First-cycle sand supply and the evolution of the eastern Canadian continental margin: Insights from Pb isotopes in the Mesozoic Scotian Basin

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ABSTRACT

Provenance analysis provides a powerful means to understand, connect, and reconstruct source-to-sink systems and Earth surface processes, if reliable toolkits can be developed, refined, and applied. Deciphering sediment routing to the Scotian Basin, offshore eastern Canada, is marred by sedimentary recycling but is critical to understanding the evolution of the Canadian margin in response to the evolving Labrador rift. In this study, Pb isotopes in detrital K-feldspars were fingerprinted in 13 wells across the Scotian Basin to track first-cycle sand supply. Unlike previous approaches, which utilized less labile proxies such as zircon, detrital K-feldspars are unlikely to survive multiple sedimentary cycles.

The Pb-isotopic data reveal a dynamic saw effect between hinterland sources across the Jurassic–Cretaceous boundary, reflecting the complex interplay between the northeasterly migration of uplift along the rising Labrador rift flank and the reactivation of fault systems in the lower drainage basin. Pb isotopes in K-feldspar record progressively increasing long-distance supply from eastern Labrador, as early as the Callovian in the central basin, alongside diminishing but persistent local sourcing from adjacent Appalachian terranes. Comparison with more resilient mineral proxies, notably zircon, appears to confirm recycling in the lower drainage basin and highlights the limitations of using a single mineral proxy in isolation.

This case study serves as an example of the growing potential of multiproxy provenance toolkits not only to decipher sediment-routing corridors in paleodrainage systems, but to better define and connect the drivers, mechanisms, and spatial and temporal ranges of Earth surface processes and tectonic events.

INTRODUCTION

Applications of provenance analysis extend far beyond simply determining the transitional or final source of a sediment. Tracking the pathway of a single grain of sand through the (paleo-)sedimentary environment can provide important insights on a range of scales, from the prevailing climate and tectonic regime (e.g., Zhang et al., 2014; Dinis et al., 2017; Litty et al., 2017; Olierook et al., 2019), the primary drivers of sediment generation, to the extent and life span of paleo-land and paleo-ice masses and the responding changes in paleodrainage systems (e.g., Tyrrell et al., 2007; Fleming et al., 2016; Licht and Hemming, 2017; Franklin et al., 2020), to the mechanisms of uplift, erosion, transport, deposition, and diagenesis (e.g., Garzanti, 2017; Garzanti et al., 2018; He et al., 2019). Sedimentary provenance analysis is therefore a critical tool for understanding continental margin development through time.

The strength of modern sedimentary provenance approaches lies in the versatility of the mineral phases that can be utilized, in particular, variations in their individual durabilities (mechanical and chemical, in surface and burial settings) and source fertility (Morton and Hallsworth, 2007). However, these differences also create a number of biases in the sedimentary record, which must be mitigated to reconstruct past sedimentary environments as accurately as possible (Garzanti et al., 2009; Malusà et al., 2016; Chew et al., 2020). Quantification of the abundance of recycled components in detrital archives remains one of the most challenging problems in determining the provenance of sandstones (Campbell et al., 2005; Dickinson and Gehrels, 2009; Tyrrell et al., 2009; Andersen et al., 2016; Lancaster et al., 2017). Having been reworked through older sedimentary deposits, polycyclic sediments are typically much more fertile sources of many heavy minerals than first-cycle crystalline basement sources, because heavy minerals are concentrated through time (e.g., Rahl et al., 2003; Be’er-Shlevin et al., 2014; Benyon et al., 2016). Resistant heavy minerals such as zircon, chromite, and tourmaline from polycyclic sandstones therefore can dominate heavy mineral assemblages and better resist the ravages of diagenesis than less stable first-cycle minerals such as muscovite and monazite (Morton and Hallsworth, 2007). Failure to identify recycled components can thus lead to erroneous provenance and paleodrainage interpretations, obscuring information that can help to constrain the sedimentary and tectonic evolution of basins and their hinterlands.

In order to overcome problems in recognizing and quantifying recycling, a multiproxy provenance approach using minerals of varying resilience and source rock lithologies must be applied (e.g., Fielding et al., 2018; Flowerdew et al., 2019; Gaschnig, 2019). A multiproxy provenance approach also helps to mitigate biases induced by variations in source fertility (Moecher and Samson, 2006; Sláma and Košler, 2012; Malusà et al., 2016; Chew et al., 2020), alteration and/or loss during transport, storage, and diagenesis (Morton, 2012; Malusà et al., 2016; Chew et al., 2020).

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Where possible, multiproxy analysis should take place across all grain-size fractions to prevent the loss and/or introduction of bias of valuable environmental signals (Garzanti et al., 2009; Jerolmack and Paola, 2010; Romans et al., 2016; Jonell et al., 2018). In this study, proxies were combined so as to interrogate a wide range of grain sizes, specifically from 63 µm (in the heavy mineral fraction) to >250 µm (in feldspar). Where available, bulk geochemistry of mudstones acquired by previous studies was also incorporated to gain greater insights into sedimentary routing. This is a larger grain-size range than is normally covered in sandstone provenance studies that focus on heavy minerals alone. However, in common with the majority of studies, this approach predominantly excludes analysis of finer fractions, particularly clay, which may provide important insights into rapid, large-scale environmental changes, especially within coupled offshore sinks such as deep-sea fans that preserve long-lived, almost continuous records of continental sedimentation (e.g., Fildani et al., 2018; Hessler and Fildani, 2019; Mason et al., 2019).

In order to reliably gauge the abundance of recycled components, one or more provenance proxies must (1) be ubiquitous in the range of host-rock lithologies present in the hinterland, (2) be unlikely to be recycled, and (3) retain a diagnostic signature of its source. Detrital monazite and muscovite are typically first-cycle minerals and retain a geochronological fingerprint characteristic of their source (Reynolds et al., 2009; Pe-Piper et al., 2014; Be’er-Shlevin et al., 2018; Moecher et al., 2019), but they may represent only minor components of sandstones. In contrast, after quartz, feldspars are the most important framework grains in most sandstones (Pettijohn et al., 2012), and have been shown to retain the Pb-isotopic composition of their source despite erosion, transport, and burial (Tyrrell et al., 2006). Critically, K-feldspars typically incorporate large quantities of Pb but negligible quantities of U and Th at the time of formation. Such low U/Pb and Th/Pb ratios are ideal for Pb-isotopic fingerprinting, as radiogenic growth over time is inhibited. K-feldspar grains therefore “lock-in” the Pb-isotopic composition of the crust from which they are eroded, creating a diagnostic fingerprint that can be matched back to their source (Tyrrell et al., 2012a). The variation in Pb-isotopic signatures of basement rocks reflects their various U-Th-Pb fractionation histories, with older sources generally being less radiogenic. Pb-isotopic fingerprinting of feldspars therefore provides an effective means of discriminating between broad source terranes. Critically, feldspars rarely survive second-cycle erosion and transport in the sedimentary environment (Tyrrell et al., 2006, 2012a), but they can travel for thousands of kilometers (Clift et al., 2001; Alizai et al., 2011; Tyrrell et al., 2012b; Blowick et al., 2019) and can therefore be used as an indicator of first-cycle supply in a vast array of active and ancient drainage systems. The combination of Pb-isotopic fingerprinting in K-feldspar with mineral tracers of varying resilience, such as zircon, can thus provide a means of distinguishing first-cycle versus polycyclic components (e.g., Tyrrell et al., 2009; Lancaster et al., 2017; Johnson et al., 2018).

