

Provenance approaches in polydeformed metasedimentary successions: Determining nearest neighboring cratons during the deposition of the Paleoproterozoic Murmac Bay Group

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ABSTRACT

The proximity and positions of cratons constituting the western Canadian Shield prior to and during the Rhyacian Period (2.30–2.05 Ga) are poorly known. In the absence of paleomagnetic data, stratigraphic correlation and detrital zircon isotopic data from sedimentary successions can be used to constrain relative craton positions during their time of deposition. The Murmac Bay Group, a multiply deformed metasedimentary succession located on the Rae craton margin in Canada, provides an opportunity to test hypotheses regarding its nearest cratonic neighbors during deposition. The polydeformed nature of the Murmac Bay Group, however, presents challenges in determining detailed stratigraphic relationships in the upper succession, which lacks distinct marker beds. Provenance analysis from detrital zircon geochronology provides one strategy for overcoming these challenges. Previous U-Pb geochronology indicates the lower succession was deposited <2.32 Ga, and the upper succession was deposited between <2.17 Ga and >1.94 Ga. We provide new U-Pb detrital zircon ages for the upper succession, including a new maximum depositional age at <2.00 Ga. We integrate our new data with published detrital zircon ages and compare them with published and public-domain igneous crystallization ages stored within a large geochronological database to identify potential provenance locations. While there is no known local source for the ca. 2.17 Ga age population, potential 2.17 Ga sources are found on the neighboring Slave craton and Buffalo Head–Chinchaga domain. Geographically, sources for the remaining dominant age populations (e.g., 2.33 Ga) exist either locally, or between the potential sources for ca. 2.17 Ga zircon grains and our study area. Our results support the interpretation that the Rae and Slave cratons were already amalgamated during upper Murmac Bay Group deposition (<2.00 to >1.94 Ga). This provides an important constraint on the timing of Rae–Slave amalgamation.

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INTRODUCTION

The southwestern Rae craton of the Canadian Shield (Fig. 1) is separated from the Hearne craton to the east by a geophysical boundary known as the Snowbird tectonic zone (Hoffman, 1988); together, the Rae and Hearne cratons constitute the western Churchill Province. The Snowbird tectonic zone has been variously interpreted as a late Archean (2.6 Ga) intracratonic shear zone (Hanmer et al., 1995a, 1995b) or an Archean suture (Regan et al., 2014) prior to the ca. 2.10 Ga breakup of a long-standing supercontinent, Kenorland (Aspler and Chiarenzelli, 1998). Alternatively, it has been hypothesized to represent a Paleoproterozoic (1.92–1.90 Ga) suture (Berman et al., 2007), possibly formed

in the early stages of the Trans-Hudson orogeny (ca. 1.92–1.80 Ga; Corrigan et al., 2009).

The southwestern Rae craton is bounded to the west by the ca. 2.00–1.90 Ga Taltson magmatic zone, which has been interpreted as the southern extension of the approximately coeval Thelon orogeny (Hoffman, 1988), and more recently as a separate entity (Card et al., 2014, 2010) resulting from either the amalgamation of the Slave and Rae cratons, or accretion of the Buffalo Head terrane to an already sutured Slave and Rae structure (Card et al., 2014). Card et al. (2014) reinforce the idea that the Taltson magmatic zone is a 1.99–1.96 Ga subduction-related magmatic arc emplaced into older rocks of the Taltson basement complex (e.g., McDonough et al., 2000) and that this arc (and related basement substrate) extends into Saskatchewan south of the Athabasca Basin. An alternative interpretation suggests emplacement in an intracontinental

setting in the hinterland of a convergent plate margin (Chacko et al., 2000; De et al., 2000), requiring that the Slave and Rae cratons would have already been assembled by 2.00 Ga.

Hence, there exists considerable debate as to the timing of amalgamation of the Rae and its neighboring cratons. Given the uncertainty regarding the interpretation of the late Archean to early Paleoproterozoic tectonic evolution of the Rae, Hearne, and Slave cratons, including their configuration and nearest cratonic neighbors during this time, these regions require further study to fully understand the origin of the Snowbird tectonic zone and Taltson–Thelon orogenies (e.g., Pehrsson et al., 2013).

The relative paleogeographic positions of cratons and cratonic blocks during the earliest Paleoproterozoic Era (prior to the Trans-Hudson orogen) are difficult to constrain, owing, at least in part, to a paucity of reliable paleomagnetic

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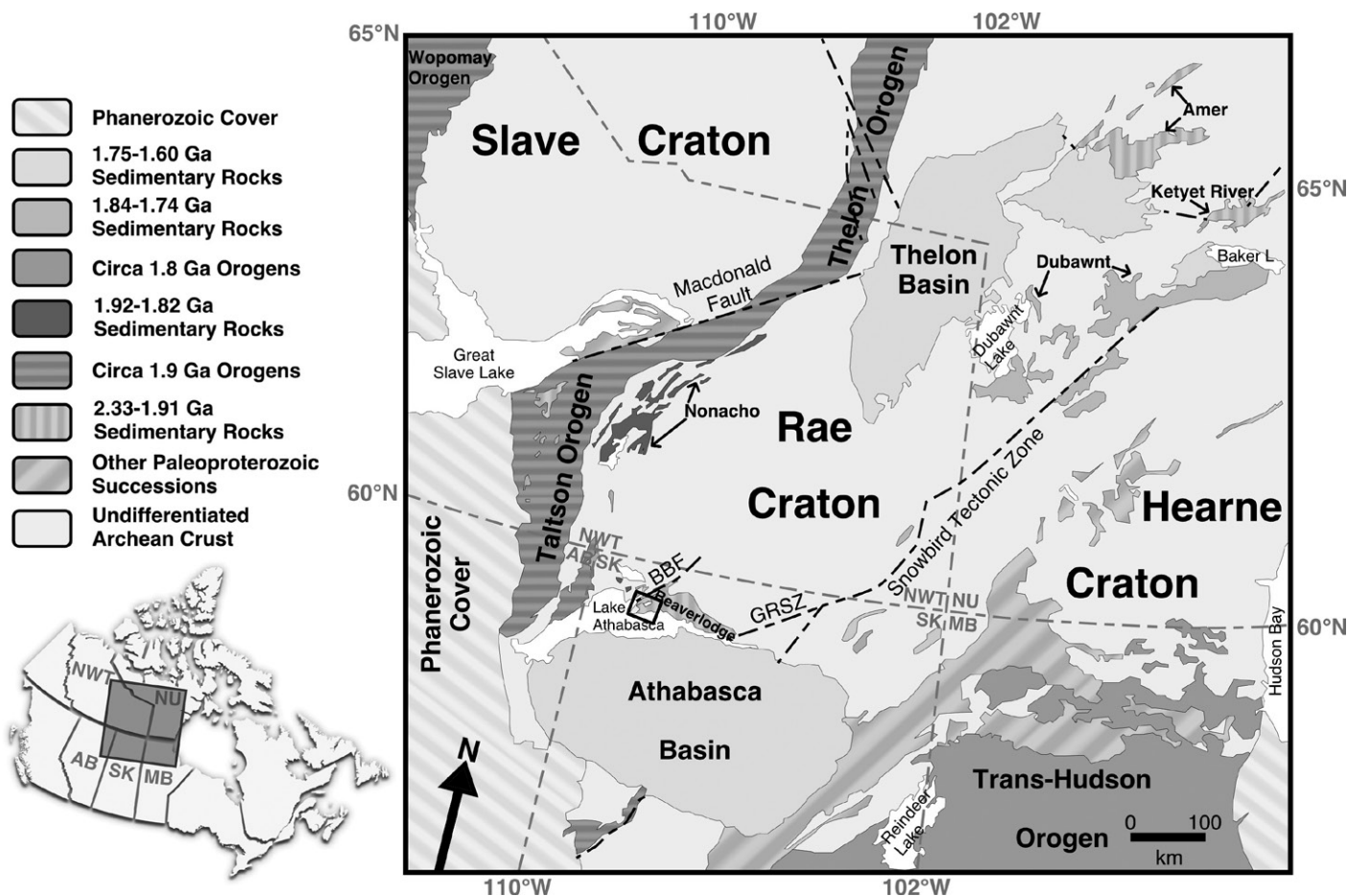


Figure 1. Currently exposed generalized geology of southern Rae and surrounding cratons in the Canadian Shield after Ashton et al. (2013). BBF—Black Bay fault, GRSZ—Grease River shear zone; black rectangle highlights study area. Canadian provinces are labeled in gray as follows: NWT—Northwest Territories, NU—Nunavut, AB—Alberta, SK—Saskatchewan, MB—Manitoba.

data. However, provenance studies of Proterozoic sedimentary basins provide an opportunity to constrain the position of surrounding cratons, if unique sediment sources can be identified. Post-depositional deformation and metamorphism of these sedimentary basins can obscure primary sedimentary structures, presenting an additional challenge, though provenance studies integrating geochronology and isotopic analysis of detrital zircon, stratigraphy, geochemistry, and structural and metamorphic data have been successful in identifying sediment provenance (e.g., Gehrels et al., 1990; Thomas et al., 2004; Weislogel et al., 2006; Horton et al., 2008; Collo et al., 2009). This approach requires robust data sets containing isotopic data from detrital zircon—common in siliciclastic sedimentary rocks—as well as a robust database of U-Pb crustal ages from a diverse suite of cratons with which to compare detrital zircon age spectra. We approach this provenance study by utilizing the DateView database, which consists of a global compilation of over 27,000 U-Pb zircon crystallization and metamorphic ages. The

database also contains more than 35,000 individual detrital zircon analyses. We present new U-Pb detrital zircon data from the Murmac Bay Group on the Rae craton and integrate this data set with available published U-Pb detrital zircon ages and compare the dominant age populations with crystallization ages recorded in DateView to discover potential sediment sources. Provenance analysis using detrital zircon geochronology can provide important insight into surrounding source terranes, and thus can be used to constrain the tectonic setting of sedimentary basins. This technique presents an opportunity, in particular, to study polydeformed or higher-metamorphic-grade sedimentary successions, since zircon is highly refractory and resistant to isotopic resetting (Corfu et al., 2003; Finch and Hanchar, 2003; Hoskin and Schaltegger, 2003).

