Northern Laurentian provenance for Famennian clastics of the Jasper Basin (Alberta, Canada): A Sm-Nd and U-Pb detrital zircon study

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ABSTRACT

Within the carbonate-dominated Devonian succession of the Western Canada Sedimentary Basin, sandstones of the Famennian Sassenach Formation represent a sedimentological and isotopic anomaly inferred to be related to western sources uplifted during Antler tectonism. Previously reported evidence for a changing tectonic regime along western Laurentia during deposition of the Sassenach renders this unit an important potential link to shifts in source areas associated with this tectonism. We report the first set of U-Pb detrital zircon ages and new Sm-Nd whole rock data from the Sassenach Formation of the Jasper Basin in the Alberta Rocky Mountain fold-and-thrust belt. The $^{147}$Sm/$^{144}$Nd ratios (0.109–0.122) and $\epsilon$Nd values (–9.6 to –10.9) at the time of deposition are within a narrow range that overlaps with published data, confirming a post-Ordovician shift to more positive $\epsilon$Nd values along the northern and western Laurentian margin coinciding with the introduction of more juvenile sources associated with Innuitian and Grenville sources. A previously recognized subtle negative shift in $\epsilon$Nd values in the Sassenach relative to underlying Frasnian deposits is also confirmed, which suggests a minor contribution from more mature sources, opposite the overall post-Ordovician positive trend. Zircon ages show a wide spread (378–3506 Ma), with three broad age groups separated by a paucity of ages in the 700–900 Ma and 2100–2500 Ma ranges: (1) a narrow Paleozoic to Neoproterozoic group (378–700 Ma), (2) a broad Proterozoic group of scattered ages (900–2100 Ma), and (3) a narrow Archean group (2500–2900 Ma). Paleozoic to Neoproterozoic detrital zircon ages are absent from the western Laurentian record, and thus link the Sassenach Formation to the Arctic realm where terranes with zircons of these ages are well known. Discordance modeling suggests a consistent Pb loss in the Sassenach zircon data set (ca. 390 Ma) that coincides with the first orogenic pulse in Innuitian–Ellesmerian tectonics in the paleo-Arctic realm. Together these data suggest that the bulk of terrigenous sediment in the Jasper Basin was recycled from Ellesmerian foreland strata and subsequently transported southward along the margins of western Laurentia. Sediment transport may have been facilitated by southward-directed, shore-parallel shallow-marine currents initiated by Northern Hemisphere wind patterns.

INTRODUCTION

The Upper Devonian (Famennian) Sassenach Formation was mapped as a distinctive unit in the Front Ranges of the Canadian Cordillera, comprising a mixture of carbonates and calcareous shales along with a significant component of siltstone and subordinate fine-grained quartz sandstone (McLaren and Mountjoy, 1962). The Sassenach was later identified in southwestern Alberta and southeastern British Columbia (Price, 1964). East of the town of Jasper, outcrops of the Sassenach Formation are exposed along a number of thrust sheets in the Front Ranges of the Rocky Mountains (Fig. 1). Late Jurassic to early Eocene eastward propagation of the Rocky Mountains fold-and-thrust belt (Pană and van der Pluijm, 2015) has displaced the Devonian strata tens of kilometers from the original Sassenach depocenter (Fig. 2).

The presence of sandstone within the Sassenach Formation renders it unique within the eastern Cordilleran Devonian stratigraphic succession, which otherwise comprises carbonate reefs and their associated fine-grained off-reef sediments. The Sassenach Formation was deposited in a western depocenter known as the Jasper Basin along the Devonian miogeocline of western Laurentia (Fig. 2) (Mountjoy, 1980). The lack of comparable sandstones in eastern subsurface equivalents, along with particular isotopic characteristics, has led to the interpretation that Sassenach clastics were derived from a newly uplifted western source (Mountjoy, 1980; Stevenson et al., 2000). This differs from the interpreted northern and eastern source areas for the detrital component of the underlying strata (e.g., Stoakes, 1980; Patchett et al., 1999a). The proposed new western source would have been a highland related to the Antler orogeny defined in the western U.S.

Much of the late Paleozoic record of western Laurentia has been obscured by Cordilleran tectonism associated with the formation of the Rocky Mountains fold-and-thrust belt. Detrital zircon provenance studies have proven useful in unravelling such complex histories and have shed light on source-area changes possibly linked to vestiges of Paleozoic tectonic activity. For example, recent tectonic models (Colpron and Nelson, 2009, 2011; Beranek et al., 2010, 2016) have been used to interpret exotic terranes outboard of the Devonian–Mississippian western Laurentia as a source for zircon ages of yet-unknown
Figure 1. Location of the study area and sample locations in the Rocky Mountains fold-and-thrust belt near Jasper, Alberta, Canada. The Sassenach Formation crops out along a series of imbricate thrust sheets in the Front Ranges. Map of geology of Alberta from Prior et al. (2013). Inset modified from Panà and Elgr (2013).

Sample locations

- Sm-Nd, U-Pb
  1. DP15-66 (Chetamon thrust sheet 1)
  2. DP15-64 (Chetamon thrust sheet 2)
  3. DP15-73 (Jasper Transfer station)
  4. DP15-77 (Snaring River bridge)
  5. DP15-76 (Morrow Peak traverse)
  6. DP16-02 (Medicine Lake)
Laurentian provenance. The detrital zircon record of parautochthonous Late Devonian strata in western Laurentia potentially records the erosional record of such exotic terranes. For example, Kraft (2013) suggested that the Okanagan–Chilliwack composite terrane of Arctic affinity was a source for Silurian-aged zircons in the Chase Formation of southern British Columbia. A fundamental underpinning of this interpretation is that the Silurian-aged zircons are linked to magmatic activity in the northern Alexander terrane (Kraft, 2013), and as such the Okanagan–Chilliwack composite terrane was linked to, and subsequently removed from, the Alexander terrane. Such an interpretation requires the sinistral translation of Arctic-affinity terranes southward and outboard of the western Laurentian margin to locations adjacent to a back-arc basin—the model of Colpron and Nelson (2009). Similar interpretations based on the same tectonic models are invoked for the detrital zircon record of Frasnian–Famennian strata of the Pioneer Mountains in Idaho (USA) (Beranek et al., 2016). In addition to the “Okanagan High” (Okanagan–Chilliwack composite terrane of Kraft, 2013), the Arctic-affinity Eastern Klamath and Northern Sierra terranes are pointed to as potential sources. Importantly, these interpretations hinge on the presence of Silurian to late Neoproterozoic zircons, including Late Devonian varieties, within the magmatic and detrital record of these terranes (Kraft, 2013; Beranek et al., 2016)—the crucial link to the paleo-Arctic realm. The possibility of a northern extension of the Antler orogen to Canadian latitudes, regardless of the style of tectonics, has been a longstanding question. The presence of a short-lived orogen as a possible western source for clastic material in Upper Devonian miogeoclinal strata would have profound implications for the Paleozoic paleogeography, depositional setting, and tectonics of the western margin of North America.

Existing provenance studies based on radiogenic isotope systems from the Jasper Basin are limited to Sm-Nd data (Boghosian et al., 1996; Stevenson et al., 2000) and one detrital zircon sample from the Sassenach Formation at an uncertain location in southern British Columbia (Gehrels and Pecha, 2014). In this study, we use whole rock Sm-Nd coupled with a new set of detrital zircon U-Pb data that provide more accurate ages of the source material to further constrain possible sources for the clastic component of the Sassenach Formation. We scrutinize the hypothesis that Sassenach sediments were derived from western sources associated with Antler-age tectonics along the western margin of Laurentia, and provide evidence that the clastic component was sourced from the northern Innuittian-Franklinian Basin and recycled in the Ellesmerian orogen. This source is traced with Sm-Nd data, U-Pb detrital zircon ages, and potential timing of tectonism (timing of a Pb loss event) in the source area derived from discordance modeling (Reimink et al., 2018).

**REGIONAL PALEOGEOGRAPHY AND STRATIGRAPHY**

The latest Neoproterozoic to Middle Jurassic Cordilleran miogeoclinal assemblages formed a westward-prograding continental margin terrace wedge (~10–15 km combined maximum thickness), which marked the interface between
the adjacent Cordilleran foreland belt (Mountjoy, 1980; Switzer et al., 1994) which are now located in the Alberta subsurface and in the thrust sheets of shale, siltstone, sandstone, and carbonate units. Form and shelf carbonate rocks and subordinate clastic rocks, which pass laterally westward into finer-grained, deeper-water facies; (2) middle and upper Paleozoic plat-

eic sequences to the west), on cratonic basement inboard of the Windermere, e.g., Nelson et al., 2002; Thompson et al., 2006); and finally (4) a combination pull-apart basins); (3) a back-arc basin above an east-dipping subduction zone (e.g., Nelson et al., 2002; Thompson et al., 2006); and finally (4) a combination of eastward subduction and sinistral transpression (Colpron and Nelson, 2009, 201 1; Beranek et al., 2016).

