Peak counting time was 360 seconds and background counting time 180 seconds. The X-ray lines and (proportional counters) used for the trace analysis were PbMa1(Xe), YLa1(flow), ThMa1(flow) and UMb1(Xe). The energy Dispersive Detector was used in the initial locating and identification of the monazite grains.

Standards

The following standards were used: ThO_2 (crystal PETJ) for Th; UO_2 (crystal PETJ) for U; $LaPO_4$ (crystal PETJ) for La; $CePO_4$ (crystal PETJ) for Ce; Fluor-apatite (crystal PETJ) for P; sanidine (crystal TAP) for Si; kaersutite (crystal PETJ) for Ca; YAG (crystal TAP) for Y; REE2-Drake (crystal LIFH) for Nd and Sm; REE1 (crystal LIFH) for Gd; REE4 (crystal LIFH) for Dy; REE3 (crystal LIFH) for Pr; crocoite (crystal PETH) for Pb.

Sample preparation

All the studied monazite grains come from polished thin sections either of sandstones or of heavy mineral separates. For the separates from core samples, the original sandstone sample was lightly disaggregated using only the finger tips and sieved. The heavy minerals either of the 63 µm to 250 µm or of the 63 µm to 177 µm fraction were separated using sodium polytungstate (density 2.90) and were then made into polished thin sections.

All thin sections and heavy mineral separate mounts used in this study were polished using loose diamond powders on cloth-covered aluminum laps, eliminating the chance of Pb contamination and therefore possible errors during the calculation of the age. Prior to trace element analysis, all samples were double carbon coated in order to increase the thickness of the carbon on the slide and reduce the effect of the electron beam burning through the coating.

Procedure for major and trace element analysis

1. Originally, the monazite grains were located by optical microscopy and their position was marked by pen on the thin section. Yet, because of the similar optical properties of monazite and zircon, it is relatively difficult to distinguish between these two minerals. A more reliable way to identify monazite grains in sandstone polished thin section or heavy mineral separate polished mount is through the use of the back-scattered properties of the mineral. The sample was placed in the vacuum chamber of a Scanning Electron Microscope (SEM) and bombarded by a high-tension electron beam. Two major types of radiation are omitted by the sample: low energy secondary electrons (SE) that give information about the surface of the sample, and high energy back-scattered electrons (BSE) that are related to the composition of the mineral. The second type

of radiation is used for the identification of the monazite grains. A particular characteristic of BSE radiation is that the larger the atomic weight of the elements in a mineral, the brighter the image of that specific mineral is. For instance, in sandstone samples, quartz generates relatively dark BSE images, whereas monazite is one of the brightest minerals. Moreover, through this procedure monazite is easily distinguished from zircon that has lower brightness in back-scattered images.

The second stage of the procedure involves the use of the Energy Dispersive Detector (EDS) of the SEM to verify that the mineral is actually a monazite. The spectrum given from the EDS is compared to a spectrum of a typical monazite and the confirmation is made.

2. A few clean monazite grains were analyzed for major and minor elements using the Wavelength Dispersive Detectors. With each batch of analyses a monazite standard (MINM25-53) was run as a control. The average weight percents of the major and minor element analysis are then inserted as fixed weights into the correction program for trace element analysis. These data are required for ZAF correction (corrections for the matrix effect considering atomic number (Z), absorption (A), and characteristic fluorescence (F)) in the trace analysis program.

To apply an appropriate ZAF correction, the average major element composition must be calculated for every grain and chemical domain. These values were transformed into element wt % and used as fixed values for mass absorption analysis. The analysis of Pb, U, Th and Y was done simultaneously, so the parameters are the same for each element measured within a single analysis.

3. Prior to trace element analysis, a wavelength scan on Pb, U, Th and Y was performed on the monazite to determine interference free positions to place the backgrounds for these elements.

4. The proper backgrounds were inserted into the trace element analysis program and after careful calibration on the standards, several random points were analysed on each monazite grain, depending on the size of the grain.

5. Another important consideration in EMP analysis of monazite is the X-ray interference problem. There are many overlaps between lines, although only three require correction. These are Y and Th lines interfering with Pb, and a Th line interfering with U. The effect of overlap is an increase in the measured signal. In the case of the monazite, analyses were done at the Pb-Ma line position on ThO_2 (Th standard) and YAG (Y standard), both Pb-free standards, as well as the U-Mb line position on the ThO_2 (U-free) standard. Because these standards are Pb-free and U-free, there should be no signal at the Pb and U peak positions. Consequently, all counts measured at that position are interpreted as interference. During the past few years of application of the chemical dating method of monazites at the Dalhousie Microprobe Lab, software was developed to calculate the correction factors for the interference of Y and Th on Pb-Ma and Th on U-Mb (Warren C., personal communication). Application of this software, prior to analysis, results in corrected U and Pb values.

6. The trace element data (Pb corrected, U corrected, Th and Y) were then imported into a spread sheet program (Excel) as ppm and the ages were determined. For age calculations, a program developed at the University of Massachusetts was used (Williams and Jercinovich, pers. comm. 2003; Jercinovich and Williams 2005).

7. As a check on precision, and as an instrument control, a monazite sample provided by the Geological Survey of Canada (GSC-8153 monazite; Williams et al, 2006), was analysed prior to

each trace element analysis batch run.

4.2.3 Documentation

Zircon U-Pb dating paper – *incomplete draft*. Findings reported briefly in Pe-Piper and Piper (2011).
Updated interpretation of heavy mineral dispersion and reworking in Tsikouras et al. (2011).
Addition data on mineralogical dispersion released in GSC Open Files 6693, 6732, 6821.
Cathodoluminescence work in Strathdee (2010) and abstract for work in progress by Sawatzky and Pe-Piper (2011).
Summary of sub-basin and member scale understanding provided below.

4.2.4 Summary of results

The key deliverable is a summary of the sources and delivery of sediment to the basin at a member and sub-basin scale. Multiple sedimentary petrology methods show that the dominant source of the sand was from the local Appalachians, supplied by at least three different rivers respectively supplying the Abenaki sub-basin, the Sable sub –basin and the La Have platform (Figs. 2, 3, 4). The new biostratigraphy and seismic interpretation from the PFA has provided a new context within which to re-interpret and synthesize our varied data on detrital petrology.
Different methods of detrital petrology provide different types of information. Nd isotopes and bulk geochemistry (after correction for diagenetic effects) track total sediment supply (Fig. 2). Geochronology and chemical fingerprinting of different minerals provide some information on ultimate source of those particular minerals (Figs 3, 4); comparison of different techniques and studies of grain morphology may help distinguish between first cycle and polycyclic minerals. Many of the stable heavy minerals appear to be uniform in relative abundance over wide areas and long time periods, suggesting that this uniformity is inherited from polycyclic sources (Tsikouras et al., 2011).

Muscovite geochronology (Reynolds et al. 2009 plus new data) indicates that throughout the late Jurassic and early Cretaceous there was significant sediment supply from bedrock on the inner shelf (Figs. 3, 4). This may indicate that there was also reworking of sediment on the inner shelf, further complicating the detrital signature.

Principal delivery in the **mid-Jurassic** appears to have been locally from the Meguma Terrane based on the detrital minerals in the Mohican, MicMac and Wyandot wells and the muscovite and feldspar geochronology of Grist et al. (1992). Sediment sources to the eastern part of the basin are unknown.

Few data are available for the **Oxfordian–Kimmeridgian** delta, sampled (in conventional core) at Dauntless, Louisbourg, South Desbarres, Venture and Thebaud. New Nd isotope data suggest predominant supply from the Meguma terrane to South Desbarres and Louisbourg, but possibly supply from more inboard Appalachian terranes to Dauntless. One muscovite geochronology sample from Venture indicates predominant muscovite supply from the Meguma terrane; monazite at Louisbourg indicate significant supply from western Newfoundland and in several wells tourmaline and chromite likely indicate significant supply from Carboniferous rocks (Figs. 5, 6).

There was a significant change in predominant sources to the **Tithonian** delta, for which most data are available at Louisbourg, Peskowesk, Venture and Thebaud. Nd isotope values are much less negative, indicating more supply from the inboard terranes of the Appalachians and less from

Meguma or Grenville sources (Fig. 2). Monazite, muscovite and zircon geochronology indicate a higher proportion of supply from the Avalon terrane than at any other stratigraphic level (Figs. 3, 4, 5, 6). It is likely that these wells are part of a single depositional system: heavy minerals, Nd isotopes, and monazite geochronology are relatively uniform. Possible evidence for a discrete sediment supply in the east is that Louisbourg has common microgranite–rhyolite lithic clasts; these are subordinate to gneiss lithic clasts at Peskowesk, and they have not been noted in the Sable sub-basin (but more work is needed on this). Muscovite geochronology indicates an important supply from the inner shelf Meguma, but also Devonian and Grenville sources particularly in the eastern part of the basin (Figs. 3, 4).

More precise correlation of new biostratigraphy with seismic profiles is needed to determine exactly where core samples are available from the **Berriasian–Early Valanginian lowstand delta**. It appears likely that these have been previous studied in some of the Venture wells. The BEICIP interpretation suggests that this delta is not present on the eastern shelf. Available Nd isotopes, monazite geochronology, and heavy mineral data from Venture show no significant difference from the Tithonian delta.

The **Late Valanginian–Early Hauterivian delta** is taken to correspond to the classic Middle Member of the Missisauga Formation. It is well sampled both in the eastern part of the basin and around Sable Island. In both areas, Nd isotopes are a little more negative than in underlying strata, indicating more supply from Meguma and/or Grenville sources (Fig. 2).

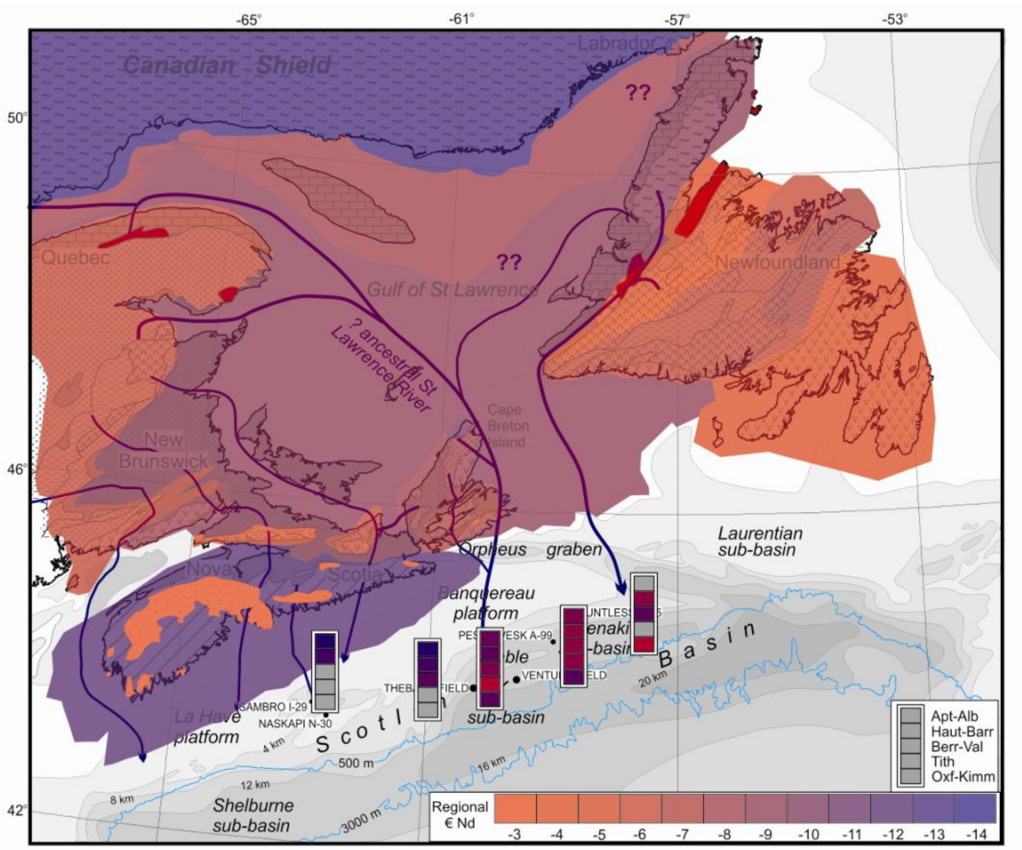

Figure 2. Map showing average eNd for bedrock in potential source areas of the Scotian Basin and the average Nd of basin sedimentary rocks at different time slices.

Nevertheless, geochronology of detrital minerals indicates supply from the inboard terranes of the Appalachians and a significant contribution from polycyclic sources, presumably principally Carboniferous rocks. For the first time, there is a clear distinction between sediment supply to the Sable and Abenaki sub –basins (Figs. 3, 4). In the Abenaki sub-basin, microgranite–rhyolite lithic clasts and K-feldspar are abundant; tourmaline and monazite are less abundant than in the Sable sub-basin. Zircon geochronology does not indicate a major supply from the Meguma terrane, but much of the muscovite was derived from the inner shelf (Fig. 4). Detrital tremolite at Musquodoboit may also be derived from the inner shelf.