Recent detrital zircon U-Pb geochronological data sets from Paleoproterozoic sedimentary successions on the Rae and Hearne cratons have highlighted important similarities and differences in their provenance. Approaches

combining geochronology with other available tools, such as radiogenic and tracer isotopic analysis, geochemical data, and stratigraphy, have been effectively applied in determining sedimentary provenance, correlating sedimentary basins, and inferring tectonic setting (e.g., Tran et al., 2008; Rainbird et al., 2010; Bethune et al., 2010, 2013; Ashton et al., 2013; Partin et al., 2014; Wodicka et al., 2014). In particular, Rainbird et al. (2010) present a compilation of stratigraphy and detrital zircon U-Pb geochronology, comparing Paleoproterozoic sedimentary successions on the Rae craton with the broadly coeval Hurwitz Group on the Hearne craton. The detrital zircon age spectra from these sedimentary successions reveal an important change in provenance in the upper stratigraphy, suggesting that the ca. 1.92–1.90 Ga units are correlative across the Rae–Hearne boundary, marking the oldest definitive trans-Churchill overlap succession (Rainbird et al., 2010). Previous tectonic models interpreted the relative positions of the Rae and Hearne cratons prior to the Trans-Hudson orogeny (ca.

1.90 Ga) differently (Hoffman, 1988; Hanmer et al., 1995a, 1995b; Berman et al., 2007; Corrigan et al., 2009; Regan et al., 2014), highlighting the need for robust and extensive data sets of geochronological and isotopic data to facilitate rigorous provenance and paleotectonic analysis.

Our study focuses on the Paleoproterozoic Murmac Bay Group, situated in the Beaverlodge domain of the southwestern Rae craton in northern Saskatchewan, Canada (Fig. 2). The Murmac Bay Group is ideally located for provenance and paleotectonic analysis because it is adjacent to the Taltson orogeny at the Rae-Slave boundary as well as to the Snowbird tectonic zone at the boundary between the Rae and Hearne cratons. We expand on traditional approaches to determining provenance by making use of a large database of geochronological data to include candidates from more distal sources, including neighboring cratons. We determined the provenance of the Murmac Bay Group by comparing the U-Pb age of crustal rocks from the Rae and neighboring cratons stored in the DateView database (Eglington et al., 2013). Using these data, we test the hypothesis that the Hearne,

Slave, or other nearby cratons could have provided sediment to the Murmac Bay paleobasin, thereby providing a constraint as to their relative cratonic configuration in the early Paleoproterozoic Era, prior to the formation of Laurentia (Hoffman, 1988).

GEOLOGICAL SETTING

The Murmac Bay Group is a key component of the Beaverlodge domain, one of several lithotectonic domains within the exposed portion of the southern Rae craton in the Athabasca region of Saskatchewan, Canada. The Beaverlodge domain is bounded by the Black Bay fault to the west, the Grease River shear zone to the east (Fig. 1), and the Oldman-Bulyea shear zone to the north. The best exposure of the Murmac Bay Group is its type locality in the vicinity of Uranium City, Saskatchewan (Fig. 2), where the metamorphic grade is lowest (greenschist to lower amphibolite facies). Thus, the Murmac Bay Group around Uranium City is the primary focus of this study. The <2.33 to >1.94 Ga Murmac Bay Group (Ashton et al., 2013)

broadly consists of a lower and upper succession unconformably deposited on Mesoarchean granitic basement. Previous mapping efforts (e.g., Hartlaub et al., 2004; Ashton et al., 2007, 2013) have provided a tectonostratigraphic framework, summarized next.

Lower Murmac Bay Group

In the vicinity of Uranium City, the lower Murmac Bay Group was deposited unconformably on the Mesoarchean granitic basement, represented by ca. 3.06–2.99 Ga granites (Persons, 1988; Hartlaub et al., 2004). The North Shore plutons, a ca. 2.33–2.29 Ga felsic plutonic suite, intrude the granitic basement and also underlie the lower Murmac Bay Group along the Cracklingstone Peninsula (Fig. 2). These plutons have been interpreted to be a product of syn- to post-collisional extension following the ca. 2.50–2.30 Ga Arrowsmith orogeny (Hartlaub et al., 2007; Ashton et al., 2009, 2013). In the Elliot Bay region (Fig. 2), the granitic basement is locally overlain by the basal polymictic conglomerate of the Murmac Bay Group, which, where

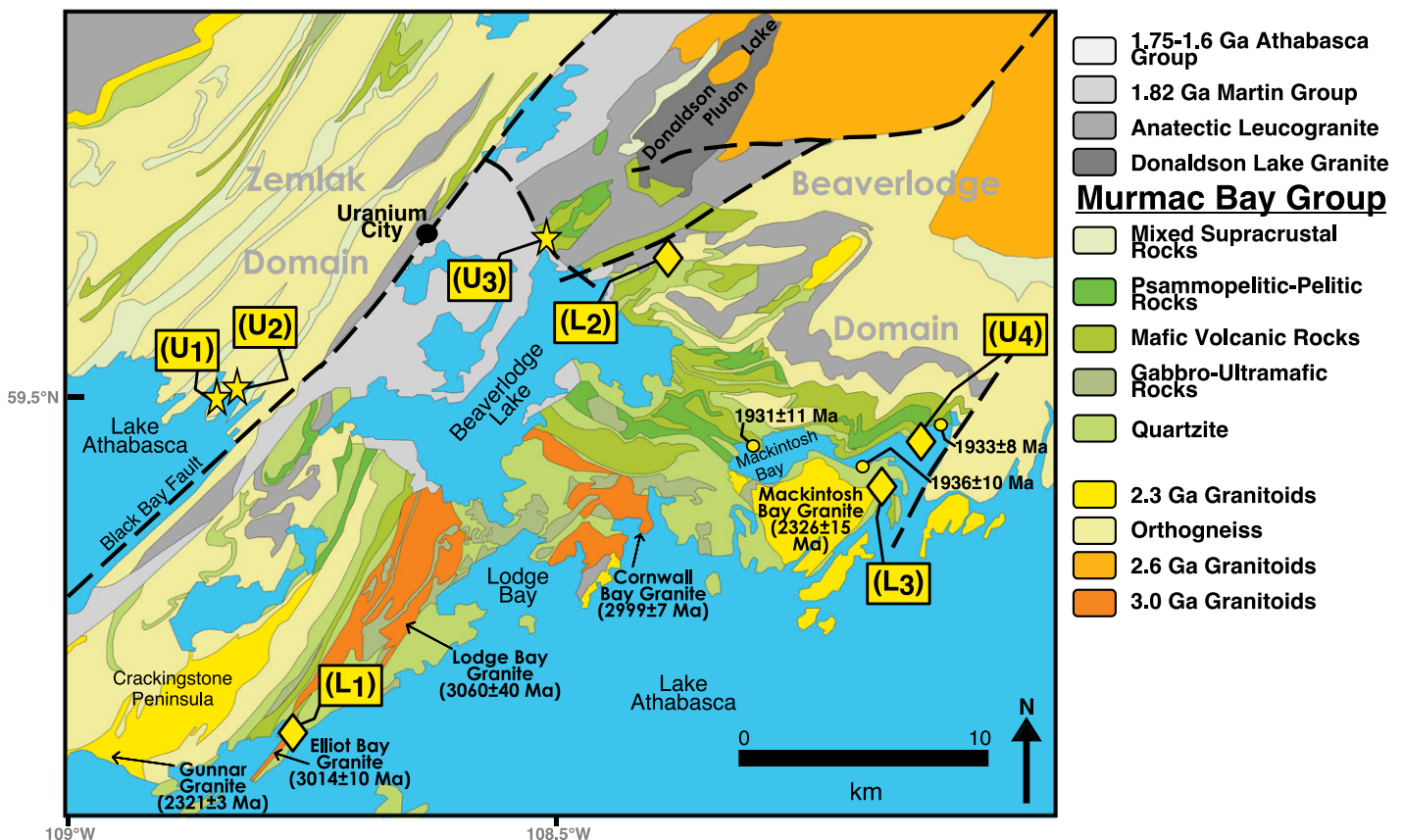


Figure 2. Sample locations in the Murmac Bay Group and simplified geology of the Uranium City, Saskatchewan area, after Ashton et al. (2013). Lithologic domains are labeled in gray. Diamonds are ages from previously published data (Hartlaub et al., 2006; Ashton et al., 2013), stars denote new samples collected for this study, and circles indicate metamorphic ages as indicated by monazite growth (Bethune et al., 2013).

present, grades into a mature gray quartzite that represents the basal unit for most of the Murmac Bay Group (Fig. 3; Hartlaub et al., 2004; Ashton et al., 2013). The quartzite is intercalated with metamorphosed psammite, oligomictic conglomerate, and dolostone, which is, in turn, interlayered with silicate and oxide facies iron formation toward the top of the unit (Hartlaub et al., 2004). Mafic volcanic rocks sit stratigraphically above the basal quartzite (Hartlaub et al., 2004; Ashton et al., 2013), representing the top of the lower Murmac Bay Group (Fig. 3). The lower Murmac Bay Group, and possibly the lowermost upper Murmac Bay Group, are intruded by ultramafic rocks and coarse-grained gabbro dikes and sills, the age of which has not been determined, but which have been interpreted as feeder dikes to Murmac Bay Group volcanism (Hartlaub et al., 2004).