The Scotian Basin, offshore Nova Scotia (Fig. 1), presents the ideal laboratory in which to demonstrate the potential of Pb-isotopic fingerprinting of K-feldspar as part of a multiproxy approach to better estimate the abundance of recycled material in detrital archives and unravel the tectonic evolution of the southeastern Canadian margin. During the Late Jurassic to Early Cretaceous, several kilometers of deltaic sandstones and shales accumulated in the Scotian Basin (Fig. 2), with accommodation linked to salt tectonics and supply related to ongoing tectonics associated with the separation of Europe and Greenland from North America (Pe-Piper and Piper, 2012). Several lines of evidence suggest that the bulk of sediment delivered to the offshore during the Tithonian to Hauterivian was locally derived from the Appalachian orogen, either directly or through recycling of Paleozoic cover: Heavy minerals, including garnet, tourmaline, and chromium spinel, can be linked to Appalachian sources (Pe-Piper et al., 2009; Tsikouras et al., 2011; Dutuc et al., 2017); geochronology of common muscovite (Fig. 3) indicates local supply from the inner Scotian Shelf and/or inland shear zones (Reynolds et al., 2009, 2012); and the bulk of detrital monazite ages (Fig. 4), interpreted as first-cycle, falls within the characteristic age range of the Appalachians (Pe-Piper, 2005; Pe-Piper et al., 2014). Only a few wells showed Mesoproterozoic monazite grains predominating (Fig. 4), suggesting limited sourcing in the Mesoproterozoic Grenville terrane in southern Labrador, eastern Quebec, and the Long Range Inlier in western Newfoundland.

In contrast, most U-Pb detrital zircon ages (Fig. 5) are Mesoproterozoic, with rare euhedral zircons of Paleoproterozoic and Archean age, suggesting limited first-cycle sediment supply from as far north as the Makkovik Province in central Labrador (Piper et al., 2012). However, approximately half of detrital zircons in the central basin are broken or rounded and interpreted to be polycyclic. U-Pb ages of euhedral to subhedral zircons and from monazite suggest a predominant Appalachian source in the Late Jurassic and some Canadian Shield input in the Early Cretaceous, before increasing in the Albanian (Piper et al., 2012; Pe-Piper et al., 2014). Whole-rock geochemistry of mudstones, and to a lesser extent sandstones, documents alkaline volcanic supply from the Labrador rift in the Late Jurassic, important polycyclic supply in the Early Cretaceous, and increased shield input in the Albanian, relative to local Appalachian contributions (Zhang et al., 2014). However, the proportion of recycled grains in offshore wells remains unresolved. Large quantities of material may have been stored, concentrated, and recycled through Paleozoic cover rocks, remnants of which are still present over large areas of the hinterland.

In this study, we used Pb-isotopic fingerprinting of K-feldspar to track first-cycle sources to the Scotian Basin during the mid-Jurassic to Early Cretaceous. In this way, we (1) assessed the abundance of polycyclic grains in offshore wells, (2) tracked the sources and pathways of first-cycle and polycyclic material to the offshore, and (3) investigated the control of the evolving Labrador rift on sediment generation and delivery in the mid-Jurassic to Early Cretaceous.

**SCOTIAN BASIN**

The Scotian Basin, offshore Nova Scotia (Fig. 1), is a passive-margin basin that formed during Triassic to Early Jurassic rifting of Nova Scotia from Morocco as the North Atlantic opened (Tucholke et al., 2007). For the purposes of this study, the basin can be divided into three principal geographical regions, the western, central, and eastern basins (Fig. 1). During rifting, accumulation of continental clastic sediment from the Eurydice Formation and evaporites of the Late Triassic to (?)Early Jurassic Argo Formation was followed by sabkha facies and shallow-water limestones and dolostones of the Iroquois Formation (Fig. 2). Terrigenous clastic sediment of the Middle Jurassic Mohican Formation in the eastern basin and coarse-grained sandstones and shales of the Middle to Late Jurassic Mohawk Formation in the western basin overlie the Iroquois Formation.

Widespread carbonate sedimentation, corresponding to the Abenaki Formation, led to the development of an extensive carbonate shelf in the late Bathonian to Tithonian in the west, whereas to the east, carbonates are interbedded with terrigenous clastic sediment in the Mic Mac Formation. Following this period of relevant quiescence in the Early to Middle Jurassic, a three to fourfold increase in terrigenous sediment supply to the basin resulted in up to 6 km of deltaic sandstones and shales accumulating in the central basin,accompanied by salt withdrawal (Wade and MacLean, 1990; Weston et al., 2012).
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In the central basin, Kimmeridgian–Tithonian deltaic sandstones of the Lower Missisauga Formation are coeval with the upper mixed carbonate and terrigenous sediments of the MicMac Formation to the northeast and carbonates of the Abenaki and Roseway equivalents to the southwest. In the Early Cretaceous, deltaic sedimentation became progressively more extensive across the Scotian Basin, depositing the middle (Berriasian to mid-Hauterivian) and upper (mid-Hauterivian to Barremian) members of the Missisauga Formation and the Aptian to early Cenomanian Logan Canyon Formation. Upper Cretaceous and Cenozoic strata are principally shales and chalk (Fig. 2). As the deltaic systems prograded from the north, the putative source lands comprised three broad, geologically distinct regions: the Appalachian orogen, the Grenville orogen, and older parts of the Canadian-Greenland craton (Fig. 1). Importantly, apatite fission-track data from the Long Range Inlier in western Newfoundland and from central Nova Scotia indicate <1 km of denudation since the Jurassic (Hendriks et al., 1993; Grist and Zentilli, 2003), providing confidence that the modern-day distribution of basement rocks is representative of the source rocks available during the Late Jurassic to Early Cretaceous. However, Carboniferous cover rocks in the lower paleodrainage basin were likely more widespread.

Critically, each of these broad source terranes has characteristic, although not completely unique, Pb-isotopic signatures. Partial overlap in Pb-isotopic compositions between source terranes such as the Grenville and Appalachian orogens can be problematic for source identification, but is typically overcome by considering the three Pb-isotopic ratios for each potential source alongside its location and areal footprint relative to the sample location. In this way, two or more source terranes that share similar Pb-isotopic compositions can be ranked in order of the likelihood of supplying detrital grains. Pb-isotopic data from the North Atlantic craton are unavailable, but they would likely be similar in isotopic range to the Archean Superior terrane.