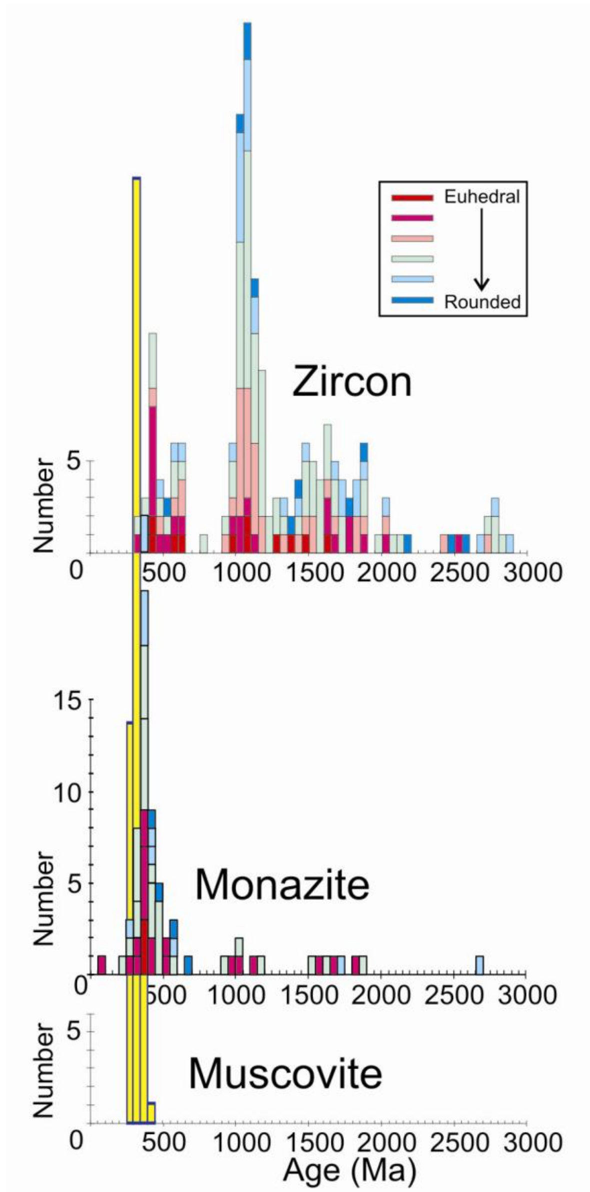

Figure 3. Comparison of single-grain geochronology of muscovite, monazite and zircon from the Sable Sub-basin. Also shows whether grains are euhedral or rounded. This diagram represents a composite of the Tithonian to Barremian and Albian intervals.

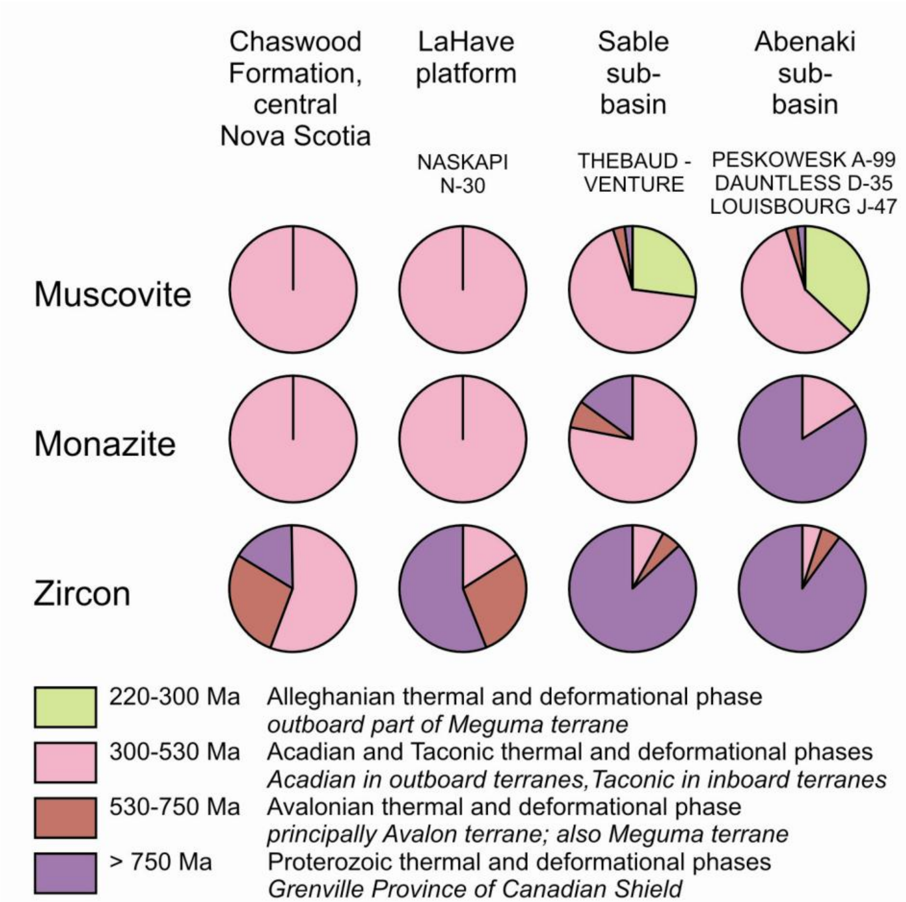

Figure 4. Comparison of muscovite, monazite and zircon abundances in four age classes in different parts of the Scotian Basin. This diagram represents a composite of the Tithonian to Barremian and Albian intervals.

The **Late Hautervian–Barremian delta** corresponds to the classic Upper Member of the Missisauga Formation. In the Sable sub-basin, the new biostratigraphy makes it clear that maximum progradation was in the Late Hauterivian, followed by a broadly transgressive succession up into the Aptian (cf. Cummings et al., 2006). In the Sable sub-basin, Nd isotopes indicate a significant change in sources, with much more negative values that appear to indicate increased supply from the Meguma terrane (Fig. 2). At the Naskapi well, muscovite and monazite geochronology (Reynolds et al. 2009) and heavy minerals (Pe-Piper et al., 2009; Tsikouras et al., 2011) indicate sediment supply only from the Meguma terrane (and probably its Carboniferous cover), with no detectable supply from more inboard terranes. This provides a reference for the Nd isotope composition of bulk sediment and age distribution of detrital zircon from the Meguma terrane. Nd isotopes (~ -12.5) are more negative than those in the Sable sub-basin (~-11.7). The Sable sub-basin has major supply of polycyclic heavy minerals and zircon. Heavy mineral samples from Glenelg, North Triumph and Alma all have an unusually high abundance of magnetite, perhaps derived from a more extensive cover of North Mountain Basalt. Zircon geochronology at Glenelg and North Triumph shows a predominant Laurentide source (consistent with reworking out of Paleozoic sandstones) with minor peaks corresponding to Meguma sources. Monazite ages from the same wells for euhedral grains are predominantly 370–420 Ma, that could be of Meguma provenance. A sample from Chebucto is the only muscovite sample with no grains older than 360 Ma, implying an exclusively Meguma provenance for this first-cycle mineral. In summary, in this interval the Sable sub-basin was supplied principally from the Meguma terrane and reworking of Carboniferous sedimentary rocks; first cycle supply from the inboard terranes of the Appalachians is minor (Figs. 5, 6). Although less data is available in the Abenaki sub-basin, In the eastern part of the Scotian Basin, available Nd isotopes are more negative those in underlying strata, but slightly less negative than in the Sable sub-basin (Fig. 2). Heavy minerals are similar to those in the underlying strata, and are different from those in the Sable sub-basin; some are probably polycyclic, but from a different source. Tourmaline is rare and chrome spinel mostly of MORB origin (Pe-Piper et al., 2009). The mix of heavy minerals and geochronology suggests a source in western Newfoundland, with the microgranite and syenite clasts perhaps derived from the Silurian Topsails sub-volcanic complex or perhaps from Cretaceous volcanism in the Laurentian sub-basin, indicated by the presence of dated Neocomian detrital zircons throughout the basin (Figs. 5, 6). However, muscovite from Dauntless is almost entirely from the Meguma terrane.

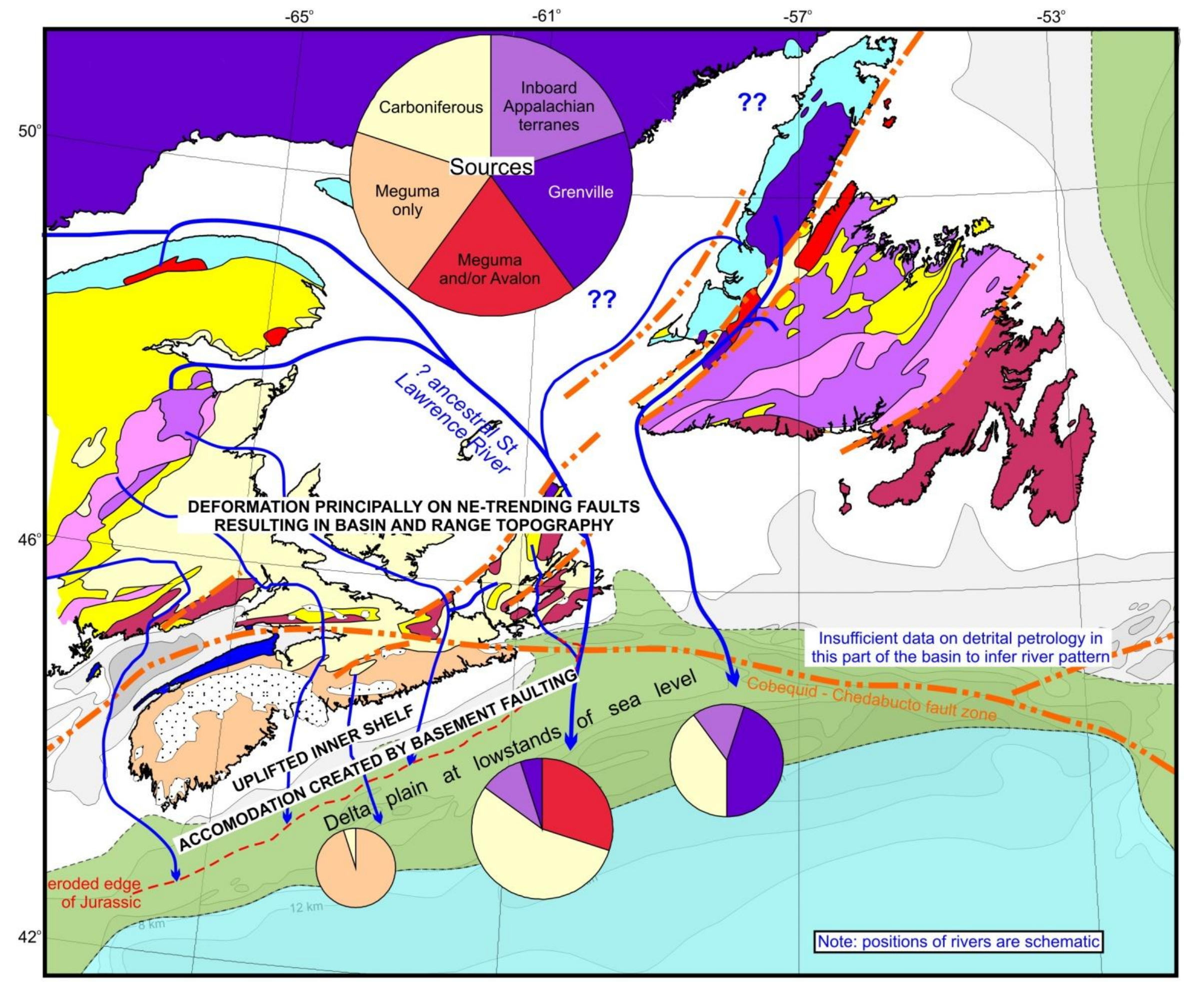

Figure 5. Map showing relative contributions of different source areas to the western, central and eastern Scotian basin in the Tithonian and Lower Cretaceous, based on detrital minerals. For further information, see Pe-Piper and Piper (2011) and Tsikouras et al. (2011).

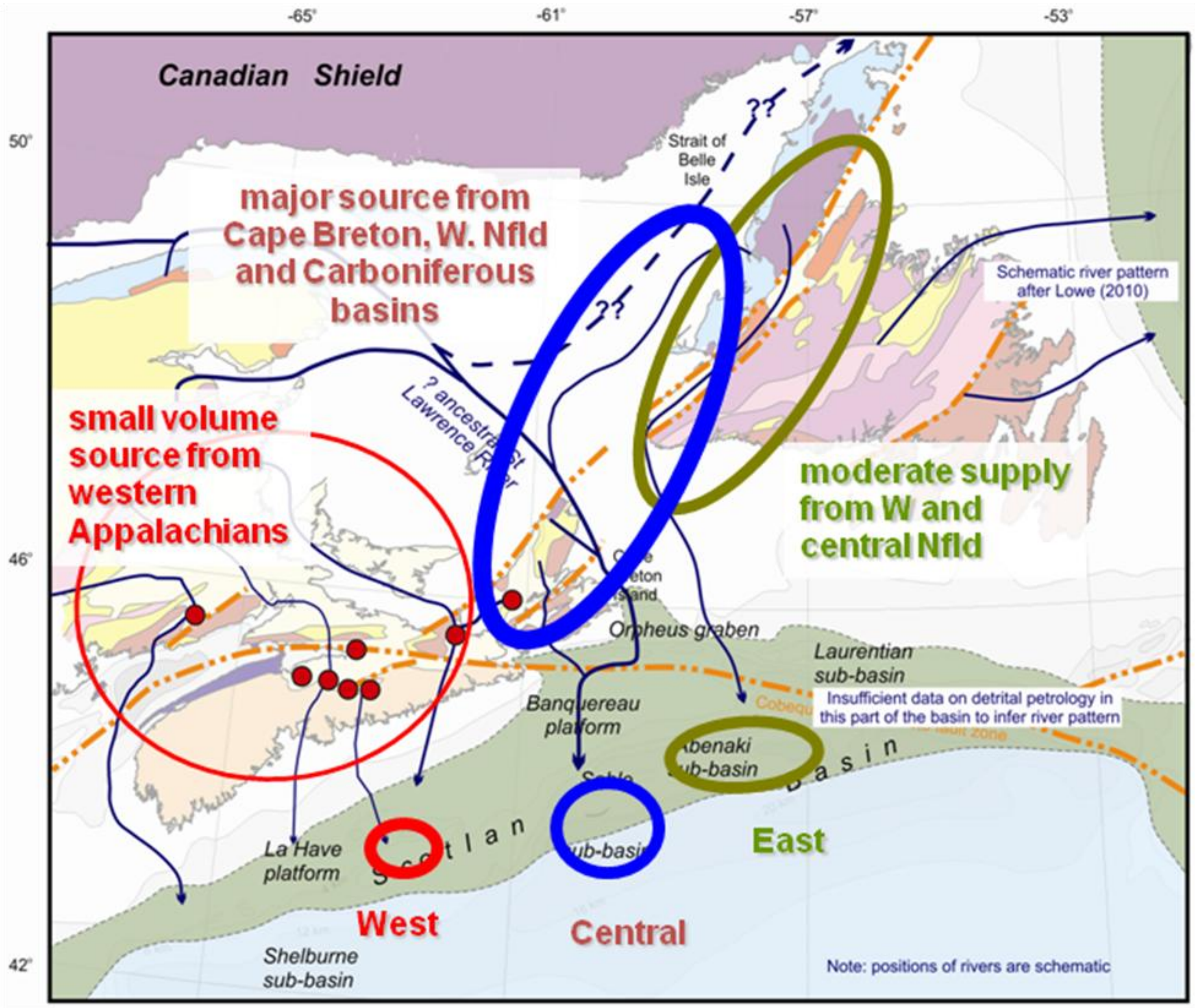

Figure 6. Cartoon showing the generalized sources of sediment to the western, central and eastern Scotian Basin in the Lower Cretaceous, based on all detrital petrology data. Positions of rivers are schematic and may not apply to all tome intervals, particularly the late Hauterivian to Aptian. For further information, see Pe-Piper et al. (2008), Pe-Piper and Piper (2011) and Tsikouras et al. (2011).