Upper Murmac Bay Group

The upper Murmac Bay Group is composed of laterally extensive quartzofeldspathic pelitic to psammopelitic rocks that are locally migmatitic at higher metamorphic grades. At the base of the upper Murmac Bay Group, the pelitic to psammopelitic rocks are locally interlayered with lower Murmac Bay Group volcanic rocks

(Hartlaub et al., 2004). The lack of preserved sedimentary structures makes it difficult to determine the cause of this interlayering, which could be a result of deformation. It has been suggested that an intraformational unconformity exists, which separates the upper and lower units of the Murmac Bay Group (Ashton et al., 2013; Bethune et al., 2013).

Metamorphism and Deformation

The Murmac Bay Group has experienced at least two episodes of metamorphism, as indicated by monazite growth in deformation fabrics at ca. 1.93 Ga (Fig. 2) and at ca. 1.91 Ga (Bethune et al., 2013). The earliest metamorphism is attributed to the terminal collision of the Rae and Slave cratons, or alternatively, the collision between the already amalgamated Slave and Rae cratons with the Buffalo Head terrane during the ca. 1.99–1.93 Ga Thelon and Taltson orogenic events (Hoffman, 1988; Card et al., 2010, 2014). The younger ca. 1.91 Ga metamorphism is attributed to the development of the Snowbird tectonic zone during the Snowbird orogeny (Berman et al., 2007; Bethune et al., 2013).

Metamorphic grade in the Murmac Bay Group is lowest (greenschist facies) just east of the Black Bay fault, which marks the boundary between the Beaverlodge domain and the Zemplin domain to the west (Fig. 2), increasing eastward in grade to upper amphibolite and local granulite facies in the central Beaverlodge domain (Hartlaub et al., 2007; Ashton et al., 2009; Bethune et al., 2013). The Black Bay fault is a long-lived discontinuity interpreted to have experienced normal displacement, causing the eastern block to be downthrown (Ashton et al., 2009) prior to ca. 1.90 Ga (Bethune et al., 2013). Rocks of the upthrown west block are of higher metamorphic grade, some intensely ductilely deformed (Hartlaub et al., 2004). Immediately west of the Black Bay fault, exposed upper-amphibolite-facies paragneisses have been interpreted as belonging to the Murmac Bay Group based on lithological association (Ashton et al., 2013).

Age and Tectonic Setting of the Murmac Bay Group: Previous Work

The Murmac Bay Group was originally interpreted to be Archean (ca. 2.70 Ga) based on thermal ionization mass spectrometry (TIMS) U-Pb geochronology of detrital zircon from two samples of lower Murmac Bay Group rocks and two granites (ca. 2.60 Ga Donaldson Lake and Dead Man) interpreted to intrude the lower Murmac Bay Group (Hartlaub et al., 2004). Further study in this region resulted in the discovery of ca. 2.30 Ga volcanoclastic rocks in the lower

Murmac Bay Group, pointing to an early Paleoproterozoic maximum depositional age, rather than Archean (Hartlaub et al., 2006, 2007).

Further mapping and analytical work reevaluated previously reported intrusive relationships between plutons and the Murmac Bay Group; for instance, the migmatitic pelite intruded by the Dead Man granite has been reinterpreted to be part of a structurally deeper basement complex distinct from the Murmac Bay Group, based on ca. 2.34 Ga metamorphic monazite (Ashton et al., 2013; Bethune et al., 2013). Several samples included in previous studies from the Murmac Bay Group and the Donaldson Lake pluton (Hartlaub et al., 2004) were subsequently reanalyzed using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) techniques to obtain a more robust data set along with newly collected samples from the lower Murmac Bay Group and one from the upper Murmac Bay Group, and an intrusive quartz-feldspar porphyry dike (Hartlaub et al., 2006; Ashton et al., 2013). The Donaldson Lake granite intrudes the entire Murmac Bay Group, and analysis of zircon from this unit originally yielded a poorly constrained crystallization age of 2634 ± 55 Ma (TIMS) from four of five moderately discordant (5%–7%) analyses (Hartlaub et al., 2004). Based on composition, style of emplacement, and reanalysis, Ashton et al. (2013) reinterpreted this unit as a crustal melt derived from regional metamorphism containing abundant inherited grains, with a U-Pb crystallization age of 1930 ± 19 Ma (LA-ICP-MS) based on two of three concordant analyses out of 12 total in this age range. Considering the constraints provided by metamorphic monazite (above) and the new age of the crosscutting Donaldson Lake granite, the deposition of the upper Murmac Bay Group must have ceased by ca. 1.93 Ga, thereby providing a minimum age constraint for the Murmac Bay Group. Conglomerates and arkoses of the ca. 1.82 Ga Martin Group unconformably overlie the Murmac Bay Group over much of the Beaverlodge domain (Hartlaub et al., 2004; Morelli et al., 2009).

A Paleoproterozoic maximum depositional age for the lower Murmac Bay Group was corroborated by a youngest detrital zircon (YDZ) of 2323 ± 2.3 Ma in the basal conglomerate unit (Ashton et al., 2013). The quartzite unit detrital zircon ages range from 3.95 to 3.40 Ga (Hartlaub et al., 2006), and detrital zircon grains from a metamorphosed psammite from within the quartzite unit range in age from 3.8 to 2.3 Ga, with the weighted mean of the four YDZ ages at 2329 ± 8.6 Ma (Fig. 4; Ashton et al., 2013).

A psammopelitic gneiss associated with minor quartzite from the southeastern Beaverlodge domain, near Fond-du-Lac, Saskatchewan,

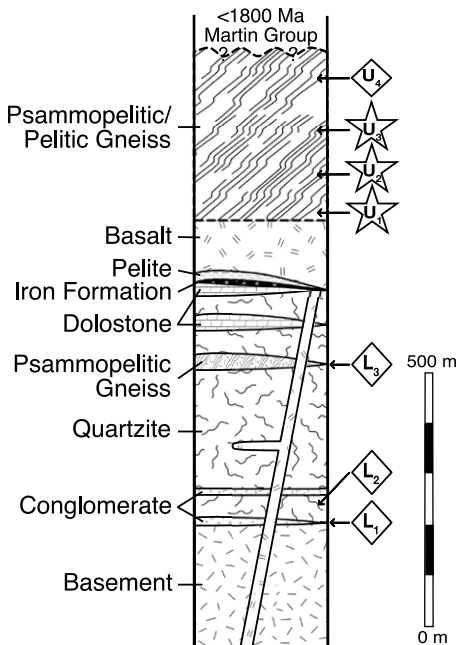
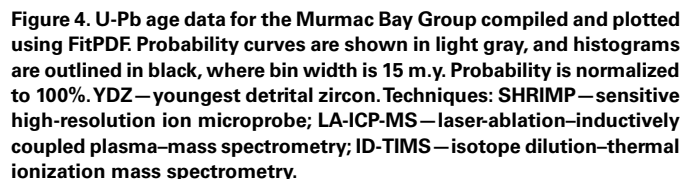


Figure 3. Simplified tectonostratigraphy of the Murmac Bay Group modified from Ashton et al. (2013) showing relative stratigraphic positions of samples. Stratigraphic order in the upper Murmac Bay Group (U_1 through U_4) is inferred, because primary sedimentary structures have been largely erased by multiple episodes of deformation in the upper succession.



The basin tectonic setting of the Murmac Bay Group during the early and late stages of formation is still poorly defined, but it could represent a rift (lower Murmac Bay Group) to passive-margin succession (upper Murmac Bay Group), an intracratonic basin for the entire Murmac Bay Group, a foreland basin setting (upper Murmac Bay Group; Hartlaub et al., 2004; Bethune et al., 2013; Ashton et al., 2013), or a combination of these. Interbedding of the basal conglomerates and quartzites may be due to episodic faulting consistent with an extensional tectonic setting (Ashton et al., 2013), possibly in a rift or an intracratonic basin setting for the lower Murmac Bay Group (Hartlaub et al., 2004; Bethune et al., 2013). The rift basin interpretation is also supported by the presence of basal conglomerates and mafic volcanic rocks in the lower Murmac Bay Group, which suggest extension (Hartlaub et al., 2004). Evidence for the foreland interpretation includes metamorphism coincident with the Taltson orogen (Bethune et al., 2013). Thus, the upper Murmac Bay Group could have been deposited in a passive-margin, intracratonic, or

foreland basin setting according to previous hypotheses. Here, we test the foreland basin hypothesis for the upper Murmac Bay Group using provenance data. If the sediment sources can be confidently attributed to either the Slave craton or Buffalo Head–Chinchaga domain, this provides evidence in favor of deposition of the upper Murmac Bay Group in the foreland of the Taltson orogen, and collision of the respective craton.

METHODS

The upper Murmac Bay Group is dominantly composed of finer-grained lithologies (pelites to psammopelites) compared to the lower succession, making mineral separation and subsequent analysis of small zircon grains from these lithologies challenging. In order to further constrain the depositional age and to investigate the provenance of the upper Murmac Bay Group, detrital zircon grains were handpicked from the three samples collected for this study, a pelite from the type section of the upper Murmac Bay Group near Uranium City, and two psammopelitic samples from upper-amphibolite-grade rocks just west of the Black Bay fault (sample locations are shown in Figure 2 and Table 1) interpreted to belong to the upper Murmac Bay Group. New samples from the upper Murmac Bay Group in this study are: 14KA-095 (U_1), 14KA-098 (U_2), and 14CAP0911-5 (U_3). For simplicity, our new results and results from previously published detrital zircon data are referred to according to relative stratigraphic order (Figs. 3 and 4), with samples from the lower Murmac Bay Group (L_1 , L_2 , L_3) below those from the upper Murmac Bay Group (U_1 , U_2 , U_3 , U_4).