The propensity for a source rock to supply a specific mineral (i.e., mineral fertility) and its areal extent must also be considered (Malusà et al., 2016; Flowerdew et al., 2019; Chew et al., 2020). In the Scotian hinterland, the Appalachian and Grenville orogens have broadly comparable abundances of granitic plutons (Fig. 1), the most common source of K-feldspar. In contrast, granitic plutons in the Paleoproterozoic and Archean terranes to the north have limited aerial exposure, and these areas are dominated by tonalite-trondhjemite-granodiorite (TTG) rocks with typically low K-feldspar content.

MATERIALS AND METHODOLOGY

In total, 25 sandstones were sampled, where possible from conventional core, but in some cases from cuttings, from 13 wells across the Scotian Basin (Table 1). The samples were selected to represent a range of stratigraphy

Figure 1. Map of southeastern Canada showing distribution of plutonic rocks and locations of studied wells and modern river samples. Cretaceous drainage pathways inferred from previous detrital mineralogy studies are shown in blue. Dashed black lines define western, central, and eastern sectors of the Scotian Basin for the purposes of this study. GB—German Bank pluton, SMB—South Mountain Batholith. Figure is modified after Zhang et al. (2014).
across the basin, but also to correspond, where possible, to previous heavy mineral chemistry and zircon and monazite geochronology determinations (Table 1). Two additional samples (from Naskapi N-30 and Alma K-85) contained no suitable feldspar, presumably because of early diagenetic destruction by meteoric water (Karim et al., 2010). Pe-Piper and Yang (2014) showed that K-feldspar authigenesis and albitionization begin at \( \sim 1900 \) m depth in the Scotian Basin. Complete K-feldspar dissolution and/or replacement by ferroan calcite and/or ankerite occur between 3800 and 4500 m. Burial depths for Middle to Upper Jurassic sandstones in the central basin exceed 4 km. Consequently, these sandstones did not contain sufficient numbers of well-preserved feldspar grains to be targeted for analysis.

Background tests using both synthetic and natural sand samples have established the number of grains per sample that must be analyzed to detect all Pb-isotopic groups with a desired level of statistical confidence (Blowick, 2017). Mirroring previous statistical studies by Vermoesch (2004) and Andersen (2005), both synthetic and published case studies of Pb-isotopic K-feldspar data show that a minimum of 40 grains is required to detect all the Pb-isotopic groups present, where these amounted to \( \geq 6\% \) of the total analyzed sample with >95% confidence (Supplementary file S1). Thus, where possible, a minimum of 40 K-feldspar grains were analyzed in each sample. Unfortunately, in a number of cases, the size of the sample available and/or the abundance of suitable detrital feldspar grains were such that only small numbers of grains were available for analysis.

In addition to the 25 offshore samples, three samples collected from sand bars in modern rivers were also analyzed to assess typical Pb-isotope signatures for (1) the Avalon terrane of Nova Scotia, (2) the Central Mobile Belt of Newfoundland, and (3) the Long Range Inlier.

Figure 2. Schematic stratigraphy of the Scotian Basin showing stratigraphic position and number of analyzed samples in Late Jurassic–Early Cretaceous intervals. Lithostratigraphy is from MacLean and Wade (1993). Figure is modified after Dutuc et al. (2017). Q—Quaternary; SDR—seaward dipping reflectors.

Supplemental Material. S1: Statistical Analysis of Pb isotopes in K-feldspar; S2: Pb isotopic compositions of K-feldspars; S3: Thorogenic Pb Plots. Please visit https://doi.org/10.1130/GSAB.S.12665390 to access the supplemental material and contact editing@geosociety.org with any questions.
and surrounding Appalachian Humber terrane (Fig. 1). In order to facilitate comparison with potential hinterland sources, Pb-isotopic analysis of K-feldspars from granites in the South Mountain Batholith in the Meguma terrane (Fig. 1), the Permian German Bank pluton, offshore Nova Scotia, and Early Cretaceous volcanic rocks sampled in the Mallard M-45 well (North Atlantic, south of St. John’s) were also analyzed. Together with published Pb-isotopic compositions of crystalline basement rocks in the hinterland, these were used to create Pb-isotope fields for each putative source, shown as colored envelopes in Figures 6–8. Currently available Pb-isotopic data for hinterland basement rocks define three broad putative source terranes: the late Neoproterozoic to Paleozoic Appalachians, the Mesoproterozoic Grenville Province, and the Archean Superior Province. Pb-isotopic compositions of other possible sources, such as the Paleoproterozoic terranes of northeastern Labrador (Loewy et al., 2003) and the Archean North Atlantic craton in Greenland (Connelly and Thrane, 2005), are not sufficiently well characterized in the literature, but where available, they tend to overlap with the three aforementioned source fields.

Prior to analysis, K-feldspar grains were imaged using backscattered scanning electron microscopy (BSEM) to identify any intragrain variations that could be avoided or characterized during subsequeent ablation. Pb-isotopic analyses were carried out on the Thermo Scientific Neptune multiple-collector inductively coupled plasma–mass spectrometer (ICP-MS) at the National Centre for Isotope Geochemistry (NCIG) at University College Dublin (UCD), Ireland. Targeted K-feldspar grains were ablated using a New Wave 193 nm excimer laser attached to the MC-ICPMS, following closely the procedures of Tyrrell et al. (2012a). Ablations were performed with laser spot sizes between 50 µm and 100 µm, a 20 Hz pulse rate, and laser energy that was adjusted to produce a fluence between 3 and 4 J/cm². These conditions resulted in 204Pb signal intensity of ~1.8 V on the NIST 612 standard (Pb = 38.57 µg/g, Tl = 15.7 µg/g). Rasters were ablated at rates between 1 and 2 µm/s, such that track lengths were typically 100–200 µm. 250 ratios were collected using a 0.262 s integration time. Standard-sample bracketing using NIST 612 glass as standard was used to monitor Tl-based fractionation. The sequence consisted of a standard followed by three unknowns, followed by a standard. NIST 612 and Shap Granite K-feldspars were also run as unknowns as part of the sequence (comprising ~1 in 6 unknowns) in order to verify the data reduction procedure, thus acting as secondary standards.

Data reduction was carried out offline using Microsoft Excel software. Isobaric interference corrections on 204Pb were made assuming a 202Hg/204Hg ratio of 4.35. External mass bias fractionation corrections were carried out based on 203Tl/205Tl (true value = 0.418922; Baker et al., 2004) measured in each standard.