Nd data from the **Aptian** Naskapi Member are more negative than in the Barremian in the Sable sub-basin and comparable with those from the Naskapi well, interpreted as derived entirely from the Meguma terrane. Preliminary heavy mineral data indicate some supply from reworking of Carboniferous sediment. Nd isitopes in the Abenaki sub-basin are a little less negative, either indicating some minor supply from more inboard Appalachian terranes or from Aptian volcanism. Overall, most of the sediment supply was from the Meguma terrane, probably more so than in the underlying Late Hauterivian–Barremian interval, suggesting that uplift south of the Cobequid-Chedabucto fault zone partly or completely blocked river supply from the inboard Appalachian terranes (Fig. 7).

The base of the **Albian** Cree Member is marked by an abrupt resumption of sand supply to the basin. The basal part of the Cree Member has abundant reworked volcanic detritus in wells as

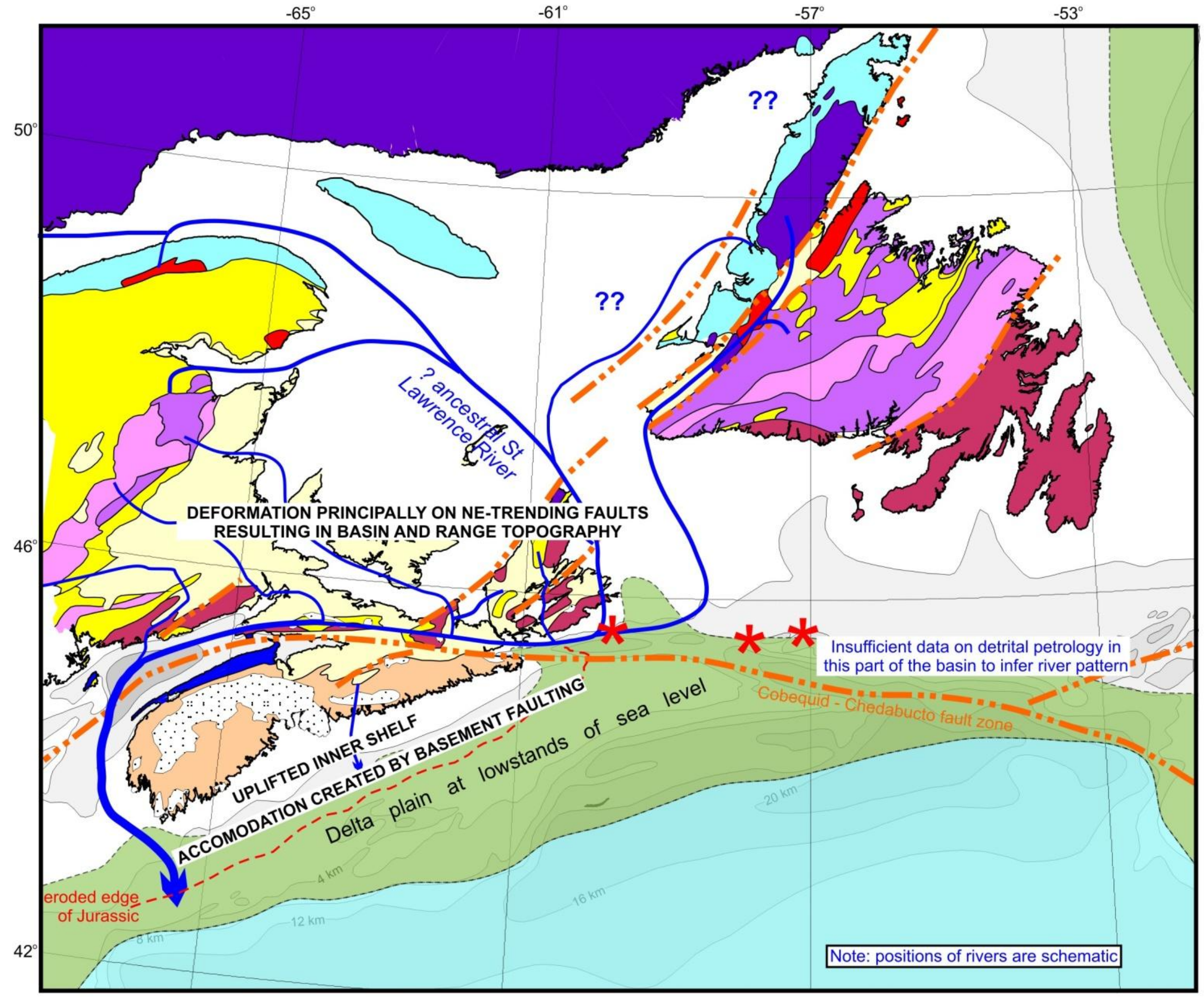

Figure 7. Map showing proposed paleogeography of Atlantic Canada during the Aptian, with the main river systems blocked by uplift south of the Cobequid-Chedabucto fault zone and related volcanism. For further information, see Pe-Piper et al. (2011).

widely spaced as Alma, Cohasset, and Peskowesk, implying that the rivers supplying these areas crossed the volcanic belt in the Orpheus graben and probably the Laurentian sub-basin. Sediment supply in the east shows the same general character as in the Valanginian to Barremian, but with more metamorphic lithic clasts and polycrystalline quartz of igneous origin. Euhedral monazite is either 322–419 Ma or Precambrian. These data suggest a western Newfoundland source, with minor reworking of Carboniferous. Farther west in the Sable sub-basin, Nd isotopes from the intervals with volcanic detritus are less negative (Fig. 2), but shales at Musquodoboit and Southampton are strongly negative implying a significant Meguma supply in the western part of the basin. Monazite (Alma) and muscovite (Sable Island) geochronology indicates some input of Avalon and Taconic detritus from the inboard Appalachian terranes (Figs. 3, 4). Even as far west as Alma and Musquodoboit, there is the same uniform mix of stable polycyclic heavy minerals that imply a significant source from Carboniferous sedimentary rocks. Regrettably, we used North Triumph as a reference well for geochronology on the Cree Member: our detrital zircon results (with Cretaceous volcanic zircons) and the new biostratigraphy at Chebucto show that our samples came from the Barremian not the Albian.

In addition, we have used various other techniques to evaluate sediment input to the basin. The hypothesis that more arid climates in the Barremian resulted in a lower kaolinite to illite ratio compared with the preceding and following time intervals has been tested with clay mineral analyses from the Scotian Basin. 72 analyses from a total of 7 wells show a distinct lowering of kaolinite abundance in the Barremian. Overall the data is rather noisy, perhaps because of variable effects of early diagenetic kaolinite authigenesis in sediments deposited in the coastal zone (Strathdee et al., 2011). In addition, spectral gamma has been used in distal wells on the Scotian Slope to examine the Th/K ratio over the same interval, which confirms the decrease in kaolinite in the Barremian. Spectral gamma data has been calibrated against bulk sediment geochemistry from wells on the Scotian Shelf. Although it does not allow specific identification of lithofacies, periods of high volcanic detrital input have been identified from spectral gamma data (Gould 2011). Kaolinite to illite ratio is already known from the coeval Chaswood Formation on land (Pe-Piper et al., 2005), confirming previous correlations between the Chaswood Formation and offshore stratigraphy.

We have continued with the use of hot cathode cathodoluminescence to characterize the sources of quartz (Sawatzky and Pe-Piper, 2011). Strathdee (2010) defined more precisely the sources of "vein quartz" pebbles in the Chaswood Formation using CL techniques and tourmaline chemistry.

4.3 Impact of detrital petrology on reservoir quality

4.3.1 Activities and methodology

Diagenetic style in eastern and northern Scotian Basin. Substantial thin section work completed, new microprobe analyses, interpretation underway. Particular emphasis on distribution of carbonate cements. Methodology as in Karim et al. (2010).
Burial depth and mineral preservation. Manuscript completed on mineral dispersion in the Scotian Basin, that shows in particular the destruction of garnet with burial. Full discussion of limitations of the published heavy mineral ratios as indicators of source. Methodology in Pe-Piper et al. (2009) and Tsikouras et al. (2011).
Geochemistry, mineralogy and diagenetic assemblage. This work has progressed most in terms of early diagenesis through the completion of an M.Sc. thesis and subsequent paper of Ann Okwese.

4.3.2 Documentation

Additional data on diagenetic minerals in NE Scotian Basin released in GSC Open Files 6693, 6732, 6821 and in Karim et al. (2011b).

Synthesis of heavy mineral alteration with burial in Tsikouras et al. (2011).

Summary of finding on relationship between detrital geochemistry and early diagenesis in Okwese et al. (in revision for Marine and Petroleum Geology)

4.3.3 Summary of results

We are still struggling to pin down the extent to which detrital petrology controls the quite different diagenetic styles in the Sable sub-basin and the Abenaki sub-basin. There is a strong contrast between the two sub-basins: the Sable sub-basin has abundant late ferroan calcite cement and in places common chlorite rims. The sandstones appear to have more porosity passing from eodiagenesis to mesodiagenesis. The Abenaki sub-basin together with more outboard wells on the eastern Scotian Basin tends to have much more cement by clays, little carbonate cement, and chlorite rims are largely lacking. These differences seem to be independant of lithofacies: for example, the delta top lithofacies at Panuke and Cohasset are similar to those at Peskowesk A-99, yet the diagenesis is quite different. The Abenaki sub-basin has more K-feldspar, whereas the Sable subbasin has more detrital plagioclase (Fig. 3 of Pe-Piper et al. 2008). Breakdown of K-feldspars favours clays; breakdown of plagioclase favours carbonates. But there are also differences in the thermal history of late carbonates in the two parts of the basin and it might be that the supply of basin fluids from the deep unsampled part of the basin is the dominant control on the distribution of late carbonate cements.

The role of early diagenesis in the development of chlorite rims may be influenced by the relative availability of Fe and Ti, but is more strongly influenced by lithofacies. Distribution of early iron silicates that are the precursors of chlorite rims are indicated by siderite as a “pathfinder” mineral, indicating suppression of more normal sulphate-reducing diagenesis. Iron silicates are favoured by slow sedimentation transgressive surfaces on top of thick prodeltaic sandstones.

The preservation of porosity in the Scotian Basin is generally the result of either the inhibition of silica cementation by chlorite rims on framework grains, or the patchy development of late carbonate cements. Work is currently underway to relate style of diagenesis to (1) variations in detrital sediment supply ; (2) the conditions of early diagenesis and particularly the formation of Fe-silicate precursors of chlorite rims and the role of seafloor diagenetic cements including Fe-calcite and siderite (Figs. 8, 9); and (3) the influence of lowstands of sea-level in providing meteoric water that corrodes early Fe-silicates and carbonates.