(1) the lower Paleozoic sequence consisting predominantly of platform and shelf carbonate buildups with subordinate shale that pass laterally westward into finer-grained, deeper-water facies; (2) middle and upper Paleozoic platform and shelf carbonate rocks and subordinate clastic rocks, which pass laterally westward into deeper-water facies; and (3) Triassic to Middle Jurassic shale, siltstone, sandstone, and carbonate units.

### JASPER BASIN PALEOGEOGRAPHY AND STRATIGRAPHY

During the Frasnian, the Alberta Basin was positioned near the paleoequator and saw widespread growth of biothermal and biostromal carbonates, which are now located in the Alberta subsurface and in the thrust sheets of the adjacent Cordilleran foreland belt (Mountjoy, 1980; Switzer et al., 1994) (Fig. 2). Carbonate complexes were bordered by off-reef basins known as the East Shale, West Shale, and Jasper basins, which were dominated by the accumulation of considerable thicknesses of detrital carbonates mixed with terrigenous clastics, mostly in the form of mudstones and shales (Fig. 2). The stratigraphic nomenclature varies from outcrop to subsurface for both the carbonates and the basal strata, but stratigraphic equivalencies are generally well established (Fig. 2). Mountain terminology will be used herein.

During the Late Devonian, Frasnian carbonate buildups in the Jasper area, and further east on the Laurentian platform, attained substantial bathymetric relief during overall transgressive global depohases IIb, IIc, and IId of John-

son et al. (1985). During maximum transgression in the Frasnian, the organic-rich shales of the Perdrix Formation were deposited outboard of the coeval Cairn and Southesk Formation buildups (Fig. 2). Basinal anoxia gave way to oxygenated conditions with the deposition of argillaceous carbonates and cal-
careous shales of the Mount Hawk Formation during the remainder of Cairn and Southesk deposition. A relative sea-level fall—global sea-level fall at the end of depohase IId of Johnson et al. (1985)—is interpreted to have preceded the deposition of the unconformably overlying Sassenach Formation and its equivalent to the east (Graminia Silt). In the Rocky Mountains, this event is recorded by erosion on the carbonates of the Fairholme Group (McLaren and Moutjoyn, 1962; MacKenzie, 1965) (Fig. 2).

Off-buildup basins record a pattern of accumulation from north and east to-
ward the south and west in gentle clinoforms during regressive and stillstand phases of deposition (Stoakes, 1980; Wendte, 1992). To the west, strata of the Perdrix and Mount Hawk formations now exposed in the thrust sheets of the Rocky Mountains had not completely filled the accommodation space leeward (present-day west) of the Fairholme Group buildups due to the east-west progradation of basinal strata, leaving a depocenter known as the Jasper Basin (Mountjoy, 1980; Stevenson et al., 2000). During the Fammennian, the Jasper Basin was filled by mixed detrital carbonates and silicilastics, including sandstone of the Sassenach Formation. Whereas the eastern margin of the Jasper Basin can be observed through onlapping relationships with Frasnian strata proximal to the Ancient Wall, Miette, and Southesk-Cairn buildups (Fig. 2), the western, northern, and southern extents of the basin have been obscured through later erosion and thrust faulting. To the east, the equivalent Graminia Silt comprises a thin unit of silt and shale throughout a large portion of the subsurface of Alberta (Fig. 2). The Graminia Silt lacks the coarser-grained silici-
clastics found in the Jasper Basin (Meijer Drees et al., 1998).

The Sassenach Formation in the Jasper Basin is predominantly a silty carbonate, comprising distinct light-orange to buff-colored dolomitic or cal-
careous silts, interbedded with limestone, dolomitic limestone, calcareous dolostone, and dolostone that show mudstone, wackestone, and packstone textures. The presence of the laminated silt- to sand-sized silicilastic component gives a distinct ribbon-like appearance to portions of the Sassenach Formation (Figs. 3C, 3D). In other areas, the formation is more argillaceous (Fig. 3E). Planar to wavy laminations and cross-bedding are common in the siltstone and sandstone components. The Sassenach Formation can be sub-

Figure 3. Photos of the Sassenach Formation in the Jasper region of Alberta, Canada. (A) Base of the Sassenach Formation grading into the recessive calcareous shales (covered) of the Mount Hawk Formation, Morrow Peak traverse. (B) Silty and sandy limestone at Morrow Peak (sample DP15-76). (C) Weathered ribbon-like silty dolomitic limestone (silty beds are more resistant) at Medicine Lake (sample DP16-02). (D) Ribbon-like silty dolomitic limestone (silt weathers light-orange color) at the Jasper Transfer Station (sample DP15-73). (E) Recessive, argillaceous silty limestone east of rail tunnel at Pyramid thrust within the Chetamon thrust sheet (sample DP15-64). (F) Dolomitic-calcareous siltstone to fine-grained sandstone near Snaring River bridge on Highway 16 (sample DP15-77). Hammer is 33 cm long; pencil is 15 cm long.
divided into a lower silty member and an upper sandy member (McLaren and Mountjoy, 1962) (Fig. 4). The regressive character of this formation suggests a transition from distal to more proximal facies upsection. The Famennian age of the Sassenach Formation in the Jasper Basin is well constrained by conodont dating (Wang and Geldsetzer, 1995; McCracken, 1996).

The Sassenach Formation has been studied intermittently since its formal naming (McLaren and Mountjoy, 1962). Because of hydrocarbon prospectivity of Frasnian Fairholme Group carbonate strata in the subsurface of Alberta (Fig. 2), early Cordilleran studies focused on their stratigraphy and sedimentology and only treated the Sassenach Formation peripherally (Price, 1964; Belyea and McLaren, 1964; MacKenzie, 1965; Mountjoy, 1965; Coppold, 1976). Subsequently, due to the relationship of the Sassenach Formation to the Frasnian-Famennian boundary, a number of studies have investigated the strata for clues as to the extinction events associated with the boundary (Geldsetzer et al., 1987; Goodfellow et al., 1988; Whalen et al., 2002; Bond et al., 2013). Becker (1997) and Mountjoy and Becker (2000) reexamined the sedimentology and stratigraphy of the Sassenach Formation in the context of sequence-stratigraphic concepts. Published studies on subsurface equivalents of the Sassenach Formation are lacking, with only Meijer Drees et al. (1998) assessing the subsurface correlative Graminia Silt (Fig. 2). Prior to isotopic work, northern Canadian Arctic orogens have been suggested as the source for fine terrigenous clastics deposited in the Alberta Basin and the miogeocline of the Cordillera during the late-Middle to Late Devonian (e.g., Stoakes, 1980). Deposition of the Sassenach Formation and filling of the Jasper Basin coincided with the earliest interpreted ages of the Antler orogeny in western United States. The westward thickening (Coppold, 1976) and upward coarsening of the Sassenach sediments, and the presence of feldspar, were interpreted to imply that a western source exposing older crust to erosion was either approaching or being increasingly uplifted (Savoy and Mountjoy, 1995; Stevenson et al., 2000).

**PREVIOUS PALEOZOIC PROVENANCE STUDIES IN THE REGION**

Provenance studies of western Canadian miogeoclinal strata (Ross et al., 1993; Gehrels and Ross, 1998) have drawn from previous geochronology work on Precambrian terranes across Laurentia (e.g., Hoffman, 1989; Ross et al., 1991; Ross and Parrish, 1991; Burwash et al., 1994). In particular, geochronology work by Ross et al. (1991) and Villeneuve et al. (1993) on the cratonic basement under the Western Canada Sedimentary Basin formed the basis for subsequent interpretations of potential sources of detrital zircon and Nd signatures for sediments in the western miogeocline. A number of studies have previously assessed the Nd isotopic values from Devonian miogeoclinal strata in western Canada (Boghossian et al., 1996; Garzione et al., 1997; Patchett et al., 1999a, 1999b), and one Nd isotope study focused in greater detail on the Upper Devonian basal strata in the Jasper Basin, including the Sassenach Formation (Stevenson et al., 2000).
Within western Canada miogeoclinal strata, Boghossian et al. (1996) showed that $\epsilon_{Nd}(T)$ (T—time at time of deposition) values increase from lows ranging from $-22.0$ to $-15.8$ in Precambrian–Ordovician rocks, representing Archean and Proterozoic basement sources of the Canadian Shield, to $-9.5$ to $-6.4$ in the Devonian–Triassic sequences, which required mixing with detritus from more juvenile sources. Possible juvenile sources include: (1) the Cordilleran miogeocline related to Antler-age tectonism; (2) the Appalachians, with detritus transported by drainage systems across the craton; or (3) the northern Innuitian and Ellesmerian orogens in the Canadian Arctic, with detritus transported southward along the Cordilleran margin. Garzione et al. (1997) confirmed this positive shift in northern British Columbia from the westerly derived Middle Devonian to Mississippiian Earn Group ($-6.6$ to $-12.9$) and its eastern and southern fringe in the Cordilleran miogeocline, the Besa River Formation ($-8$ to $-10.5$). They interpreted the Sm-Nd systematics in the Ordovician to Lower Devonian strata as a mixture of Canadian Shield sources with locally erupted, juvenile volcanics, and inferred a contribution from the Innuitian orogen of the Canadian Arctic in the post–Middle Devonian strata. Patchett et al. (1999a, 1999b) reported Sm-Nd data from North American strata that included Arctic Canada. They interpret the positive $\epsilon_{Nd}$ shift to represent: (1) Grenville-age signatures indirectly sourced from the Caledonian orogen along eastern Greenland into the Franklinian Basin and subsequent mobile belt of the Canadian Arctic, and ultimately into the western Canadian miogeocline; or alternatively (2) a combination of Arctic orogenic material with arc- or extension-related magmatic sources along the Cordilleran margin.