Figure 3. Kernel density estimates (KDEs) of detrital muscovite ages from Late Jurassic to Early Cretaceous sandstones in relative stratigraphic and geographic position across the Scotian Basin. Data are from Reynolds et al. (2012).
in the sequence and assuming a linear stepped fractionation between each standard. All errors were <0.1%. All Pb-isotopic data are listed in Table S2.1 (Supplementary File S2; see footnote 1). For the purposes of this paper, Pb-isotope ratios (206Pb/204Pb, 207Pb/204Pb, and 208Pb/204Pb) are denoted as 206Pb, 207Pb, and 208Pb, respectively. We used 206Pb versus 207Pb plots to show Pb-isotopic groups, because they offer the optimal resolution to distinguish between source terranes (Figs. 6–8). Thorogenic (i.e., 208Pb-based) Pb plots can be found in Supplementary File S3 (see footnote 1). Kernel density estimates (KDEs) shown in Figures 3–5 were created using the Provenance Package (Vermeesch et al., 2016) in the R working environment. The bandwidth was determined adaptively.

RESULTS

Potential Source Rocks

The Pb-isotopic signatures of K-feldspars carried by modern rivers represent the average composition of the basement rocks from which they erode and therefore can be used to characterize the average Pb-isotopic composition of hinterland source terranes. In total, 46 K-feldspars were analyzed from the three modern river samples.

K-feldspars from the Gander River (n = 6), which traverses the Central Mobile Belt of Newfoundland within the Appalachian Gander terrane (Fig. 1), plot as a tightly constrained cluster (Figs. 6A–6C), closely corresponding with Devonian Appalachian granites in Newfoundland (Fig. 6D).

The Main River drains the Long Range complex in NW Newfoundland, with inboard Appalachian terranes and Grenville inliers (Fig. 1). The 30 K-feldspars analyzed from the Main River formed two distinct Pb groups (Fig. 6A), where 24 out of 30 grains (80%) plot within the Grenville field, while the remaining 6 grains all exhibit higher Pb-isotopic signatures, plotting within the Appalachian field (Fig. 6D).

In contrast, the Debert River of the Avalon terrane in Nova Scotia (Fig. 1) exhibit a dominance of K-feldspar grains with an Appalachian affinity. All 10 grains analyzed plot within the Appalachian field (Fig. 6D). These grains shared similar Pb-isotopic compositions to the grains analyzed in the Gander River, demonstrating the inability to distinguish between the individual terranes of the Appalachians based on the small number of grains analyzed here.

Overall, the data therefore reveal that Pb isotopes of modern river K-feldspars provide a means of resolving broad hinterland source terranes, but cannot distinguish between individual Appalachian terranes when used in isolation. Thus, we combine Pb-isotopic data from all Appalachian terranes within a single field in the following sections. K-feldspars analyzed from the Late Devonian South Mountain Batholith of the Meguma terrane (n = 39) and the Permian German Bank pluton, offshore of SW Nova Scotia (n = 29), partially overlapped with the composite Appalachian field (Figs. 6E–6F), but they are shown separately because they represent the most proximal sources to wells in the west of the basin. Pb-isotopic compositions of K-feldspars sourced from Lower Cretaceous volcanic rocks sampled in this study in the Mallard M-45 well also overlapped with those of the Appalachian terranes (Figs. 6E–6F).

Figure 4. Kernel density estimates (KDEs) of detrital monazite ages across the Scotian Basin in relative stratigraphic and geographic position. Data are from Pe-Piper et al. (2014).
Mid-Jurassic Sandstones

In Mohawk B-93, in the far west of the basin, K-feldspars from mid-Jurassic sandstones formed two distinct Pb groups (Fig. 7A). Group 1 grains have $^{206}$Pb < 18.0 and represent 45% of the analyzed sample. These less radiogenic K-feldspars fall within the area of overlap between the German Bank and Grenville fields for $^{206}$Pb and $^{207}$Pb. In this plot, they closely resemble the tight local Grenville field defined by the Main River (denoted by pink dashed line in Fig. 7D), but they exhibit a range of $^{208}$Pb values similar to German Bank rather than to Grenvillian granitoids (see Supplementary File S3). Group 2 grains, representing 50% of the sample, predominantly fall within the South Mountain Batholith envelope (Fig. 7A). Two grains plot within the broader Grenville field.

Two hundred kilometers to the east, in the Mohican I-100 well, two closely spaced mid-Jurassic sandstones share almost identical spreads in Pb isotopic composition and are most similar to the South Mountain Batholith (Fig. 7B). Five grains also plot along the boundary of the German Bank pluton field and within the Main River Grenville field.

In the far east of the basin, mid-Jurassic sandstones in Bandol-1 (sampled at 3905 m) record at least three Pb isotopic groups, despite the small number of grains analyzed (Fig. 7C). Most K-feldspars plot within the Appalachian field, but a few grains ($n = 5$) fall within the Grenville and Superior fields (Fig. 7C). One less radiogenic grain plots outside the defined source terranes and thus may represent a currently uncharacterized source. The same Pb-isotopic groups are present in shallower sandstones sampled at 2990 m (Fig. 7C). The majority of K-feldspars plot within the Appalachian field, but five grains plot within the Grenville field in the tight Main River cluster, and one plots in the Superior field. The source of the single, more radiogenic grain plotting outside the defined source envelopes is currently unresolved.

Late Jurassic Sandstones

K-feldspars from Oxfordian sandstones in Mohawk B-93 resemble those from the Callovian (Fig. 7D); 60% of grains correlate with the Main River Grenville cluster and with the German Bank pluton, while the remaining 35% of grains fall within the Appalachian field. Two grains plot within the broader Grenville field. In contrast, 80% of grains sampled in late Kimmeridgian to Tithonian sandstones in Mohawk B-93 exhibit an Appalachian affinity, with only 15% of grains plotting within the German Bank pluton and Main River fields (Fig. 7D). Two grains also plot within the broader Grenville field.

Further east in Mohican I-100, two sandstones reveal strong Appalachian affinities (Fig. 7E). All 10 K-feldspar grains sampled at 2685.29 m plot within the South Mountain Batholith field. Likewise, at 2688.34 m, all but one grain plot within the Appalachian and South Mountain Batholith fields (Fig. 7E). A single grain also plots along the boundary between the German Bank pluton and the Main River/Grenville field. At the greater depth of 3474.72 m, the Late Jurassic sandstone yielded no K-feldspar but did provide a small number of plagioclase grains ($n = 10$). These plagioclase grains reveal comparable Pb-isotopic compositions to Appalachian sources, with a strong correlation to both the German Bank pluton and the South Mountain Batholith (Fig. 7F).
TABLE 1. Samples Analyzed for Detrital K-feldspar Pb isotopes

