River Sources and the Transfer of Sands to Deepwater, Lower Cretaceous, Scotian Basin

Final Report

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2. Summary

This project focusses on the question of the source and petrographic variability of sands to the major Upper Jurassic–Lower Cretaceous deltas of the Scotian Basin. The mineralogical and geochemical composition of detrital sand influences the growth of diagenetic minerals and hence reservoir quality. The project also examines sedimentological evidence for how sand has been transferred from the deltas to deep water.

The significance of the study to industry is that it provides constraints to exploration models for reservoir sandstones, both on the shelf and in deep water. Furthermore, an understanding of the dispersal system has important implications for both regional tectonics, which determines uplift and source areas, and also reservoir quality, because of the influence of detrital petrology on diagenesis. Academically, the principal investigators are recognised as cutting-edge researchers in (a) the application of multiple petrographic techniques to basin-provenance studies and (b) the transfer of sand from deltas to deep water. The Scotian basin is an excellent opportunity to make advances in both of these fields.

The original objectives of the study were three-fold, with objective 1 being the most important in terms of budget and level of effort.

1. To carry out sufficient new mineralogical and geochemical analysis of samples from the Missisauga and Logan Canyon formations to define the number of source rivers to the Scotian basin and the variation through time in the composition of sediment that these rivers supplied to the basin.
2. To estimate paleogradients and paleodischarge of the rivers and the nature of river supply to the delta front and hence deep water, using both modern analogues and information from cores and seismics, so as to identify which parts of the deep-water Scotian basin have the greatest probability of deep-water sands.
3. To evaluate the interpretations of objectives 1 and 2, using available seismic data in deep-water areas.

The methodology of the study was unique in its use of multiple methods to determine provenance of sediment. We believe we are the first group anywhere to have data on detrital muscovite, monazite and zircon from the same samples, supported by textural, petrographic and geochemical data on individual grains, which allows estimates of distance of transport and the role of second cycle minerals. We have applied Mineral Liberation Analysis (MLA) techniques to

identifying second cycle minerals from their morphology and have carryied out quantitative chemical fingerprinting using large numbers of grains by these techniques. We have only the second hot-cathode CL microscope in Canada and in our understanding are the only group in Canada working on characterizing detrital quartz by CL. The journal publication on bulk geochemical analyses from the Scotian basin evolved into a study of the challenges of discriminating provenance from areas like the Appalachians and suggested procedures.

Our data show that there was major sediment supply from the southern margin of the exposed Appalachian orogen, on the basis of abundant Devonian and Carboniferous monazite and muscovite. The Sable sub-basin was supplied by one river sourced principally from Cape Breton Island and the Gulf of St Lawrence, the eastern Scotian basin by another sourced principally from western Newfoundland. 30-50% of the zircon supplied is polycyclic, suggesting considerable reworking of Paleozoic sedimentary rocks. Sediments supplied to the Sable sub-basin show little change through time, but sediments supplied to the eastern Scotian Basin suggest major Aptian–Albian uplift and unroofing of Grenville in western Newfoundland and changes in predominant source between the Upper Jurassic and Lower Cretaceous. Data from the Naskapi N-30 well in the western Scotian Basin shows that at times the central Nova Scotian Chaswood River flowed southward, depositing sediment in the Shubenacadie-Elsmvale region, and at other times was diverted along the Cobequid-Chedabucto fault system. The detrital muscovite shows an inner shelf source of 90% of the muscovite implying considerable erosion and tectonic uplift on the inner shelf during the Lower Cretaceous.

The Scotian basin was thus supplied by at least three medium-sized mountainous rivers and that only some “shelf-edge” deltas extended to the continental slope. A delta plain prograded 50–100 km seaward of the zone of intermittent uplift and erosion on the inner shelf, landward of the hinge line. In modern systems, turbidity currents form off such deltas either by direct hyperpycnal flow of rivers or by slumping of prodelta sands, with turbidity current type controlling the location and style of the deep-water sands. Evidence from conventional core shows that both processes were also active in the Late Jurassic–Early Cretaceous deltas. Hyperpycnal flow of fluvial sediment at river mouths was an important component of sediment supply to the basin. Such hyperpycnal flows deposit thick sand beds just seaward of the river mouth in shelf-edge deltas (such as at Venture and Thebaud) and may flow seawards to deliver sand to deep-water. The flows reaching deep-water are likely fully turbulent and would deposit sand principally on the continental rise.

Additional work that follows on from this study is being carried out as part of the Play Fairway Analysis of the Scotian Basin. This includes using Nd-Sm isotopes to better define bulk sediment supply to the basin; relating variations in detrital petrography to variations in diagenesis; and further definition of sedimentary facies, particularly the lateral variability of facies. The sediment supply pathways proposed in this study will be tested by the planned basin modelling by Beicip.

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4. Introduction

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5. Objectives, Methodology and Results

5.1 Scientific Objectives

The original objectives of the study were three-fold, with objective 1 being the most important in terms of budget and level of effort.

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5.2 Methodology

Underpinning this project was the concept that the sources of sediment to the Lower Cretaceous deltas of the Scotian Basin could only be interpreted by bringing different techniques of detrital petrology to bear on the problem. This approach has proved very fruitful and contrasts with the common approach in the literature of using only one or two techniques.

Three approaches to interpreting sediment provenance have been used: the geochronology of detrital minerals, varietal detrital mineral analysis, and bulk geochemical analysis. Each technique has its own advantages and disadvantages as an indicator of provenance.