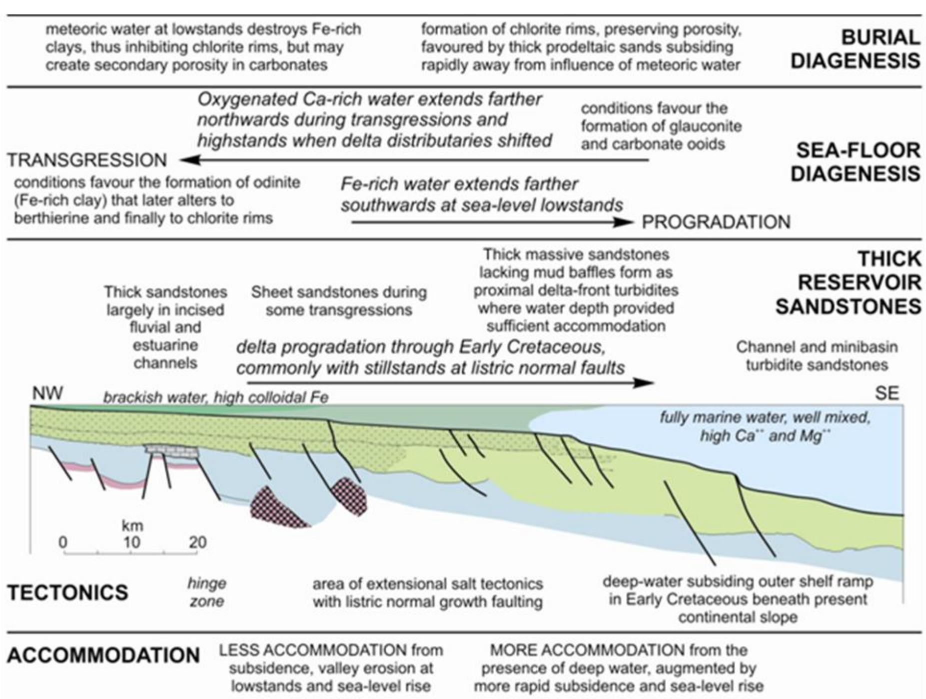

Figure 8. Model showing the inter-relationship of tectonics, accommodation, deposition and diagenesis. Cross section of the Scotian Basin near the Thebaud Field, truncated at the middle Cretaceous. Magenta = Triassic; Blue = Jurasssic; green = Lower Cretaceous; stipple = sand dominated Lower Cretaceous

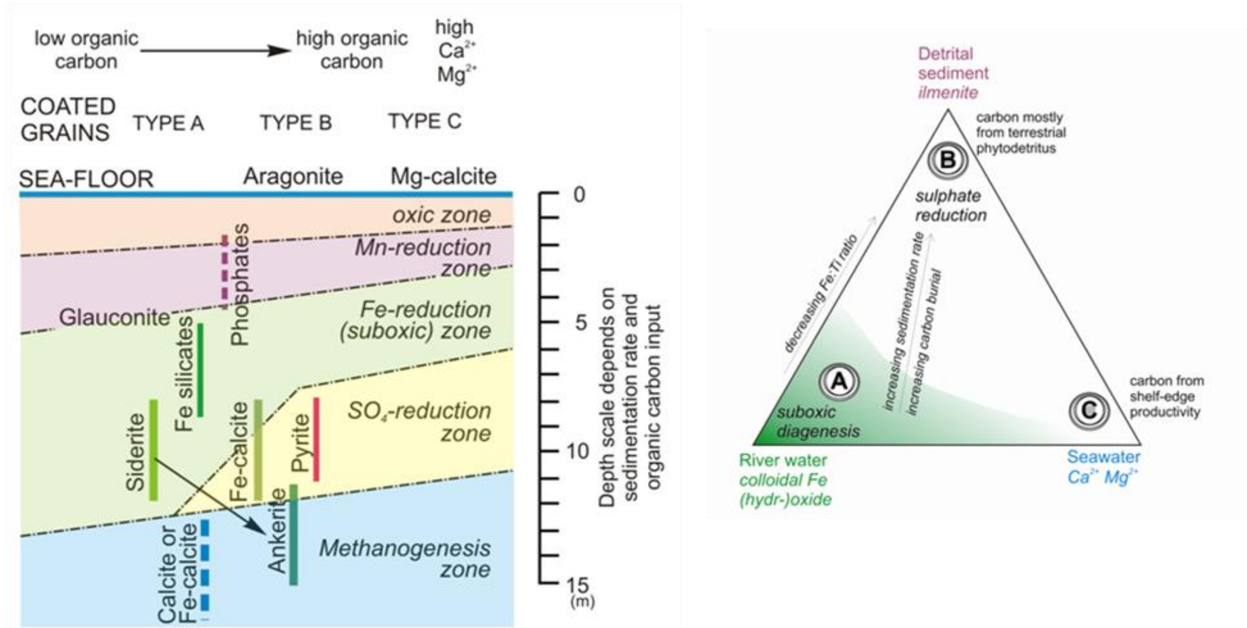

Figure 9. The role of suboxic vs. sulphate reduction seafloor diagenesis in creating precursor minerals for chlorite rims, as revealed by types A, B and C coated grains. (left) Variation in sea-floor diagenesis with availability of organic carbon and of fully marine water with high Ca^{2+} and Mg^{2+}; (right) ternary diagram illustrating schematically the roles of shelf-edge ocean water, high detrital sediment input and high river water input in controlling the distribution of suboxic diagenesis that favours the formation of Fe-silicates, the precursor of chlorite rims. Further information in Okewese at al. (in revision).

4.4 Diagenetic processes and fluid flow in the basin

4.4.1 Activities and methodology

Fluid inclusions

This has been a time-consuming part of the project. Fluid inclusions were first identified in thin sections and then resampled from conventional core from seven wells: Dauntless D-35, Louisbourg J-47, Tantallon M-41, Peskowesk A-99, Sable Island C-67, Panuke B-90 and Cohasset A-52. Dr Karim located and identified fluid inclusions and prepared new thin sections under this contract: she made the actual measurements under the Hanley project. Methodology is reported in Karim et al. (2010a, 2010b, 2011c) and in the Hanley report to OETR.

Diagenetic processes

Our diagenetic understanding of more outboard wells in the Sable Sub-basin has been extended to inboard wells such as Panuke and MicMac and to additional wells in the Abenaki sub-basin such as North Banquereau, through thin section, SEM, and electron microprobe analyses of new samples collected in the first quarter of 2010. The work on diagenesis provided a framework for interpreting the timing of fluid inclusions and hydrocarbon charge. Methodology similar to that in Karim et al. (2010).

4.4.2 Documentation

Interpretation of previous fluid inclusions in Karim et al. (2010a) and Karim et al. (2010b).

New fluid inclusion work reported by Hanley (2010).

New diagenetic work on Panuke, Cohasset and nearby wells, and contrasts with the Glenelg field, reported in Karim et al. (2011a)

4.4.3 Summary of results

The paragenetic sequence of diagenetic minerals recognized from the Thebaud and Glenelg fields (Karim et al. 2010) also applies to the more inboard wells around the Panuke and Cohasset fields (Fig. 10). The discontinuous sequences in the more inboard wells have more evidence for eodiagenesis by meteoric water, that appears to commonly oxidise iron silicates, thus inhibiting chlorite rims. Late ankerite appears to be depth controlled.

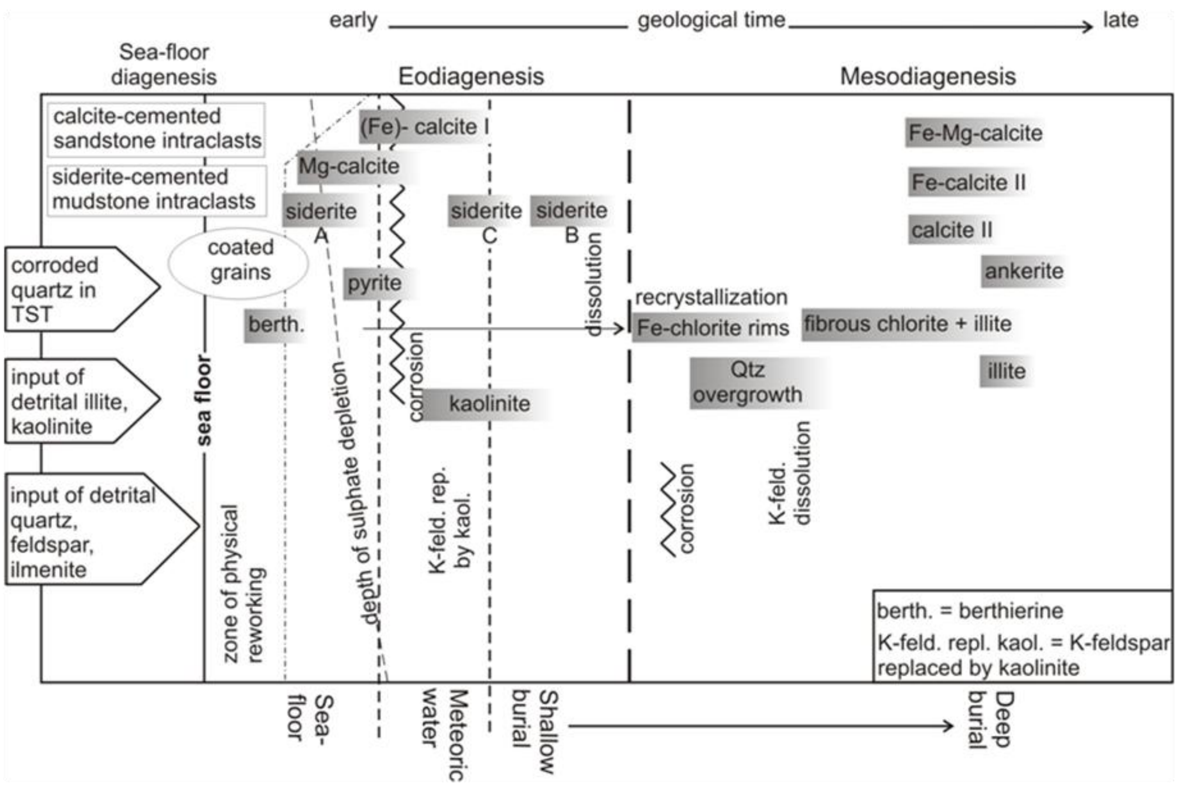

Figure 10. Paragenetic sequence deduced from mutual textural relationship in sandstones from the studies wells (Karim et al. 2011a).

Previous studies of fluid inclusions in Jurassic limestones (Wierzbicki et al. 2006) and apatite the rmochronology of Cretaceous sandstones (Li et al. 1995) have suggested a late-Mesozoic thermal event. To better constrain this event, fluid inclusions in different cements from the Glenelg and Thebaud fields were analyzed to determine the relative timing, composition and temperature of basinal fluid and hydrocarbon migration and entrapment (Figs. 11, 12, 13). Fifty one sandstone samples were analyzed for stable isotope composition ($d^{18}O$ and $d^{13}C$) of carbonate cements. Trapping conditions for primary aqueous inclusions hosted in quartz overgrowths (89 to 175 °C) and in late carbonate cements (138 to 173 °C) are higher than predicted from burial alone (Figs. 11, 12, 13). These inclusions show high salinity (mostly 19–22 wt.% NaCl equivalent). Secondary, predominantly aqueous inclusions have much lower salinities (5.2–6.7 wt.% NaCl equivalent) and some contain liquid hydrocarbons (Figs. 11, 12, 13).

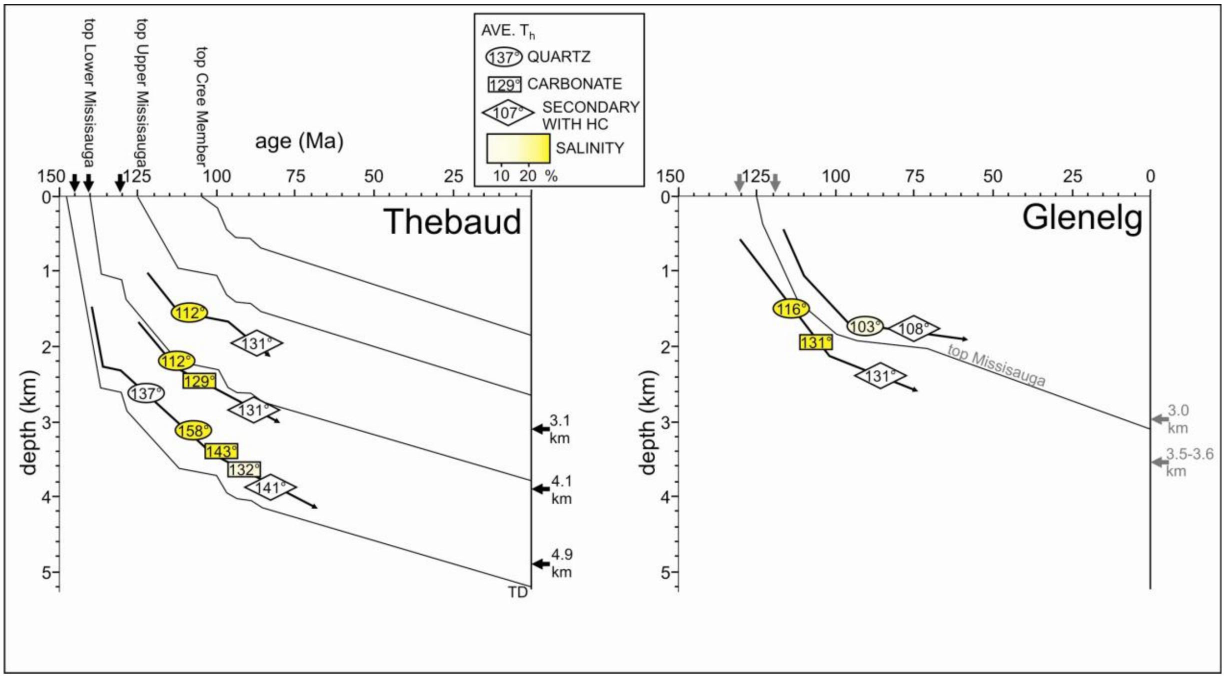

Figure 11. Burial history curves and observations on homogenization temperatures (Th) on fluid inclusions for the Thebaud and Glenelg fields.