To decrease bias, grains were picked to include a representative sample with respect to grain size, color, and morphology. Zircon grains were mounted at the Canadian Centre for Isotopic Microanalysis, University of Alberta, in a 25 mm epoxy mount along with zircon standards (Temora2 and MudTank) for U-Pb calibration, and polished using diamond grits to expose the midsections of the crystals. In order to characterize internal zircon structures (e.g., zoning) and alteration, imaging was carried out using a Zeiss EVO MA15 scanning electron microscope equipped with a high-sensitivity, broadband cathodoluminescence (CL) detector and a backscattered electron (BSE) detector. These images revealed that most zircon grains in this study exhibited zoning in the centers of the grains characteristic of igneous growth, as well as numerous fractures and common inclusions. The majority of grains also had unzoned overgrowth rims that appeared dark under CL imaging, while several grains also showed signs of recrystallization, some zoned and some unzoned (see Fig. DR1 in the Data Repository item¹ for zircon images).

U and Pb isotope ratios were determined at the Geological Survey of Canada in Ottawa using an O_2 -primary beam on the sensitive high-resolution ion microprobe (SHRIMP) following the procedures of Stern (1997) (Table DR1).

¹GSA Data Repository Item 2016268, Figure DR1 (backscattered electron and cathodoluminescence images of select detrital zircon grains), Figure DR2 (plot of grain age vs. depositional age annotated with Th/U ratios), Figure DR3 (rock sample photos), and Table DR1 (detrital zircon U-Pb geochronological results), is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

Imaging guided selection of the target areas for analyses, dominantly within the centers of the grains, unless otherwise noted in Table DR1. Grains were targeted to avoid fractures and inclusions, where possible. In order to obtain the igneous crystallization age of zircon grains, target spots were chosen in the interior of grains where igneous growth zoning could be identified in BSE and CL images. Most grains in this study exhibited this characteristic growth zoning in their centers, and care was taken to avoid any areas of grains where this growth-zoning pattern appeared mottled, recrystallized, or otherwise altered. Full U-Pb analysis results are included in Table DR1.

The crystallization age data used for comparison in this study were compiled from relevant literature into the DateView (Eglington, 2004) and StratDB databases (Eglington et al., 2013). DateView contains more than 100,000 published and public-domain isotope geochemical records, which are tied to lithostratigraphy, metamorphism, tectonism, ore deposits, large igneous provinces, and full references in StratDB (Eglington et al., 2013). We added records for published zircon U-Pb geochronology on the Murmac Bay Group (Table 1), as well as igneous and metasedimentary rocks on the southern Rae and proximal cratons from zircon, including U-Pb geochronological data obtained by TIMS, LA-ICP-MS, and SHRIMP methods (Hartlaub et al., 2004, 2006; Tran et al., 2008; Rainbird et al., 2010; Ashton et al., 2013; Mumford, 2013), to provide a comprehensive data set from which to explore potential provenance locations.

Probability density function curves and histograms were calculated using FitPDF software (Eglington, 2013), screening data for $\pm 10\%$

TABLE 1. DETRITAL ZIRCON GEOCHRONOLOGY DATA FOR THE MURMAC BAY GROUP

Sample ID	Field sample ID	Rock type	Sample locations		Age range (Ga)	Primary age peak (Ga)	Secondary age peaks (Ga)	YDZ§ (Ga)	Technique#	Reference
			Latitude (°N)	Longitude (°W)						
U4	4707-0210	Pelite	59.4841	108.2695	3.14–1.90	2.17	2.60, 2.13	2.17	SHRIMP	Ashton et al. (2013)
U3	14CAP0911-5	Metapelite	59.5634	108.5276	3.05–1.99	2.17	2.33, 2.10	1.99	SHRIMP	This paper
U2	14KA-098	Psammopelitic gneiss	59.5132	108.7520	2.41–1.85	2.33	2.09	2.00	SHRIMP	This paper
U1	14KA-095	Psammopelitic gneiss	59.5044	108.7695	2.54–1.91	2.33	2.12, 2.08, 1.94	2.01	SHRIMP	This paper
L3	RH98-46	Psammopelitic gneiss	59.4668	108.2929	3.80–2.33	3.60	3.05, 2.72, 2.33	2.33	LA-ICP-MS	Ashton et al. (2013)
L2	4700-6106	Quartzite	59.5561	108.4400	3.95–3.41	3.75	3.86, 3.71	3.41	LA-ICP-MS	Hartlaub et al. (2006)
L1	4701-0765	Conglomerate	59.3876	108.7233	2.33	2.33	N.A. [†]	2.32	TIMS	Ashton et al. (2013)

Note: In our study, we assessed the youngest detrital zircon (YDZ) to reflect the zircon grains with the youngest age that did not show textural evidence of alteration. Younger ages were obtained in our analysis, but they do not provide a robust indication of maximum depositional age. The YDZ from literature data is cited from the source. Full U-Pb data for samples collected for this study are provided in Table DR1 (Data Repository).

^{*}Sample locations provided in WGS84.

[†]N.A.—not applicable.

[§]YDZ—youngest detrital zircon.

[#]Techniques: SHRIMP—sensitive high-resolution ion microprobe; LA-ICP-MS—laser-ablation—inductively coupled plasma—mass spectrometry; TIMS—thermal ionization mass spectrometry.

discordance; maximum probabilities were normalized to 100% for ease in comparison of data sets (Fig. 4). Primary and secondary age modes were identified qualitatively from peaks in the probability density function, and a list of potential source candidates with isotopic ages matching these peaks was compiled using StratDB. These potential candidates were also filtered to include only those records with $\pm 10\%$ discordance, and which were interpreted to be either igneous crystallization or inherited ages in their publication. In total, 2556 records matched these criteria within Canada, the ages of which were spatially referenced using ArcMap to determine their geographic relationships to the source locations (Figs. 5–7). Provenance candidates matching the most dominant detrital zircon age populations were then further investigated to determine their suitability as sources for upper Murmac Bay Group sediments.

RESULTS

Sample Descriptions

Sample 14KA-095 (U_1)

The two samples collected just west of the Black Bay fault for this study (14KA-095, U_1 and 14KA-098, U_2) are upper-amphibolite-facies paragneisses attributed to the upper Murmac Bay Group based on their lithological association (quartzite-mafic volcanic-psammopelitic gneiss; Ashton et al., 2013). Since these samples were obtained from the upthrown west block of the Black Bay fault, they are likely from a lower stratigraphic level than the sample collected east of the fault (14CAP0911-5, U_3), though precise stratigraphic relationships are difficult to determine in the upper succession due a lack of preserved sedimentary structures. Sample 14KA-095 (U_1) is an upper-amphibolite-facies,

gray-brown, quartzofeldspathic, psammopelitic gneiss with anastomosing penetrative foliation. It contains 30–40% quartz (up to 1 cm), ~25% feldspar (up to 1.5 cm), 15–20% biotite, ~10% muscovite, ~10% chlorite after biotite, and minor titanite, zircon, and sulfides. Sixty-seven analyses were performed on a total of 65 grains from this sample. Detrital zircon grains in this sample are euhedral to subhedral, and cloudy to translucent brown, with an average length of 190 μm and an average length-to-width ratio of 1.9. Grain morphology ranges from rounded to equant to elongate, and most nonrounded grains are doubly terminated. Analyses were targeted to avoid fractures and inclusions present in most grains. The centers of these grains typically (88%) showed oscillatory growth zoning, though in about half of the grains, this zoning was altered or convoluted. One zircon grain analyzed had a featureless interior in images.