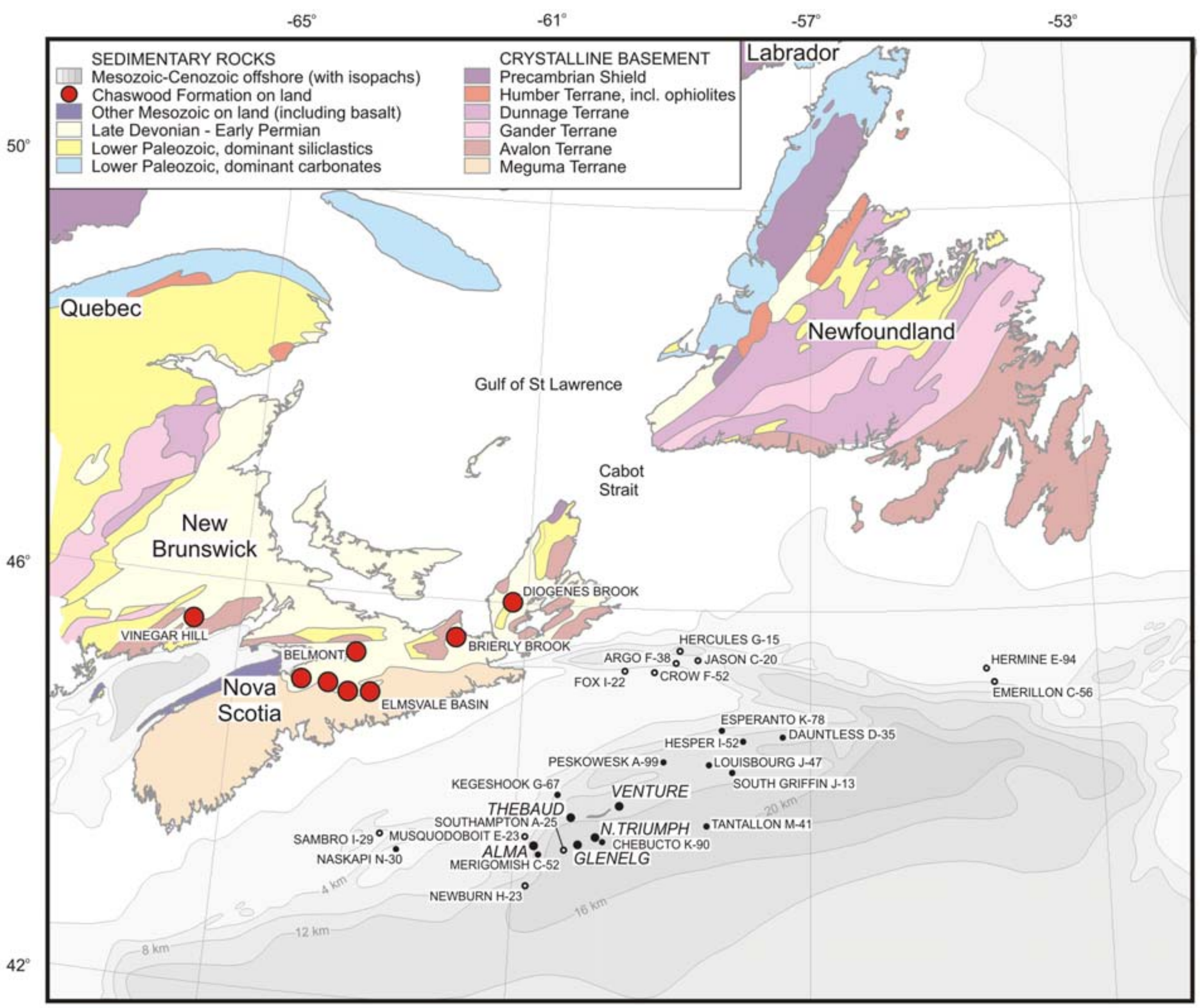

Figure 1. Wells and fields in the Scotian Basin from which samples have been studied. Also shows the principal Appalachian source rocks and distribution of the Lower Cretaceous Chaswood Formation. Base map modified from Williams and Grant (1998).

Almost all our analyses are based on samples from conventional core (Fig. 1) 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 facies 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).

5.2.1 Geochronology of detrital minerals

Geochronology of detrital minerals provides a first-order assessment of the source of detrital sediment. The detrital minerals muscovite, monazite and zircon can all be dated, but have different mechanical and chemical stability. Monazite has a hardness of 5–5.5 compared with 7.5 for zircon. Monazite has been observed to be susceptible to chemical leaching in permeable facies of the Cretaceous Chaswood Formation (Pe-Piper and MacKay, 2006), suggesting that prolonged chemical weathering in the source area will also destroy monazite. Monazite is thus well suited to identification of first-cycle supply of detritus to a sedimentary basin, although some monazite grains may be polycyclic in origin. Much of the stable zircon may be recycled through older sedimentary rocks. Muscovite grains are very susceptible to physical abrasion, so that they are preferentially derived from proximal first-cycle sources: our studies suggest transport distances of < 50 km are common (Reynolds et al., 2009).

Detrital zircons were separated in heavy mineral concentrates and identified by Mineral Liberation Analysis (MLA) and dated by Laser-Ablation Inductively-Coupled Plasma Mass Spectrometry (LA-ICPMS) at the CREAIT facility in the Inco Innovation Centre at Memorial University. Scanning electron microscope (SEM) images were used to interpret zoning, morphology and reworking of detrital zircons.

Detrital monazite was separated in heavy mineral concentrates or analysed directly from polished thin sections using the Regional Electron Microprobe Facility at Dalhousie University. Individual grains can be dated by the U-Pb method because monazite contains Th and U but insignificant common Pb. In addition, the abundance of selected rare-earth elements (REE), P, Si and Ca were measured. Morphology of monazite grains and the types of inclusions present were determined from backscattered electron (BSE) and secondary electron (SE) images.

Individual muscovite grains ~0.3-1.0 mm in diameter were picked from mica concentrates. The selected grains were placed individually into holes machined in aluminum disks and were irradiated in the McMaster University nuclear reacto using standard dated minerals as flux monitors, as documented by Reynolds et al. (2009). Laser analyses were made with a Nd-YAG system operated in continuous mode with the beam expanded to approximately cover the grain. Power was increased in a series of steps until complete fusion was achieved and all gas released from the grain was then collected. All isotopic analyses were made using a VG 3600 mass spectrometer. In addition, electron microprobe geochemical analyses were made of selected muscovite grains

5.2.2 Varietal mineral analysis

Varietal heavy mineral analysis (or "chemical fingerprinting") is the study of variation in chemical composition or other properties of a single mineral species. It is a useful tool in provenance analyses because it is relatively insensitive to modification during weathering, diagenesis, and sedimentation (e.g., Morton, 1991). Although the technique has been generally applied to heavy minerals, we have also used this approach on the cathodoluminescence properties of detrital quartz.

Most varietal heavy mineral analysis was carried out on heavy minerals, either from separates or in polished thin sections of rock samples. More than a thousand high-quality electron microprobe analyses of detrital minerals were made from sandstones from the Scotian Basin (Pe-Piper et al., 2009). Where possible, these analyses were compared with published chemical analyses from the literature on potential source rocks on land, commonly by the use of binary or ternary element plots that allow the discrimination of different sources (e.g. the Henry and Guidotti, 1985, plots for tourmaline).

These chemical analyses of minerals were then used as the basis for rapid automated classification of heavy mineral separates using the Mineral Liberation Analysis procedure at Memorial University. The Mineral Liberation Analyzer™ (MLA) (FEI Company, 2009) includes an ultra-fast Scanning Electron Microscope (SEM) FEI QUANTA400 equipped with an energy dispersive spectrometer Bruker SDD-type (Silicon Drift Detector). It acquires low noise, high-resolution, backscattered electron images (BSEI) of sediment grains in a polished epoxy mount. Individual mineral phases are discriminated by X-ray analysis using the energy dispersive spectrometer. The data were processed with the software Mineral Liberation Analysis by JKTech™. This image analysis software determines the shape and size of grains of each mineral phase and whether such grains are "liberated" (monomineralic) or polymineralic (such as altered monomineralic grains, lithic clasts and aggregates). The MLA does not measure and store compositional data for each mineral grain. Rather, the X-ray spectrum is compared with a library of standard minerals that can be pre-set by the operator and assigns each grain to its closest compositional match in the library. The mineral types defined by elemental composition determined by electron microprobe were expressed as unique and unambiguous elemental ratios in order to apply the classification to the working library of mineral spectra for the MLA. For each heavy mineral mount, at least $3x10^4$ particles were imaged and spectra were acquired. The MLA image analysis software determines the area of each mineral in each grain or particle and can thus determine modal mineralogy. Various size and shape parameters can also be determined for each grain or particle, such as angularity, aspect ratio and shape factor of grains.

Using funding from Saint Mary’s University, OETR, and PR-AC, a hot-cathode cathodoluminescence microscope was acquired for use in this study, particularly for using CL colour shifts in detrital quartz as an indicator of provenance. Quartz makes up more than 95% of framework grains in offshore sandstones and thus provides a comprehensive sampling of most coarse-grained sediment sources, in contrast to heavy minerals which may have a very restricted distribution in source rocks. A hot-cathode cathodoluminescence (hot-CL) microscope combines high sensitivity with high intensity and high stability of the electron beam current (Gotte and Richter, 2006). Hot-CL microscope with digital analysis and spectroscope analysis gives the ability to analyze the CL colour shift in quartz from the initial to the final colour. The shift is due to defects in the crystal structure that are formed during crystallization by the physical and chemical conditions surrounding the grain and therefore depends on the provenance of the quartz grain (Gotte and Richter, 2006). Much of our initial work involved setting up procedures for using the instrument and acquiring an atlas of the CL colour, colour shift and colour inhomogeneity in different types of source rocks.

5.2.3 Bulk chemistry

The use of bulk chemistry does not require particular analytical sophistication: the challenge is in the interpretation of data, which is discussed below under 5.3 Results. Von Eynatten et al.

(2003) concluded that bulk chemical analyses including trace elements were more effective than the study of heavy minerals in determining sediment provenance, largely because identification and counting of heavy minerals required skill and was time consuming. This drawback of heavy minerals has been reduced by our use of MLA techniques. On the other hand, rock chemistry is a consequence of the mineralogical composition of a rock, so that petrographic studies are intrinsically more informative than bulk chemistry. Furthermore, bulk geochemistry records the entire solid input into the basin: in many cases, heavy minerals have a very limited source (e.g. chromite from ultramafic rocks in ophiolites).

Depending on the size of sample available, the samples were either crushed by hand using an agate pestle and mortar (for small samples) or were crushed using a shatterbox with an iron bowl (for larger samples). Major and trace elements were determined by Activation Laboratories according to their Code 4Lithoresearch and Code 4B1 packages, which combine lithium metaborate/tetraborate fusion ICP rock analyses with a trace element ICP-MS package.

