Cambrian detrital zircon signatures of the northern Canadian Cordilleran passive margin, Liard area, Canada: evidence of sediment recycling, non-Laurentian ultimate sources and basement denudation.
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ABSTRACT

Detrital zircon U-Pb age probability distributions for the Cambrian Vizer formation (informal) and Mount Roosevelt Formation (middle member) of the northern Canadian Cordilleran passive margin indicate extensive recycling from ~1.7 to 1.6 Ga Paleoproterozoic sandstones and Proterozoic and Lower Cambrian strata, respectively. The units have minor or no first cycle input from Laurentian basement. The lower part of the Vizer formation contains North American Magmatic Gap (1610 to 1490 Ma) detrital zircons and lacks ultimate Grenvillian sourced grains, indicating that the grains were likely sourced from a nearby Mesoproterozoic basin and have an ultimate non-Laurentian source. Detrital zircon U-Pb ages of 670 to 640 Ma from the middle member of the Mount Roosevelt Formation indicate associated volcanic clasts were locally sourced, and are not of syn-sedimentary Middle Cambrian age. Provenance of these units was indirectly impacted by the Liard Line basement feature.

Detrital zircon U-Pb age probability distributions from the northern Canadian Cordilleran passive margin indicate sediments were sourced from the east in the Early Cambrian (Terreneuvian; Vizer formation and correlatives) and the northeast during Early Cambrian
(Series 2) deposition of Sekwi Formation and correlative strata. In the early Middle Cambrian the middle member of the Mount Roosevelt Formation was primarily locally sourced, whereas the upper member was derived from Laurentian basement to the east and southeast. The change from reworked Paleoproterozoic cover in the Terrenuvian to primary basement sources in the Middle Cambrian suggests significant denudation of the basement occurred southeast of the Liard Line.

Keywords: detrital zircon, Cambrian, sediment recycling, non-Laurentian sources, Cordilleran passive margin
INTRODUCTION

The area now forming the western margin of Laurentia has had a protracted history of extension, sediment accumulation and shortening. Rifting events in the middle and late Neoproterozoic (Cryogenian, Ediacaran) established the margin (e.g. Stewart 1972; Arnott and Hein 1986; Ross et al. 1995) and resulted in the deposition of two prominent sedimentary successions: the Neoproterozoic Windermere Assemblage and the Ediacaran to Middle Devonian Cordilleran passive margin. Several northeast-trending, basement-controlled fault zones affected sedimentation within the Laurentian continental margin succession of the Canadian Cordillera. The most prominent occurs near 60° N at a feature termed the Liard Line, which has been interpreted as a Neoproterozoic and lower Paleozoic transfer fault zone separating a wide lower plate margin on the north from a narrow upper plate margin on the south (Fig. 1; Cecile et al. 1997). This paper describes the detrital zircon U-Pb age signatures of the pre-Silurian quartz arenite of the Vizer formation (informal) and Middle Cambrian volcanic clast-bearing conglomerates of the Mount Roosevelt formation exposed near the Liard Line and uses this information together with published detrital zircon age information from the various units described in the geological framework below to constrain their provenance and outline the major changes in detrital zircon source areas during the Early and Middle Cambrian. Our results indicate: 1) extensive recycling from the ~ 1.70 to 1.6 Ga Paleoproterozoic sedimentary blanket deposited over northern Laurentia and a complete absence of ultimate Grenville sourced grains in the Vizer formation and middle member of the Mount Roosevelt formation; 2) the component of North American magmatic gap (1610 to 1490 Ma) aged zircons found in the lower part of the
Vizer Formation were ultimately derived from non-Laurentian sources and most likely recycled from a nearby Mesoproterozoic basin; 3) the Vizer formation is most likely Lower Cambrian Terreneuvian in age; 4) the major change to first-cycle basement sources in the upper member of the Mount Roosevelt Formation likely reflects denudation of the Laurentian basement; and 6) stratigraphic changes associated with the Liard Line had an impact on the provenance of the Vizer and Mount Roosevelt formations.