| Well/location         | Sample type               | Age               | Stratigraphic unit                  | Sample depth (top; m below RT) | Latitude (°N) | Longitude (°W) | Other data† |
|-----------------------|---------------------------|-------------------|-------------------------------------|---------------------------------|----------------|----------------|--------------|
| **Onshore**           |                           |                   |                                     |                                 |                |                |              |
| Gander River, Central Mobile Belt, Newfoundland | Bulk sand               | Modern            | Modern river sand                   | 48.74792                       | 55.50425       |                 |              |
| Main River, Long Range Inlier, NW Newfoundland | Bulk sand               | Modern            | Modern river sand                   | 49.28523                       | 56.97464       |                 |              |
| Debert River, Avalon terrane, Nova Scotia  | Bulk sand               | Modern            | Modern river sand                   | 45.48898                       | 63.61883       |                 |              |
| **Offshore wells**    |                           |                   |                                     |                                 |                |                |              |
| Western Basin         |                           |                   |                                     |                                 |                |                |              |
| Mohawk B-93           | Cutting                   | Lower Kimmeridgian-Tithonian | Roseway | 16.4979–1662 | 42.70928       | 64.7314        | Z            |
| Mohawk B-93           | Cutting                   | Oxfordian-Kimmeridgian | Mohawk | 17.5565–17.587 | 42.70928       | 64.7314        |              |
| Mohawk B-93           | Cutting                   | Callovian         | Mohawk | 1932.43–1935.48 | 42.70928       | 64.7314        | Z            |
| Mohican I-100         | Core                      | Hauterian-Barremian | Upper Missisauga | 2203.7 | 42.94184       | 62.48092       |              |
| Mohican I-100         | Core                      | Kimeridgian-Late Tithonian | Roseway | 2685.29 | 42.94184       | 62.48092       |              |
| Mohican I-100         | Core                      | Kimeridgian-Late Tithonian | Roseway | 2688.34 | 42.94184       | 62.48092       |              |
| Mohican I-100         | Core                      | Late Balthonian-Callovian | Abenaki | 3474.72 | 42.94184       | 62.48092       |              |
| Mohican I-100         | Core                      | Bajocian-Barremian | Iroquis | 3852.67 | 42.94184       | 62.48092       |              |
| Mohican I-100         | Core                      | Bajocian-Barremian | Iroquis | 3855.72 | 42.94184       | 62.48092       |              |
| **Central Basin**     |                           |                   |                                     |                                 |                |                |              |
| MidMac H-86           | Cutting                   | Early Cenomanian | Top Marmura Member | 1070.74–2000.12 | 44.59135       | 59.45069       |              |
| MidMac H-86           | Cutting                   | Cenomanian        | Base Dawson Canyon | 1033.72 | 44.59135       | 59.45069       |              |
| Cohasset A-52         | Core                      | Albian            | Upper Cre | 2130.04 | 43.85227       | 60.62875       |              |
| Alma K-85             | Core                      | Mid-Hauterivian-Barremian | Upper Missisauga | 2469.08 | 43.57879       | 60.71714       | Z            |
| Thibaud 1-93          | Core                      | Berriasian-mid-Hauterivian | Middle Missisauga | 3030.38 | 43.87904       | 60.23682       | Z M         |
| Glenelg E-58          | Core                      | Berriasian-mid-Hauterivian | Upper Missisauga | 3709.78 | 43.62161       | 60.14772       | M            |
| Glenelg N-49          | Core                      | Mid-Hauterivian-Barremian | Upper Missisauga | 3462.9 | 43.64963       | 60.11722       | Z            |
| North Triumph G-43    | Core                      | Mid-Hauterivian-Barremian | Upper Missisauga | 3230.3 | 43.70533       | 59.8564       | Z M         |
| **Eastern Basin**     |                           |                   |                                     |                                 |                |                |              |
| Peskowesko K-99       | Core                      | Albian            | Lower Crea | 2228.82 | 44.40705       | 58.98705       | Z M         |
| Peskowesko K-99       | Cutting                   | Berriasian-mid-Hauterivian | Middle Missisauga | 2952.75 | 44.40705       | 58.98705       |              |
| Esperanto K-78        | Cutting                   | Berriasian-mid-Hauterivian | Middle Missisauga | 2576.8–2576.86 | 44.7055 | 58.18886 | M S         |
| Dauntless D-35        | Core                      | Mid-Hauterivian-Barremian | Upper Missisauga | 3166.1 | 43.75536       | 57.34628       | Z            |
| Bandol-1              | Core                      | Mid-Hauterivian-Barremian | Upper Missisauga | 2300 | 45.18543       | 56.17690       |              |
| Bandol-1              | Cutting                   | Berriasian-mid-Hauterivian | Middle Missisauga | 2560 | 45.18543       | 56.17690       |              |
| Bandol-1              | Cutting                   | ?Callovian         | Mohican | 2900 | 45.18543       | 56.17690       |              |
| Bandol-1              | Cutting                   | ?Bajocian          | Mohican | 3905 | 45.18543       | 56.17690       |              |
| **Putative Hinterland Sources** | Outcrop                    |                   |                                     |                                 |                |                |              |
| South Mountain Batholith, Meguma terrane | Outcrop                    |                   |                                     |                                 |                |                |              |
| German Bank pluton, offshore Nova Scotia | Outcrop                    |                   |                                     |                                 |                |                |              |
| Mallard M-45 well     | Cutting                   | Mid-Hauterivian-Barremian | Upper Missisauga | 2532.888–2663.952 | 44.24615       | 52.12289       |              |

Note: Stratigraphic units are from MacLean and Wade (1993). RT—rotary table.

† Z—zircon, M—monazite, MS—muscovite.
Figure 6. (A–C) Pb-isotopic compositions for three modern river sands analyzed in this study and (D) plotted with published Pb-isotopic data from the hinterland basement terranes (colored envelopes). (E) Pb-isotopic compositions of K-feldspars from putative source rocks analyzed in this study—the South Mountain Batholith, the German Bank pluton, and Early Cretaceous volcanic rocks sampled in Mallard M-45 well, and (F) plotted with hinterland basement terranes.
Figure 7. Pb-isotopic compositions of (A–C) mid-Jurassic and (D–F) Late Jurassic feldspars analyzed in this study from 13 wells across the Scotian Basin, plotted against hinterland basement Pb compositions (colored envelopes). Dashed pink line indicates the local Grenville trend outlined by the Main River in Figure 6D. Data labels indicate sample depths in meters. Parentheses indicate number of K-feldspar grains analyzed. Asterisk indicates grains analyzed were exclusively plagioclase.

exclusively in the Grenville field (Fig. 8E). Only three grains in Glenelg N-49 and one grain in Glenelg E-58 plot within the Appalachian field. In Glenelg N-49, a single grain also plots outside the Appalachian field, whereas one grain falls in the Superior field in Glenelg E-58 (Fig. 8E).

In the east of the basin, the majority of K-feldspars (89%) in Dauntless D-35 fall within the Grenville field (Fig. 8F), with just four grains plotting within the Appalachian field (Fig. 8F). Three grains bridge the boundary between the Grenville and Superior fields (Fig. 8F), but only one plots exclusively within the Superior field in 208Pb (Supplementary File S3). In sharp contrast, 7 out of the 9 K-feldspars (i.e., 78%) sampled at 2200 m in Bandol-1 show a strong Appalachian affinity with just two grains plotting within the Grenville field (Fig. 8F).