The shift from older cratonic to younger Grenville-aged sources, as recognized in Nd isotopes, occurred at ca. 450 Ma (Late Ordovician) across North America due to the overwhelming input from Caledonian-Appalachian orogenic sources (Patchett et al., 1999a). Stevenson et al. (2000) reported $\epsilon_{Nd}(T)$ values from the Upper Devonian stratigraphy in the Jasper area that confirmed the post-Ordovician overall positive shift. They also noted a deviation to slightly more negative values ($-8.5$ to $-11$) in the Famennian Sassenach Formation compared to strata above and below it. This excursion to more negative $\epsilon_{Nd}(T)$ values—which requires a contribution of detritus from older rocks—corroborated with sedimentological evidence suggesting a western source, was interpreted to record derivation of the Sassenach clastics from sources exposed in the Antler orogen at or near Canadian latitudes.

A general pattern of the evolution of source areas for detrital zircons in the western miogeocline has emerged in recent years, with sedimentary recycling as a common theme (Ross et al., 1993; Gehrels et al., 1995; Gehrels and Ross, 1998; Gehrels and Pecha, 2014). Neoproterozoic through Middle Devonian strata are dominated by sediments shed from local basement rocks and clastic rocks with Grenville orogen signatures. Grenville-sourced material has been recognized in basins as old as the Neoproterozoic along the western part of the Canadian Arctic as well as correlative strata in the Canadian miogeocline (Rainbird et al., 1992). A shift in dominant source areas is observed in Ordovician rocks, where miogeoclinal strata were influenced by sediments originating from the emergent Peace River Arch in west-central Alberta (Ross et al., 1993) (Fig. 1). These sediments were dispersed >2000 km along the western miogeocline as far south as California and Nevada (USA) and Sonora (Mexico) (Gehrels and Pecha, 2014). Isotopic signatures of the Upper Devonian to Triassic strata shift back to local sources, including recycled miogeocline strata, along with significant proportions of detritus derived from the northern Innuitian-Franklinian orogen (Gehrels and Pecha, 2014).

In recent years, detrital zircon geochronology and provenance studies of Paleozoic strata from the Canadian Arctic and the northern Canadian Cordillera have greatly contributed to our understanding of the evolution of the northern margin of Laurentia and its possible contribution to sediments within Alberta and along the western miogeocline. In particular, linkages have been proposed with parts of Siberia and Baltica through terrane accretion along northern Laurentia, as suggested by zircon ages anomalous for Laurentia (Beranek et al., 2010, 2015; Lemieux et al., 2011; Anfinson et al., 2012a, 2012b). These include detrital zircon populations with Grenville-Sveconorwegian (1000–1300 Ma) and Silurian to Neoproterozoic (420–700 Ma) ages that are found within clastic strata along the northern and western margin of the continent. In the northern Cordillera, the presence of these non-Laurentian zircon populations was explained by recycling and dispersal of these detrital zircons into Devonian strata (Beranek et al., 2010, Lemieux et al., 2011). The presence of such populations as far south as Eastern Klamath and Northern Sierra terranes of the western U.S. prompted Colpron and Nelson (2009) to invoke southward translation of Arctic affinity terrane(s) to central Cordilleran paleolatitudes along a Devonian sinistral transpressional fault system located outboard of the miogeocline. The model offered a possible source of exotic (Arctic) zircon subsequently found in the parautochthonous strata in southern British Columbia (Chase Formation; Kraft, 2013; Beranek et al., 2016) and the Sassenach Formation of the cratonic platform (Beranek et al., 2016).

### SAMPLE LOCATIONS

Six samples, ~25 kg each, were collected from outcrops of the Sassenach Formation from the Colin and Chetamon thrust sheets along the Athabasca River valley and near Medicine Lake east of the town of Jasper, Alberta (Fig. 1). At each location, we attempted to sample the coarsest, or most siliciclastic-rich, part of the Sassenach Formation such as the silty beds of the ribbon stone (Figs. 3C, 3D). Rock description and sample site coordinates are compiled in Table 1.

### ANALYTICAL TECHNIQUES

#### Sm-Nd

Samarium-neodymium isotopic analysis was performed on the six Sassenach samples collected from the Jasper Basin. Analyses were performed on a Triton-Ti mass spectrometer at GeochronEx Analytical Services and Consult-
The maximum depositional age (MDA) was determined with Isoplot (Ludwig, 2003). The MDA is derived from the mean square weighted deviation of the youngest three detrital zircon ages within our samples (Supplemental Materials [see footnote 1]) (see Spencer et al., 2016, for a discussion on determining MDA).

Lower intersection ages were assessed using the discordance modeling program of Reimink et al. (2016) within the computer software R (R Core Team, 2014). It is common practice in single-grain detrital zircon provenance studies to discard U-Pb analyses with relatively high discordance (usually 5%–30% discordance). The modeling program from Reimink et al. (2016) includes all data from a detrital zircon U-Pb geochronology study in a statistical analysis aiming to define probable discordia lines and their associated lower and upper intercept ages on concordia diagrams. Providing hints on both the timing of zircon crystallization (upper intercept age) and Pb-loss event (lower intercept age) in the analyzed population may significantly contribute to a more plausible identification of the source basins where both emplacement and tectonothermal evolution is known.

## RESULTS

### Sm-Nd

Our sample lithologies range from slightly calcareous siltstones to slightly argillaceous limestones (Table 1; Fig. 3). All samples are fine grained and contain variable proportions of carbonate debris from adjacent carbonate complexes and siliciclastics derived from outside the Jasper Basin. The Sassenach Formation is generally fine grained, does not contain turbidite flows, and shows coherence of the Nd isotopic system, hence its Nd isotopic composition represents the average Nd composition of the contributing sources (e.g., Nelson and DePaolo, 1988; Gleason et al., 1995; Stevenson et al., 2000).

### U-Pb

In situ U-Pb zircon data were collected using laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Canadian Centre for Isotopic Microanalysis at the University of Alberta using procedures modified from Simonetti et al. (2005). Analytical techniques can be found in the Supplemental Materials (see footnote 1). Additionally, isotopic ratios and apparent ages are found in Table S1 in the Supplemental Materials. Data points were discarded if it was obvious that an inclusion contributed to analysis, there was extreme common Pb component, or the grain was in fact not zircon. For plotting purposes, data were filtered using a 10% discordance filter. For ages >600 Ma, the $^{206}\text{Pb}/^{238}\text{U}$ age was used if <10% discordant, otherwise the $^{207}\text{Pb}/^{206}\text{Pb}$ age was used. We assessed concordance by comparing $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages except for analyses <500 Ma, where $^{208}\text{Pb}/^{232}\text{U}$ and $^{208}\text{Pb}/^{238}\text{U}$ ages were compared. All zircon age plots—kernel density estimations (KDE) and probability density functions (PDF)—were generated using the software DensityPlotter (Vermeech, 2012). Multi-dimensional scaling was employed to compare data sets (Vermeech, 2013; Spencer and Kirkland, 2015; Saylor and Sundell, 2016). This statistical approach constrains our correlations with other zircon data sets using a Kolmogorov-Smirnov (K-S) test, which measures the maximum distance between two cumulative probability functions (Spencer and Kirkland, 2015). A dissimilarity matrix can then be produced for all data sets, which provides an objective comparison of the likeness of detrital zircon age spectra (see treatment in Vermeech, 2013; Spencer and Kirkland, 2015). Dissimilarity matrices were produced using the Microsoft Excel macro (K-S Test) developed at the Arizona Laserchron Center (Guynn and Gehrels, 2010).