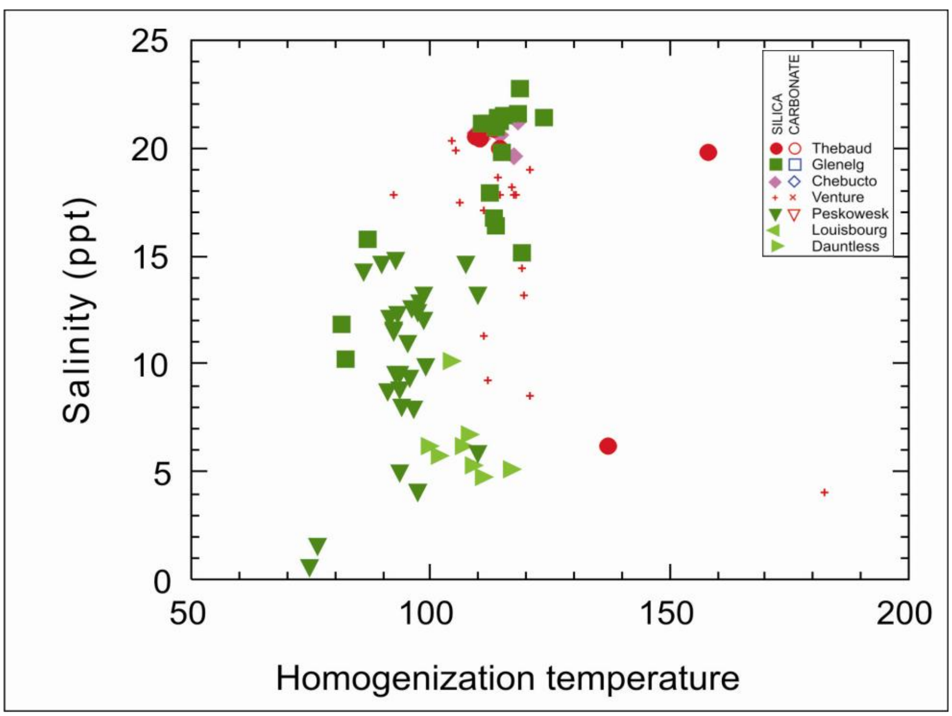

Figure 12. Homogenization temperature (°C) vs. salinity of primary and secondary inclusions in quartz (Qtz) overgrowths and late carbonate cement.

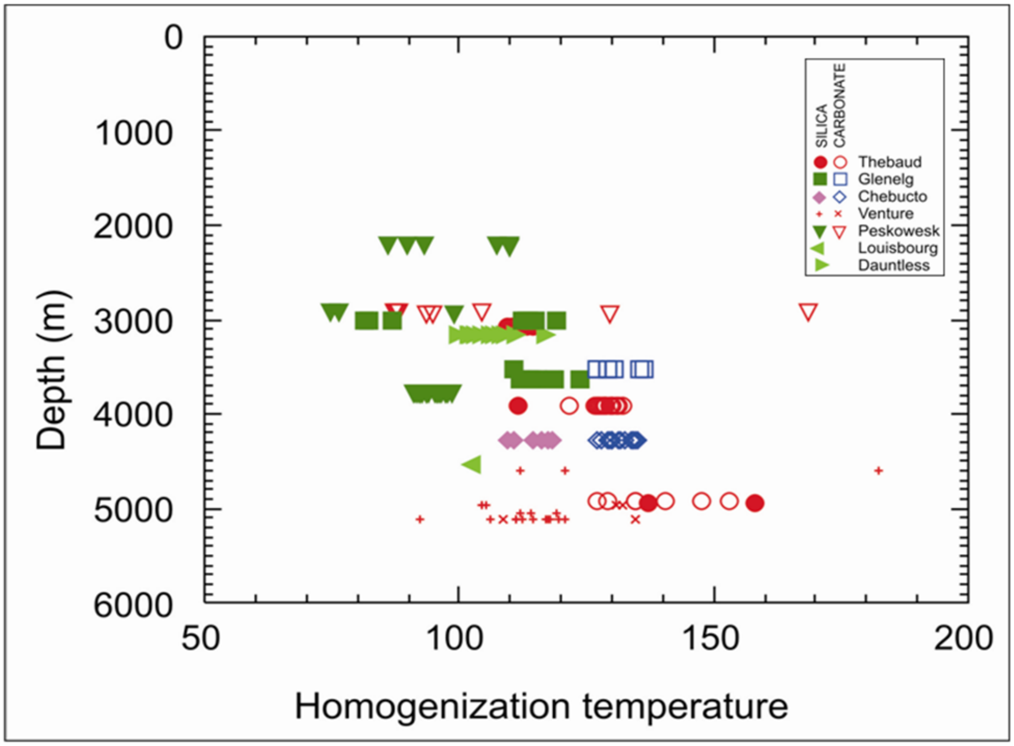

Figure 13. Homogenization temperature (Th) vs. depth of primary and secondary inclusions in quartz (Qtz) overgrowths and late carbonate cement.

Late Fe-calcite cement shows a negative peak in $d^{13}C$ (-9.2 to -13.17 ‰ PDB) in Hauterivian sandstone, whereas cements in deeper and shallower sandstones have higher $d^{13}C$ (Fig. 14). The maximum entrapment temperatures are recorded by diagenetic carbonate in the same Hauterivian sandstones. In order to achieve suitable burial, these temperatures must have occurred around the Aptian–Albian. They would have required a geothermal gradient of at least 55°C/km. This correlates both with regional evidence of volcanism and rapid salt-tectonic deformation in the deep basin. The thermal event impacted thermal maturation in the basin. Hydrocarbon charge to the outer shelf wells was after this thermal event and not before the Late Cretaceous.

In the Venture field, diagenetic minerals from six wells were analysed by optical petrography, SEM, and electron microprobe and a total of 122 primary and secondary fluid inclusions were analysed from different cements. Primary aqueous inclusions in quartz overgrowths have homogenization temperatures (Th) of 111.8±7.1 °C (1s) and in later carbonate cements 126.5±2.1 °C; inclusions in both cements are highly saline (16 to 26.1 wt.% NaCl equivalent; Figs. 11, 12). Secondary aqueous and hydrocarbon-bearing inclusion trails cross-cutting silica cement and detrital quartz have Th of 121.6±13.6 °C and low salinities (8.7±6.0 wt.%). Secondary carbonic inclusions have CO_2 melting temperatures (-56.6±0.1 °C) and Th (-9.3±0.8 °C) indicating a high density carbonic phase. The silica and late carbonate cementation involved highly saline fluid flow, likely at about ~135 Ma. Hydrocarbon migration postdated carbonate cementation and was associated with secondary fracturing, suggesting that it corresponded to the onset of overpressure. Homogenisation and entrapment temperatures were lower in Venture, and also in the wells Peskowesk A-99, Sable C-67, Tantallon M-41 and Louisbourg J-47 wells, compared to wells

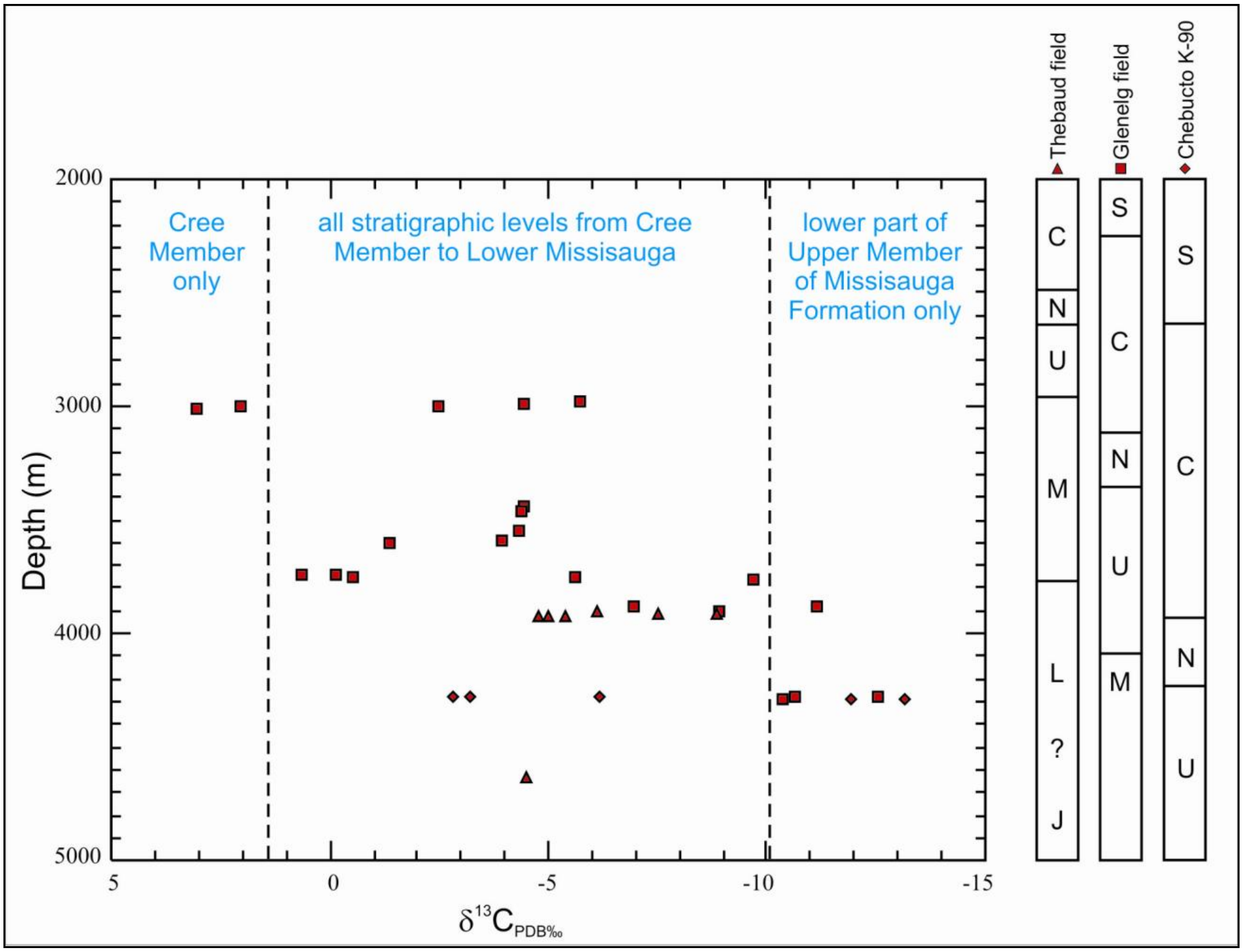

Figure 14. $\delta^{13}C$ vs depth diagram showing the variation in carbon composition of carbonate cements at different stratigraphic levels. Sandstones from the Cree Member have the highest $\delta^{13}C$ whereas sandstones from the lower part of the Upper Member of the Missisauga Formation (MF) have he most negative $\delta^{13}C$. (S = Sable Member; C = Cree Member; N = Naskapi Member; U = Upper Member; M = Middle Member; L = Lower Member).

near Glenelg and Thebaud (including Panuke and Cohasset; Fig. 13). Only in the Dauntless D-35 well in the eastern Scotian Basin were high temperatures found similar to those in the western Sable sub-basin (Fig. 13). Nevertheless, at Louisbourg J-47 and South Griffin J-13, in the eastern part of the basin, sphalerite and barite mineralisation has been found, implying hot saline fluids.

Further interpretation of the significance of the fluid inclusion data will come with the planned BEICIP basin modelling. The interpretative uncertainty is the relative importance of (a) migration of deep, hot saline brines from the basin and (b) hydrothermal circulation related to volcanism along major fault trends in producing the fluid inclusions. Where hottest entrapment temperatures are found are either in Dauntless, closest to the main volcanic centres in the Laurentian sub-basin, or near the major NE-trending fault trend at the edge of the Abenaki platform.

4.5 Cretaceous volcanism and heat flow

4.5.1 Activities and methodology

U-Pb dating. Attempted a TIMS U-Pb date on the sill at Emerillon (the major non-dated volcanic feature) – insufficient zircon present in the available cuttings. Previous U-Pb dating of detrital Cretaceous zircons interpreted to provide more age control on volcanism.

Volcanic products in wells: re-examination of style of volcanism from logs and sidewall cores, biostratigraphic control, seismic profiles through volcanic rocks, implications of heat flow for maturation, review of other evidence of high heat flow all in the M.Sc. thesis of Bowman (2010).

Chaswood Formation ash distribution. Re-interpreted from previous Open File data, correlated to offshore on basis of tectonics and interpretation of Barremian dry interval (Pe-Piper and Piper, 2010b).

4.5.2 Documentation

Sarah Bowman M.Sc. thesis.

Cretaceous zircons in the draft of U-Pb zircon paper.

4.5.3 Summary of results

All of the work on volcanism has come together with the other work with the following major findings (Figs 15, 16, 17):

- SW Grand Banks volcanism is likely only of Hauterivian and Barremian age (biostratigraphy, lack of older detrital zircons) and may have extended into the Laurentian sub-basin (detrital zircons).
- Volcanism was derived from local bedrock highs; basalt flows can be traced into basins at both Mallard and Brant.
- By analogy, Hesper is a flow derived from Scatarie Ridge, not a sill, dating from the mid-Aptian. It correlates with flows in Argo, Jason and Hercules. Major pyroclastic flow deposits recognised from log response in Orpheus graben.
- Simple 1D modelling shows that if there was regional elevated heat flow related to dispersed volcanism, then there was a small but significant effect on maturation. Such elevated heat flow accounts for the old Zentilli apatite fission track results, without requiring basin inversion. It also accounts for the high heat flow shown by vitrinite reflectance in the lower part of the Chaswood Formation.
- Pre-existing faults were important pathways for magma. The inferred tectonic lineament along the SE margin of the Abenaki platform may have been the site of hydrothermal fluids producing the high fluid inclusion temperatures in that region.
- Stratigraphic relationships on eastern Scotian Shelf suggest Naskapi Member was not a regional transgressive unit, but rather a time of uplift of the inner shelf cutting off much of the supply of sand.