In addition, a scoping study of Nd-Sm isotope composition was carried out. This will be completed under the Play Fairway Analysis contract. Nd-Sm isotope analyses were carried out by Geospec Consultants Limited using facilities at the University of Alberta. Rock powders are were spiked with a known amount of mixed ^{150}Nd-^{149}Sm tracer solution. Nd and Sm were separated by conventional cation and HDEHP-based chromatography. Chemical processing blanks are < 120 picograms of either Sm or Nd, and are insignificant relative to the amount of Sm or Nd analyzed for any rock sample. The isotopic composition of Nd is determined in static mode by Multi-Collector ICP- Mass Spectrometry. All isotope ratios are normalized for variable mass fractionation to a value of ^{146}Nd / ^{144}Nd = 0.7219 using the exponential fractionation law. The ^{143}Nd / ^{144}Nd ratio of samples is presented relative to a value of 0.511850 for the La Jolla Nd isotopic standard, monitored by use of an Alfa Nd isotopic standard for each analytical session. Sm isotopic abundances are measured in static mode by static mode by Multi-Collector ICP- Mass Spectrometry, and are normalized for variable mass fractionation to a value of 1.17537 for ^{152}Sm / ^{154}Sm also using the exponential law. The reproducibility for ^{147}Sm / ^{144}Nd is ~ ± 0.1% for real rock powders.

5.2.4 Innovation in methodology

This study has provided the opportunity for innovation in methodological approaches to the study of sediment provenance. Specifically:

- The journal publication on bulk geochemical analyses from the Scotian basin evolved into a study of the challenges of discriminating provenance from areas like the Appalachians and suggested procedures. This paper has been widely requested internationally and I was invited to present on it at a Petrobras conference in Brazil in March 2009.
- We believe we are the first group anywhere to have data on detrital muscovite, monazite and zircon from the same samples, which allow estimates of distance of transport and the role of second cycles minerals.
- We believe we are the first group anywhere to be using Mineral Liberation Analysis (MLA) techniques to identifying second cycle minerals from their morphology and to be carrying out quantitative chemical fingerprinting using large numbers of grains by the MLA techniques.
- We have only the second hot-cathode CL microscope in Canada and believe we are the only group in Canada working on characterizing detrital quartz by such CL.

5.3 Results

5.3.1 Detrital sources to the Lower Cretaceous deltas

Potential source areas for the rivers that built the Lower Cretaceous deltas are in the Appalachian orogen of southeastern Canada, successor Late Paleozoic basins filled principally with fluvial sandstones, and the eastern Canadian Shield (Williams, 1995). In early work on geochronology of detrital minerals in the Missisauga Formation, Grist et al. (1992) obtained ~1 Ga ages from detrital potassium feldspars by $^{40}Ar/^{39}Ar$ dating, that were interpreted as derived from the Grenville Province of the Canadian Shield. This work appeared to confirm the proposal of Wade and Maclean (1990) that the eastern Canadian Shield was an important source of sediment. However, the ages of some muscovite indicated derivation of that mineral from the Appalachian orogen (Grist et al. 1992).

Geochronology of detrital minerals

Geochronology of detrital minerals provides a first-order assessment of the source of detrital sediment. Almost all detrital **muscovite** from the Lower Cretaceous sandstones of the Sable Sub-basin ranges in age from ~ 420–240 Ma based on single grain $^{40}Ar/^{39}Ar$ dating (Reynolds et al., 2009). In the LaHave Platform, muscovite from the Naskapi N-30 well ranges in age from 372 to 350 Ma (Fig. 2). In both areas, grains of Carboniferous age (300–360 Ma) were derived from basement metasedimentary rocks of the inner continental shelf that experienced resetting during the Alleghanian orogeny. Devonian (360–417 Ma) grains were derived from metasedimentary rocks and granite plutons of the Acadian orogeny on land. Mass-balance calculations (Reynolds et al., 2009) require a few tens to a few hundreds of metres of exhumation of the inner continental shelf during the Early Cretaceous in order to supply the observed detrital muscovite in the Scotian Basin. In the Chaswood Formation, detrital muscovite appears to be reworked from local Carboniferous sandstones (Reynolds et al., 2010). Muscovite is readily abraded during transport, so that the paucity of older ages probably results from abrasion during transport from more inboard Appalachian terranes.

Electron-microprobe geochronology of detrital **monazite** is reported by Pe-Piper and MacKay (2006) and Triantaphyllidis et al. (in review). In the Chaswood Formation of Nova Scotia, the dominant grains are Ordovician–Silurian, reflecting the Taconic orogeny and early Paleozoic plutonism of the more inboard terranes of the Appalachians. Grains of Devonian age and those derived from the Avalon terrane, with latest Neoproterozoic plutonism, are rare and older Precambrian grains are lacking. In the Sable Sub-basin, most monazite grains are Devonian, but Taconic, latest Neoproterozoic, Mesoproterozoic and Paleoproterozoic grains each make up about 10% of the total monazite

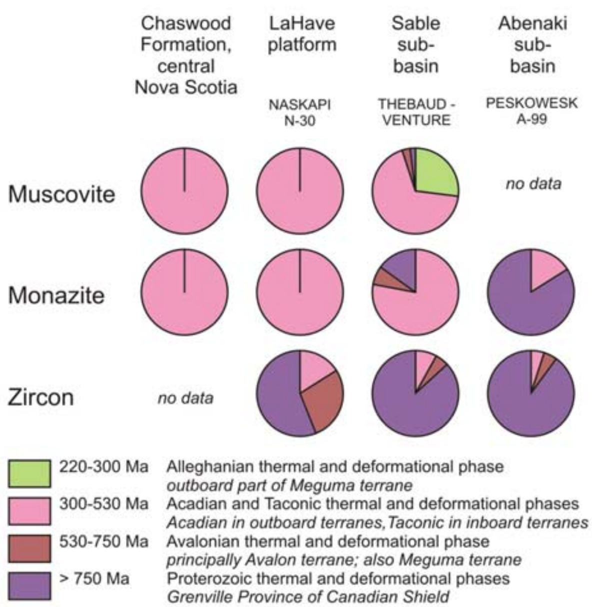

Figure 2. Summary of regional variation in the relative abundance of detrital muscovite, monazite and zircon from different orogenic phases.

assemblage (Fig. 3). In contrast, in the Abenaki Sub-basin in the east, a higher proportion of monazites (~60%) are of Meso- or Paleoproterozoic age, implying a source in the Canadian Shield. Although monazite is relatively resistant to mechanical abrasion, it is readily broken down chemically under acid conditions. Monazites were classified according to whether they were euhedral, subhedral, rounded or irregular. There is no systematic variation of morphology with age, except that euhedral grains are over-represented in middle Paleozoic ages, characteristic of the outboard Appalachians, and involving short transport distances. We interpret this variation to mean that most monazite is likely to be of first cycle origin.

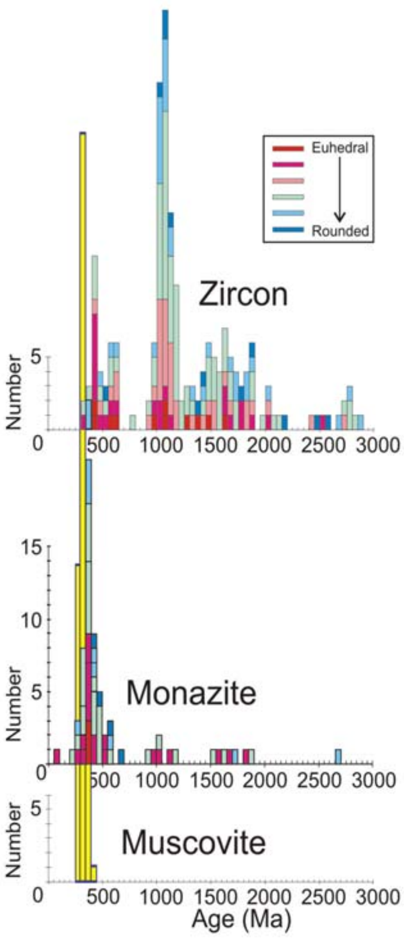

Figure 3. Comparison of geochronology of muscovite, monazite and zircon from the Sable sub-basin. All musovite shown in yellow; for monazite and zircon, first cycle grains are in reds and polycyclic grains in blues.