### Supplemental Materials

Detrital zircon U-Pb analyses from the Sassenach Formation of the Jasper Basin, Alberta, Canada. Complete details on analytical techniques used at GeochronEx are listed in the Supplemental Materials. A depositional age of 365 Ma was assigned to all samples for $\epsilon_{Nd}(T)$ calculations, which allowed for comparisons with previously reported $\epsilon_{Nd}(T)$ values for the Sassenach of the Jasper Basin (Stevenson et al., 2000). Uncertainty of $\epsilon_{Nd}$ values is ~0.5 units.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Location description</th>
<th>Sample description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP15-64</td>
<td>52.920564</td>
<td>118.052719</td>
<td>East of rail tunnel at Pyramid thrust (off Highway 16)</td>
<td>Shaly, resistant silty dolomitic limestone beds (&lt;1 cm thick) (Fig. 3E)</td>
</tr>
<tr>
<td>DP15-66</td>
<td>52.919251</td>
<td>118.052948</td>
<td>Near rail tunnel at Pyramid thrust (off Highway 16)</td>
<td>Ribbon rock, dolomitic limestone with light-orange wavy siltstone partings</td>
</tr>
<tr>
<td>DP15-73</td>
<td>52.940650</td>
<td>118.045080</td>
<td>Jasper Transfer Station (north of Highway 16)</td>
<td>Ribbon rock, interbedded dolomitic limestone and wavy bedded silty dolomitic limestone (Fig. 3D)</td>
</tr>
<tr>
<td>DP15-76</td>
<td>53.041825</td>
<td>118.083158</td>
<td>Traverse at Morrow Peak, west of Cold Sulphur Springs (off Highway 16)</td>
<td>Centimeter-bedded silty limestone with fine-grained sandstone beds (cross-bedded) (Fig 3B)</td>
</tr>
<tr>
<td>DP15-77</td>
<td>53.041639</td>
<td>118.087772</td>
<td>Parking lot at Snaring River bridge on Highway 16</td>
<td>Calcareous to dolomitic silty sandstone, cross-bedded, some limestone interbeds (Fig 3F)</td>
</tr>
<tr>
<td>DP16-02</td>
<td>52.850045</td>
<td>117.725232</td>
<td>North of Medicine Lake off Maligne Lake Road</td>
<td>Ribbon rock, interbedded dolomitic limestone and wavy bedded silty dolomitic limestone (Fig. 3C)</td>
</tr>
</tbody>
</table>

**Table 1. Location and Description of Samples Collected from the Sassenach Formation in the Jasper Region, Alberta, Canada**
the deposition age of 365 Ma for the calculation of ε\text{Nd}(\text{T}) and depleted-mantle model ages in order to directly compare our data to those reported by Stevenson et al. (2000) and Boghossian et al. (1996). The ε\text{Nd}(\text{T}) values are very consistent, with five out of six samples varying within 1.3 epsilon units (~9.6 to ~10.9). One exception is sample DP15-64, with a less negative value of ~6.9 collected from a thinly bedded, silty dolomitic limestone interbedded with calcareous shales (Fig. 3E) in the upper half of the Sassenach Formation exposed along the rail tracks north of the town of Jasper. Depleted-mantle model ages (\text{T}_{\text{DM}}) also show a narrow range from ca. 1.94 to 2.04 Ga, with the exception of the same sample DP15-64, which yielded an anomalously young model age of 1.7 Ga. The most negative epsilon value of ~10.9 and oldest \text{T}_{\text{DM}} of 2067 Ma is from a silty, dolomitic fine-grained sandstone ~5 m below the Sassenach Formation–Palliser Formation contact exposed in the parking lot east of Snaring River bridge (sample DP15-77, Fig. 3F).

**DISCUSSION**

Prior to radiogenic isotope studies, a western, Antler-related source for the clastic component of the Sassenach Formation had been inferred based on sedimentological and stratigraphic evidence (Mountjoy, 1980; Savoy and Mountjoy, 1995; Becker, 1997; Mountjoy and Becker, 2000). A switch from northern and eastern sources to a western source for the siliciclastic component of the Sassenach Formation was deduced from the lack of a comparable sand-sized fraction in the correlative Graminia Silt to the east and a general western coarsening and increase infeldspar content within the Jasper Basin (Mountjoy, 1980; Mountjoy and Becker, 2000). In addition, the eastward onlapping relationship with carbonate buildups recognized in the Jasper–Saskatchewan Crossing region is opposite of the general westward downlapping trend of Perdrix–Mount Hawk shales and their equivalent strata from the east (Mountjoy, 1980; Stoakes, 1980). The results of geochemical and Nd isotope studies have been interpreted to support the concept of a western source (Savoy et al., 2000; Stevenson et al., 2000). However, none of these studies incorporated detrital zircon provenance to further elucidate potential source areas.
Figure 5. Detrital zircons from the Sassenach Formation samples examined in this study (see Table 1). Zircon grain sizes vary between sample locations and with stratigraphic position within the Sassenach Formation (generally larger toward the top). The majority of zircon grains are rounded, with low to medium sphericity. Subhedral grains are common, whereas euhedral crystals are rare (e.g., grain E in the enlarged area “i” of sample DP15-64) and appear to be associated with samples that contain a greater proportion of large zircon grains. Blue coloration of DP16-02 results from a different colored zircon mounting resin.
Significance of Sm-Nd Data

Our Sm-Nd data are consistent with previously reported data from the Sassenach Formation and are typical of continental shale-siltstone and mudstone (Stevenson et al., 2000; Boghossian et al., 1996; Dia et al., 1990) (Fig. 7). The \(^{147}\text{Sm}/^{144}\text{Nd}\) ratios reported here (0.109–0.122) are within the narrow range of 0.107–0.123 reported by Stevenson et al. (2000) from 11 Sassenach samples which also encompasses the two ratios of 0.121 and 0.117 previously reported by Boghossian et al. (1996). The \(\epsilon_{\text{Nd}}\) range of –6.9 to –10.9 obtained in this study partly overlaps with the values from other studies: two \(\epsilon_{\text{Nd}}\) values of –9.4 and –9.5 reported by Boghossian et al. (1996) and the –8.6 to –10.6 range reported in Stevenson et al. (2000). Finally, \(T_{\text{DM}}\) values in the 1.7–2.04 Ga range (Table 2) encompass the previously reported values ranging between 1.7 and 1.8 Ga (Stevenson et al., 2000; Boghossian et al., 1996).

Sampling across several intervals of the Devonian stratigraphy, Stevenson et al. (2000) noticed a trend to more negative \(\epsilon_{\text{Nd}}\) values and older model ages upward from Perdrix \(\epsilon_{\text{Nd}}\) of –7.6 to –7.8 and \(T_{\text{DM}}\) of 1.4–1.5 Ga to Mount Hawk \(\epsilon_{\text{Nd}}\) of –6.5 to –8.7 and \(T_{\text{DM}}\) of 1.4–1.7 Ga into the Sassenach Formation (–8.6 to –10.6 and 2.0 Ga). Our data confirm the more negative \(\epsilon_{\text{Nd}}\) values and older model ages (–9.6 to –10.9 and 1.76–2.07 Ga) from the Sassenach Formation. These more negative \(\epsilon_{\text{Nd}}\) values correlate with a greater proportion of older terrigenous material (siltstone and sandstone) and an overall upward-coarsening trend into the Sassenach Formation (McLaren and Mountjoy, 1962; Becker, 1997; Stevenson et al., 2000). This may indicate a more vigorous input of clastics and/or a decreasing source-to-sink distance during the deposition of the Sassenach Formation.

The correlatives of the Sassenach, Mount Hawk, and Perdrix formations to the east in the subsurface of the Alberta Basin show comparable Sm-Nd systematics (Stevenson et al., 2000; Boghossian et al., 1996). Thus, a drill core sample from the Graminia Silt yielded an \(\epsilon_{\text{Nd}}\) value of –10.0 and a \(T_{\text{DM}}\) of 1.8 Ga, within the range of the correlative Sassenach Formation. The similar Sm-Nd systematics of the Sassenach Formation and its eastern correlatives—the Graminia Silt—suggest a common source. Similarly, the subsurface Calmar Formation (Fig. 2) of the Alberta Basin has an \(\epsilon_{\text{Nd}}\) value of –9.1 and a \(T_{\text{DM}}\) of 1.7 Ga, which are consistent with the most negative \(\epsilon_{\text{Nd}}\) values and oldest \(T_{\text{DM}}\) ages found in the partly correlative Mount Hawk Formation in the Rocky Mountains (Fig. 2). One sample from the subsurface Duvernay Formation (Boghossian et al., 1996) yielded a similar \(T_{\text{DM}}\) (1.55 Ga) but a slightly more negative \(\epsilon_{\text{Nd}}\) value compared to its exposed equivalent in the Rockies, namely the Perdrix Formation (1.4 and 1.5 Ga, and \(\epsilon_{\text{Nd}}\) values of –7.6 and –7.8).