GEOLOGICAL FRAMEWORK

The ancestral North American continent Laurentia, comprising Archean to Early Proterozoic microcontinents separated by collisional and magmatic orogenic belts, formed between 2.0 and 1.8 Ga (Hoffman 1989; Whitmeyer and Karlstrom 2007) as part of a larger continental amalgamation termed Columbia (Rogers and Santosh 2002). Between 1.7-1.68 Ga and 1.65-1.60 Ma juvenile orogens formed along the southeastern side of Laurentia (Whitmeyer and Karlstrom 2007) and thick skinned deformation of the Forward Orogeny occurred inboard of the northwest Laurentia margin prior to 1.663 Ga (Cook and MacLean 1995). Rifting along the northwestern margin of Laurentia around 1.65 Ga resulted in rapid deposition of the 13 km thick Wernecke Supergroup (Furlanetto et al. 2016) and most likely the 6 km thick Muskwa assemblage (Fig. 2). Detrital zircon studies record a predominant Laurentian provenance for both Wernecke (Furlanetto et al. 2009, 2016) and Muskwa (Ross et al. 2001) strata. Paleocurrent indicators and age constraints suggest they are the distal equivalents of a sandstone package derived from westward flowing river systems that blanketed at least the northern part of Laurentia in the late Paleoproterozoic. Eastern remnants of this package are now preserved in the Athabasca, Thelon, and Hornby Bay basins (Fig. 1; Young 1978; Ross et al. 2001; Rainbird et al. 2005). Similar
detrital zircon age distributions from the Athabasca and Muskwa basins support their correlation, whereas, detrital zircon age distributions from the Dubawnt Supergroup of the Thelon Basin are dissimilar and indicate a different provenance (Rainbird et al. 2005; Rainbird and Davies 2007).

Local intense deformation of the northwestern edge of Laurentia during the Racklan Orogeny occurred after deposition of the Wernecke Supergroup and before intrusion of the Wernecke breccia ca. 1595 Ma (Thorkelson et al. 2005; Furlanetto et al. 2013). By 1.5 Ga north Australia, south Australia and eastern Antartica were firmly attached to the western margin of Laurentia (Karlestrom et al. 2001; Thorkelson et al. 2005; Ross and Villeneuve 2003; Stewart et al. 2010; Furlanetto et al. 2013; Medig et al. 2014).

Extension along the western margin of Laurentia between about 1490 to 1400 Ma did not produce full continental separation. It is recorded in western Canada by the PR1 (basal Fifteen Mile Group, Medig et al. 2014) and Belt-Purcell basins (Fig. 1; Ross and Villeneuve 2003). Sometime after 1380 Ma, renewed subsidence of the northwestern margin of Laurentia initiated deposition of the Pinguicula Group (Medig et al. 2010) and the roughly correlative Dismal Lakes Group (Cook and MacLean, 1995). Extension along the northern margin of Laurentia resulted in intrusion of the Mackenzie dyke swarm (1267 ± 2 Ma, LeCheminant and Heaman 1989) and the extrusion of the Coppermine River basalts above the Dismal Lake Group. After a period of planation, predominantly platformal strata of the Mackenzie Mountains Supergroup and Shaler Group (Fig. 1) were deposited within an intracratonic basin developed along the northwest edge of Laurentia between about 1000 Ma and 775 to 720 Ma (Heaman et al. 1992; Rainbird et al. 1996; Milton 2015). Thick sandstones in the lower part of the succession with 1600 to 1000 Ma detrital zircons derived predominantly from the Grenville orogenic belt of eastern Laurentia were deposited by west-northwest flowing rivers (Rainbird et al. 1997, 2012).
The local extrusion of mantle sourced volcanic rocks at 775 Ma (Little Dal Basalts) in the Mackenzie Mountains correlates with the Gunbarrel magmatic event and signals the initiation of continental extension along this part of the western edge of Laurentia that would ultimately lead to the deposition of the Windermere Supergroup (Milton, 2015). In northwest Laurentia, the first narrow rift basin formed in the Mackenzie Mountains and was filled by the Coates Lake Group whose uppermost strata have yielded a $732.2 \pm 3.9$ Ma Re-Os age (Rooney et al. 2014). The onset of continental rifting along the length of the western margin of Laurentia to form either the proto-Pacific Ocean (e.g. Stewart 1972; Arnott and Hein 1986; Ross et al. 1989; Ross et al. 1995) or a large intercontinental rift basin (Colpron et al. 2002) resulted in deposition of the Windermere Supergroup. Along the segment north of $57^\circ$ N sedimentation began sometime after 728 $+8/-7$ Ma (Evenchick et al. 1984) and before $717.43 \pm 0.14$ Ma (Macdonald et al. 2010). In this same area local rift-related volcanism is recorded by the Gataga volcanics ($689.1 \pm 4.6$ Ma; Ferri et al. 1999).