Albian–Cenomanian Sandstones

Detrital K-feldspars from Albian sandstones sampled in Cohasset A-52 in the central basin form two dominant Pb-isotopic groups (Fig. 8G). Group 1 grains fall within the Grenville field and represent 59% of the analyzed sample. Group 2 grains, accounting for 37% of analyzed grains, exhibit a strong affinity to the South Mountain Batholith (Fig. 8G). Two grains plot outside of the defined hinterland sources.

Farther east, K-feldspars (n = 25) sampled in Peskowesk A-99 show a continuance of Grenville-dominated supply: 76% of K-feldspar grains plot within the Grenville field (Fig. 8G). Contributions from the Appalachian and Superior terranes are indicated by four grains plotting in the Appalachian field and a single grain falling in the Superior terrane field. The source of an outlier grain, with greater 207Pb than any known source terrane, is unresolved.

In the central basin, a 36 m interval of cuttings samples of sandstones from the Cenomanian was sampled in Mic Mac H-86. Most K-feldspars (74%) show affinity to the Grenville terrane (Fig. 8H). However, nine grains plot within the Appalachian field. A single grain
cryptic, but decipherable, record of the evolution of the North Atlantic rift and the Canadian continental margin. The new Pb-isotope data from detrital K-feldspar collected in this study (summarized in Figs. 6–10) are here interpreted in the light of previous provenance data and tectonic reconstructions to determine the evolution of sediment sources to the Scotian Basin in response to the evolving North Atlantic rift. Previously collected data include detrital zircon geochronology (Piper et al., 2012; Chavez et al., 2019); detrital monazite geochronology (Pe-Piper et al., 2014); detrital muscovite geochronology (Reynolds et al., 2012; Reynolds et al., 2009); information on modal abundance and varietal geochemistry of detrital heavy minerals (Tsikouras et al., 2011; Li et al., 2012; Dutuc et al., 2017); and bulk-rock geochemistry of sandstones and mudstones (Zhang et al., 2014; Chavez et al., 2018). Key data from these previous studies are presented in Figures 3–5.

**Middle to Late Jurassic**

By the mid-Jurassic, sufficient subsidence of the Nova Scotian–Moroccan rift shoulder had taken place for sediment to accumulate on the Scotian Shelf (Fig. 11A), and at least the lower drainage basin was arid (Jansa and Wade, 1975). In the region of what would become the Labrador rift, various intrusions in the range of 166–160 Ma (Larsen et al., 2009; Tappe et al., 2012) suggest the onset of rifting by the mid-Jurassic. In the western part of the basin, our new detrital K-feldspar data from Middle to Late Jurassic sandstones indicate predominant supply from the Meguma terrane and offshore German Bank pluton (Fig. 9), in line with varietal heavy minerals and detrital geochronology of muscovite and monazite (Figs. 3–4). Geochemical compositions of tourmalines and garnets in Mohawk B-93 are also similar to Early Cretaceous sandstones at Mohawk B-93 (Dutuc et al., 2017), where muscovite and monazite geochronology indicated exclusive sourcing from the Meguma terrane (Reynolds et al., 2012; Pe-Piper et al., 2014). Further evidence of a Meguma terrane source is provided by abundant greenschist-grade metapelite and metapsammitic lithic clasts, characteristic of metasedimentary rocks of the Meguma Supergroup (Dutuc et al., 2017). High abundances of unaltered ilmenite, interpreted to be first-cycle material, and low numbers of the ultraresistant heavy minerals spinel, rutile, and zircon identified in the SW Scotian Basin are consistent with the bulk of sediment being sourced from crystalline basement rocks rather than older sedimentary rocks through recycling (Dutuc et al., 2017).

The Callovian and Oxfordian intervals at Mohawk B-93 (Fig. 9) also contain some K-feldspars of Grenville affinity, which are less radiogenic than either the German Bank or the Main River feldspars. In addition, some uncertainty remains as to whether some feldspars falling in the Grenville Province, and rare chrome spinel derived from ophiolites of the inboard Appalachian terranes (Dutuc et al., 2017). The absence of such grains in Mohican I-100 and Mic Mac H-86 farther east (Li et al., 2012) supports an entirely Appalachian source to these two wells and suggests that the limited supply from the Grenville Province reached the Mohawk B-93

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**IMPLICATIONS FOR POLYCYCLIC SOURCING AND DRAINAGE BASIN EVOLUTION**

The variations in sediment supply observed across the basin reflect the dynamic interplay between uplift of the Labrador rift flank and reactivation of fault systems in the lower drainage basin in response to the rifting of Newfoundland from Iberia and Ireland. In this way, the mid-Jurassic to Early Cretaceous sandstones in the Scotian Basin preserve a cryptic, but decipherable, record of the evolution of the North Atlantic rift and the Canadian continental margin. New Pb-isotope data from detrital K-feldspar collected in this study (summarized in Figs. 6–10) are here interpreted in the light of previous provenance data and tectonic reconstructions to determine the evolution of sediment sources to the Scotian Basin in response to the evolving North Atlantic rift. Previously collected data include detrital zircon geochronology (Piper et al., 2012; Chavez et al., 2019); detrital monazite geochronology (Pe-Piper et al., 2014); detrital muscovite geochronology (Reynolds et al., 2012; Reynolds et al., 2009); information on modal abundance and varietal geochemistry of detrital heavy minerals (Tsikouras et al., 2011; Li et al., 2012; Dutuc et al., 2017); and bulk-rock geochemistry of sandstones and mudstones (Zhang et al., 2014; Chavez et al., 2018). Key data from these previous studies are presented in Figures 3–5.

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First-cycle sand supply and the evolution of the eastern Canadian continental margin

During the late Kimmeridgian to Tithonian in the central basin, where detrital K-feldspars have been destroyed by burial and diagenesis, a large influx of Mesoproterozoic and Paleoproterozoic zircons, and smaller amounts of detriatal monazite and muscovite, together with a several-fold increase in sediment flux, is interpreted to reflect the initial uplift of the Labrador rift (Piper et al., 2012). Zhang et al. (2014) showed that unusually high Nb and Ta contents in mudstones in this interval correlate with Middle to Late Jurassic alkaline volcanism along coastal regions of Labrador and West Greenland (Secher et al., 2009; Dickie et al., 2011). In contrast, the lack of high Nb and Ta contents in the eastern basin is interpreted to reflect the predominance of local Appalachian sources, uplifted during the Late Jurassic continental rifting between the Grand Banks and Iberia as the North Atlantic rift propagated northward.