To the southwest of the Jasper Basin in southern British Columbia, the Frasnian–Famennian Chase Formation (Lemieux et al., 2007; Kraft, 2013) on the western side of the miogeocline displays very similar \(\epsilon_{\text{Nd}}\) values (–6.7 to –10.8) to the Sassenach in the Jasper Basin (Fig. 8G), suggesting that both had access to more mature crustal material.

The interpreted source for much of the Devonian miogeoclinal basin fill in Alberta (i.e., Mount Hawk Formation and equivalents) is the Franklinian
mobile belt in the Canadian Arctic (Patchett et al., 1999a). There, lower Cambrian to Upper Devonian clastic strata show an abrupt shift in $\varepsilon_{Nd}$ values in the Late Ordovician (ca. 450 Ma) from $-25$ to $-17$ in older rocks to $-13$ to $-5$ in younger rocks (Patchett et al., 1999b). The ultimate source of these sediments was inferred to be the Caledonian orogen (Patchett et al., 1999b). To the south, in the Cordilleran miogeocline of Canada, Boghossian et al. (1996) had previously noted a similar positive shift in $\varepsilon_{Nd}(T)$ values from the Late Ordovician to Late Devonian time lasting until foreland basin formation in the Late Jurassic, and Garzione et al. (1997) confirmed the general positive trend from the Precambrian into the Permian in the Yukon, Northwest Territories, and British Columbia. These data led Patchett et al. (1999b, p. 578) to infer that the foreland clastic wedge of the Franklinian orogen propagated southwestward into the Cordilleran miogeocline “to give rise to the thick Upper Devonian Imperial Assemblage in the north and to thinner Devonian clastic rocks over a wide region of the miogeocline and continental interior, at least as far south as Alberta”.

Figure 7. Existing Upper Devonian $\varepsilon_{Nd}(365)$ values placed at their approximate stratigraphic position, except for the samples analyzed by Boghossian et al. (1996), who did not specify the stratigraphic position of their samples within a given formation. $\varepsilon_{Nd}$ at time of deposition of 365 Ma.
Figure 8. Detrital zircon plots (probability density function and kernel density estimation) and $\varepsilon_{\text{Nd}}(T)$ ($T$ is timing of deposition) for Devonian strata from northern and western Laurentia. Light gray bands represent age clusters interpreted from the Jasper Basin Sassenach Formation data. Light orange bands represent the 500–700 Ma zircon ages of Arctic affinity, and the North American magmatic gap (NAMG; van Schmus et al., 1993). Number in parentheses after a formation name represents number of sample locations. Average of two or more $\varepsilon_{\text{Nd}}(T)$ values is in parentheses. See Figure 11 for general location of samples A to H. (A, C) Data from Anfinson et al. (2012b); $\varepsilon_{\text{Nd}}$ for the Parry Islands and Blackley Formations are as reported in Patchett et al. (1999b). (B) Data from Anfinson et al. (2012a); $\varepsilon_{\text{Nd}}$ for the Beverly Inlet, Hecla Bay, and Bird Fiord Formations are as reported in Patchett et al. (1999b). (D) Data from Beranek et al. (2010) and Lemieux et al. (2011); $\varepsilon_{\text{Nd}}$ values are as reported in Garzione et al. (1997). (E) Sassenach data from the Jasper Basin (this study). (F) Sassenach data reported in Gehrels and Pecha (2014); sample is reported from southern British Columbia, although precise location is unknown. (G) Chase Formation data reported in Lemieux et al. (2007) and Kraft (2013). Sample 04TWL072 of Lemieux et al. (2007) is excluded from the data set as it is likely part of the Mississippian Milford Group (Kraft, 2013). (H) Data from Beranek et al. (2016). Abbreviations: B.C.—British Columbia; Fm.—Formation; Sst.—sandstone.
A second-order shift to more negative $\epsilon_{Nd}$ values (–11.4) in the otherwise positive regional shift can be noticed in the uppermost Frasnian to Famennian Imperial Formation of the northern Cordilleran miogeocline (Garzione et al., 1997). Here, from the underlying Canol Formation (–4.8 to –5.0) into the Imperial Formation (–5.0 to –11.4; Fig. 8D), there is a negative shift in $\epsilon_{Nd}$ values similar to that observed in the Perdrick–Mount Hawk to Sassenach formations of the Jasper Basin. Whereas this negative shift in $\epsilon_{Nd}$ values of Famennian strata within the Cordilleran miogeocline has not been noticed in the Franklinian data set (Patchett et al., 1999b), the Eifelian Bird Fiord and Givetian Hecla Bay Formations have negative $\epsilon_{Nd}$ values (as low as –11.4 and –12.1, respectively) similar to negative values observed in Imperial and Sassenach strata (Fig. 8). The overlying Frasnian Beverly Inlet Formation has comparable negative $\epsilon_{Nd}$ values (–10.1) (Fig. 8B). Thus, the northern Laurentian strata younger than Middle Devonian appear to have had access to sources comprising older crustal material. The Franklinian margin strata are interpreted to have been uplifted during the Ellesmerian orogeny and subsequently distributed southward (e.g., Lemieux et al., 2011). The negative $\epsilon_{Nd}$ values reported in these strata may have contributed to similar $\epsilon_{Nd}$ values observed in the Sassenach of this study. However, the westward coarsening both in the northern Cordilleran miogeocline from fine-grained Besa River Formation to Imperial Formation (partly equivalent to the Earn Group) and in the Jasper Basin from the Graminia Silt to the western Sassenach, corroborated with the lack of such a second-order shift in the Arctic, suggests that the Late Devonian negative shift in $\epsilon_{Nd}$ values within the northern Cordilleran miogeocline may be related to an additional western source for these sediments.

The subtle negative $\epsilon_{Nd}$ shift recorded in the Sassenach Formation requires contributions from pre–Late Ordovician rocks with negative $\epsilon_{Nd}$ values. The nature of the Sm-Nd isotopic system, namely the averaging of the isotopic composition and age of source rocks, leaves some ambiguity in the interpretation of $\epsilon_{Nd}$ values for provenance from Devonian miogeocline strata of western Laurentia. Mixing of even small amounts of very negative $\epsilon_{Nd}(T)$ values from uplifted Neoproterozoic Windermere Supergroup (–20 to –22) and/or lower Paleozoic strata (–21 to –29) to the west could have produced the second-order Late Devonian shift to more negative $\epsilon_{Nd}(T)$ in the Sassenach Formation. At the same time, the Givetian to Frasnian Canadian Arctic strata and the Frasnian strata of the Northwest Territories and Yukon (Imperial Formation) have negative $\epsilon_{Nd}$ values overlapping with those of the Sassenach.

**Significance of Detrital Zircon Data**

There are a number of visual and statistical differences between zircon spectra of the six Sassenach samples from the Jasper Basin (Fig. 6). While the general age gaps of 700–800 Ma and 2100–2500 Ma are mostly consistent, some samples contain a few ages within these troughs (three and 10 zircon ages, respectively). Data density (shown in KDE plots) varies between samples within the age clusters outlined in gray in Figure 6, which is in part due to the fine-grained nature of the sediment and the small zircon numbers retrieved from some sample locations. These data suggest that in addition to the effects of sample size, the Sassenach Formation, which can reach thicknesses >200 m in some areas, can have varying proportions of contributing material both geographically and over the time span of its deposition, which cautions against the use of a single sample location and stratigraphic level for comparative analysis (see Fedo et al., 2003, for a discussion of spatial and stratigraphic variability). However, the composite U-Pb spectrum of our detrital zircon samples defines three age populations, (1) 378–700 Ma, (2) 900–2100 Ma, and (3) 2500–2900 Ma, that are similar to those of the single Sassenach sample reported by Gehrels and Pecha (2014) from an uncertain location in southern British Columbia (Fig. 8F).

**Lower Neoproterozoic to Archean Zircons (900–3500 Ma)**

A significant number of zircons (64%) from the Sassenach in the Jasper Basin fall within the 900–2100 Ma age cluster. An additional 15% of zircons fall within the 2100–2900 Ma age population (Fig. 8E). Direct derivation of Paleoproterozoic and older zircon grains from the Canadian Shield into the Jasper Basin is unlikely. However, the shield was the primary source for the pre-Devo- nian terrigenous units at the western margin of Laurentia, hence any highland to the west of the Jasper Basin could have exposed the underlying strata that may have acted as secondary sources of cratonic zircon grains into the Sassenach Formation.