Single grain laser ablation **zircon** dating (Piper et al., in review) shows that in most samples, zircons of Precambrian age predominate, with peaks at 1.0 Ga and 1.7 Ga that are characteristic of Appalachian rocks of Laurentian provenance (e.g. Waldron et al., 2008) (Fig. 4). A few samples show small peaks at 0.6 and 2.0 Ga, characteristic of Appalachian rocks of Gondwanan provenance (e.g., Krogh and Keppie, 1990) that occur in the more outboard terranes. The only sample with the highest proportion of zircons in these peaks is from the Naskapi well in the LaHave Platform. All samples have variable but relatively low abundance of 300–550 Ma zircons representing Appalachian crystalline basement.

Comparison between the proportion of monazite and zircon grains of different ages in the same sample or unit may provide information on the importance of polycyclic reworking of sediment. For example, in the Lower Missisauga Formation of the Thebaud field, 78% of the monazites are of middle Paleozoic age from the Appalachians and 15 % are of Shield origin. By contrast, 86% of the zircons are of Shield origin and only 8% of middle Paleozoic age from the Appalachians. There are several reasons for such variability: different abundances of monazite and zircon in different source rocks and the effects of hydraulic

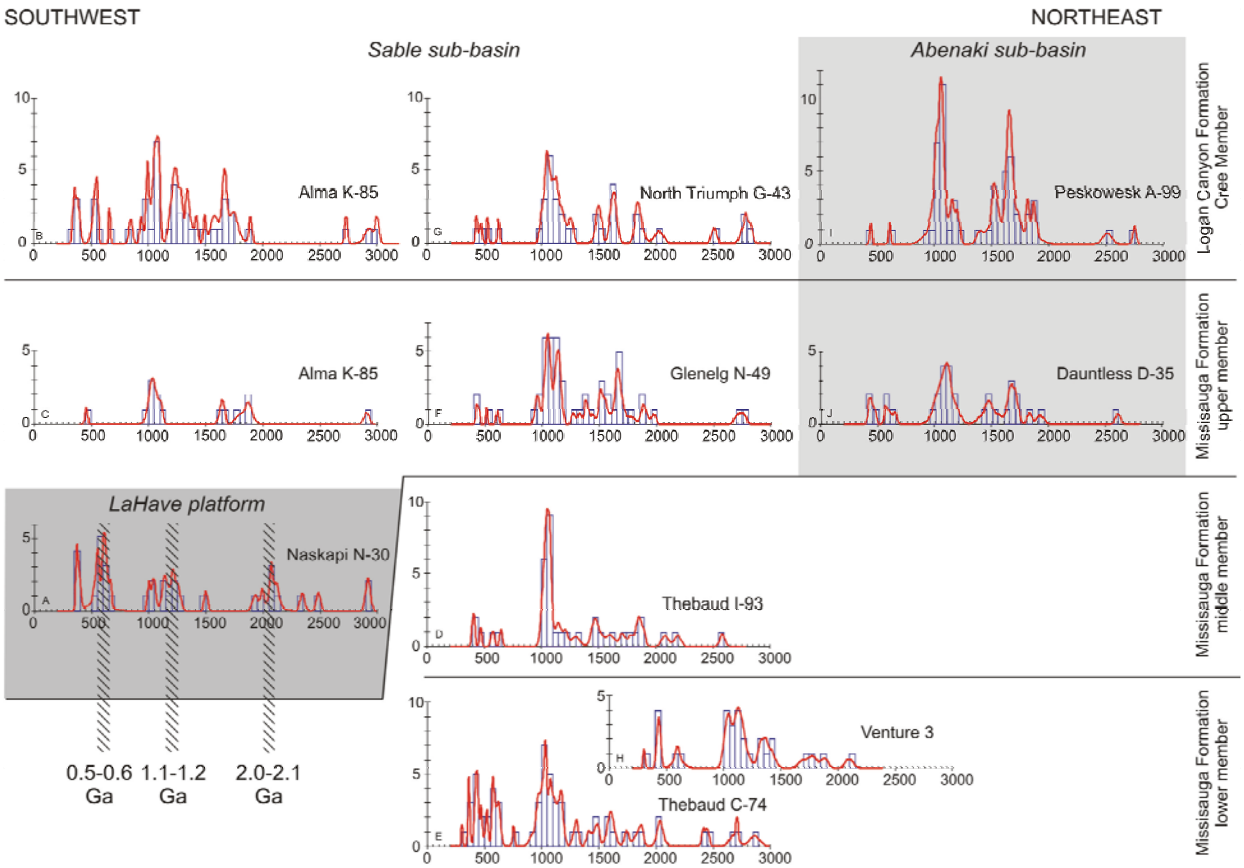

Figure 4. Histograms and probability plots for detrital zircon ages within 10% of concordia from various stratigraphic levels and geographic settings in the Scotian Basin.

sorting of grains. However, zircon and monazite ages show almost no mismatch in some localities, such as in the Logan Canyon Formation of the Peskowesk well, where the abundance of monazites and zircons of Shield and Appalachian origin are identical to within sampling error. It is therefore likely that whereas most of the monazites in the Thebaud field are first cycle, only a few of the zircons are first cycle. A high proportion of the zircons are polycyclic and reworked from Lower Paleozoic or Precambrian sediments that contain a high proportion of zircons of Shield origin: this accounts for the high proportion (56 %) of well-rounded zircon grains at Thebaud. In contrast, at Peskowesk where the distribution of monazite and zircon ages are similar, suggesting that a high proportion of the zircons are first cycle, only 30% of the zircons are well rounded.

The limitations of using zircon dating alone to interpret provenance is shown by a sample from the Upper Missisauga Formation at Naskapi N-30, in the LaHave Platform. All monazite grains date between 305–431 Ma, with peaks in abundance in the Late Devonian and Early Carboniferous.

Muscovite grains show a very similar age distribution. Nevertheless, only 16% of the zircons give middle Paleozoic ages characteristic of first-cycle Appalachian provenance. The remaining zircons are of Precambrian age, with peaks in abundance at 0.6 and 2.2 Ga, similar to detrital zircons reported from metasedimentary rocks of the Meguma Terrane (Krogh and Keppie, 1990) and are therefore interpreted as polycyclic.

Overall, the geochronology of detrital minerals indicates that the Appalachian orogen was the predominant source of sand to the Scotian Basin. Only in the Abenaki Sub-basin is there evidence for significant supply from Canadian Shield rocks, likely those exposed in inliers in western Newfoundland. If there were a proto-St Lawrence River, it did not supply significant Shield detritus to the Scotian Basin.

Varietal detrital minerals

Many distinctive detrital minerals are found in the Scotian Basin, but a database of mineral compositions in Appalachian bedrock is lacking with which comparison can be made. Because the terranes of the Appalachians are sub-parallel to the continental margin, it is difficult to compile a useful database from modern rivers, analogous to the one that Morton et al. (2004) used to identify sources of garnets around the North Sea.

Distinct chemical varieties of the abundant mineral groups garnet, spinel, tourmaline, muscovite, biotite and feldspar have been recognised in the Scotian Basin and Chaswood Formation (Pe-Piper et al., 2009; Tsikouras et al. in review) and are of value in refining mineral provenance (Fig. 5). Feldspar from the Abenaki Sub-basin and the LaHave Platform is predominantly K-feldspar, whereas plagioclase is more abundant in the Sable Sub-basin. Abundant tourmaline from the Sable Sub-basin has a predominant metasedimentary source, using the criteria of Henry and Guidotti (1985), whereas that from the Chaswood Formation of Nova Scotia includes ~30% tourmaline from a granitic source. Tourmaline is rare in the Abenaki Sub-basin.

Distinctive detrital minerals, from the Meguma Terrane, are found in the Naskapi N-30 well. About 35% of the muscovite is sodium rich, characteristic of muscovite from Alleghanian shear zones in the Meguma terrane (Reynolds et al., 2009). The garnets closely resemble those found in the Meguma Terrane; and tremolitic amphibole from two wells in the western Sable Sub-basin is also likely derived from the Meguma Terrane (Pe-Piper et al., 2009).