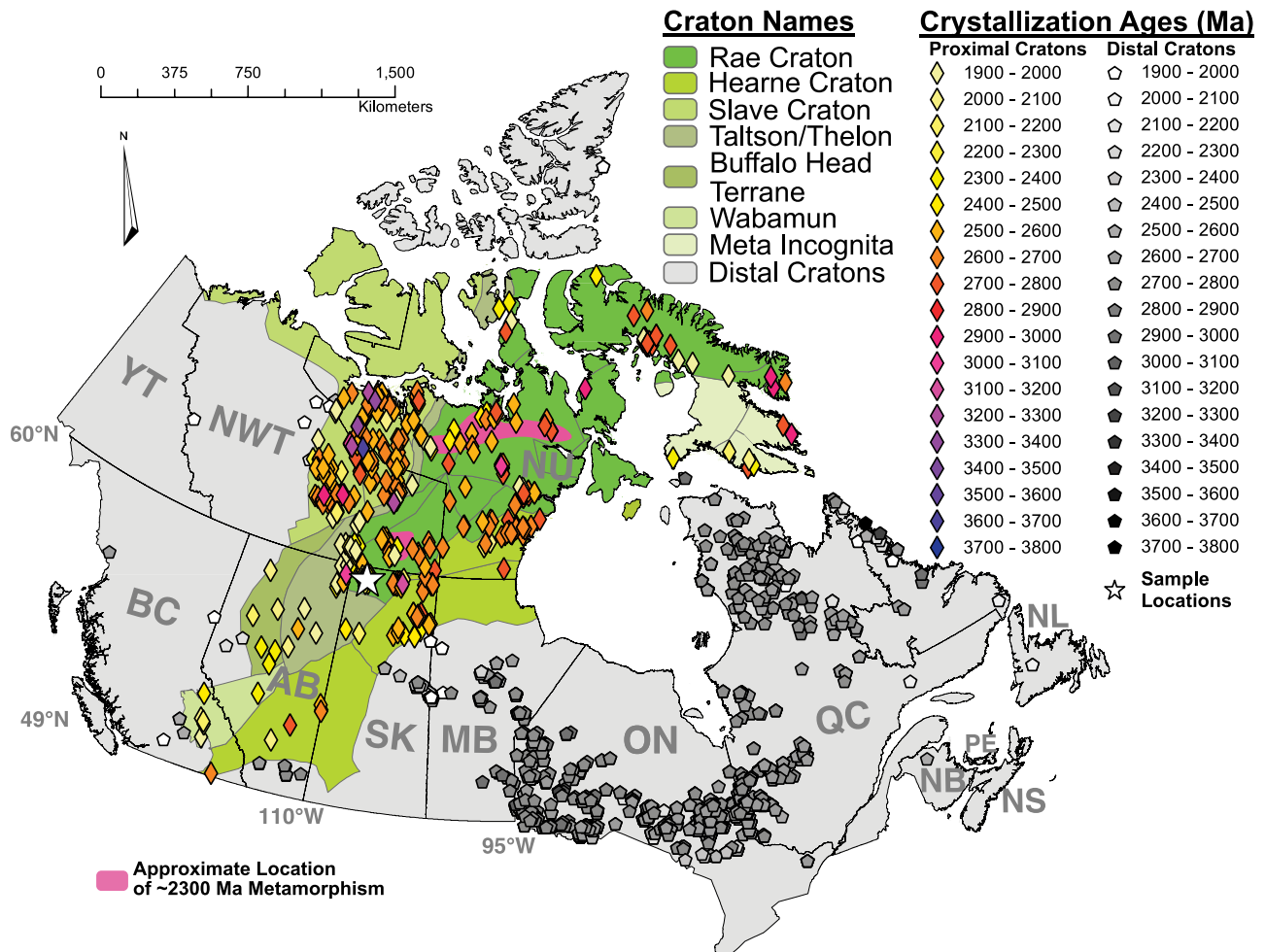


Figure 5. Potential provenance locations for Murmac Bay Group detrital zircon age peaks within Canada derived from the DateView database. Candidate source locations on proximal cratons are shown in color, and distal cratons are in gray scale. Canadian provinces are labeled in gray as follows: NWT—Northwest Territories, NU—Nunavut, AB—Alberta, SK—Saskatchewan, MB—Manitoba, BC—British Columbia, YT—Yukon, ON—Ontario, QC—Quebec, NB—New Brunswick, PE—Prince Edward Island, NS—Nova Scotia, NL—Newfoundland.

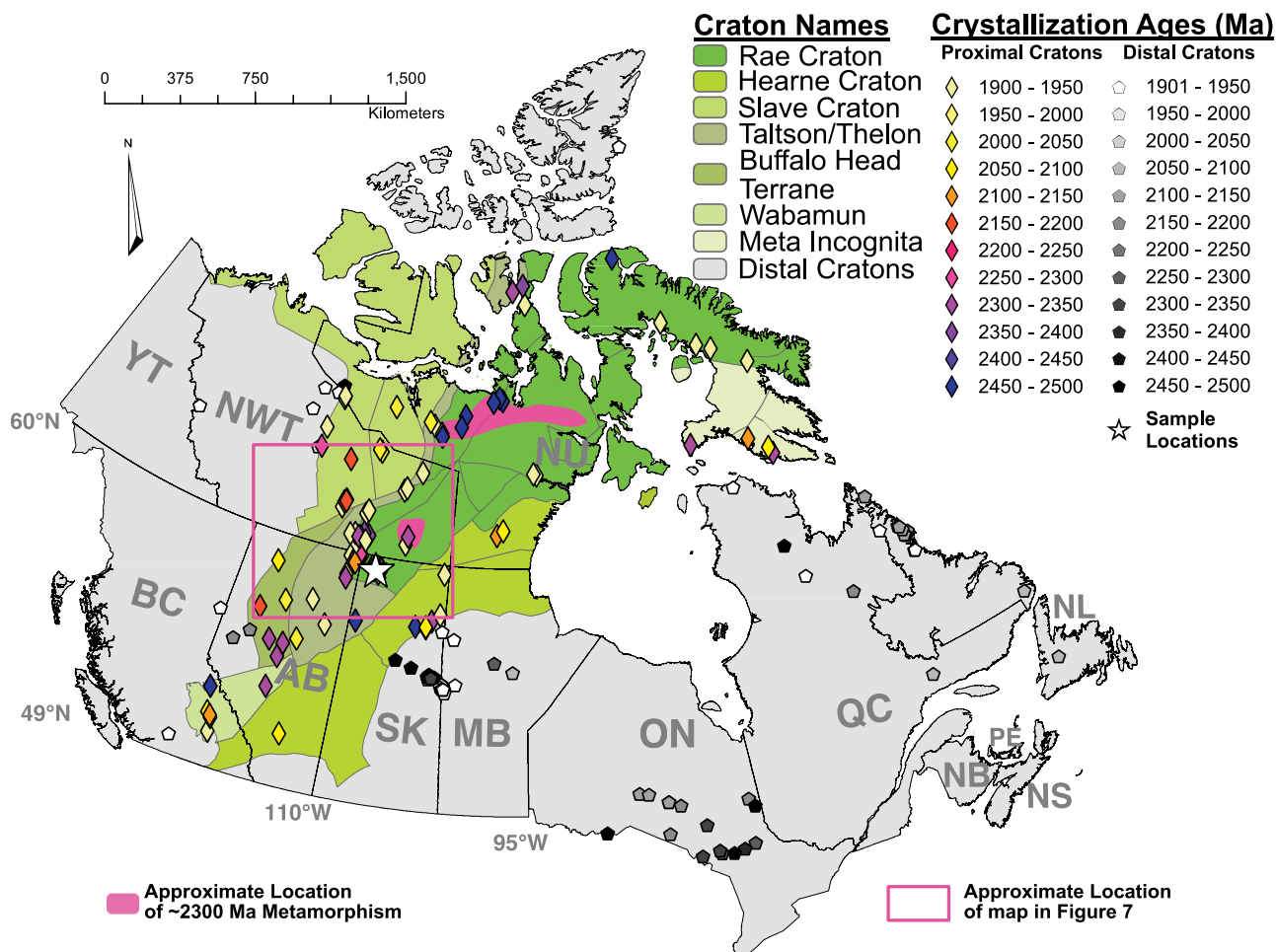


Figure 6. Potential provenance locations for Murmac Bay Group detrital zircon age peaks of Paleoproterozoic age derived from the DateView database. Inset box shows approximate location of map in Figure 7. Canadian provinces are labeled in gray as follows: NWT—Northwest Territories, NU—Nunavut, AB—Alberta, SK—Saskatchewan, MB—Manitoba, BC—British Columbia, YT—Yukon, ON—Ontario, QC—Quebec, NB—New Brunswick, PE—Prince Edward Island, NS—Nova Scotia, NL—Newfoundland.

Dark CL overgrowths were present in all zircon grains in this sample, averaging 35 μm in thickness (Fig. DR1). Two analysis spots were targeted in metamorphic domains where they were large enough to accommodate the spot size: one on an overgrowth rim that was dark in CL images (s3177–067.2), and one on an interpreted recrystallized zone that embayed a zone exhibiting igneous growth zoning (s3177–071.1). The Th/U ratio ranges from 0.004 to 1.05, and all grains in this sample with Th/U ≤ 0.47 exhibit evidence of alteration of original igneous growth zoning (e.g., mottling) in CL images. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages in sample U₁ range from 2.54 to 1.91 Ga. The largest population ($n = 17$) of zircon ages is centered on 2.31 Ga, with minor populations at 2.12 Ga ($n = 13$), 2.08 Ga ($n = 10$), and 1.93 Ga ($n = 9$; Fig. 4). The youngest grain that does not exhibit evidence of alteration of igneous zoning in images in this sample is 2005 ± 18 Ma (S3177–001.1, 4.8%

discordance, Th/U = 0.52) and thus is interpreted as the YDZ in this sample. This grain is prismatic in shape with a metamorphic overgrowth around the rim too narrow for analysis; thus, the analysis was targeted in the interior of the grain in an igneous domain exhibiting both sector and igneous growth zoning. Only two grains in this sample yielded ages ≥ 2.50 Ga (Fig. 4). The analyses collected from metamorphic overgrowth of two grains yielded $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1917 ± 15 Ma (s3177–067.2) and 1931 ± 11 Ma (s3177–071.1) and Th/U values of 0.06 and 0.01, respectively, corresponding to the timing of known metamorphic events in this region (Bethune et al., 2013).

Sample 14KA-098 (U₂)

This sample, from the west of the Black Bay fault (Fig. 2), is similar in appearance and character to sample 14KA-095 (U₁), but it is coarser grained. It consists of ~40% quartz, ~20%

feldspar, ~20% biotite, and ~10% muscovite, with minor cordierite, garnet, sillimanite, apatite, and zircon. In total, 64 analyses were performed on 60 detrital zircon grains taken from sample 14KA-098 (U₂). Grains in this sample are mainly transparent to cloudy to translucent brown, with an average length of 170 μm , and an average length-to-width ratio of 1.6; grain morphology is also similar to that seen in sample U₁. Most grains (79%) showed oscillatory growth zoning at their centers; two-thirds of the grains showed evidence of alteration fronts extending into their centers. All zircon grains in this sample also showed overgrowth rims that appeared dark under CL, with an average thickness of 32 μm (Fig. DR1). One grain in this sample had a metamorphic zone that was thick enough to accommodate the U-Pb spot, which was thus targeted for analysis, in a featureless, recrystallized outer rim (S3178–068.1). The Th/U ratio in this sample ranged from 0.17 to 0.89, and all grains with