Berriasian to mid-Hauterivian

Extension across the eastern Grand Banks margin persisted with variable intensity from Oxfordian to Aptian time. Rifting of continental basins was most intense in the Kimeridgian to Tithonian, whereas crustal thinning and hyperextension resulting in exhumed upper mantle took place in three phases culminating in the Berriasian, late Hauterivian, and late Aptian (Tuchoijke et al., 2007). The relative motion between hyperextended segments of the rift and the less rapidly extending parts of the Labrador rift to the north resulted in dextral strike-slip motion along preexisting north-east-trending strike-slip faults in the outboard Appalachians. This faulting uplifted horsts and focused fluvial deposition within narrow
strike-slip basins from the Valanginian to Barremian (Pe-Piper and Piper, 2012). The major E-W Cobequid-Chedabucto fault was also reactivated, inverting the Fundy Basin, which shed Jurassic detritus to the Scotian Basin in the Valanginian to Hauterivian (Weston et al., 2012), and leading to variable uplift and tilting of the Meguma block until at least the Aptian (Reynolds et al., 2012), supplying the dominant source of sediment to wells in the western basin (Figs. 11B–11D). At the same time, a shift from arid conditions in the Late Jurassic to more humid, subtropical conditions in the Berriasian–Barremian, as indicated by weathering indices in offshore mudstones, resulted in consistently low weathering rates in the Late Jurassic and faster weathering rates in the Early Cretaceous (Zhang et al., 2014).

Detrital K-feldspars in the Berriasian to mid-Hauterivian interval in the central and eastern parts of the basin record the continued dominance of local Appalachian sources, but, critically, they also reveal an increasing influx of Grenville feldspars, representing up to 40%
of samples, and much lesser amounts of older Canadian Shield detritus (Fig. 10). In contrast, U-Pb zircon signatures in the Tbetaud I-93 (Fig. 5) show an overwhelming dominance of Mesoproterozoic to Paleooproterozoic ages (representing over 70% of all grains analyzed), characteristic of the Grenville Province and older rocks of central Labrador. Lesser abundances of Paleooproterozoic to late Neoproterozoic ages (24%) and rare Archean ages are also observed. Neither mineral fertility nor diagenetic purging can account for the smaller proportion of K-feldspars of Grenvillian affinity; the Appalachians and Grenville Province have comparable abundances of felsic source rocks (Fig. 1). Loss of K-feldspar via dissolution is recorded across the Scotian Basin, but below all the sample depths analyzed in this study, between 3.8 and 4.5 km (Pe-Piper and Yang, 2014). Furthermore, there is no evidence to suggest preferential dissolution of feldspars of specific Pb-isotopic signatures over others. The disparity between the detrital K-feldspar and zircon archives therefore points toward recycling of zircons originally sourced from the Grenville Province.

**Mid-Hauterivian to Barremian**

In the Early Cretaceous, continuous deformation of basins (Gobeil et al., 2006) and corresponding uplift of horsts supplied local Appalachian sediment to the offshore areas, particularly in the western part of the basin. Farther east, supply from the rising Labrador rift is documented in the central basin, indicating progressive uplift of coastal Labrador and long-distance transport of sediment via the Sable and Banquereau Rivers. By the mid-Hauterivian, the relative abundance of detrital K-feldspars of Grenville affinity surpassed the relative abundance of K-feldspars of Appalachians in wells across the basin, from Mohican I-100 in the west to Dauntless D-35 in the east (Fig. 10). Detrital zircon geochronology in the central and eastern basins likewise indicates principal supply from southern Labrador, dominated by Mesoproterozoic ages (Fig. 5). Paleoproterozoic, Devonian to late Neooproterozoic, Cretaceous, and Archean ages are also present in decreasing abundance, respectively. As detrital K-feldspars reveal increasing input from the Grenville Province, its outliers, and adjacent Archean to Paleooproterozoic sources, it is also likely that the number of first-cycle zircons directly sourced from the Grenville Province also increased. As a result, it is difficult to estimate the proportion of recycled zircon grains. The ratio of monazite relative to zircon is lower than in the Late Jurassic to mid-Hauterivian interval in the central basin, suggesting a smaller proportion of first-cycle grains (Tsikouras et al., 2011). Detrital monazite geochronology in the central basin similarly indicates a consistent supply from the Appalachians, but noteworthy peaks clustering at 1.0 Ga and 1.8 Ga and rare Archean grains (Fig. 4) are consistent with supply from the Canadian Shield.

Between 10% and 35% of detrital zircons are of Cretaceous age, and are interpreted to represent reworking of felsic trachytic tuffs in the Orpheus graben (Bowman et al., 2012). No corresponding detrital K-feldspar Pb group is observed (Fig. 10), highlighting an issue of nonuniqueness between hinterland sources. Pb-isotopic compositions of K-feldspars sourced from Early Cretaceous volcanic rocks, sampled in this study in Mallard M-45 well (Fig. 6E), overlap with those of the Appalachian terranes (Fig. 6D). Detrital K-feldspar Pb-isotopic fingerprinting alone is therefore insufficient to distinguish between these two sources.

The high proportion of Appalachian feldspars in the Berriasian to mid-Hauterivian interval, and progressive decline through to the Barremian, may reflect diminishing relief in Appalachian horsts. There is no clear signal of the late Hauterivian culmination of tectonic activity reported by Tucholke et al. (2007) from the northern part of the Grand Banks margin. The increased Canadian Shield input may also have resulted from greater supply from Labrador due to either continued uplift or change in climate, and resulted in rapid southwestward progradation of the Sable delta to the Alma K-85 well in the central basin and the Mohican I-100 well in the western basin (Fig. 11B).

In the far east of the basin, detrital K-feldspar and heavy minerals (Sales de Oliveira et al., 2017) are almost exclusively of Appalachian affinity, supplying further evidence of uplift of outboard Appalachian terranes. Detrital monazite geochronology and muscovite geochronology in Tantallon M-41 and Peskowesk A-99, respectively, are consistent with sourcing from the Appalachian terranes of central Newfoundland (Figs. 3–4).

In the far west of the basin, at Naskapi N-30 and Mohawk B-93, detrital muscovite, monazite, and zircon geochronology indicates uplifted sediment routing with first-cycle supply by local rivers draining principally the Meguma terrane (Figs. 3–5).

Sedimentation at the base of the Aptian was accompanied by fault reactivation and uplift along the Scotian margin, associated with a prominent Barremian-Aptian unconformity on the inner Scotian Shelf (Bowman et al., 2012) and regional deformation of Chaswood Formation basins (Pe-Piper and Piper, 2012). Regionally, the base Aptian corresponds to the diminution of enhanced magmatism in the J-anomaly ridge, which had been active since the late Hauterivian (Tucholke et al., 2007), and which may have resulted in westward-directed motion on the crustal block south of the Cobequid-Chedabucto fault (Fig. 11C). Uplift and tilting of the Meguma block (Reynolds et al., 2012) are interpreted to have diverted fluvial supply from inboard Appalachian terranes of the Maritime Provinces and eastern Quebec, potentially through the St Lawrence valley toward western Canada (Piper et al., 2018). Previous hypotheses that the Sable River was diverted into the Fundy Basin have been disproved by the lack of thick Aptian sands (Chavez et al., 2018). Sedimentation rates in the Scotian Basin dramatically declined, as shale was deposited widely, comprising the bulk of the Aptian Naskapi Member. Bulk geochemistry of mudstones suggests that Aptian sediment was locally sourced from the Meguma terrane (Chavez et al., 2018).