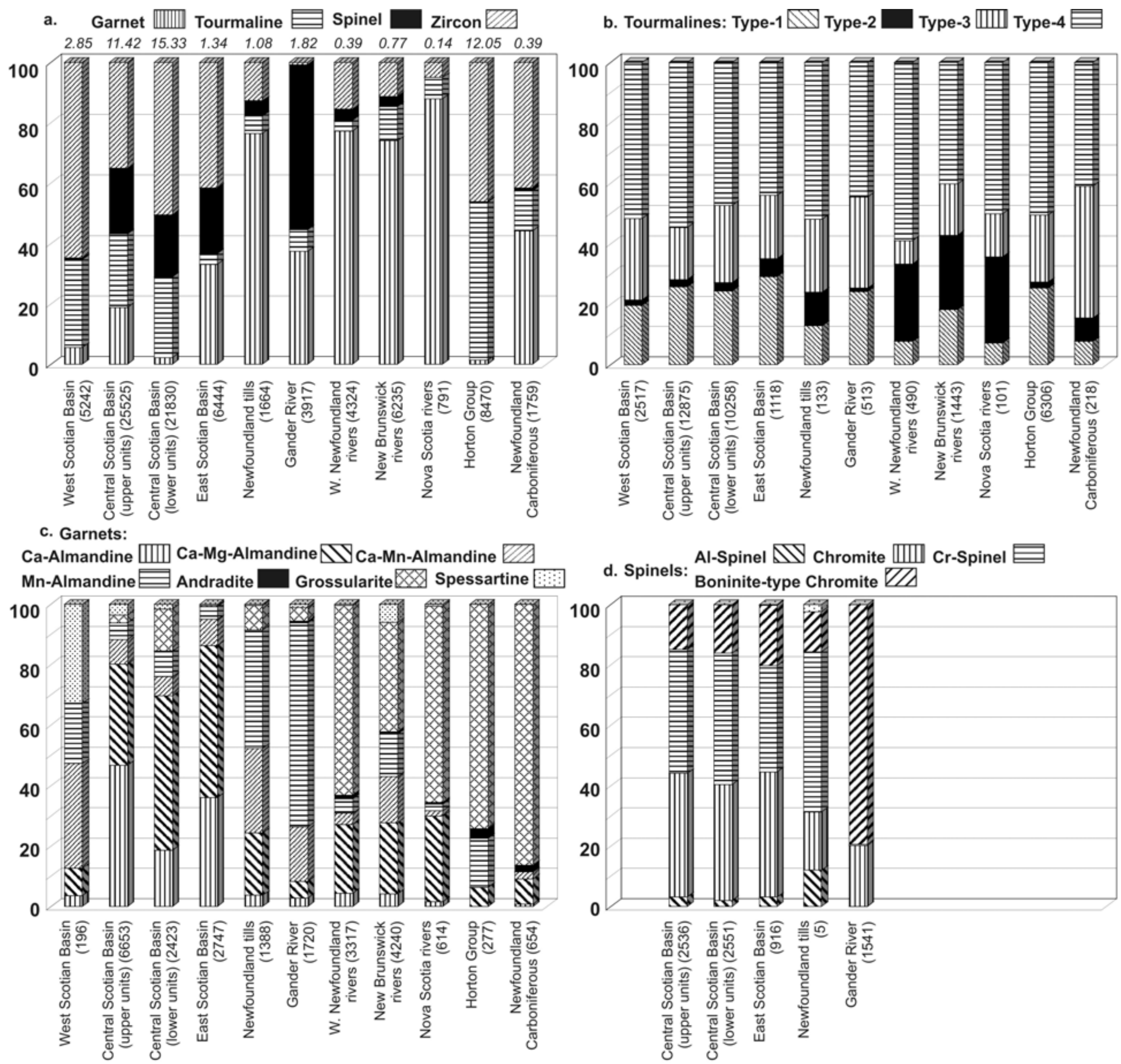

Figure 5. Variation in relative modal abundance of (a) tourmaline, chrome spinel, garnet and zircon; (b) varieties of tourmaline; (c) varieties of garnet; and (d) varieties of chrome spinel, for different parts of the Scotian Basin and for samples representing Appalachian sources (from Tsikouras et al., in review).

Detrital minerals indicate that the LaHave Platform, the Sable Sub-basin and the Abenaki Sub-basin received sediment from different sources, an interpretation that can also be made from detrital zircon and monazite geochronology. Chemical analysis of specific minerals, such as garnet and tourmaline, can be used to constrain provenance interpretations. For example, although amphibole suggests some supply from the Meguma Terrane to the western Sable Sub-basin, the abundance of different types of garnets indicates that such supply likely makes up less than 20% of the total sediment. The difficulty of distinguishing minerals from polycyclic sources and the lack of a good database from source areas limits the use of chemical fingerprinting of detrital minerals.

Bulk geochemistry

The limitation of techniques using geochronology or chemical fingerprinting of minerals is that they track only sediment sources with characteristic minerals. Use of whole-rock geochemistry may provide a method to assess the bulk supply of detrital sediment, as summarized for the Scotian Basin by Pe-Piper et al. (2008). This first requires screening out rocks that have experienced significant chemical change as a result of diagenesis; rocks with large amounts of carbonate cement can be recognised on the basis of abnormal Ca, Mg, Fe and P. The terrigenous Lower Cretaceous rocks of the Scotian Basin have unusually high Ti and Fe compared with global averages of sediment, in part reflecting the abundance of ilmenite as a detrital mineral (Pe-Piper et al., 2005). They also have unusually low Ca, perhaps the result of the paucity of plagioclase and mafic igneous rocks in the Appalachian source area.

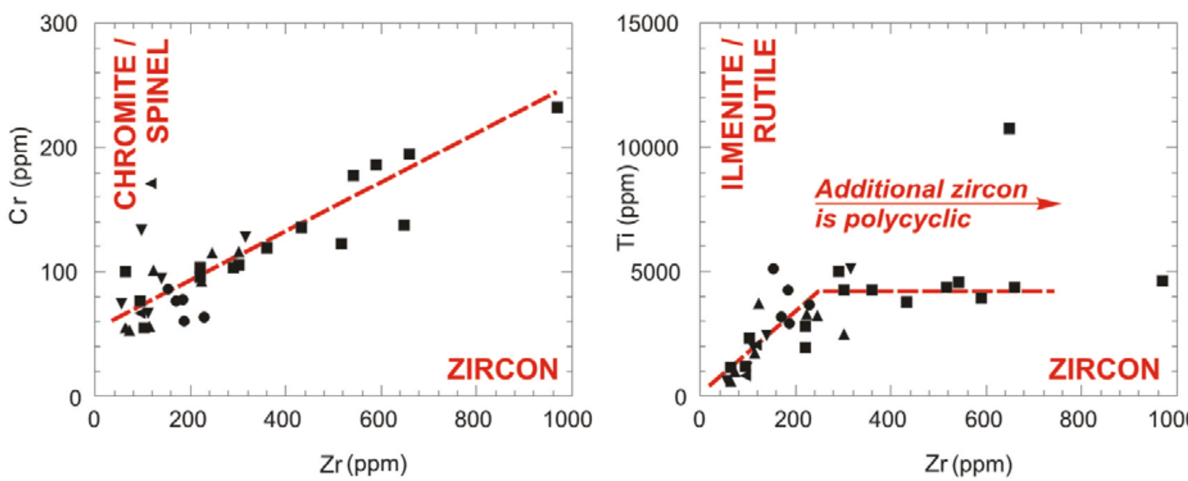

Figure 6. Variation in Cr, Zr and Ti in sandstones of the Scotian Basin, illustrating the polycyclic origin of most Cr (in chromite) and Zr (in zircon). In contrast, much ilmenite and rutile is first cycle. (Modified from Pe-Piper et al. 2008).

The co-variation of the elements Ti (predominantly in ilmenite), Zr and Cr (predominantly in zircon and chromite respectively) allows estimates of the effects of hydraulic sorting of heavy minerals and the proportion of first-cycle to polycyclic minerals (Fig. 6). Zircon and chromite are sourced principally by granites and ophiolites respectively, so that their strong covariance does not reflect a common source, but rather the concentration of ultrastable minerals in polycyclic sediments and the effects of size and density sorting during deposition. In contrast, ilmenite is predominantly a first cycle mineral (Pe-Piper et al., 2005). Its covariance with zircon at low concentrations is probably the effect of depositional sorting by size and density, but at high concentrations of zircon there is no corresponding high concentration of ilmenite.