In the late Ediacaran a major thermal and rifting event initiated deposition of the Ediacaran to Middle Devonian Cordilleran passive margin succession (e.g. Bond and Kominz 1984), from which our samples were obtained. In most areas along the eastern edge of this passive margin an Ediacaran to Lower Cambrian sandstone package forms the basal unit (Gog Group and correlatives). This facies appears to be offset 250 km to the northeast across the Liard Line (Aitken 1993). Changes in older strata suggest this feature may have been established during Cryogenian (Aitken 1993) or Paleooproterozoic (?) rifting events and reactivated in the Ediacaran (Aitken, 1993). Local depositional thickening and volcanism within the Canadian Cordilleran passive margin indicate widespread episodic extension beginning in the Middle Cambrian (Goodfellow et al. 1995). In the Liard area this resulted in the development of the northwest-
trending Roosevelt graben system above the western Liard Line and the local deposition of coarse clastic strata of the Mount Roosevelt Formation (Taylor and Stott 1973; Fritz 1979, 1991; Post and Long 2008).

SAMPLES ANALYSED

Samples were collected from two Lower Paleozoic horizons along the western part of the Liard Line: the Vizer and Mount Roosevelt formations (Fig. 1).

Vizer formation (informal)

A quartz arenite unit exposed in the Cariboo Range immediately south of the B.C. – Yukon border (Locality 3b in Fig. 1, 2) has been informally called the Vizer formation by Benjamin et al. (2011), who studied the unit in detail as a potential source for fine-grained, pure (>97%) quartz sands to be used by the petroleum industry in the fracking process. The Vizer formation is comprised mainly of pale grey to white, fine- to medium-grained, thin- to thick- bedded, sub-angular to subrounded quartz arenite (Benjamin et al. 2011). It is unconformably overlain by Silurian carbonate and its base is not exposed because it lies in the immediate hangingwall of the Larsen Fault (McMechan et al. 2012). One of our samples is from the lowermost exposures and the other comes from the middle part. Taylor and Stott (1980) suggested a Lower and (?) Middle Cambrian age and correlated these strata mainly with strata now called the Mount Roosevelt Formation, whereas McMechan et al. (2012) suggested an Ediacaran to Lower Cambrian age based on lithologic similarity with the undated quartz arenite unit underlying the Mount Roosevelt Formation in the southwest Liard area, as shown in Figure 2. Recently, Fallas et al. (2014) suggested these strata should be assigned to the uppermost Cambrian to Ordovician Crow Formation. The Crow Formation comprises variably subarkosic sandstone, conglomerate,
maroon siltstone, minor carbonate and local volcanics in exposures immediately northwest of the Cariboo Range (Pigage 2009; Fig. 1, localities 2, 3a). From a sedimentology and compositional perspective it seems unlikely that the nearly pure quartz arenite succession exposed in the Cariboo Range is part of the variably subfeldspathic package comprising the Crow Formation, particularly since crossbeds in the Crow Formation indicate a west to southwest transport direction (Pigage, 2009). Detrital zircon U-Pb age results for 6 samples of the Crow Formation reported by Pigage (2009) are compared with detrital zircon signatures from the Mount Roosevelt and Vizer formations below.