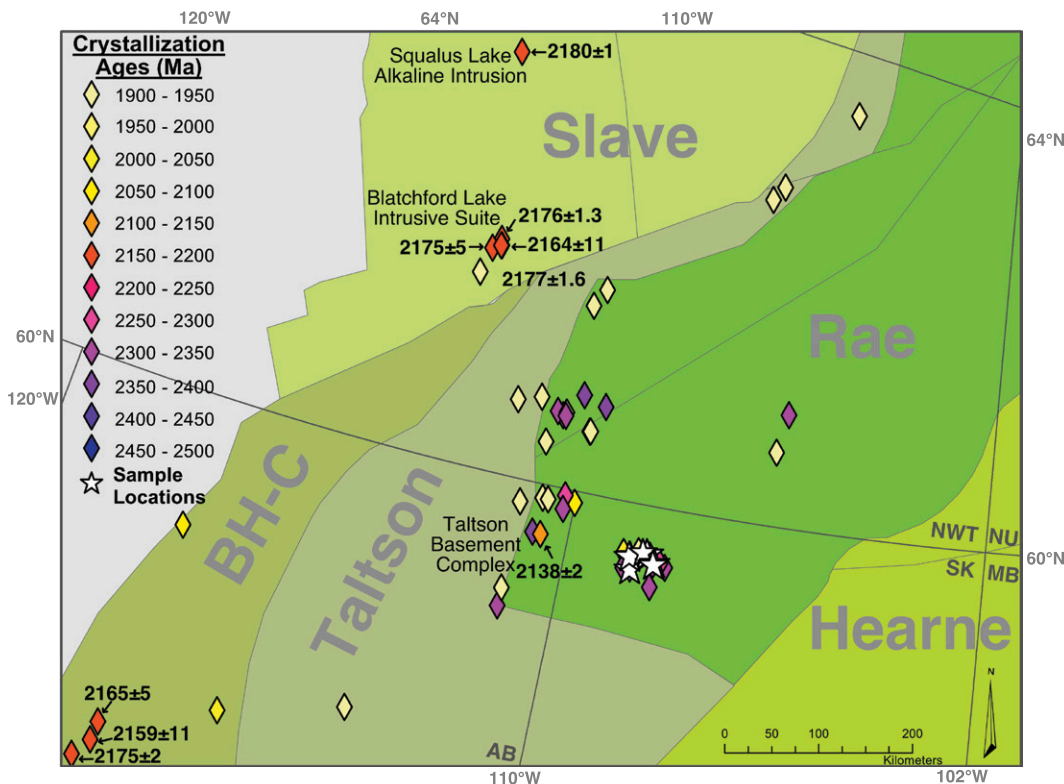


Figure 7. Close-up view of study area showing potential provenance locations proximal to study area. Candidate sources for the dominant ca. 2.17 Ga detrital zircon age population are annotated with their interpreted crystallization ages. Reference data for these ages appears in Table 2. Potential source for ca. 2.14 Ga age population is annotated in the Taltson basement complex (McNicoll et al., 2000). BH-C—Buffalo Head–Chinchaga domain. Canadian provinces are labeled in gray as follows: NWT—Northwest Territories, NU—Nunavut, AB—Alberta, MB—Manitoba, SK—Saskatchewan.

Th/U ≤ 0.40 showed evidence of alteration of the igneous growth zoning in CL images. The range of $^{207}\text{Pb}/^{206}\text{Pb}$ ages in this sample is from 2.41 to 1.85 Ga, with the dominant population ($n = 25$) of detrital zircon ages centered around 2.31 Ga. Secondary populations can be seen at 2.26 Ga ($n = 7$), 2.17 Ga ($n = 6$), and 2.07 Ga ($n = 9$), and there are no Archean zircon grains in this sample (Fig. 4). The YDZ that does not show any evidence of alteration of igneous zoning or recrystallization in this sample is dated at 2056 ± 14 Ma (S3178–121.1), a prismatic grain that shows evidence of alteration around the rim, but was targeted for analysis in an interior domain that showed characteristic igneous growth zoning in BSE and CL images. The analysis performed on the recrystallized rim yielded an age of 1999 ± 9 Ma (S3178–068.1), with Th/U of 0.20 (Fig. 4). Because the age of this metamorphic rim is older than the interpreted crystallization age of the Donaldson Lake pluton, which intrudes the Murmac Bay Group (ca. 1.93 Ga; Ashton et al., 2013), this metamorphism may have occurred prior to transportation and deposition of this grain, making this the youngest detrital age from sample U₂.

Sample 14CAP0911–5 (U₃)

A greenschist-facies pelitic schist was collected from the upper Murmac Bay Group in the vicinity of Uranium City (Fig. 2). This sample

is very fine-grained with planar foliation, ~50% micas (biotite and chlorite), 20%–25% quartz, and ~5% rutile and feldspar, with minor chlorite, quartz, and carbonate occurring as either veins or along cleavage planes. This sample did not yield abundant detrital zircon grains; in total, 40 grains were selected for U–Pb analysis. The zircon grains in this sample are cloudy to medium translucent brown, with an average length of 85 μm , and average length-to-width aspect ratio of 1.5. The zircon grains in this sample are mostly equant to rounded, and several of these grains are broken fragments. Analysis spots were chosen to avoid fractures within the grains, most (90%) of which exhibited oscillatory growth zoning, though a few grains were clear and featureless. The majority (75%) of grains in this sample also had thin (≤ 15 μm) overgrowth rims, which were dark in CL images (Fig. DR1). The Th/U ratio ranged from 0.07 to 1.01, with the lowest values (≤ 0.36) occurring on grains that exhibited evidence of alteration in CL images. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages for this sample range from 3.05 to 1.99 Ga. Most analyses plot between 2.33 and 2.00 Ga, with the highest population ($n = 7$) plotting at 2.17 Ga and secondary populations at 2.33 Ga ($n = 5$) and 2.10 Ga ($n = 4$; Fig. 4). The YDZ in sample U₃ is 1989 ± 29 Ma (S3179–046.1, $\sim 2\%$ discordance, Th/U = 0.48), for a small broken grain with apparent igneous growth zoning (Fig. 4). The next youngest grain

(with a smaller error) is 2014 ± 11 Ma. The probability density plot shows that most of the analyzed grains have Paleoproterozoic crystallization ages, whereas only five grains exhibit Archean crystallization ages (Fig. 4).

Detrital Zircon Age Probability Density Plots and Histograms

Zircon U–Pb age data are displayed in probability density plots and histograms keyed to stratigraphic position, where known, in Figure 4. Ashton et al. (2013) reported the age of the YDZ grain in the lower succession as 2329 ± 8.6 Ma, from the psammopelitic gneiss (L₃) sample near the stratigraphic top of the lower Murmac Bay Group; this, together with zircon analyses from the basal conglomerate (L₁) defining a single peak ca. 2.30 Ga, establishes a maximum depositional age for the lower Murmac Bay Group ca. 2.30 Ga, while the quartzite (L₂) contains only Archean ($>3412 \pm 11$ Ma) grains (Hartlaub et al., 2006). The psammopelitic gneiss (L₃) also contains zircon grains with both late Archean and early Paleoproterozoic ages, implying that the sediments comprising L₃ had a more diverse provenance than that of the quartzite (Ashton et al., 2013). Both L₂ and L₃ have dominant zircon populations with ages between 3.90 and 3.60 Ga. Overall, the lower Murmac Bay Group (L₁, L₂, L₃) contains a greater abundance of Archean

grains than samples from the upper Murmac Bay Group.

In contrast, the upper Murmac Bay Group samples exhibit a paucity of Archean zircon grains, reinforcing the idea of a shift in sediment source between deposition of the lower and upper Murmac Bay Group. The samples (U_3 and U_4) collected east of the Black Bay fault (Fig. 2) contain minor amounts of Neoproterozoic grains, the latter (U_4 ; Ashton et al., 2013) with a secondary peak near 2.60 Ga. In both of these samples, the dominant population is ca. 2.17 Ga. The two gneissic samples (U_1 and U_2) collected for this study from the west side of the Black Bay fault (Fig. 2) have dominant populations centered around 2.30 Ga and secondary peaks around 2.10 Ga. These samples both contain a similar range of zircon ages (2540–1850 Ma).

DISCUSSION

Assessing Metamorphic versus Igneous Origin of Zircon Grains

Care was taken to interpret the YDZ in each sample by choosing grains that did not show significant alteration textures or that might indicate metamorphic zircon growth by Th/U ratios. The Th/U ratio reflects the crystallization environment of the zircon, with Th/U > 0.2 indicating crystallization from a melt and Th/U < 0.07 associated with metamorphic zircon (Hoskin and Schaltegger, 2003; Rubatto, 2002). Th/U ratios similar to or greater than magmatic values have been recorded, however, in metamorphic zircon (Möller et al., 2003; Timms et al., 2006). Möller et al. (2003) suggested that low Th/U may be an indicator of metamorphic zircon growth only in a system where other phases such as monazite and allanite compete for Th. The Th/U ratio may also be affected during metamorphism by a grain boundary fluid phase with a high Th/U value, or an enrichment in Th relative to U in response to deformation due to differential element mobility (Timms et al., 2006). Thus, Th/U may not always be in itself a robust indicator of metamorphic zircon growth and must be combined with observations from imaging as well. Only four zircon analyses in our study yielded Th/U ratios less than 0.07, two of which were obtained from rims in sample U_1 (Fig. DR2).

Visual analysis was an important factor in distinguishing whether the targeted analysis spots came from metamorphic or igneous sectors of the zircon grains. Zircon grains picked for this study exhibited a pitted surface texture characteristic of detrital zircon. Most zircon grains in the three samples had overgrowth rims that were very dark in CL images; one such rim

was wide enough to accommodate the beam size and was targeted for analysis to investigate the timing of this overgrowth, yielding an age of 1917 ± 15 Ma (Th/U = 0.06). Another analysis targeted in an area that appeared to be recrystallized, where zircon of a different texture was “embayed” into the regular growth-zoned texture, was used to further investigate the timing of metamorphism, which yielded an age of 1931 ± 11 Ma (Th/U = 0.01). These correspond to the previously reported ages of metamorphic monazite growth in the Murmac Bay Group (Bethune et al., 2013). Considering that most zircon grains in this study, from many different ages, exhibit overgrowth rims, we interpret that these rims formed during postdepositional metamorphic events.