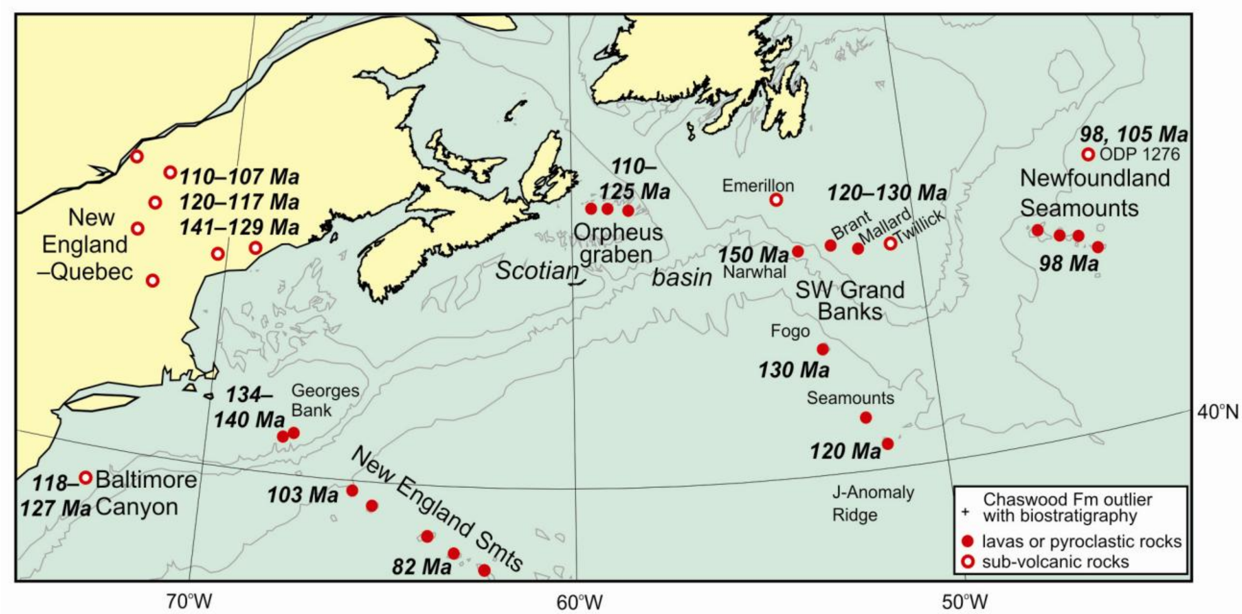

Figure 15. Regional location map showing distribution and ages of Lower Cretaceous volcanic rocks in Atlantic Canada and New England. (Based on Pe-Piper et al. 1990)

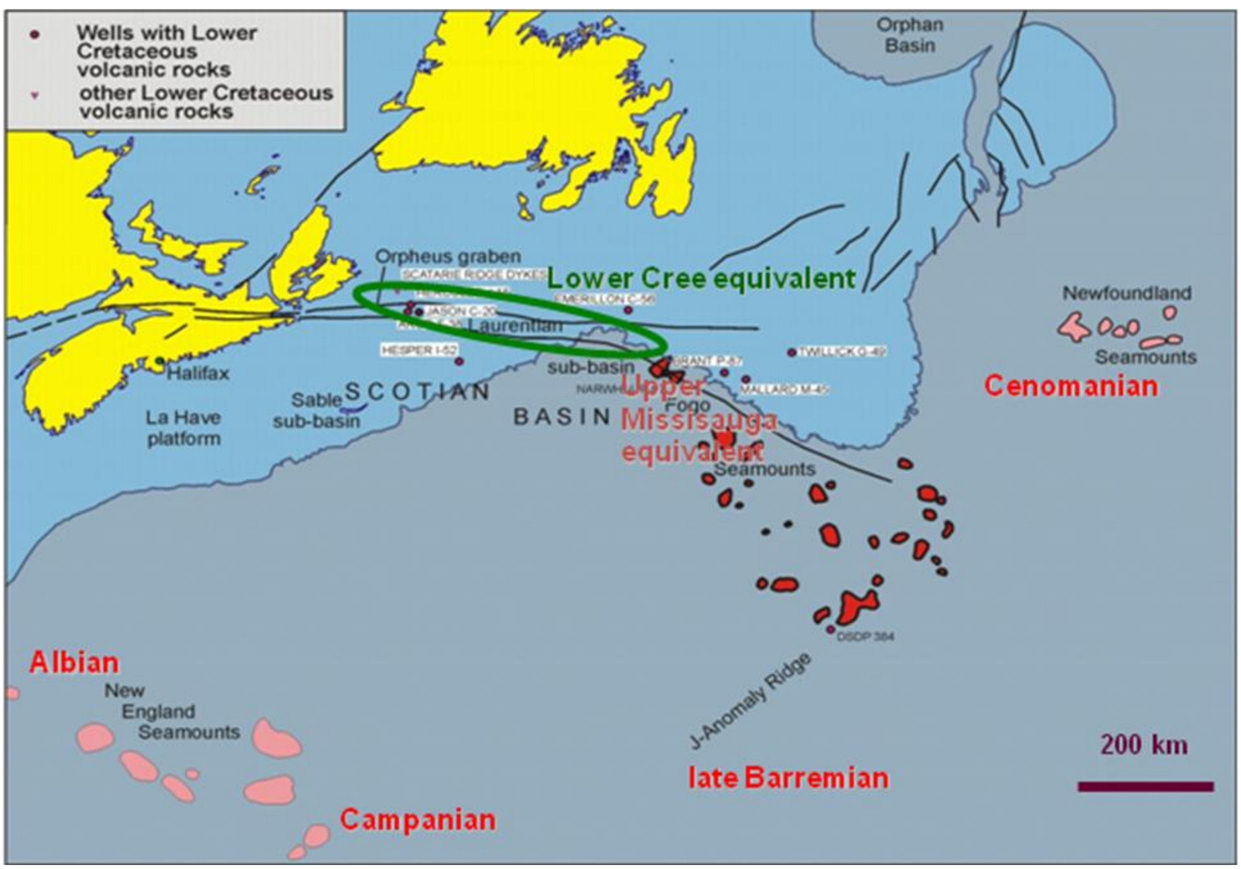

Figure 16. Map showing the age and distribution principal Cretaceous volcanic edifices around the Scotian Basin.

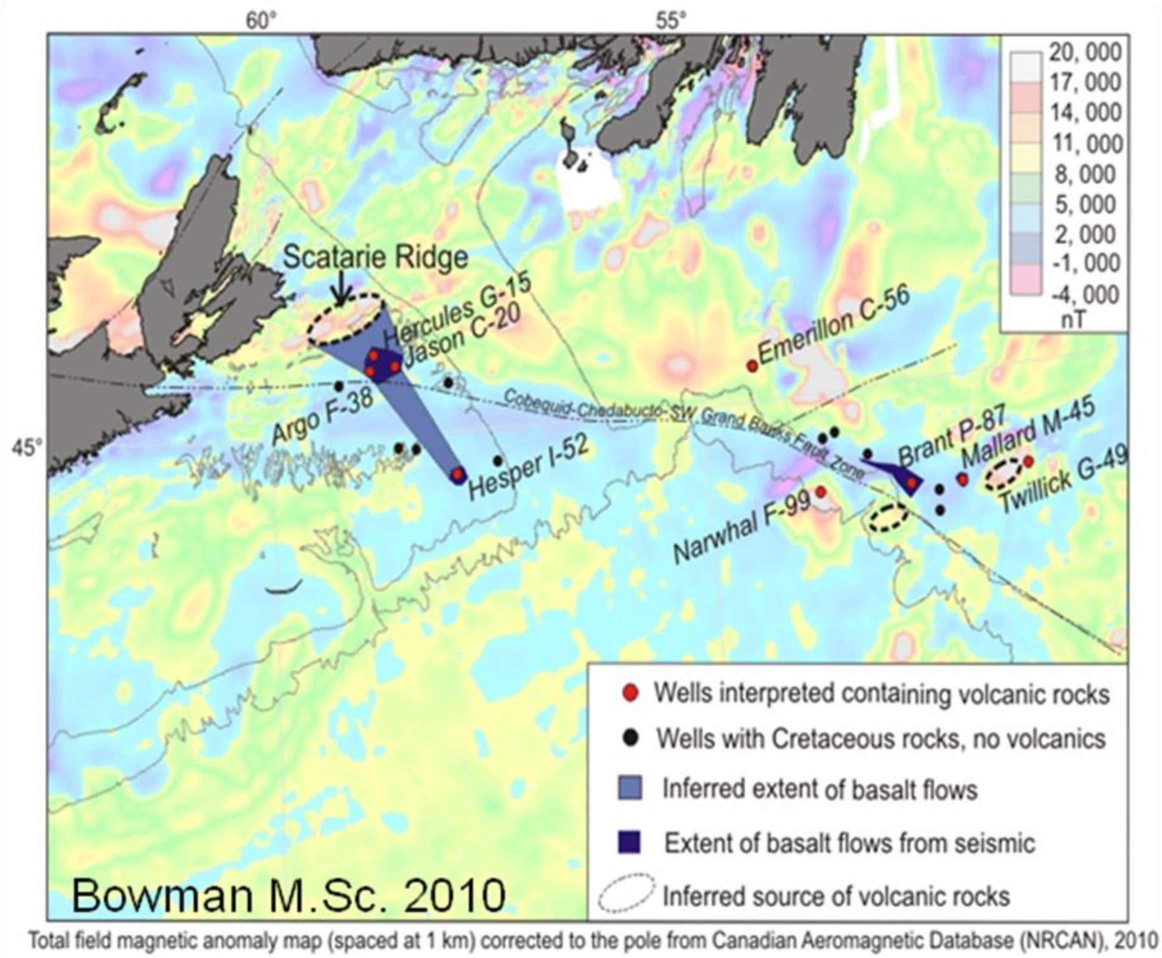

Figure 17. Total magnetic anomaly map showing interpreted volcanic centers (now eroded basement highs with high magnetization) with mapped and inferred extend of basalt flows. (from Bowman, 2010).

4.6 Depositional systems

4.6.1 Activities

Almost all our analyses are based on samples from conventional core archived at the Geoscience Research Centre of the Canada-Nova Scotia Offshore Petroleum Board. We placed emphasis on thoroughly understand the setting of all samples analysed. Conventional core was described on a decimetre scale directly onto core photographs. A systematic lithofacies interpretation was built up through several iterations: the key features are reported by Karim et al. (2008, 2010) and Gould et al. (2010a). An update has been prepared as part of the Play Fairway Analysis contract and older core descriptions have been revised to this updated version (Gould et al. 2010b). The logged cores are presented in Table 1.

Lithofacies interpretation. The identification of lithofacies underpins much of the rest of our work. For example, we have found it essential to analyze variability in early diagenesis by lithofacies (Okwese et al., submitted). In addition, logging of inboard wells has tempered and

D#	Well Name	Top (m)	Bot (m)	Formation cored
D320	Balmoral M-32	1966.00	1984.00	Logan Canyon Fm
D294	Cohasset A-52	2069.65	2613.05	Logan Canyon Fm (Cree&Naskapi Mb)/Missisauga Fm (Upper Mb)
D305	Como P-21	2188.20	3068.00	Missisauga Fm (Upper&Middle Mb)
D319	Lawrence D-14	2253.00	2285.00	Missisauga Fm (Upper Mb)
D098	Marmora P-35	3007.16	3025.14	Missisauga Fm (Upper Mb)
D160	Mic Mac D-89	2497.53	2590.80	Missisauga Fm (Middle Mb)
D008	Mic Mac H-86	4717.69	4725.31	Mohican Fm
D007	Mic Mac J-77	2813.61	2822.75	Missisauga Fm (Middle Mb)
D074	Mohican I-100	3691.13	3700.27	Mohican Fm
D214	North Banquereau I-13	3237.60	3471.50	Logan Canyon Fm (Naskapi Mb)/Missisauga Fm (Upper Mb)
D022	Onondaga O-95	3266.24	3275.32	Missisauga Fm (Middle Mb)
D300	Panuke B-90	2036.00	2439.23	Logan Canyon Fm (Cree&Naskapi Mb)/Missisauga Fm (Upper Mb)
D001	Sable Island C-67	2470.71	4093.77	Logan Canyon Fm (Cree&Naskapi Mb)/Missisauga Fm (Middle&Lower Mb)
D250	South Desbarres O-76	3799.00	5959.00	Missisauga Fm (Lower Mb)/Mic Mac Fm
D224	Venture B-52	5018.60	5131.60	Missisauga Fm (Lower Mb)
D232	Venture H-22	4957.00	5076.00	Missisauga Fm (Lower Mb)
D164	Wenonah J-75	3069.95	3088.23	Missisauga Fm (Upper Mb)
D277	West Olympia O-51	4462.58	4557.06	Missisauga Fm (Lower Mb)
D252	West Venture C-62	5072.75	5258.41	Missisauga Fm (Lower Mb)
D249	West Venture N-91	4999.02	5141.36	Missisauga Fm (Lower Mb)
D018	Wyandot E-53	2872.44	2872.44	Abenaki Fm (Scatarie Mb)/Mohican Fm

Table 1. The logged conventional cores with current funding.

strengthened our understanding of delta-front turbidites, a major new lithofacies concept for the interpretation of Scotian basin sandstones (Gould et al. 2010a; Table 2).

Lateral correlation. Logging of correlative conventional core sections in (a) Como, Cohasset, Panuke, Balmoral and Lawrence and (b) West Olympia, West Venture and Venture allows us to make statements about the scale of lateral continuity of particular sandy lithofacies (less than implied in the literature) (Gouid et al., 2011)..