**Mount Roosevelt Formation**

The lower Middle Cambrian Mount Roosevelt Formation (Fritz 1979; 1991) represents the progradation of an alluvial fan delta into a marine environment (Post and Long 2008). Three members comprise the up to 1500 m thick formation. The lower member is characterized by ooid-bearing siltstone and sandstone, interbedded with carbonate and hematitic conglomerate. The thick middle member comprises polymict, cobbly pebble conglomerate and the upper member is comprised of karstified dolostone, calcareous cemented conglomerate and sandstone and limestone. Deposition of the Mount Roosevelt Formation occurred in fault-controlled basins with the thickness and distribution of the formation controlled by the location of active faults (e.g. Fritz 1991; Ferri et al. 1999). The thickest development of the Mount Roosevelt Formation occurs in the hanging wall of the Forcier fault immediately northwest of Muncho Lake (Post and Long, 2008). Our sample (locality 3B in Fig. 1, 2) comes from a volcanic clast-bearing polymict conglomerate in the middle member of the formation.
Detrital zircons from a second sample of the Mount Roosevelt Formation were analysed by Gehrels and Ross (1998) and reanalysed by Gehrels and Pecha (2014), who included this sample in the Atan Group following the now discontinued terminology used by Taylor and Stott (1973). This sample is from a coarse-grained to pebbly, carbonate-cemented quartz arenite horizon in a clastic unit that is overlain by shale and limestone (Gehrels and Ross 1998). It comes from the upper member of the Mount Roosevelt Formation exposed 14 km southeast of the middle member sample location. In the Liard area, the Middle Cambrian Mount Roosevelt Formation unconformably overlies Paleoproterozoic strata of the Muskwa assemblage in the east and up to 300 m of fine- to coarse-grained quartz arenite that likely correlates with the Vizer formation of the Cariboo Range in the west (Fig. 2, see above).

**METHODS**

Detrital zircons from three new samples, two from the Vizer formation quartz arenite and one from conglomerate of the Middle Cambrian Mount Roosevelt Formation, were processed and analysed by AtoZ Incorporated, Bosie, Idaho using the LA-ICP-MS at the Geoanalytical Laboratory, Washington State University, Pullman, Washington. Full details of the analytical approach, grain descriptions and the data can be found in the Supplementary Information.

For grains that yield ages older than ca. 1000 Ma, the $^{207}\text{Pb}/^{206}\text{Pb}$ age is used, whereas for younger grains the $^{206}\text{Pb}/^{238}\text{U}$ age is used. Analyses were filtered following the criteria of Gehrels and Pecha (2014). Analyses with $>10\%$ uncertainty ($1\sigma$) in $^{206}\text{Pb}/^{238}\text{U}$ or the $^{206}\text{Pb}/^{207}\text{Pb}$ age are not included in our analysis. Concordance is based on $^{206}\text{Pb}/^{238}\text{U}$ age/$^{206}\text{Pb}/^{207}\text{Pb}$ age, with 100% considered concordant. Analyses with $>20\%$ discordance ($<80\%$ concordance) or $>5\%$ reverse discordance ($>105\%$ concordance) are not included.
The resulting detrital zircon U-Pb age distributions for our samples and the Mount Roosevelt Formation sample analysed by Gehrels and Pecha (2014) are compared with: 1) the U-Pb zircon age distributions for other late Ediacaran and Cambrian aged strata; and 2) potential intermediate sources (i.e. Proterozoic sedimentary strata through which grains may have been recycled) using direct comparison of normalized probability plots (calculated using the Excel™ plug-in Isoplot v. 4.15; Ludwig 1998, Ludwig 2012, Berkeley Geochronolgy Center, 2016) and multidimensional scaling (MDS). MDS is a method of objectively interpreting large datasets.