The location of Belt-Purcell Supergroup strata at the western edge of Laurentia (Ross and Villeneuve, 2003) makes it a potential source of Precambrian zircons for the younger strata along the western margin of Laurentia. All of the pre-Mesoproterozoic detrital zircon age groups we have obtained from the Sassenach samples have been reported from the Mesoproterozoic Belt-Purcell Supergroup (Ross and Villeneuve, 2003), including grains in the 1610–1490 Ma North American magmatic gap (NAMG), which are atypical for Laurentia (van Schmus et al., 1993). A number of zircon grains (19) in our Sassenach samples yielded ages that fall within the NAMG (Fig. 8); however, such zircon ages are known in the Prichard Formation of the Belt Supergroup where they were interpreted to represent an influx of sediment from a western, subsequently tectonically removed source (Ross and Villeneuve, 2003).

The detrital zircon budget of the Horsethief Creek Group (the southern metamorphosed portion of the Neoproterozoic Windermere Supergroup) appears dominated by late Paleoproterozoic (1753–1874 Ma) and random Archean (2564–3085 Ma) grains (Gehrels and Ross, 1998). To the north, in the Cariboo Mountains, two samples from the Kaza Group, the local representative of the Windermere Supergroup, yielded zircon ages with a bimodal distribution: 1.6–2.16 Ga and >2.5 Ga, with a distinct lack of ages between 2.1 and 2.5 Ga (Ross and Parrish, 1991). Although grits of these Neoproterozoic units were inferred to be derived from erosion of Laurentian source rocks to the east, which include extensive 2.1–2.4 Ga rocks (particularly 2.3–2.5 Ga rocks of the Arrowsmith orogeny; Berman et al., 2013), this age gap remained unexplained. Noteworthy is that a similar age gap is obvious in the zircon spectrum of our Sassenach samples (Fig. 8E).
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There is no data set for the clastic strata of the Cambrian Gog Group, but one sample from the Hamill Group, its correlative to the west in the Omineca belt, yielded a pattern almost identical to that of the underlying Neoproterozoic Horsethief Creek dominated by zircon ages in the 1750–1859 Ma range (Gehrels and Ross, 1998). The Middle to Upper Ordovician Mount Wilson Formation yielded cogenetic zircons of 1030 Ma and 1053 Ma, ranges of 1816–1967 Ma and 2025–2110 Ma, and a few isolated grains in the 2276–2598 Ma range (Gehrels and Ross, 1998). Although a few grains with these ages are also present in the Sassenach Formation, there are no clear criteria to assign these grains to the underlying stratigraphic units.

The large Proterozoic populations in the 1000–2100 Ma age range are very common in the kilometers-thick clastic deposits of the Neoproterozoic Windermere and clastic Cambrian to Ordovician deposits. Mesoproterozoic and older zircon grains were also available from the Belt-Purcell strata. Paleoproterozoic (older than ca. 1800 Ma) and Archean-age zircons including those defining the 2500–2900 Ma cluster likely reflect Canadian Shield sources; the Mesozoic-Paleoarchean zircon ages (3100–3500 Ma) that fall outside the clusters are likely multiply recycled from ancient basement provinces of the western Canadian Shield (Gehrels and Ross, 1998).

The Neoproterozoic to Archean zircons in the Sassenach samples share common ages with those of Devonian clastic strata of the northern and western margins of Laurentia (Fig. 8), although the proportion of zircons in the age populations varies. These old populations do not offer clear discrimination criteria between western versus northern sources. As described above, many of these zircon ages can be explained by indirect (recycled) provenance from the Laurentian craton. The 900–1200 Ma populations, in addition to potential sources from Windermere and Cambrian deposits along the western Laurentian margin, may be sourced from Arctic terranes, such as Crockerland (Fig. 9), which has been interpreted to record zircons produced during the Grenville-Sveconorwegian orogenies (Anfinson et al., 2012b).

In reviewing the published data sets from the older clastic units in the adjacent Cordilleran miogeocline, the identification of uniquely characteristic features in the underlying clastic strata is not possible at this time.

Neoproterozoic to Paleozoic Zircons (378–700 Ma)

In contrast to the lower Neoproterozoic to Archean zircon populations, there are unique features in the zircon age spectra obtained from the Sassenach Formation between 378 Ma and 700 Ma that are similar to those reported from Middle and Upper Devonian strata of the Canadian Arctic, the northern and southern Canadian miogeocline, and south-central Idaho that link these strata to the paleo-Arctic region of northern Laurentia (Figs. 8A–8C). Zircons in this age group can be tied to terranes that accreted to the northern margin of Laurentia, such as Arctic Alaska–Chukotka, Pearya, and Crockerland (Fig. 9) (Colpron and Nelson, 2009; Beranek et al., 2010, 2015; Anfinson et al., 2012a, 2012b; Lemieux et al., 2011). These terranes contain non-Laurentian zircon populations, particularly in the 430–700 Ma range, sourced from the Caledonian and Timanian orogenetic belts (Beranek et al., 2010; Lemieux et al., 2011; Anfinson et al., 2012a, 2012b; Beranek et al., 2016). In particular, the 500–700 Ma cluster is an age range atypical for Laurentia, but characteristic of granitoids associated with the Timanide orogen of Baltica. The oldest influx of Timanian zircons to Laurentia is recorded in upper Silurian deposits of Franklinian margin strata (Beranek et al., 2015). Subsequent uplift of Franklinian margin strata during Ellesmerian orogenesis in the mid-Paleozoic is recorded by Timanian zircon ages in Devonian strata of the Arctic archipelago (Anfinson et al., 2012b) and Devonian to Lower Mississippian strata of the Northwest Territories and Yukon (Beranek et al., 2010; Lemieux et al., 2011). Recycling of the Ellesmerian clastic wedge containing the exotic Caledonian and Timanide zircon popula-
Comparing Zircon Ages along Northern and Western Laurentia

In comparing the geographically disparate Devonian detrital data sets (Fig. 8), it is clear that in general all share the three age clusters described above (378–700 Ma, 900–2100 Ma, and 2500–2900 Ma). Kernel density estimations, however, highlight the variation in data density in each age cluster. For example, the Chase Formation from southern British Columbia and the Jefferson and Milligen Formations from Idaho have relatively low data densities in the Paleozoic to Neoproterozoic age group, particularly in the 500–700 Ma range (Figs. 8G, 8H). The number of 500–700 Ma zircons increases to the north from the Jasper Basin of this study toward Eifelian to Famennian strata of the Yukon, Northwest Territories, and the Canadian Arctic archipelago. Zircon age data density also varies within the broad Proterozoic group (900–2100 Ma). For example, zircon ages from the uppermost Frasnian–Famennian Parry Islands Formation have fewer zircons in the 900–2100 Ma range but many more in the Paleozoic to Neoproterozoic group, which was interpreted to reflect the overwhelming input from younger source terranes colliding with northern Laurentia over eastern Caledonian sediment sources (Anfinson et al., 2012b).

Kraft (2013) noticed a peculiar Proterozoic age gap in the Chase Formation from 1.22 Ga to 1.32 Ga (Fig. 8G). This age gap is also present in the Milligen and Jefferson Formations of Idaho (Fig. 8H; Beranek et al., 2016). However, this age gap is not present in the Sassenach or the rest of the Devonian strata in areas northward of the Jasper Basin (Figs. 8A–8F), which suggests potential differences in sources containing Proterozoic zircons.

The differences between the data sets, as described above, are borne out by K-S tests (Table 3). The Sassenach appears to correlate best with the partly coeval Imperial Formation of the Yukon and Northwest Territories and the Eifelian Blackley Formation of the Arctic region, whereas the Jefferson and Milligen Formations are more similar to the Parry Islands Formation and the Milligen Formation (Beranek et al., 2016).

| TABLE 3. P VALUES FROM KOLMOGOROV-SMIROV STATISTICAL TEST* |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | A               | B               | C               | D               | E               | F               | G               | H               |
| North           | Canadian Arctic | Yukon and N.W.T. | Jasper Basin    | Southern B.C.   | Quesnellia      | South-central Idaho |
| A               | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| B               | 0.000           | 0.738           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| C               | 0.000           | 0.738           | 0.147           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| D               | 0.000           | 0.000           | 0.147           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| E               | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| F               | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| G               | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |
| H               | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           | 0.000           |

*P values greater than 0.05 (gray shading and bold values) considered statistically indistinguishable, and thus have the same provenance. P values of 0 have statistical certainty of different source areas.

Note: Sample locations: A—Parry Islands Formation (Anfinson et al., 2012a, 2012b); B—Beverly Inlet, Fram, Hecla Bay, Strathcona Fiord, Bird Fiord Formations (Anfinson et al., 2012a); C—Blackley Formation (Anfinson et al., 2012b); D—Imperial Formation (Beranek et al., 2010; Lemieux et al., 2011); E—Sassenach Formation (this study); F—Sassenach Formation (Gehrels and Pecha, 2014); G—Chase Formation (Lemieux et al., 2007; Kraft, 2013); H—Jefferson Formation and Independence sandstone (Milligen Formation) (Beranek et al., 2016).
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Formations (Idaho) and the Parry Islands Formation (Arctic) do not appear to correlate to any other data sets despite visual similarity in PDF and KDE plots (Table 3). The K-S tests suggest a closer link to partly coeval Devonian clastics from northern areas of the western Laurentian margin.