Variability in salt. In response to persistent concerns from RPS and BEICIP about the nature of the original salt basin, we have worked with Dr Andrew MacRae to carry out a petrographic and geochemical study of salt from five wells: Eurydice P-36, Adventure E-80, Weymouth A-45, Glooscap C-63 and Sable Island E-48. Salt colour has been measured by spectrophotometer, mineral composition determined by X-ray diffraction, and bulk geochemical composition including Br content has been analysed. Interpretation is ongoing.

4.6.2 Documentation

Open File 6745 (Gould et al. 2010b) consists of public release of core logging results and includes the new lithofacies scheme.

Facies	Subfacies	Lithology and texture	Primary sedimentary structures	Biogenic structures	General interpretation	Related facies
0	0g	sandstone, generally fine but may reach coarse	medium bedded; laminated or cross laminated, common erosional base; possible wave and current ripples	absent to sparse biot	River mouth to shoreface; prodeltaic turbidites	commonly overlies 1 and 2; may interbed with 9
	0b	fine sandstone, siltstone, mudstone (sandstone > mudstone)	sharp, erosive based beds (<25 cm thick) with sltst laminae, interbedded with mst with sltst laminae; some lenticular bedding; parallel and cross laminae; variable sed structures as in Lamb et al, 2008; possible wave and current ripples	sparse to uncommon biot		
	0m	mudstone, siltstone, very fine sandstone (mudstone >> sandstone)	some sltst or very fine sst laminae; parallel lam, x-lam, lenticular bedding; possible wave and current ripples	uncommon biot		
	0a	fine and coarse sandstone, mudstone (sandstone ><mudstone)	alternation of coarse and fine sst beds with interbedded mst; parallel lam, x-lam, lenticular bedding; possible wave and current ripples	absent to sparse biot		
1		mudstone, <5% fine sandstone or siltstone	thin beds and laminae of parallel fine sst or sltst laminae	abundant to complete biot (*Chondrites* ichnofacies); uncommon thin shelled fossils - echinoderms, ammonites	Shelf	commonly overlies 3 and underlies 2 or 0
2	2b	mudstone, fine sandstone (10-60%)	destroyed by biot, possible remnants of storm beds with parallel lamination, wave ripples and wave dominated structures	generally moderate to common biot; possible shells, *Cruziana* ichnofacies; may have reworked shell frags at base of preserved beds	Shoreface	interbeds with 0; possibly grades into 3
	2c	fine sandstone (60-95%), mudstone	destroyed by biot, possible remnants of storm beds with parallel lamination, wave ripples and wave dominated structures	common to complete biot, multiple species; possible shells; *Cruziana* ichnofacies; may have reworked shell frags at base of preserved beds		
	2o	fine sandstone	generally thin to thick massive beds	sparse to moderate biot, horizontal *Ophiomorpha* burrows		
	2x	fine-rare medium sandstone	cross-bedding, mostly low angle, thin bed sets; rare mud drapes	sparse biot		
3	3x	sandy mudstone (10-50% sand); granules; poorly sorted; common brown staining due to early siderite	may have intraclasts	moderate to complete biot; thick shells	Condensed unit on shelf, commonly transgressive	commonly overlies 3y
	3y	muddy sandstone (50-90% sand), granules; poorly sorted; common brown staining due to early siderite	may have intraclasts	moderate to complete biot; thick shells		commonly overlies 3l or an erosion surface
	3i	intraclast conglomerate; common brown staining due to early siderite	may have intraclasts	may include shells		
	3c	lithic conglomerate; common brown staining due to early siderite	may have intraclasts	may include shells		
	3f	firm ground	evidence of strong sed.; commonly associated intraclasts; erosion or incision of underlying sediment	some burrow penetrating firm ground, *Glossifungites*		
	3l	bioclastic limestone	parallel lam	abundant shell fragments, possibly in place		
	3o	oolitic limestone and sandstone	parallel lam	possible biot		

Table 2. Summary of sediment facies description and interpretation from Gould et al. (2010b).
Table 2 continued below.

4.6.3 Summary of results

A new consistent descriptive lithofacies classification applicable to the Scotian Basin has been developed (Gould et al., 2010b; Table 2), building on previous work of MacRae and Jauer (2002), Cummings et al. (2005, 2006) and previous work in our group (e.g. Gould, 2010a; Karim et al., 2010a). As a result, our detrital petrology and diagenesis results are from samples whose depositional environment is well understood.

Lateral continuity of lithofacies at Panuke–Cohasset and at Venture–West Venture provides information on the lateral extent of reservoir facies (Gould et al. 2011). For example, within the

Panuke–Cohasset area, the middle Cree Member in the Cohasset A-52 well shows tidal inlet

Facies	Subfacies	Lithology and texture	Primary sedimentary structures	Biogenic structures	General interpretation	Related facies
4	4o	principally fine sandstone	thin to medium bedded, may be cross-bedded; mud drapes	sparse to common biot, *Ophiomorpha* , *Skolithos* ichnofacies	Tidal estuary to fluvial	passes up into 5 or 2
	4g	medium to coarse sandstone; may have coarse grained lag at base of unit	typically thin-bedded, mud drapes; bedding parallel to low angle	absent to sparse biot		
	4x	medium to coarse sandstone; mudstone intraclasts; may have coarse grained lag at base of unit	thin to thick beds, many high angle cross-bedded	biot absent; coal intraclasts		
	4n	mudstone, siltstone, very fine sandstone (sandstone>mudstone)	"tidal bundles" of poorly sorted sand and silt; or well-sorted fine sand, rarely with ripples; mud partings 1-2 mm	biot absent or sparse		
5	5m	>75% sandstone, predominantly fine may have medium or coarse grained beds, mudstone	thin bedded; variable mud drapes; mud, slt, and vf sst parallel & x-lam; mud on ripples	variable biot - sparse to moderate, or common to abundant, *Skolithos* ichnofacies; ?plant frags	Mixed flat - intertidal	
	5s	>95% sandstone, generally fine may be medium or coarse grained, minor mudstone	possible thin to med bedded; some x-bedding	sparse to mod biot; shells	Sand flat - intertidal to subtidal	may pass up into 4o
	5b	20-75% sandstone, predominantly fine may have medium or coarse grained beds	destroyed	abundant to complete biot - common large and long subvertical burrows; may have shells	Mixed flat - intertidal	transitional to 2
	5c	medium sandstone	sharp based, thin beds	absent	Tidal channel - subtidal	within 5/6
6	6s	subequal fine sandstone,mudstone; or 60-75% mudstone, fine sandstone; may have minor medium-coarse sandstone, e.g. in burrows	mud dominant sections with wavy or current ripples and mud on ripple lam, interbedded with prominant parallel lam sst and mst (pinstripe-shaped)	small *Skolithos* ichnofacies burrows absent to common; possible plant frags	Mixed flat- intertidal	commonly interbedded with 4, 5, 7, 8
	6b	>80% mudstone, minor very fine to fine sandstonemay have minor medium-coarse sandstone, e.g. in burrows	destroyed; rare preserved parallel lam, current ripples	common to complete biot; may have whole or fragments of oyster shells	Mudflat- intertidal	
	6m	>95% mudstone, may have minor medium-coarse sandstone, e.g. in burrows; may have minor medium-coarse sandstone, e.g. in burrows	rare discontinuous sltst lam, broken by subvertical to vertical burrowing	biot absent to common, may have burrows (horizontal and subvertical) filled with m-c sst; ?oyster shells	Mudflat- intertidal	
7		lignite or carbon-rich mud		rootlets beneath	Tidal marsh	may overlie 6
8		mudstone, rare siltstone	planar parallel to low angle cross siltstone lam	biot generally absent to sparse, with locally intense biot	Lagoon	interbeds with 5 & 6
9	9g	very coarse to fine sandstone, some graded beds	sharp-based beds, some with erosive structures (sole marks); predominantly massive beds, generally >25cm thick, with minor parallel or cross laminae at top of some beds; possible mud intraclasts	absent to moderate biot at top of beds; plant detritus; possible reworked coastal deposits (shells, sid nodules)	River mouth to prodelta turbidite	commonly interbedded with 0, overlain by 4o
	9s	fine sandstone, minor mudstone, minor interbedded facies 0	sharp-based beds, some with erosive structures (sole marks); generally >25 thick, parallel lamination at base and cross lamination at top; some beds have mud intraclasts near base	moderate biot at top of beds; plant detritus; possible reworked coastal deposits (shells, sid nodules)		
10	10f	mudstone to muddy sandstone	destroyed by deformation; secondary structures - massive texture, horizontal foliation	-	Deformed facies	commonly interbedded with 0
	10g	sandstone	destroyed by deformation; secondary structures - liquified beds	-		
	10s	sandstone, siltstone, mudstone,	mostly destroyed by deformation; secondary structures - sheared and folded beds	variable biot		

Table 2. (continued) Summary of sediment facies description and interpretation from Gould et al. (2010b).

lithofacies, whereas 3 km away in the Balmoral M-32 well it shows trangressive offshore lithofacies (Fig. 18). The base of the Cree Member in the Cohasset well has a blocky gamma character, with estuarine channel and river mouth lithofacies not seen in the gamma ray logs at Panuke B-90. Sand packages near the top of the Upper Missisauga Member are tidal flat to tidal estuary in Panuke, shoreface and river-mouth turbidites in Cohasset, and reworked sands and

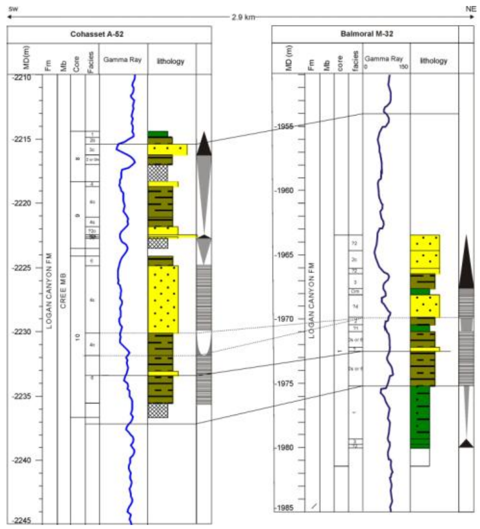

Figure 18. Lateral passage from tidal inlet lithofacies to transgressive offshore lithofacies at the Middle Cree Member in the Cohasset A-52 and Balmoral D-14 wells.

thick turbidites in Lawrence D-14. Down section, in the Upper Member of the Missisauga Formation, the Panuke well has muddy tidal deposits, whereas the Lawrence well remains sandy and less clearly tidal. Overall, lithofacies become more distal to the NE. River mouth sand complexes have lateral dimensions of 15 km. Some sandstone packages are laterally continuous, even if depositional environment changes. Gamma logs are most effective for regional correlation, but since lithology and sedimentary lithofacies change laterally on a scale of 10 km, gamma can only correlate major lithological changes related to sand input or transgressions (Fig. 19).

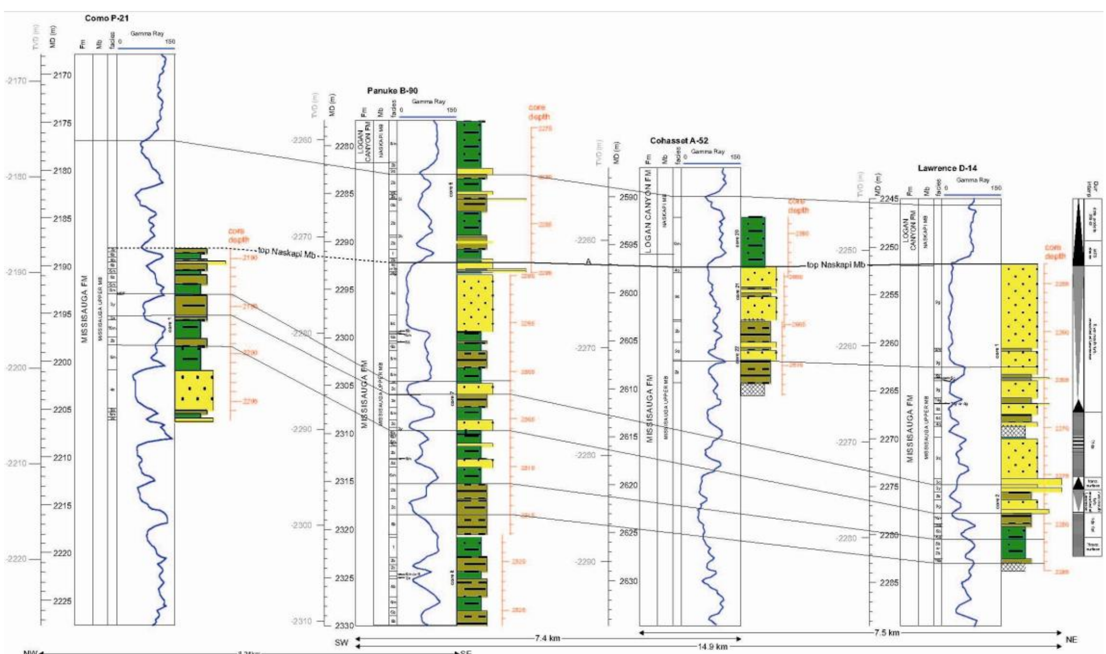

Figure 19. Lateral variation in depositional facies at the top of the Missisauga Formation in the Como P-21, Panuke B-90, Cohasset A-52 and Laurence D-14 wells based on our logging of conventional core. Further details in Gould et al. (2011).