**Albian to Early Cenomanian**

The Aptian-Albian boundary marks a major change in the evolution of the North Atlantic Ocean. It represents the time when normal oceanic spreading began between Iberia and the Grand Banks (Tucholke et al., 2007), and it is marked by a magmatic pulse in the eastern Scotian Basin (Bowman et al., 2012). With the onset of seafloor spreading, differential extension could no longer produce strike-slip motion on the Cobequid-Chedabucto fault. North Atlantic rift propagated farther north, with a change in extension direction (Fig. 11D) and the onset of hyperextension in the Orphan Basin (Dafoe et al., 2017). A return to high siliciclastic supply to the Scotian Basin in the Albam resulted from subsidence and/or erosion of the volcanic barrier along the Cobequid-Chedabucto fault and the reestablishment of southward drainage from Labrador (Fig. 11D). Uplift of the Labrador rift shoulder across the Aptian-Albian boundary is inferred from a prominent Aptian-Albian unconformity within and north of the Orphan Basin (Dafoe et al., 2017), and it is reflected by the dominance of first-cycle Grenvillian K-feldspar and Proterozoic and Archean monazite and zircon grains in the central and eastern basins (Figs. 4–5). In addition, lower weathering indices in Albam sandstones are interpreted to have resulted not from aridity in the hinterland, but rather from greater supply from high-grade metamorphic rocks of Labrador (Zhang et al., 2014).
IMPLICATIONS FOR SAND TRACKING AND DISTINGUISHING POLYCYCLIC SOURCES USING DETRITAL K-FELDSPAR

In this study, we combined Pb-isotope characterization of K-feldspar with other first-cycle geochronological proxies (monazite, muscovite) together with provenance proxies of greater resilience, such as zircon, tourmaline, chromite, and rutile. In doing so, we were able to evaluate the potential strengths and limitations of estimating the relative abundance of recycled components in detrital archives using detrital K-feldspar.

Comparisons between detrital K-feldspar Pb isotopes and zircon, monazite, and muscovite geochronology indicate a progressive decrease in the abundance of recycled grains delivered to the Scotian Basin from the mid-Jurassic to Early Cretaceous, which is interpreted to reflect the continued reworking and ultimate removal of much of the Carboniferous sedimentary cover on horsts in the lower drainage basin. However, differences in provenance signals between detrital minerals may reflect not only recycling but a combination of potential biases such as variations in the fertility of a mineral at its source (Flowerdew et al., 2019; Malusà et al., 2016; Chew et al. 2020) and modification or loss during transport, burial, and diagenesis (Morton and Hallsworth, 2007; Sláma and Košler, 2012). As a result, potential biases must be evaluated on a case-by-case basis. In the Scotian Basin, the two principal source terranes, the Appalachian orogen and the Grenville Province, have broadly similar abundances of granitoid plutons, the main source of K-feldspar. There is also no evidence of strong differences in zircon fertility in crystalline rocks in the hinterland, although Neo- proterozoic rocks in the Appalachians appear to be underrepresented by detrital zircons (Piper et al., 2012).

In contrast, modification and loss during transport, burial, and diagenesis have influenced certain provenance signals preserved in offshore wells. Loss of garnet and ilmenite during burial diagenesis and authigenesis of apatite and titania minerals limit use of both modal abundance and diagenetic and authigenetic of apatite and titanio. And in this study, we combined newly acquired detrital K-feldspar data with other mineral proxies within the sandstone grain-size window, together with the bulk geochemistry of mudstones, where available. Mudstone signals proved most effective where there was an important source of limited geological variability. For example, the strong Nb and Ta signature from alkaline volcanics of Labrador in the Tithonian rocks in the central basin was more clearly identifiable in mudstones than in sandstones (Zhang et al., 2014). Likewise, mudstones derived predominantly from the Meguma terrane can be distinguished from those sourced from more regional drainage from the Appalachians and Grenville Province (Chavez et al., 2018). However, mudstone signatures have been much less effective in discriminating between the dominant Appalachian supply to the eastern basin compared to the mixed Appalachian-Grenville supply to the central basin (Zhang et al., 2014). This case study therefore demonstrates the importance of analyzing multiple provenance proxies across a large grain-size window to ensure reliable provenance reconstructions.

CONCLUSIONS

Pb-isotopic fingerprints of over 700 detrital K-feldspars from 13 wells across the Scotian Basin have been analyzed. The newly acquired K-feldspar Pb-isotopic data: (1) reveal an overall switch in the principal source of first-cycle material from the proximal Appalachians in the Middle to Late Jurassic to more distal Canadian Shield sources in the Early Cretaceous; (2) confirm previous assertions of major recycling of heavy minerals, most notably detrital zircon, in the lower drainage basin; (3) help to constrain the timing of regional uplift along the western Labrador rift flank, with supply from Archean basement evident as early as the Cretaceous; and (4) demonstrate the interplay between rifting and hyperextension between Iberia and Grand Banks and reactivation of strike-slip faults in the lower drainage basin, which controlled drainage patterns and sediment supply to the Scotian Basin during the Early Cretaceous.

Improved and expanded characterization of hinterland source rocks, including the offshore German Bank pluton and South Mountain Batholith, confirms that the Meguma terrane was the principal supplier of sediment to the western basin. Uplift and variable tilting of the Meguma terrane throughout the Early Cretaceous were driven primarily by lateral movement along the major Cobequid-Chedabucto fault zone. The Shelburne delta, at the western end of the basin, was supplied from more distant sources, including rare K-feldspars from the Superior Province. In the central basin, increasing quantities of Canadian Shield detritus are recorded from the Valanginian to Albian, highlighting the growing significance of sediment pathways from Labrador and, at least in the Albian, the decreasing uplift of horsts in the Appalachian terranes. Strike-slip faults and associated volcanism controlled the river courses in the lower drainage basin, notably in the Aptian, when sediment was rerouted to the west. In the eastern basin, local rivers draining uplifted Appalachian terranes of Newfoundland consistently supplied the bulk of sediment to offshore wells. Detrital K-feldspars of Proterozoic and Archean affinity were transported to the Bandol-1 well site in the Jurassic, but increasing subsidence of the Labrador rift terminated supply in the Early Cretaceous.
This study demonstrates the utility of Pb-in-K-feldspar analysis as a broad-scale provenance tool for sandstones, highlighting not only its ability to distinguish first-cycle supply when used as part of a multiproxy provenance approach, but also the insights that can be gained into complex paleogeographic reconstructions and continental margin evolution. A critically important approach in settings like the Scotian Basin, where the potential for recycling of intermediate sedimentary sources is high, the multiproxy approach also demonstrates the profound influence of both rift-related uplift and continental strike-slip faulting during hyperextension prior to seafloor spreading on sediment supply and routing of rivers. A detailed understanding of sediment supply, across as broad a size fraction as possible, is therefore a key factor in understanding the interplay of tectonic and sedimentary processes along continental margins like southeastern Canada during the Mesozoic.

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