**Discordance Modeling**

To further constrain the source, we have modeled our U-Pb data using the discordance modeling program by Reimink et al. (2016) (Fig. 10). The ca. 390 Ma lower intercept derived from the discordia modeling is not an exact age of the potential alteration of the zircons; it represents a peak with a likelihood that is larger than one-third of the maximum likelihood in the data set (Reimink et al., 2016). However, the lack of any other conspicuous peaks in the lower-intercept line (Fig. 10C) strengthens the interpretation of one major resetting event that has affected a significant proportion of the Sassenach zircons with a range of crystallization ages.

The 390 Ma lower-intercept age calculated here appears to be too old for the Antler orogeny, although no precise dating constrains Antler-equivalent tectonism in the Canadian Cordillera. Instead, this early Eifelian age coincides with the first of three tectonic loading events inferred in the Innuitian-Ellsworth orogen. There, accelerated subsidence at the initiation of unconformity-bounded sequences in the foreland basin (early Eifelian–earliest Frasnian, early Frasnian–late Frasnian, and late Frasnian–mid-Famennian, followed by a concluding phase of deformation and uplift of the foreland basin in late Famenian–Tournaisian) has been triggered by three major thrusting pulses during southwestward propagation of the Ellesmerian orogenic belt (Embry, 1988).

**POSSIBLE SOURCES FOR THE SASSENACH FORMATION**

In the context to the Western Canada Sedimentary Basin, potential source areas for the terrigenous-clastic component of the Sassenach Formation in the Jasper Basin include one, or a combination, of the following sources: (1) an eastern source in the Canadian Shield, including the Peace River Arch; (2) the western Laurentian margin at paleolatitudes proximal to the Jasper Basin, such as the “Okanagan High” and/or an exotic terrane related to Antler tectonics; and/or (3) sediment recycling from Franklinian strata during the Ellesmerian orogeny along the western Laurentian margin.

**Eastern Sources**

Our detrital zircon and Sm-Nd data show that eastern, shield-derived sources alone can be discounted based on their lack of Neoproterozoic and younger zircons. The Peace River Arch, which exposed cratonic basement just north of the Jasper Basin, can also be discounted as the sole source based on zircon ages (lack of Neoproterozoic to Paleozoic zircon ages) and its less negative εNd values (~9.7 to ~5.6, average of ~2.3; Thériault and Ross, 1991) that cannot explain the negative deviation of εNd values of the Sassenach Formation (Fig. 7). Moreover, the arch was mostly covered by Devonian sediments during the Famennian deposition of the Sassenach Formation and exposed only as a small island north of the Jasper Basin.

Whereas the existing Nd isotope data from the Sassenach Formation suggest contributions from an older, possibly western source, the recognition of Arctic-affinity detrital zircon grains (500–700 Ma age range) and of a Pb-loss event coincident with an Ellesmerian tectonic event are consistent with a Canadian Arctic source for the detrital component of the Sassenach Formation. Whether these Arctic-affinity zircons were delivered directly from the Arctic through south-directed Late Devonian shore-parallel shallow-marine currents along western Laurentia, or alternatively from western sources, either highlands related to the Antler orogen or Arctic-affinity terranes that migrated south and were tectonically juxtaposed against the western margin of Laurentia during the Middle to Late Devonian, will be discussed further below.

**Western Sources**

The interpretation of a western source for the clastic material in the Sassenach Formation has been intrinsically associated with the manifestation of Antler tectonics at Canadian latitudes. Antler-age tectonism was inferred from the Late Devonian through mid-Mississippian flooding of the Cordilleran miogeocline by westerly derived clastics, which required a highland to the west. This clastic influx is represented by the coarse clastics of the Guyet Formation at Alberta latitudes in the Cariboo Mountains (Campbell et al., 1973) and by the Earn Group farther north in the Cassiar Mountains and the Yukon (Gordey et al., 1987), with their eastern fine fringe consisting of the Exshaw Formation and Besa River Formation, respectively, which spread far into the interior of the platform from Frasnian to earliest Mississippian time (Campbell et al., 1973; Struijk, 1986; Gordey et al., 1991). The western sequences that include coarse sandstone and conglomerate are associated with growth faults and local alkaline volcanic rocks of continental-rift geochemistry (Goodfellow et al., 1995). Their original interpretation as deposited in half-grabens formed in the outer miogeoclone (Templeman-Kluit, 1979) has been reconsidered as deposits of pull-apart basins along a broad sinistral strike-slip fault zone (Eibsacher, 1983; Gordey et al., 1987; Ketner, 2012). The sediment sources could have been local uplifts (highlands) at compressional bends along the major fault zone outboard of the preserved margin of the miogeoclone, which were partly removed or obscured by subsequent tectonism.

Smith et al. (1993) postulated, however, that the Antler orogen of central Nevada and southern Idaho extended to the north, and that the Late Devonian and Mississippian extensional setting in the Canadian Cordillera is the expression of “foreland flexural extension” east of the advancing orogen. In spite of its highly speculative nature and striking differences between the western U.S. and Canada (e.g., compressional versus extensional tectonic setting, well-defined fold-thrust belt versus modest local deformation, no foreland volcanics versus abundant volcanics, respectively), over time this extrapola-
tion has propagated into the local literature (e.g., Stevenson et al., 2000; Root, 2001). Various Silurian to Mississippian tectonic processes at the western margin of ancient North America have been conveniently assigned to the Antler orogeny (see Root, 2001).

Antler-age compressional deformation along the Canadian Cordillera has been assumed at two locations in southern British Columbia, one in the Kootenay parautochthon and the other on the Middle Devonian “Purcell arch”: At both locations the structural interpretations are tenuous and will be briefly reviewed here.

Gehrels and Smith (1987) proposed that the Lardeau Group of the Kootenay arc was an “Antler” allochthon correlative with the Covada Group in the Roberts Mountains of the northwestern U.S., and that it was emplaced over mid-oceolinal strata (Badshot Formation) during mid-Paleozoic time. Colpron and Price (1999) showed instead that the Lardeau Group is depositionally linked...
to and conformable with underlying rocks that form part of the North American Cordilleran miogeocline. Subsequent detailed mapping in the Kootenay arc (Thompson et al., 2006) has provided stratigraphic evidence that supports a change from a trough-like setting during the Lardau deposition, to stable platform-like conditions in the mid-Devonian, to back-arc extension and magmatism in the Late Devonian to Mississippian; in modern coordinates, the west-facing continental margin arc developed on the Okanagan High above an east-dipping subduction zone (Thompson et al., 2006). According to Kraft (2013), volcanic lithochemical data from the Kootenay arc show a progression from early to mid-Paleozoic rift-related volcanism (in the Lardau Group), to Devonian and Early Mississippian arc-related volcanism (in the Mount Sproat assemblage), followed by Permian oceanic spreading-center volcanism (in the Kaslo Group, the local expression of Slide Mountain “ocean”).

An episode of (middle Paleozoic?) contractual deformation in the Kootenay arc was inferred based on truncation of foliation surfaces, folds, and thrust faults in the early Paleozoic Lardau Group by the Lower Mississippian Milford Group (e.g., Read and Wheeler, 1975; Klepacki and Wheeler, 1985; Smith et al., 1993). Kraft (2013) has shown that old D1 compressional structures in the Lardau Group have only been observed in the northern Kootenay arc, and internal deformation in the Index Formation to the south (interpreted as a possible Mississippian thrust zone), were both manifestations of local shortening due to heterogeneities in a back-arc environment. At southern Canadian Cordilleran latitudes, the Slide Mountain basin was closed through thrusting and folding (the “Whitewater event”) as late as late Permian to Middle Triassic, and obduction would have occurred after Late Triassic–Early Jurassic arc magmatism, hence too late to be assigned to the Antler orogeny (Thompson et al., 2006).

The other frequently cited evidence of Antler compression at Canadian latitudes is in the Purcell Mountains, where the geology within a very limited area (~10 km²) was interpreted to record the “most precise view of the nature and timing of the mid-Paleozoic deformation...in western Canada” (Root, 2001, p. 17). At this location, the Neoproterozoic Horsethief Creek Group (Windermere Supergroup) is overlain above a major regional unconformity by three Middle Devonian formations (Eifelian to late Givetian conodont zones), each separated by angular unconformities. In ascending order these are the Mount Forster, Harrogate, and Starbird formations. The Mount Forster Formation (and inferred correlatives to the east) comprises an easterly thinning wedge that pinches out against the West Alberta Ridge, which was the source for sandstone and conglomerate present in exposures near the eastern zero edge of the sequence (Belyea and Norford, 1967). Root (2001, p. 17) described two faults with uncertain sense of displacement: F2 was considered “poorly understood” but was mapped as a normal fault, and F3 was believed to be “a normal fault that has created an omission of strata” amongst other possibilities. The author viewed “the structural and stratigraphic geometries (as being) produced by Devonian syndepositional deformation...with abundant angular unconformities...created by syndepositional fold- and fault-related growth structures.” Paradoxically, although an extensional depositional environment is suggested by the normal faults and by the volcanic flows in the Mount Forster Formation, Root (2001) interpreted the tectonic setting as “foreland basin during (early Antler) contractual deformation”.