The major minerals present in salt are the same throughout the basin: halite, sylvite, carnallite, anhydrite and barite in decreasing order of abundance. Br is rather lower (less marine) in the more inboard wells: Eurydice P-36 and Glooscap C-63 . Other geochemical data have not yet been interpreted and this work is ongoing.

5. Dissemination and Technology Transfer

Our general approach to dissemination of information is (a) powerpoint presentations at frequent PFA meetings, each one emphasising new material; (b) direct communication with RPS and BEICIP staff; (c) steady publication of data (in GSC Open Files) and interpretations (in journal papers); and (d) promotion of the Scotian Basin through international and regional conferences.

(a) Powerpoint presentations were made at the Plate Tectonic Workshop (May 2010 - *in absentia*), the late June PFA integration meeting, the September PFA audit in Paris, and the December PFA review in Paris (*by web and phone*).

(b) We have made team members freely available during visits by BEICIP and RPS staff and have maintained email contact with key players.

(c) Details of publications are given below.

(d) Senior members of the team have presented scientific results on the Scotian Basin in the 2010 NS Energy Forum, the AAPG Annual convention (April 2010), the International Sedimentological Congress (September 2010), the 2nd Central Atlantic Conjugate Margins Conference (September 2010 - *in absentia*), and the British Sedimentological Research Group. Students and post-docs have presented their work at the NS Energy Forum and will present at the Atlantic Geoscience Society annual symposia in February 2011.

6. Conclusions and Recommendations

6.1. Conclusions

a) The history of sediment supply in the Late Jurassic and Early Cretaceous has been defined. In the late Jurassic, there was probably a single major river entering the basin through Cabot Strait, but from the late Valanginian to the Albian there is clear evidence that the Sable sub-basin and the eastern part of the basin were supplied by different rivers. Significant tilting and uplift of the Meguma terrane took place in the late Hauterivian and may have blocked fluvial sediment supply through Cabot Strait in the Aptian. This supply was re-established in the early Albian as volcanic activity ended.

b) Differences in diagenesis between the Abenaki and Sable sub-basins is in part a consequence of different sediment supply, with the abundant K-feldspar in the east favouring clay cements. The development of chlorite rims may be influenced by the relative availability of Fe and Ti, but is more strongly influenced by lithofacies. Precursor iron silicates are favoured by slow sedimentation transgressive surfaces on top of thick prodeltaic sandstones and chlorite rims are best developed in thick delta-front turbidite beds.

c) Fluid inclusions and carbon isotopes clearly define a mid-Cretaceous thermal event in the basin and show regional variation in the nature and timing of hydrocarbon charge. Further interpretation of these data will be aided by the planned BEICIP basin modelling.

d) The new understanding of the Hesper basalt as the remnant of a flow derived from Scatarie

Bank has resulted in new understanding of Barremian–Aptian tectonics. New ideas about the origin of the Naskapi shale by blocking fluvial input through Cabot Strait will be tested over the coming months. The temporal relationship of the thermal event in the basin to the Aptian volcanicity suggests that the two are related.

e) A consistent lithofacies scheme has been applied to all the long sections of Upper Jurassic–Lower Cretaceous conventional core. The importance of delta-front turbidites as reservoir rocks has been confirmed, and their spatial extent better defined.

6.2 Recommendations for year 2

The work this year has been done in haste in order to get information to BEICIP and RPS for the PFA. Year 2 work was planned to clean up loose ends, acquire strategically selected additional data to resolve uncertainties, thereby develop more solid interpretations of the data, and write up.

Our overall plans for year 2 are much as originally outlined in the proposal and contract. In particular:

Workpackage 1. Sediment provenance and diagenesis. Uncertainties in the Aptian, Berriasian–early Valanginian and Kimmeridgian should be resolved with the new Nd isotope data coming shortly and better biostratigraphic and seismic control on critical samples. Biostratigraphy will require help from Rob Fensome at GSC in re-interpreting published biostratigraphy of Sable sub-basin wells. Resolving the uncertainties will also require some more analytical work: Nd isotopes, zircon dating, and bulk geochemistry. We plan collaborative work with University College Dublin on fingerprinting K-feldspar sources to the Abenaki basin to better define their provenance, which should resolve questions about whether they relate to volcanism. Specific problems may be resolved by more MLA work and/or more hot cathode cathodoluminescence work. We still await 4 new muscovite dates from the eastern basin. A major part of the 2011 work will be synthesising a substantial amount of bulk geochemical data, using methods of Pe-Piper et al. (2008).

Work on detrital clays and their diagenesis by M.Sc. student Greg Strathdee will continue. This will contribute to a better understanding of climate influence on sediment supply and the timing and nature of fluids released during compaction of shales.

More work needs to be done on the influence of bulk chemistry on diagenesis.

Workpackage 2. Diagenetic processes and fluid flow. The bulk of the work will be following up the ideas on thermal and diagenetic history in the light of the results from the BEICIP basin modeling. Parts of the diagenesis work need writing up for journal papers, particularly a new synthesis of the significance of chemical variation in siderite, and work on the diagenetic minerals on the Panuke-Cohasset area. More work needs to be done relating observed diagenetic cements to measure porosities and permeabilities.

Workpackage 3. Volcanism and heat flow. There are considerable gaps in the volcanism and heat flow story: more work needs to be done on the relationship of volcanism with active tectonics, but the tectonics need to be better defined from WP1 and from the seismic interpretation of BEICIP. The thermal component of the BEICIP basin modeling is also important for testing hypotheses. The role of recently discovered volcanic products in the Newfoundland Basin needs to be correlated with volcanic rock geochemistry.

Workpackage 4. Depositional systems. Four current research issues need following up:

a) the use of climate-controlled indicators in refining stratigraphic correlation in the basin, particularly the Barremian arid period.
b) the use of spectral gamma as an indicator of clay mineral type and input of volcanic ash in the basin.
c) lithofacies distribution and sediment dispersion in the Naskapi member (with Andrew MacRae).
d) the work on salt petrography and geochemistry needs to be completed (with Andrew MacRae).

In addition, synthesizing and writing up the sedimentological work is a major objective of year 2 of this project.

7. Publications

This list includes only papers written or substantially revised in 2010. Many of these papers rely on data (and in some cases, interpretation) from previous OETR and PR-AC/NSERC funding. There is thus some overlap with papers reported to OETR from previous funding.

Refereed journal publications

Pe-Piper, G., and D. J. W. Piper, 2010b, Volcanic ash in the Lower Cretaceous Chaswood Formation of Nova Scotia: source and implications: Canadian Journal of Earth Sciences, v. 47, p. 1427-1443.

Tsikouras, V., G. Pe-Piper, D. J. W. Piper, and M. Schaffer, 2011, Varietal heavy mineral analysis of sediment provenance, Lower Cretaceous Scotian Basin, eastern Canada : Sedimentary Geology, v. 237, p. 150-165.

Refereed publications accepted and in press

Pe-Piper, G., and D. J. W. Piper, 2011, Cretaceous re-activation of the passive-margin Scotian Basin. In Busby C., and A. Azor, eds., Recent advances in tectonics of sedimentary basins,

Karim, A., G. Pe-Piper, D. J. W. Piper, and J. J. Hanley, 2011c, in press, Thermal and hydrocarbon-charge history and the relationship between diagenesis and reservoir connectivity: Venture field, offshore Nova Scotia, eastern Canada: Canadian Journal of Earth Sciences.

Refereed publications submitted or in revision following journal review

Okwese, A., G. Pe-Piper, and D. J. W. Piper, in revision. Controls on regional variability in sea-floor diagenesis in Upper Jurassic-Lower Cretaceous pro-deltaic sandstone and shales, Scotian Basin, eastern Canada. Marine and Petroleum Geology.

Karim, A., J. J. Hanley, G. Pe-Piper, G., and D. J. W. Piper, 2011b, accepted subject to revision, Paleohydrological and thermal events recorded by fluid inclusions, stable isotopes and geochemistry of diagenetic minerals in Lower Cretaceous sandstones, offshore Nova Scotia, Canada. AAPG Bulletin.

Pe-Piper, G., A. Karim, and D. J. W. Piper, in revision, Authigenesis of titania minerals in pro-deltaic sandstones, Cretaceous Scotian Basin: Journal of Sedimentary Research.

Piper, D. J. W., G. Pe-Piper, M. Tubrett, S. Triantaphyllidis, and G. Strathdee, in internal review. Detrital zircon geochronology and polycyclic sediment sources, Cretaceous Scotian Basin, southeastern Canada.

Other publications including Open Files (including those in advanced preparation or review)

Gould, K.M., A. Karim, D. J. W. Piper, and G. Pe-Piper, 2010b, A standard lithofacies scheme for the Missisauga and Logan Canyon formations of the Scotian Basin and its application to long sections of conventional core. Geological Survey of Canada, Open File 6745, 119 p.

Gould, K.M., D. J. W. Piper, and G. Pe-Piper, 2011, Lateral correlation of sediment facies in the Panuke and Venture fields, Scotian Basin: implications for reservoir connectivity: Geological Survey of Canada Open File 6838.

Gould, K.M., 2011, Comparison of spectral gamma and whole-rock geochemistry as a potential tool for provenance and diagenetic studies. Internal report will be submitted after revision to Geological Survey of Canada, Current Research.

Karim, A., G. Pe-Piper, G., D. J. W. Piper, and J. J. Hanley, 2010b, Thermal history and the relationship between diagenesis and the reservoir connectivity: Venture field, offshore Nova Scotia, eastern Canada: Geological Survey of Canada, Open File 6557, 69 p.

Karim, A., G. Pe-Piper, and D. J. W. Piper, 2011a, in review, Distribution of diagenetic minerals in Lower Cretaceous sandstones and their relationship to lithofacies from a proximal to distal transect: Como P-21, Panuke B-90, Cohasset A-52, Balmoral M-32 and Lawrence D-14 wells, Geological Survey of Canada Open File

Karim, A., G. Pe-Piper, and D. J. W. Piper, 2011b, in review, Distribution of diagenetic minerals in conventional core in selected wells from the eastern Scotian Basin: Geological Survey of Canada, Open File.

Pe-Piper, G., and D. J. W. Piper, 2010a, Nova Scotia Play Fairway Analysis Upper Jurassic-Lower Cretaceous Depositional Systems. 2nd Central Atlantic Conjugate Margins Conference, Lisbon, September 2010 (extended abstract).

Pe-Piper, G., E. Brown, D. J. W. Piper, and A. DeCoste, 2010, Upper Jurassic–Lower Cretaceous lithofacies, detrital petrology and diagenesis of the Louisbourg J-47 well, Scotian Shelf: Geological Survey of Canada Open File 6693.

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Pe-Piper, G., D. J. W. Piper, K. M. Gould, and A. DeCoste, 2011, Lower Cretaceous lithofacies, detrital petrology and diagenesis of the Hesper I-52, Esperanto J-47 and South Griffin J-13 wells, Scotian Shelf: Geological Survey of Canada Open File 6821, 121 p.

Pe-Piper, G., D. J. W. Piper, J. Foley, and A. DeCoste, 2011, in advanced prep. Detrital petrology and diagenesis of Lower Cretaceous sedimentary rocks, Kegeshook G-67 well, Scotian Basin: Geological Survey of Canada Open File.

Pe-Piper, G., D. J. W. Piper, D. Lefort, and S. Ledger-Piercey, 2011. Alma K-85 well, Scotian Basin: Detrital petrology and diagenesis of the Lower Cretaceous sedimentary rocks: Geological Survey of Canada Open File.

Sawatzky, C., and G. Pe-Piper, 2011, in advanced prep., Atlas of hot-cathode cathodoluminescence and optical microscope images of quartz as indicators of detrital provenance: Geological Survey of Canada, Open File.

Triantafyllidis, S., G. Pe-Piper, R. MacKay, D. J. W. Piper, and G. Strathdee, 2010, Monazite as a provenance indicator for the Lower Cretaceous reservoir sandstones, Scotian Basin: Geological Survey of Canada Open File 6732.

Student theses

Bowman, S. J., 2010, Cretaceous tectonism and volcanism in the eastern Scotian Basin, offshore Nova Scotia. M.Sc. thesis, Saint Mary's University.

Ledger-Piercey, S., 2010, The use of rutile as a provenance indicator: application to the Scotian Basin. M.Sc. thesis, Saint Mary's University [to be submitted in March 2011]

Okwese, A. C., 2010, The relationship of transgressive systems tracts to sea-floor diagenesis, Lower Cretaceous, Scotian Basin. M.Sc. thesis, Saint Mary's University.

Strathdee, G., 2010, Determining the Provenance of the Chaswood Formation using Optical Microscopy, Geochemical Analysis and Hot Cathode Cathodoluminescence Microscopy. B.Sc. honours thesis, Saint Mary's University, 69 p. + 4 appendices

Sawatzky, C. 2011. Application of hot cathode cathodoluminescence to the provenance of quartz in the Scotian Basin. B.Sc. honours thesis, Saint Mary's University.

Abstracts at conferences

Gould, K. M., D. J. W. Piper, and G. Pe-Piper, 2011, Facies interpretations and lateral variability based on correlation of conventional core in the Logan Canyon and Missisauga formations of the Scotian Basin: Atlantic Geoscience Society 2011 Colloquium.

Okwese, A. C., G. Pe-Piper, and D. J. W. Piper, 2011, Controls on regional variability in sea-floor diagenesis in Upper Jurassic–Lower Cretaceous pro-deltaic sandstones and shales, Scotian Basin, eastern Canada: Atlantic Geoscience Society 2011 Colloquium.

Pe-Piper, G. and D. J. W. Piper, 2011, Denudation of the Appalachians in the Cretaceous: tracking fluvial dispersion with mineral geochronology and geochemistry: Atlantic Geoscience Society 2011 Colloquium.

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