Using the IsoplotR program of Vermeesch (2013; 2017) a ‘map’ of data points is produced on which ‘dissimilar’ or unrelated samples plot far apart and ‘similar’ samples, such as samples with similar provenance, or a sample and its ultimate or intermediate provenance, cluster closely together. The ‘map’ is based on the D values (the maximum vertical separations between two cumulative density functions) that are produced as part of the Kolmogorov-Smirnov test (Vermeesch 2013). This study uses data from numerous sources including a few with small sample sizes (n <50). Recent work by Pullen et al. (2014) suggests that the number of concordant grains analysed for each sample needs to approach 300 for more meaningful statistical analysis.

Analyses from these other publications were also filtered using the criteria of Gehrels and Pecha (2014).

**DETRITAL ZIRCON GEOCHRONOLOGY**

**Results**

Detrital zircons from two samples of the Vizer formation were analysed. Sample FF10-1 from the lowest exposures of the unit contains a dominant 1900 to 1500 Ma age fraction with a lesser 2900 to 2500 Ma population. A distinct “shoulder” between 1700 and 1500 Ma is formed in part
by 5 concordant grains with ages between 1605 and 1538 Ma that fall into a hiatus in Laurentian
magmatism between 1610 and 1490 Ma termed the North American magmatic gap (NAMG; Ross and Villenueve 2003; Fig. 3). Sample 11EPF55A from the middle part of the formation has a preponderance of 2000 to 1600 Ma grains with less common 3000 to 2200 Ma grains. Both samples have a significant peak between 1900 and 1750 Ma. Neither contains zircons younger than 1500 Ma and thus the zircon ages provide no useful information on the depositional age of the Vizer formation. The samples are similar and have therefore been grouped together on the normalized probability and MDS plots (Fig. 4, 5).

One sample from the middle member of the Middle Cambrian Mount Roosevelt Formation (11EPF67A) yielded dominantly 2100 to 1600 Ma and 2800 to 2300 Ma grains, with two concordant 700 to 600 Ma grains and one reliable ca. 3200 Ma grain. The probability plot has a prominent peak between 1900 and 1700 Ma and a lesser peak between 2650 and 2500 Ma (Fig. 3). Zircons older than 2200 Ma make up a greater proportion of the zircons in this sample than in the Vizer formation quartz arenites. There were no Early or Middle Cambrian (541 to 497 Ma) grains.

**DISCUSSION**

**Comparison with Cordilleran Passive Margin Cambrian to Ordovician Units**

Detrital zircon results from our samples and the sample from the upper member of the Mount Roosevelt Formation (Gehrels and Pecha, 2014) were compared with those of other Late Ediacaran to Cambro-Ordovician units in the Canadian Cordilleran passive margin to determine which units could have had similar detrital zircon provenances.
Direct comparison of normalized probability plots (Fig. 4) for these units suggest the Vizer formation has a different detrital zircon provenance from 1) the Franklin Mountain and Sekwi formations and the Sekwi correlative unit because of the abundance of 1490 to 1000 Ma grains and relative lack of 2000 to 1750 Ma grains in those samples; 2) the upper member of the Mount Roosevelt Formation sample because of the abundance of 2500 to 2300 Ma grains and absence of a strong 1880 to 1750 Ma peak in that sample; 3) the Crow Formation Northwest Liard locality samples because of the presence of Ordovician aged zircon and the absence of 1750 to 1500 Ma grains in those samples; 4) the Yanks Peak Formation because of the lack of 1700 to 1600 Ma grains and presence of 1400 to 1000 Ma grains in that sample; and likely 5) the Crow Formation Coal River locality samples because of the subdued 2000 to 1750 Ma peak and component of 1400 to 600 Ma grains (8%) in those samples.