Located inboard of the Lardau trough, in a back-arc (extensional) tectonic setting, the syn-depositional deformation in the Mount Forster Formation had a local character, and could not have been “part of an orogenic event of sufficient magnitude to generate a foreland basin...along the Devonian Cordilleran margin” (Kraft, 2013, p. 149). We consider Root’s (2001) interpretation of an Antler fold-and-thrust belt to be tenuous at best and its propagation into continental-scale paleostructures involving an Antler orogen all along western Laurentia (Smith et al., 1993) unwarranted. Although we are well aware that the tectonic setting, timing of events, and structural style may vary along a continental-scale orogenic belt, and that its vestiges could be obscured by Mesozoic–Cenozoic Cordilleran tectonics, the frequently invoked Antler orogen has yet to be firmly established at Canadian latitudes. We favor the interpretation of a local western highland(s) within or beyond the miogeocline.

The extensional, back-arc basin setting of the miogeoclinal-terrace wedge at the western margin of Laurentia throughout the middle to late Paleozoic implies a west-facing magmatic arc on the outboard margin of Laurentia (Thompson et al., 2006). Arctic-origin terranes migrating to the south could have been placed adjacent to the arc during the Late Devonian (Colpron and Nelson, 2009) and shed Arctic zircons to the western Laurentian miogeocline, including the Jasper Basin (Beranek et al., 2016). Assuming that a transport mechanism could be imagined to deliver zircons from across the ~300-km-wide back-arc basin (Thompson et al., 2006), it is striking that the Sassenach Formation does not contain syndepositional zircon from the extensive Late Devonian–Mississippian Eagle Bay magmatic suite of the Okanogan High (Paradis et al., 2006). It is also intriguing that the Chase Formation on the Okanogan High at the western shoulder of the back-arc basin lacks syndepositional zircons from the proximal Eagle Bay Formation (Kraft, 2013).

Whereas a mixture of northern and western sources related to southward-migrating terranes cannot be discounted due to the potential masking of western-derived zircons by the northern sources, the discordia modeling herein suggests a common zircon alteration event ca. 390 Ma in the Sassenach zircon population, which may be linked to Eifelian convergent tectonism during Ellesmerian orogenic events along the northern margin of Laurentia.

Northern Sources

The interpretation of a common source for strata of the northern regions of Laurentia and those of the Jasper Basin requires significant southward transport of sediments by shelf-parallel, shallow-marine currents along the western margin of the Laurentia (Fig. 11). Based on the Nd isotopic system, a northern source for the mid-Devonian to Lower Jurassic sediments of the western North American miogeocline has already been postulated (e.g., Boghossian et al., 1996; Pattchet al., 1999a). Stoakes (1980) and Mountjoy (1980) suggested that the fine-grained terrigenous clastics of the Mount Hawk Formation of the southern Canadian Rocky Mountains and its equivalent Iretan Formation in the subsurface of Alberta were derived from the north, and Stoakes (1980)
Figure 11. Late Devonian paleogeography of northern and western Laurentia (375 Ma) (modified from Ron Blakey, Colorado Plateau Geosystems Inc.). The Jasper Basin (Sassenach Formation) is located in the southern Canadian Cordillera, west of palinspastically restored Frasnian reef complexes. Arrows denote the general sediment pathways interpreted for the Frasnian–Famennian basin fill, including the Sassenach Formation (yellow arrows), from the Innuitian-Ellesmerian orogen in the Canadian Arctic. Two positions of the equator are shown for different 10 m.y. time slices: equator 1 is Late Devonian, whereas equator 2 is Late Devonian–Early Mississippian; see text. Locations A to H represent areas of existing Devonian detrital zircon chronology studies with zircon age spectra compiled in Figure 8. White line off NW Laurentia represents a hypothetical oceanic spreading ridge. Abbreviations: AB—Alberta, Canada; MT—Montana, USA; PRA—Peace River Arch; SK—Saskatchewan, Canada.
suggested the Franklinian orogen as a potential source. The Sassenach Formation, however, is siltier and contains fine-grained sandstone, and its equivalent in the subsurface, the Graminia Silt, is relatively thin and contains no significant sandstone. The fact that the Graminia Silt and other northern Devonian sequences as old as the Eifelian contain \(^{137}C\) values that overlap with the most negative values in the Sassenach suggests that they share a common source, possibly Franklinian margin strata recycled through Ellesmerian orogenesis.

One suggestion is that more vigorous shore-parallel currents were directed along the outer shelf of Laurentia, west of the West Shale Basin (Fig. 2), during Famennian Sassenach deposition (Fig. 11). This scenario is consistent with Northern-Hemisphere-clockwise currents (south-directed currents) set up along the western margin of Laurentia due to the Famennian shift of the Jasper Basin to the Northern Hemisphere. Similar processes were invoked for the distribution of zircons southward from the exposed Peace River Arch during the Ordovician (Gehrels and Ross, 1998; Gehrels and Pecha, 2014). Southward transport of coarser sediment may also have been facilitated by a significant relative sea-level fall at the Frasnian-Famennian boundary, recognized from numerous Devonian locales in Euramerica (top of transgressive-regressive cycle lld of Johnson et al. [1985]). Fairholme Group carbonates, which underlie the Sassenach in the Cordillera, show evidence of erosion corresponding to this sea-level fall event (McLaren and Mountjoy, 1962; MacKenzie, 1965). Stratigraphic relationships suggest that the Sassenach filled the Jasper Basin during the ensuing eastward transgression and continually onlapped the Fairholme Group carbonate buildups (Mountjoy and Becker, 2000).

The detrital zircon budget of the Sassenach Formation of the Jasper Basin appears to be tied more closely to northern Devonian strata than to the southern and western margin of Laurentia. For example, there is a higher proportion of zircons within the 500–700 Ma range in the Sassenach from the Jasper Basin and the northern Devonian strata (Fig. 8). Additionally, zircons within the 700–900 Ma range are present in the Jasper Basin and the northern strata, but are absent in the southern locations. The few Devonian zircon ages found in the Sassenach, which are also found in the Devonian Arctic to northern Cordilleran strata, have potential common sources tied to plinths in the Pearya terrane (ca. 390 Ma; Trettin, 1987). The results of K-S tests (Table 3) also suggest a closer link to Devonian sediments from northern Laurentia. Given the lack of unequivocal evidence for exotic terranes of Arctic affinity at or near Jasper Basin paleolatitudes containing Paleozoic to late Neoproterozoic zircons (e.g., the Okanangan subterrane), coupled with discordance modeling suggesting ties to Innuitian-Ellesmerian tectonics, we favor a northern Laurentian derivation for the Sassenach clastics in the Jasper Basin.

\section*{CONCLUSIONS}

The Nd isotopes and detrital zircon U-Pb data reported herein from the Sassenach Formation of the Jasper Basin in the Alberta Rocky Mountains fold-and-thrust belt suggest in part a common source with the Middle to Upper Devonian strata from the Yukon, Northwest Territories, and the Canadian Arctic (Figs. 7, 8, and 11). The post-Ordovician \(^{137}C\) positive trend in Devonian strata is common in the Canadian Arctic and Canadian Cordillera miogeocline. Furthermore, subtle negative \(^{137}C\) deviations in the post-Ordovician trend are recorded in both the Middle to Late Devonian northern strata and the Late Devonian Sassenach of the Jasper Basin.

A northern Laurentian source area for the Sassenach Formation is supported by similarity in detrital zircon age populations, specifically in non-Laurentian ages in the 500–700 Ma range. Silurian to Devonian zircon ages within the Sassenach are also common within the Devonian of northern Laurentia, with a common potential source in the Pearya terrane. Discordance modeling of the Sassenach zircons points to a common period of tectonothermal overprinting at ca. 390 Ma, which corresponds to the first pulse in tectonism in Innuitian-Ellesmerian orogenic events. These data suggest that the bulk of the clastic sediment in the Sassenach Formation was derived from the recycled Ellesmerian foreland basin, and that this sediment propagated along the western side of Laurentia during the Famennian.

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tonic setting in the Rae craton, with implications for pre-Nuna supercontinent reconstruct-