Multivariate statistical analysis by principal component analysis showed that variation in major elements in sandstones and mudstones supports the hypothesis that the Abenaki Sub-basin, Sable Sub-basin and LaHave Platform received sediment of different composition (Pe-Piper et al., 2008). Only a few trace elements were found to be diagnostic of different sources, namely Rb, Sr, U, Th, Nb, and Ti, with the latter two of value only for sandstones. All of these are elements that are abundant in the granites of the Appalachians.

In the Chaswood Formation on land, stratigraphic variations in bulk geochemistry show the influence of episodic tectonism in the source area (Piper et al., 2008). Diagenetic processes partially obscured the detrital signature, as a result of concentration of K, P, Sr and U at three regional unconformities intersected by the borehole and recognised from seismic-reflection profiles. As in the offshore sandstones and mudstones, the elements Ti (in ilmenite and its alteration products), Zr (in zircon), Th and Y are largely controlled by the abundance of heavy minerals in the rocks. Ilmenite is the dominant first-cycle heavy mineral, whereas much of the zircon is of polycyclic origin, so that the Ti/Zr ratio is a guide to the proportion of first-cycle sediment supply from crystalline basement. High concentrations of Cr (given the absence of detrital chromite in the Chaswood Formation) and Sr (except where diagenetic P-bearing minerals are present) and the high Ni/Co ratio in mudstones appear related to supply from weathered mafic crystalline basement. The observed stratigraphic variations in geochemistry suggest three cycles of sediment supply to the Chaswood Formation, each overlying a regional unconformity (Piper et al., 2008). Each cycle reflects uplift of horsts bounded by strike-slip faults that resulted first in shedding of readily eroded Carboniferous sandstones, followed by rapid erosion of crystalline basement and, finally, greater supply of deeply weathered regolith remote from the active faulting.

Use of bulk geochemistry is hampered by the diagenetic concentration of both major and trace elements and in many cases by hydraulic sorting of heavy minerals that contain the highest abundances of trace elements. However, such sorting does provide a means of assessing the relative abundance of first cycle and polycyclic heavy minerals. If diagenetic change in element abundance is minor, bulk geochemistry is an effective means of assessing stratigraphic variation in supply. However, Pe-Piper et al. (2008) showed that most published source discrimination diagrams based on bulk geochemistry do not correctly discriminate sources to the Scotian Basin.

Synthesis

At the Naskapi N-30 well on the **LaHave Platform**, the geochronology of detrital monazite and muscovite shows a mode for detrital muscovite of 350-370 Ma and for detrital monazite of 300-450 Ma. Older ages are lacking. This suggests that the Naskapi well at that time had a predominantly local source from the Meguma terrane. The zircon chronology shows a small peak at ~375 Ma, probably corresponding to the South Mountain Batholith and broad peaks at 550-650 Ma and ~2.1 Ga corresponding to the principal peaks found in Meguma Supergroup metasedimentary rocks (Waldron et al. 2009). A small peak at 3.0 Ga has also been reported from the Meguma Supergroup (Krogh and Keppie 1990). However, the prominent double peak at 1.0 and 1.2 Ga has not been reported from the Meguma Terrane and such grains are very rare in Horton Group rocks of the St Marys basin (Murphy and Hamilton 1990). All well-imaged grains of this age from Naskapi are rounded with some preserved subhedral features (Fig. 4). These two peaks are likely characteristic of Laurentian sources (e.g. Waldron et al. 2008) and are probably polycyclic from Upper Carboniferous rocks. As noted above, muscovite, garnet and tremolite are all distinctive and the bulk geochemistry differs from that farther east in the basin.

Wells in the **Sable sub-basin** have zircons that dominantly have a Laurentian source, with characteristic age peaks at 1.1 Ga, 1.4-1.9 Ga and 2.7 Ga. A Devonian peak at 350-400 Ma is present only in Alma K-85 (Cree Member) and Thebaud C-74 (lower member of Missisauga Formation); these two samples also have higher peaks than any other samples at ~0.6 and ~2.0 Ga, similar to the LaHave platform well suggesting a Meguma terrane source. Garnet and tremolite at Alma and Musquodoboit also suggest a Meguma terrane input. In the Sable sub-basin, ~0.4 Ga monazites predominate. A few monazites have ages between 0.9 and 1.9 Ga: they are rounded with subhedral features and are interpreted as likely first-cycle grains with long transport distance. The difference in the age distribution between zircon and monazite is because much of the monazite is first cycle, whereas much of the zircon is not.

Some Precambrian zircons are likely first cycle: 12% are euhedral and 19% subhedral, principally 1.0-1.1 Ga. The presence of a few rounded monazites with subhedral features, with ages of 0.9-1.9 Ga, suggests that there was an actively eroding Laurentian basement source in the Grenvillian. Although the Blair River Complex of northern Cape Breton Island is Grenvillian, we consider this source too small to account for the persistent presence of first cycle 0.9-1.1 Ga zircons and monazites through a large stratigraphic range. The Long Range inlier of western Newfoundland seems a much more probable source. The abundance of polycyclic chrome spinel in the Sable sub-basin suggests a source from sandstones containing ophiolitic detritus. The principal ophiolite sources are either in western Newfoundland, or in the Eastern Townships of Quebec: the varietal types of chrome spinel suggest a western Newfoundland source..

Of the 70% rounded Precambrian zircons, few show textures that suggest rounding was the result of a metamorphic origin. Thick Lower Paleozoic and Carboniferous clastic successions in the Appalachians were substantially sourced from Laurentian craton and are know to contain detrital zircon. A polycyclic origin is supported by the good correlation between Zr and Cr in Sable sub-basin sandstones resulting from concentration of zircon and chromite respectively, derived from different rock types and concentrated by sedimentary sorting processes.

The uniformity of zircon age distributions in the Sable sub-basin may be due to the predominant polycyclic source in older sedimentary rocks, which has the effect of mixing detrital zircons potentially from many different sources. Minor differences in relative abundance of different ages may be the result of either different first cycle sources (estimated to provide 15- 35% of the zircons) or variability in the polycyclic sources.

Wells in the **eastern part of the Scotian Shelf**, principally in the Abenaki sub-basin, contain 40% of euhedral or subhedral ~1.1 and ~1.6 Ga zircons that are likely first cycle, given that subhedral monazites of the same age are also common. More rounded zircons from these age peaks, and from the small peaks at ~430 Ma and ~600 Ma, are probably polycyclic. The paucity of first cycle Paleozoic igneous sources in both monazite and zircon is an important difference from the Sable sub-basin, but the abundance of K-feldspar, presumably from granitoid rocks, is higher than in the Sable sub-basin from both mineralogical and chemical data. As in the Sable sub-basin, Cr and Zr co-vary as a result of concentration of polycyclic resistant minerals. Tourmaline is distinctly rare compared with the Sable sub-basin, suggesting that it may be largely first cycle in the Sable sub-basin. These pronounced mineralogical and chemical differences indicate a different river or rivers supplying sediment to the eastern Scotian Shelf; this system is reflected in a tongue of high net to gross across the centre of Banquereau (Tyrrell, 2007). The abundance of ~1.1 Ga first cycle zircon and monazite suggests that this area was also source from western Newfoundland, presumably by a river system lying to the east of the Long Range. Polycyclic sources were likely from Lower Paleozoic metasediments of west-central Newfoundland and the Carboniferous rocks of the eastern part of the Sydney Basin beneath the Burin Platform.