The MDS plot for comparison of detrital zircon signatures of Ediacaran to Cambro-Ordovician units along the Canadian Cordilleran passive margin (Fig. 5) suggests the detrital zircon signature of the Vizer formation is most similar to those of the McNaughton, Hamill, Vampire-Narchilla units and the middle member of the Mount Roosevelt Formation. The similar detrital zircon profiles of the Vizer formation with Lower Cambrian (Terrenevian) aged samples from the McNaughton and Hamill formations suggests that the Vizer is most likely part of the regionally extensive transgressive sandstone package at the base of the Cordilleran passive margin succession. In the Mackenzie Mountains stratigraphic relationships (Aitken 1993; MacNaughton et al. 2008) show that the Vampire interval is the basinal equivalent of nearshore sandstones of the Backbone Ranges Formation. Comparable detrital zircon profiles of the Vampire-Narchilla and Vizer formations in the Liard area suggests that a similar facies relationship likely occurs between the Lower Cambrian (Terreneuvian; Pigage et al. 2015)
Vampire-Narchilla formation and the nearshore sandstones of the Vizer formation. This would also indicate a Terrenuevian Early Cambrian age for the quartz arenites of the Vizer formation.

Direct comparison of normalized probability plots of Ediacaran to Cambro-Ordovician units along the Canadian Cordilleran passive margin (Fig. 4) suggest that our sample from the middle member of the Mount Roosevelt Formation 1) is most similar in provenance to the Vizer formation samples because of the width of the 2000 to 1600 Ma peak and subdued presence of 2500 to 2000 Ma grains, 2) has a different provenance from the Franklin Mountain and Sekwi formations and Sekwi correlative unit because of the abundance of 1490 to 1000 Ma ultimate Grenville sourced grains in those samples and 3) has a different provenance from the upper member of the Mount Roosevelt Formation sample because of the relative abundance of 2400 to 2300 Ma aged grains and lack of a 1900 to 1700 Ma peak in that sample. The MDS plot (Fig. 5) suggests the detrital zircon signature of the middle member of the Mount Roosevelt Formation sample is most similar to the McNaughton, Hamill and Vampire-Narchilla units. Both direct comparison of normalized probability plots (Fig. 4) and the MDS plot (Fig. 5) suggest the detrital zircon signature of the upper member of the Mount Roosevelt Formation differs from all the other Ediacaran to Cambro-Ordovician units sampled to date in the Canadian Cordilleran passive margin succession.

**Comparison with Potential Intermediate Detrital Source Units**

Due to its mechanical durability, zircon is commonly recycled from one sedimentary unit to another without impacting the reliability of the U-Pb age determinations (e.g. Dickenson et al., 2009). The significance of sedimentary recycling for Neoproterozoic and Cambrian strata in northwestern Laurentia has been documented by Hadlari et al. (2012) and Lane and Gehrels
who concluded most Neoproterozoic and Cambrian units in the Mackenzie – Wernecke Mountains and adjacent Richardson Trough were recycled from intermediate (Proterozoic sedimentary) sources. Almost all the Proterozoic successions mentioned previously in the Geological Framework were exposed during the Cambrian (Fig. 1), making them potential intermediate sources of detrital zircons found in the Vizer and Mount Roosevelt formations. Direct comparison of normalized probability plots for the Vizer and Mount Roosevelt formation with those from potential Proterozoic intermediate sources (Fig. 6) rules out the Neoproterozoic Shaler, Mackenzie Mountains and Windermere supergroup units exposed in the Wernecke and Mackenzie mountains and northwest Liard area (Fig. 1, 2, localities 1, 3b) as intermediate source units for both the Mount Roosevelt and Vizer formations because they contain abundant 1490 to 1000 Ma (Grenville source) aged grains that the Vizer and Mount Roosevelt formations lack. Unit Ps is not considered an important intermediate source for the Vizer formation because of the abundant 2.0 to 1.9 Ga aged detrital zircons in that unit. Paleoproterozoic sandstones of the Athabasca, Muskwa and Wernecke successions and Neoproterozoic deep water turbidites of the Horsethief Creek Group and Ediacaran Yusezyu Formation are potential sources for the Vizer formation. However, none of the potential intermediate source units contain the robust contribution 2.5 to 2.2 Ga contribution found in the upper Mount Roosevelt Formation (Fig. 6).