Age of the Upper Murmac Bay Group

U-Pb ages younger than ca. 2.00 Ga were obtained either from overgrowth rims, or from zircon grains that exhibited evidence of alteration of the original oscillatory growth banding in CL and/or BSE images, such as convoluted zones propagating through fractures (Corfu et al., 2003; Hoskin and Schaltegger, 2003), recrystallization, or metamorphism (Fig. DR1), which might have occurred prior to transport and deposition, or may represent mixed ages. The interpreted YDZ grains in our samples were dated at 2005 ± 18 Ma (U_1), 1999 ± 9 Ma (U_2), and 1989 ± 29 Ma (U_3), giving a weighted mean of 1999 ± 13 Ma. The dominant population in zircon aged younger than this is centered around 1.93 Ga, which corresponds to the aforementioned ca. 1.93 Ga crosscutting Donaldson Lake pluton and ca. 1.93 to ca. 1.91 Ga metamorphic monazite ages (Bethune et al., 2013). Although a single ca. 1.97 Ga grain is not within error of known metamorphic events or our YDZ age, a second spot in the same domain of this grain yielded a younger age of ca. 1.91 Ga, suggesting the U-Pb age of this grain could represent a mixed age. We interpret zircon grains from our samples with ages ≤ 2.00 Ga as having been metamorphosed or otherwise altered after deposition. The three grains aged between 1.93 Ga and 1.98 Ga all are within error of either known metamorphism at ca. 1.93 Ga or our interpreted maximum depositional age. These, as well as other grains that exhibit alteration textures, might also have been affected by Pb loss, either before or after deposition, resulting in erroneously young ages. Therefore, we interpret the YDZ age in our samples to be 1999 ± 13 Ma (weighted mean), representing a new maximum depositional age constraint for the upper Murmac Bay Group in its type locality.

Identifying Potential Sources

Provenance candidates were determined by matching dominant age peaks in the Murmac Bay Group detrital zircon spectra to published igneous crystallization ages stored within the DateView database (Eglington, 2004; Eglington et al., 2013). The least common crystallization ages from the database that matched detrital zircon age peaks in our data were identified and investigated further as potentially unique sediment sources. This approach does present limitations in that only published isotope data were considered, and so any undated, undiscovered, eroded, or buried potential source rocks could not be assessed in our study. The Precambrian geologic record itself is inherently incomplete. Additionally, much of the Canadian Shield has only been mapped and dated at a reconnaissance level; however, as more data become available over time, this method will benefit from an increasingly robust data set.

Approximately 2800 spatially referenced potential source rocks were identified for zircon grains in these samples within the Canadian Shield (Fig. 5), as identified from igneous crystallization ages recorded in the DateView database; Rae and neighboring cratons are highlighted in green (Fig. 5). Potential sources for dominant populations of 3.90–3.60 Ga in the lower Murmac Bay Group samples L_2 and L_3 were found solely on the neighboring Slave craton, though there are a number of potential source locations for the 2.70–2.30 Ga populations from samples L_1 and L_3 proximal to the study area on the Rae craton, as well as on neighboring cratons.

To narrow the search for sources for the upper Murmac Bay Group, only Paleoproterozoic (2.50–1.90 Ga) potential source locations are plotted in Figure 6, and it can be seen that there are a great number of candidates for the dominant populations ca. 2.30 Ga in samples U_1 , U_2 , and U_3 . A close-up view of the study area highlights the lack of ca. 2.17 Ga source candidates for the dominant populations from samples U_3 and U_4 locally on the Rae craton (Fig. 7). Potential sources for this ca. 2.17 Ga age mode can be found, however, on the neighboring Slave and Buffalo Head cratons, the ages of which are identified in Figure 7.

Provenance of the Lower Murmac Bay Group

The maturity of the quartzite in the lower Murmac Bay Group indicates a long period of weathering, erosion, and transportation that could support an interpretation of far-traveled sediment sources. The only 3.90–3.60 Ga

provenance locations identified from this study are located in the Acasta Gneiss complex on the Slave craton (Fig. 5), though rocks of this age are globally quite rare. Ages for the Acasta Gneiss complex include tonalitic gneisses dated at 3611 ± 11 Ma (Bowring and Williams, 1999) and 3661 ± 47 Ma (Iizuka et al., 2007), corresponding to dominant age modes from samples L_2 and L_3 (Fig. 4). Also, a granitic and a quartz dioritic gneiss from the Acasta region were interpreted to have crystallized at 3941 ± 43 Ma and 3931 ± 34 Ma, both with overgrowths suggesting anatexis or a recrystallization event at 3689 ± 61 Ma and 3677 ± 49 Ma, respectively (Iizuka et al., 2007). Yamashita et al. (2000) examined a series of clastic sedimentary rocks proximal to the Acasta Gneiss complex with depositional ages ranging from ca. 3.13 Ga to ca. 2.58 Ga, and reported depleted mantle model ages (T_{DM}) ages between 3.70 and 2.90 Ga, including three zircon grains with U-Pb ages older than 3.40 Ga. The authors suggested that the disagreement between U-Pb and T_{DM} ages may be due to Pb-loss shifting the apparent U-Pb age younger than the actual crystallization, as the rocks described were interpreted to have undergone extensive crustal reworking and recycling. Although limited Eoarchean crustal preservation might be a contributing factor to the paucity of other identified sources for zircon grains of this age, the Acasta Gneiss complex is still permissible as a sediment source for the lower Murmac Bay Group, though other as-yet unidentified sources might exist.

Many potential source locations were identified for zircon in sample L_3 with a dominant age mode of 2.65–2.75 Ga, both proximally on the Rae craton (Ashton et al., 2013), and on the neighboring Hearne and Slave cratons (Fig. 5) as 2.70 Ga granite-greenstone belts. Rae craton potential sources include plutonic rocks in the Snowbird Lake region near the boundary between the Rae and Hearne cratons (Martel et al., 2008). The Thluicho Lake Group, a metasedimentary succession deposited <1.92–1.82 Ga in the neighboring Zemlak domain, also has a minor population of detrital zircon grains that fall within this age range and are interpreted to have been locally derived (Bethune et al., 2010). If the sediment transport was directed from the Acasta Gneiss complex to the Murmac Bay Group, there exist several potential sources for this age mode between these locations in the current craton configuration. Thus, ca. 2.70 Ga is not a unique age population from which to distinguish sediment source.

Likewise, the 2.30–2.38 Ga dominant populations seen in samples from both the upper and lower Murmac Bay Group are centered around ca. 2.33 Ga and correspond to several

proximal potential source locations (e.g., North Shore plutons; Hartlaub et al., 2007), as well as more distal locations from the neighboring Taltson orogen, Buffalo Head–Chinchaga domain, and Slave craton (Fig. 6). Thus, the ca. 2.33 Ga age mode is also not a unique age mode for determining provenance via the methods of this study. The maturity of the quartzite in the lower Murmac Bay Group is consistent with a distal source for these sediments; hence, the proximal ca. 2.30 Ga plutonic rocks (Hartlaub et al., 2007) might not be the most likely source. However, ca. 2.50–2.30 Ga rocks of the Arrowsmith orogeny along the western and northern margins of the Rae craton (Berman et al., 2005, 2013) could permissibly be a source of detritus of this age recorded in the psammopelitic to pelitic rocks of the upper Murmac Bay Group (U_1 , U_2 , and U_3). Th/U ratios less than 0.1 were also found in a few grains aged 2.33–2.35 Ga (Fig. DR2) in the upper Murmac Bay Group samples, which can be attributed to Arrowsmith orogenesis. The neighboring Thluicho Lake Group also contains abundant detrital zircon of Arrowsmith age (2.47–2.25 Ga; Bethune et al., 2010).

While there is a dominant age population at ca. 2.33 Ga in both the upper and lower Murmac Bay Group, the upper Murmac Bay Group shows several dominant age populations that are younger than this. If ca. 2.33 Ga represents the maximum depositional age of the lower unit and ca. 2.17 Ga represents that of the upper unit (Ashton et al., 2013), then a hiatus of at least 160 m.y. between deposition of the upper and lower Murmac Bay Group is possible. Therefore, it is permissible that the boundary between the upper and lower Murmac Bay Group represents a significant unconformity, consistent

with previous work asserting this possibility (Ashton et al., 2013; Bethune et al., 2013). Our contribution widens this gap by another ~160 m.y., which would allow for up to an ~320 m.y. unconformity between the lower and upper Murmac Bay Group.

Provenance of the Upper Murmac Bay Group

The paucity of Archean grains in the upper Murmac Bay Group samples, along with the abundance of grains aged <2.33 Ga, is consistent with a shift in sediment source between deposition of the upper and lower successions. The hiatus between deposition of the upper and lower Murmac Bay Group could permissibly have been up to ~320 m.y. Only one sample (U_4) from the upper Murmac Bay Group has a dominant Archean population ca. 2.60 Ga. Detrital zircon grains from the nearby Thluicho Lake Group also exhibit dominant populations of this age, which were attributed to proximal widespread felsic plutonism in the Rae craton ca. 2.64–2.58 Ga (Skulski and Villeneuve, 1999; Bethune et al., 2010).