The Peskowesk A-99 (Pe-Piper et al., 2006) and Louisbourg J-47 (Pe-Piper et al., 2010) wells provide a good stratigraphic section from the Mic Mac Formation through the Missisauga Formation to the Cree Member of the Logan Canyon Formation. In general, the detritus to the Mic Mac Formation more closely resembles that to the Cree Member and differs from that in the Missisauga Formation. The Mic Mac Formation at Louisbourg has a higher plagioclase to K-feldspar ratio than the Missisauga Formation and has chrome spinel compositions that resemble those in the Cree Member at Peskowesk. The Cree Member at Peskowesk shows an increase in lithic clasts from metamorphic rocks and mylonitized polycrystalline quartz compared with the Missisauga Formation. The Cree Member at Peskowesk also has a greater proportion of first cycle ~1.1–1.9 Ga zircon compared to the Missisauga Formation at Dauntless. These observations suggest that in the Aptian–Albian Cree Member there was uplift and unroofing of Grenville metamorphic basement in western Newfoundland. The abundance of K-feldspar is associated with common lithic clasts of alkali granite (notably at Peskowesk: Pe-Piper et al., 2006). It is uncertain whether these are derived from reworking of Cretaceous subvolcanic rocks erupted along the Cobequid–Chedabucto fault zone, or from the Silurian Topsails Complex of west-central Newfoundland. The presence of such clasts in the Mic Mac Formation at Louisbourg, prior to evidence of Cretaceous volcanism, suggests that at least some of the alkali granite clasts were derived from the Topsails Complex.

In summary, our data shows that there was major sediment supply from the southern margin of the exposed Appalachian orogen, on the basis of abundant Devonian and Carboniferous monazite and muscovite. The Sable sub-basin was supplied by one river sourced principally from Cape Breton Island and the Gulf of St Lawrence, the eastern Scotian basin by another sourced principally from western Newfoundland (Fig. 7). 30-50% of the zircon supplied is polycyclic, suggesting

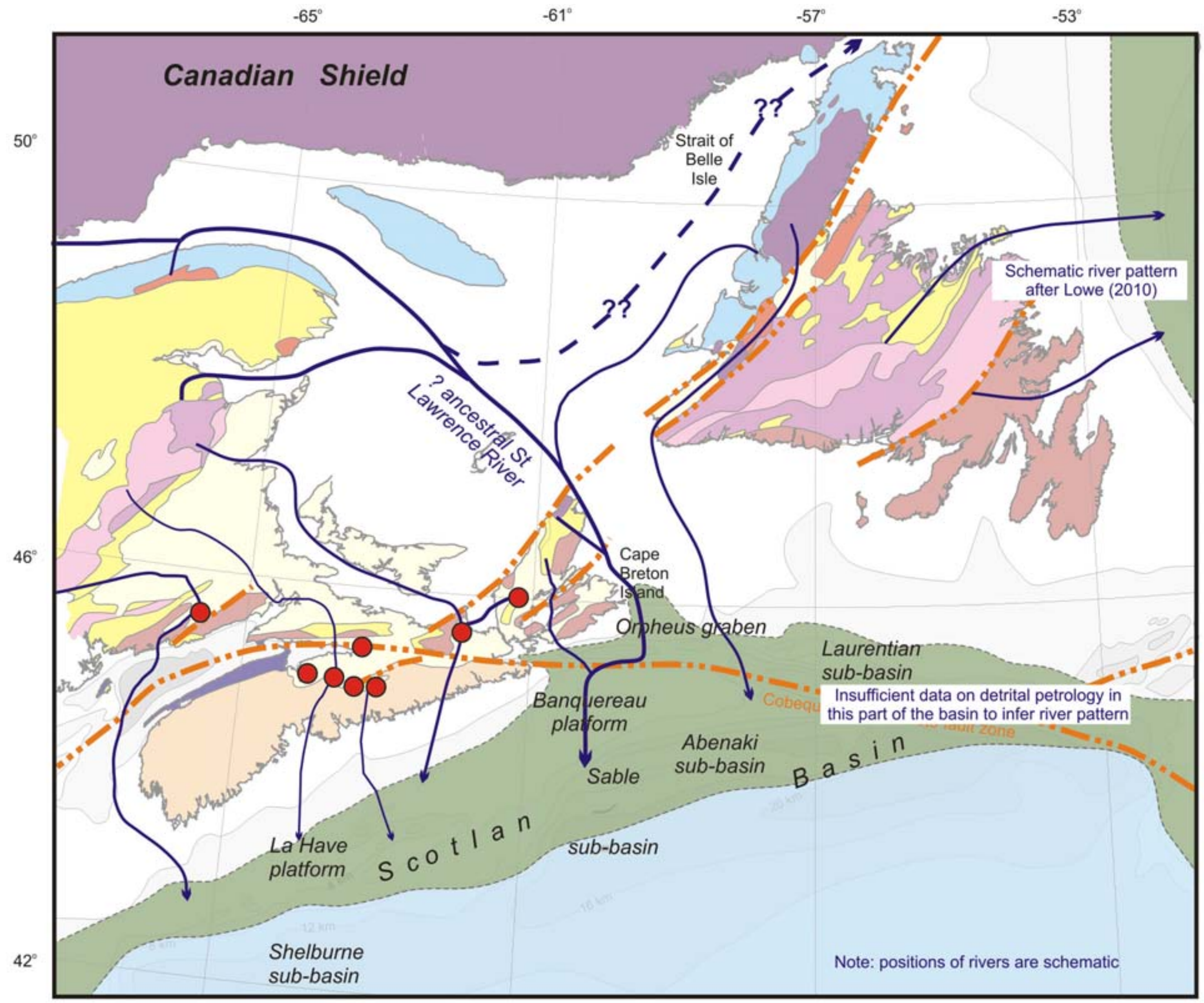

Figure 7. Interpretation of river dispersal system in the Early Cretaceous to the Scotian Basin.

considerable reworking of Paleozoic sedimentary rocks. Sediments supplied to the Sable sub-basin show little change through time, but sediments supplied to the eastern Scotian Basin suggest major Aptian–Albian uplift and unroofing of Grenville in western Newfoundland and changes in predominant source between the Upper Jurassic and Lower Cretaceous. Data from the Naskapi N-30 well shows that at times the central Nova Scotian Chaswood River flowed southward, depositing sediment in the Shubenacadie-Elsmvale region, and at other times was diverted along the Cobequid-Chedabucto fault system (Pe-Piper and Piper, 2007). The detrital muscovite shows an inner shelf source of 90% of the muscovite (Reynolds et al. 2009) implying considerable erosion and tectonic uplift on the inner shelf during the Lower Cretaceous.

5.3.2 Sedimentology and sand transfer to deep water

Depositional environments of the Missisauga Formation have been recently interpreted by Cummings and Arnott (2005) and Cummings et al. (2006a, b). These authors identified many of the deltaic facies either as tidally-influenced fluvial to estuarine deposits or storm-dominated delta-front deposits. Lowstands created during third-order eustatic cycles created incised valleys (Cummings and Arnott, 2005), filled with predominantly estuarine deposits (Cummings et al., 2006b). These authors envisioned a complex low-gradient "shelf-edge" delta built by a large proto-St Lawrence River with some local supply from the Appalachians — in other words, a typical passive margin deltaic succession.

Several lines of evidence suggest that this interpretation needs modification. The deltas in the eastern part of the basin did not reach the edge of the continental shelf, but rather prograded across an outer shelf ramp hundreds of metres deep (Piper et al., 2010). Farther west some deltas did build out at the top of the paleo-slope, in a true shelf-edge position (Deptuck et al., 2009). The evidence from detrital petrology and geochemistry shows that there was variability in sediment supply along the length of the basin, implying several different rivers with predominantly Appalachian sources. Muscovite geochronology and the evidence of the erosional edge of the O-marker suggest that large parts of the present inner shelf were not a wide coastal plain, but rather an emergent sediment source during deposition of much of the Lower Cretaceous in the Scotian Basin. The Chaswood Formation in central Nova Scotia shows no evidence for marine incursions and preserves braided gravelly fluvial deposits (Gobeil et al., 2006). Seismic interpretation of the most proximal part of the Scotian Basin, in Orpheus graben, shows multiple shallow channels suggestive of braided river conditions, rather than a major low-gradient trunk river (Weir-Murphy, 2004).

Thick-bedded, delta-front sandstones in the Missisauga and Logan Canyon formations show graded beds up to decimeters to meters thick, apparently deposited during single depositional events. Cummings and Arnott (2005) interpreted many of these delta-front sandstones as strongly influenced by storms and thus likely to have shoreface architecture. These sandstones have been re-interpreted as delta-front turbidites by Gould et al. (2010) in the light of recent work by MacEachern et al. (2005), Pattison et al. (2007) and Myrow et al. (2008). Such turbidite sand beds were derived from hyperpycnal flows from flooding rivers. In places turbidites interbed with tidal deposits in the highstand estuaries. The rivers draining from the uplifted Appalachians to the Scotian Basin were susceptible to flash flooding in the monsoonal climate (Herrle et al., 2003). Such hyperpycnal flow deposition is commonly associated with storm waves, so that the resulting deposits may show evidence both of deposition from a unidirectional suspension current and the influence of storm waves (Lamb et al., 2008). The depositional environment of these prodeltaic facies is important for understanding sandstone diagenesis. The high deposition rates and porewater composition created a sea-floor diagenetic system that favoured the preservation of porosity by chlorite rims during burial diagenesis (Gould et al., 2010).

Our original objective of estimating paleogradients and paleodischarge of the rivers from sedimentological data proved to have been naïve. No systematic geographic or stratigraphic variation in grain size of sandstones was recognised: very coarse sandstones are found sporadically in many wells. The widths of incised valleys (e.g. Cummings et al., 2005, 2006) and lateral facies variation in closely spaced wells suggest rivers a few hundred kilometres in length rather than thousands of kilometres, but this argument is not well constrained. Although sedimentological data may not have constrained the gradient of the rivers, the interpretation of significant erosion of muscovite from the inner Scotian Shelf (Reynolds et al., 2009) and the gravelly braided character of the Chaswood Formation fluvial pathways (Gobeil et al., 2006) provide evidence that the fluvial system was steep.

Our work shows that the Scotian basin was supplied by at least three medium-sized mountainous rivers and that only some "shelf-edge" deltas extended to the continental slope. A delta plain prograded 50–100 km seaward of the zone of intermittent uplift and erosion on the inner shelf, landward of the hinge line. In modern systems, turbidity currents form off such deltas either by direct hyperpycnal flow of rivers or by slumping of prodelta sands, with turbidity current type controlling the location and style of the deep-water sands (Piper and Normark, 2009).

Most conventional core from Upper Jurassic–Lower Cretaceous "shelf-edge" prodelta slopes of the of the Scotian basin shows submarine slides and debris flows: examples are Cores 1 and 2 at Tantallon M-41 (Piper et al., 2010); cores from the Alma field (Piper et al., 2004); and Core 5 from Louisbourg J-47 (Pe-Piper et al., 2010). Seismic reflection profiles show that the steep prodelta slopes at both localities, the gradients are have a sufficient gradient for any sand beds that failed to evolve into turbidity currents, as known from the modern sea floor (Piper et al., 1999). Such flows tend to be highly turbulent and deposit distally, unless trapped by minibasins (Piper and Normark, 2009).

Sand may also be transported into deep water by direct hyperpycnal flow of rivers. Hyperpycnal flow is most common in high-bedload small mountainous rivers, of the type inferred to have supplied sediment to the Scotian basin in the early Cretaceous (Pe-Piper and MacKay, 2006). Evidence for hyperpycnal flow is provided by sedimentary facies in wells from the Scotian Shelf (Piper et al., 2008) and from the reverse grading at the base of some overbank turbidites in Core 3 of Tantallon M-41 (Piper et al., 2010). Hyperpycnal flows may rapidly deposit hyperconcentrated bedload proximally (Plink-Björklund and Steel, 2004), but most flows are fully turbulent and deposit in distal settings (Piper and Normark, 2009).

Thus on the Scotian margin, there is ample evidence for transport of sand into deep water. Core 3 at Tantallon contains numerous thin overbank turbidites. Prodeltaic sediment failure is widespread and the gradients are sufficient to initiate sandy turbidity currents if there is sufficient sand in the sediments that fail. Small salt-controlled minibasins were present in the early Cretaceous (Kidston et al., 2007; Deptuck et al., 2009), but the available data suggests that most did not trap large amounts of sediment. Sands in highly turbulent currents would have largely bypassed the minibasins and deposited on the continental rise.

6. Dissemination and Technology Transfer

Our general approach to dissemination of information is (a) presentations at relevant conferences; (b) steady publication of data (in GSC Open Files) and interpretations (in journal papers); and (c) direct communication with those in industry who have shown an interest.

(a) Senior members of the team have participated in the 2008 and 2010 NS Energy Forum, the 2008 Conjugate Margins Conference (including running a field trip), the AAPG in 2008 (invited) and 2010, the International Association of Sedimentology 2007 meeting (invited), and have participated fully in the OETR Play Fairway Analysis process. Students and post-docs have presented their work at the NS Energy Forum and the Atlantic Geoscience Society annual symposia.

(b) Details of publications are given below.

(c) One-on-one discussions have taken place over the project lifespan with staff of ExxonMobil, ConocoPhillips, Murphy Oil, Shell Canada, and Husky. We have maintained close contact with the CNSOPB. We were invited to present detrital geochemistry work at a Petrobras conference in Rio de Janeiro; had to decline because of scheduling conflicts.

The principal, publicly acknowledged uptake of this work for petroleum activity in the Scotian Basin has been by RPS and Beicip in the Play Fairway Analysis. However, we understand that our demonstration of sediment sources to the Scotian Basin played a role in the decision by ConocoPhillips to go ahead with the Wolverine well.

7. Conclusions and Recommendations

1. Multiple methods of detrital petrology and geochemistry have provided a clear understanding of different sources of sediment to the Scotian Basin. The sediment was derived predominantly from the Late Jurassic–Early Cretaceous uplift of the Appalachian orogen in Atlantic Canada, including from the Grenville inliers of western Newfoundland. Much of the mineralogical and geochemical signature results from polycyclic reworking of heavy minerals. More sediment may have been derived from polycyclic sedimentary rocks than from crystalline basement. Meguma basement rocks uplifted on the inner shelf were a significant source of sediment. Where there are stratigraphic variations in the character of detritus, the regional tectonic activity makes it difficult to distinguish whether these differences are due to progressive unroofing of deeper structural levels, or changes in the river patterns in the drainage basins: evidence for both effects has been found.

2. Hyperpycnal flow of fluvial sediment at river mouths was an important component of sediment supply to the basin. Such hyperpycnal flows deposit thick sand beds just seaward of the river mouth in shelf-edge deltas (such as at Venture and Thebaud: Gould et al. 2010) and may flow seawards to deliver sand to deep-water. The flows reaching deep-water are likely fully turbulent and would deposit sand principally on the continental rise. Widespread prodeltaic failure also had the potential to initiate turbulent turbidity currents that transported sand long distances in deep water.

Additional work that follows on from this study is being carried out as part of the Play Fairway Analysis of the Scotian Basin. This includes:

1. Use of Nd isotopes to better define bulk sediment supply to the basin.
2. Relating variations in detrital petrography to variations in diagenesis.
3. Further definition of sedimentary facies, particularly the lateral variability of facies.

Furthermore, the sediment supply pathways proposed in this study will be tested by the planned basin modelling by Beicip.

8. Publications

Refereed journal publications

Gould, K., Pe-Piper, G. and Piper, D.J.W., 2010a. Relationship of diagenetic chlorite rims to depositional facies in Lower Cretaceous reservoir sandstones of the Scotian Basin. Sedimentology, 57, 587–610.

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Reynolds, P.H., Pe-Piper, G. and Piper, D.J.W., 2010. Sediment sources and dispersion as revealed by single-grain $^{40}Ar/^{39}Ar$ ages of detrital muscovite from Carboniferous and Cretaceous rocks in mainland Nova Scotia. Canadian Journal of Earth Sciences, 47, 957–970.

Refereed publications accepted and in press

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

Refereed publications submitted or in internal review

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

Tsikouras, V., Pe-Piper, G., Piper, D.J.W., and Schaffer, M., submitted. Varietal heavy mineral analysis of sediment provenance, Lower Cretaceous Scotian Basin, eastern Canada . Sedimentary Geology

Other publications including Open Files (including those in review)

Karim, A., Pe-Piper, G., Piper, D.J.W., and Hanley, J.J., 2010. 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.

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Triantafyllidis, S., Pe-Piper, G., Yang, X. and Hillier, C., 2008: Detrital zircons as provenance indicators in the Lower Cretaceous sedimentary rocks of the Scotian Basin, Eastern Canada: A SEM-CL study of textures. Geological Survey of Canada, Open File 5746.
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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

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