The 2.15–2.19 Ga dominant age modes present in samples U_3 and U_4 correspond to only a few potential sources identified on the Slave craton and Buffalo Head–Chinchaga domain (Table 2); therefore, it is an ideal detrital zircon age population with which to investigate provenance. Figure 7 highlights the potential sources for these zircon populations (centered around ca. 2.17 Ga), the most proximal being in the Blatchford Lake intrusive suite on the Slave craton, which intrudes the ca. 2.68 Ga Burwash Formation turbidites (Bleeker et al., 2004). Interpreted

TABLE 2. SUMMARY OF POTENTIAL PROVENANCE CANDIDATES FOR THE CA. 2.17 GA DOMINANT DETRITAL ZIRCON AGE POPULATION FROM THE UPPER MURMAC BAY GROUP

Sample ID	Crystallization age (Ma)	Technique	Description	Reference
Slave craton				
79-13	2175 ± 5	TIMS	Hearne Channel Granite–Blatchford Lake intrusive suite	Bowring et al. (1984)
90TL-16	2176 ± 1.3	TIMS	Grace Lake Granite–Blatchford Lake intrusive suite	Sinclair et al. (1994)
600A	2164 ± 11	LA-ICPMS	Nechalacho Layered Suite–Blatchford Lake intrusive suite	Mumford (2013)
1201A	2177 ± 1.6	TIMS	Thor Lake Syenite–Blatchford Lake intrusive suite	Mumford (2013)
VN-92-XX	2180 ± 1	TIMS	Squalus Lake alkaline intrusion	Villeneuve and van Breemen (1994)
Buffalo Head–Chinchaga domain				
Chevron Irving Cadotte	2165 ± 5	TIMS	Core from Buffalo Head terrane	Villeneuve et al. (1993)
Chevron et al Sheldon	2159 ± 11	TIMS	Core from Chinchaga low	Villeneuve et al. (1993)
Pan Am A-1 Bald Mt	2175 ± 2	TIMS	Core from Chinchaga low	Villeneuve et al. (1993)

Note: TIMS—thermal ionization mass spectrometry; LA-ICP-MS—laser-ablation–inductively coupled plasma–mass spectrometry.

crystallization ages for possible sources within the Blatchford Lake intrusive suite include: the Nechalacho layered suite at 2164 ± 11 Ma (LA-ICP-MS; Mumford, 2013), the Hearne Channel granite at 2175 ± 5 Ma (TIMS; Bowring et al., 1984), the Grace Lake granite at 2176 ± 1 Ma (TIMS; Sinclair et al., 1994), and the Thor Lake syenite at 2177 ± 2 Ma (TIMS; Mumford, 2013). A more distal potential source candidate on the Slave craton is the Squalus Lake alkaline intrusion to the north of the Blatchford Lake intrusive suite, with an interpreted crystallization age at 2180 ± 1 Ma (TIMS; Villeneuve and van Breemen, 1994). Three samples from core in the Buffalo Head–Chinchaga domain, which is currently buried beneath Phanerozoic cover, were interpreted to have crystallized at 2159 ± 11 Ma, 2165 ± 5 Ma, and 2175 ± 2 Ma (TIMS; Villeneuve et al., 1993), respectively.

The upper Murmac Bay Group samples also contain a large number of grains ranging in age from 2.00 to 2.14 Ga. The nearby 2.13–2.09 Ga Rutledge River metasedimentary succession (Taltson) contains a population of 2.17–2.13 Ga detrital zircon grains and records metamorphic zircon and monazite growth at ca. 2.09–2.06 Ga (Bostock and van Breemen, 1994). A few grains from this study exhibit Th/U ratios that may be indicative of metamorphic origin (<0.2) within the same age range as the Rutledge River metamorphic zircon (Fig. DR2). Gneisses in the subsurface from the Buffalo Head–Chinchaga domain also record crystallization ages between ca. 2.09 Ga to 2.07 Ga and 2.19 Ga to 2.16 Ga (Villeneuve et al., 1993). A syenogranite gneiss from the Taltson basement complex has been dated at ca. 2.14 Ga, though the majority of the metaplutonic gneisses in this complex have ages ca. 2.40–2.30 Ga (McNicoll et al., 2000). These potential sources from the Taltson basement complex lie geographically between the ca. 2.17 Ga provenance candidate locations and the Murmac Bay Group (Fig. 6). This suggests that sediment transport could have been directed from either the Slave craton or Buffalo Head domain during the time of deposition of the upper Murmac Bay Group.

Provenance Summary

The detrital zircon U–Pb age data from our samples highlight the lack of Archean grains in the upper Murmac Bay Group. As noted in Ashton et al. (2013), detrital zircon grains in the upper Murmac Bay Group are primarily younger than 2.33 Ga, whereas detrital zircon grains in the lower unit are all ≥ 2.32 Ga, which demonstrates a shift in sediment source between the upper and lower Murmac Bay Group. This shift could be the result of burial

or denudation of previous source rocks, exhumation of new sources associated with tectonic activity (Ashton et al., 2013), or evolution of drainage pathways. We consider the possibility of a potentially long-lived unconformity (Ashton et al., 2013; Bethune et al., 2013) to be plausible, based on the time gap indicated by our new age constraints. Since sediment was most likely sourced from the direction of the more proximal Blatchford Lake intrusive suite of the Slave craton, the ca. 2.30 Ga zircon grains were most reasonably sourced either locally, or from the Taltson basement complex. The depositional age constraints of the upper Murmac Bay Group (<2.00 Ga to >1.93 Ga) suggest a connection with the Taltson orogen. The likelihood of sediment sources from the Slave craton and/or Buffalo Head domain supports the hypothesis that the upper Murmac Bay Group was deposited in the foreland of the Taltson orogen.

CONCLUSIONS

New detrital zircon geochronological data from the upper Murmac Bay Group constrain the maximum depositional age of this succession at 1999 ± 13 Ma, which represents the weighted mean of the three youngest detrital zircon ages. By comparing our new data with previously published geochronological data for the Murmac Bay Group (Fig. 4; Table 1), we were able to assess the differences in age populations between the upper and lower units of the Murmac Bay Group. While the lower unit contains only early Paleoproterozoic and Archean detrital zircon grains (3.95–2.33 Ga), the upper unit is dominated by <2.33 Ga zircon grains and exhibits a distinct lack of zircon grains older than 2.33 Ga. Our findings reinforce the idea of a long-lived hiatus in deposition between the upper and lower Murmac Bay Group based on this difference in dominant age populations and disparity in inferred depositional ages, during which time there was a change in sediment source to the Murmac Bay Group basin (Ashton et al., 2013; Bethune et al., 2013). Additionally, U–Pb results of zircon overgrowth rims of 1931 ± 11 Ma and 1917 ± 15 Ma in our study agree with metamorphic monazite ages (Bethune et al., 2013).

The dominant age peaks in the lower Murmac Bay Group point to the Acasta Gneiss complex as a possible provenance location, as these are the only known exposed rocks within the database with crystallization ages matching the 3.90–3.60 Ga peaks seen in samples L_2 and L_3 . Provenance candidates matching younger peaks in lower Murmac Bay Group samples (2.70 Ga and 2.33 Ga) are located both locally, and geographically between the Acasta Gneiss complex

and the Murmac Bay Group, confirming it as a potential source for sediments in the lower Murmac Bay Group, though other as-yet undiscovered potential sources might exist.

The ca. 2.17 Ga dominant age population in the upper Murmac Bay Group samples has two possible provenance locations, the most proximal being the Blatchford Lake intrusive suite located on the Slave craton, and also from within the Buffalo Head–Chinchaga domain in Alberta, the latter of which is currently buried under Phanerozoic cover. Geographically between the Blatchford Lake intrusive suite and the Murmac Bay Group, there are several potential source rocks that could provide the source for the ca. 2.33 Ga dominant age peaks seen in the upper Murmac Bay Group, along with several proximal sources; however, there are fewer candidates for zircon aged between 2.00 and 2.14 Ga, dominantly ca. 2.13 Ga, which are located geographically between the Blatchford Lake intrusive suite and the Murmac Bay Group in the Taltson basement complex. We thus conclude that the most likely provenance source from currently known potential sources contained within the database for the ca. 2.17 Ga detrital zircon is the Blatchford Lake intrusive suite. Consequently, the ca. 2.33 Ga contributions to the Murmac Bay Group are likely to have been sourced locally or by the Taltson basement complex. Evidence from proximity, overlap in timing, and now provenance supports the interpretation that the upper Murmac Bay Group was deposited in the foreland of the Taltson orogenic belt.

The most probable identified sources of both the 3.90–3.60 Ga and 2.17 Ga detrital zircon grains are located on the Slave craton, indicating that the Slave and Rae cratons would have been proximal during the time of Murmac Bay Group deposition in order for the Slave craton to have contributed to Murmac Bay Group sediments. The youngest detrital zircon grains in the lower Murmac Bay Group place timing of initial deposition in the Murmac Bay basin after 2.33 Ga. Thus, the Rae and Slave cratons would have to have been proximal sometime after 2.33 Ga in order for the Slave craton to be a sediment source for the lower Murmac Bay Group sediments, if sediments in the lower unit indeed originated from the Acasta Gneiss complex. The two cratons would have remained in proximity during the deposition of the upper Murmac Bay Group. The upper Murmac Bay Group shows a distinct shift in sediment source, possibly due to new tectonic activity resulting from amalgamation of the Slave and Rae cratons, or from accretion of the Buffalo Head–Chinchaga domain to the already sutured Rae and Slave cratons (Card et al., 2014).

With our interpreted sediment transport into the Murmac Bay Group basin being directed from the present-day north and west, we see no unambiguous contribution from the Hearne craton in these Murmac Bay Group sediments, and thus are unable to determine its position relative to the Rae craton in this study.

Determination of sedimentary provenance in polydeformed terranes faces numerous challenges, particularly if primary sedimentary structures are altered or erased by deformation. Tracer isotopic analysis (e.g., Hf) can serve as a next step to further elucidate sediment provenance and tectonic setting. The methods presented in this paper are a first step in identifying potential sediment sources and highlight a practical application for integrating large geochronological databases into provenance analysis.

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