Comparison with published probability density plots for samples from the Mesoproterozoic Fifteen Mile and Pinguicula groups in the Hart Creek Inlier (Medig et al. 2012, 2014) suggest that these would be unlikely intermediate sources for the Vizer and Mount Roosevelt formations because they contain abundant detrital zircons with ages less than or equal to 1500 Ma (Fig. 7). Whereas, the basal unit of the Pinguicula Group in the Wernecke inlier (Fig. 1, location 1a) has very few <1500 Ma detrital zircon grains and could be a potential intermediate source (Fig. 7 A-
C). Two of the three samples from this unit contained 1610 to 1490 Ma aged NAMG detrital zircons (Fig. 7; Medig et al. 2012).

The MDS plot for comparison of detrital zircon signatures of the Vizer and Mount Roosevelt formations with potential Proterozoic intermediate sources (Fig. 8) suggests that 1) the detrital zircon signature of the Vizer formation is most similar to that of the Ediacaran Yusezyu Formation; 2) the detrital zircon signature of the upper member of the Mount Roosevelt Formation differs significantly from all the potential intermediate sources; and 3) the detrital zircon signature of the middle member of the Mount Roosevelt Formation is similar to those of the Paleoproterozoic Muskwa succession, Neoproterozoic Horsethief Creek Group and the Ediacaran Yusezyu Formation. Data for the Pinguicula Group is not yet available for MDS comparison.

The close similarity of detrital zircon signature for the Vizer formation to those of Proterozoic intermediate sources suggests there is little if any first cycle Laurentian basement sourced material in this unit. The abundance of 2500 to 2300 Ma zircons in the upper member of the Mount Roosevelt Formation (25%, Fig. 4) as compared to the Muskwa (5%) implies a direct cratonic source (Gehrels and Ross 1998). Magmatism between 2500 and 2300 Ma has a limited distribution in western Canada (Fig. 1, Canadian Geochronology Knowledgebase 2013). The most likely ultimate source for the 2500 to 2390 Ma grains are basement rocks in the western Trans-Hudson Orogen. Other potential source areas include the La Ronge arc, Taltson magmatic belt, Rae and Hearne provinces and eastern Trans-Hudson Orogen (Fig. 1). Abundant 2380 to 2300 Ma grains in the upper Mount Roosevelt Formation could have come from the Buffalo Head, Thorsby or Wabamun terranes (Gehrels and Ross 1998) or rocks exposed near the western margin of the Rae Province, north of the Athabasca basin (Fig. 1). Basement rocks in the eastern
Trans-Hudson Orogen are considered a less likely source for 2500 to 2300 Ma grains because the Trans-Hudson Orogen would provide a significant component of 1900 to 1800 Ma detrital zircons, which are not observed in the upper Mount Roosevelt Formation sample. Recycled zircons with 2500 to 2300 Ma ages occur in the northern Hottah Terrane (Davis et al. 2015). This is considered to be an unlikely source since Cambrian sandstone samples unconformably overlying the northern Hottah terrain at Great Bear Lake contain only a small component (~10%) of these grains and a large component of 2000 to 1750 Ma grains (Hadlari, 2012). The 2050 to 1800 Ma grains in the upper Mount Roosevelt sample match well with plutons in several nearby terranes to the east. The 2900 to 2500 Ma grains could have come from the Rae, Hearn or Slave provinces (Fig. 1). The middle member of the Mount Roosevelt Formation contains a noticeable component of 2500 to 2400 Ma aged detrital zircon grains that were ultimately derived from the Laurentian basement areas mentioned above. They may indicate that a small component of first cycle Laurentian basement material made its way into the Roosevelt graben or a lack of sufficient sampling of zircon from feldspathic strata at the top of the underlying Muskwa Assemblage (Tuchodi Formation, n = 19; Ross et al. 2001). Two concordant first-cycle approximately 670 and 640 Ma detrital zircon grains occur in the middle Mount Roosevelt Formation sample. Magmatism of this age is known from only two localities in western Canada (Canadian Geochronology Knowledgebase, 2013; Yukon Geochronology Database, 2015). The Gataga volcanics (689.1 ± 4.6 Ma; Ferri et al. 1999), which outcrop 75 km southwest of the middle Mount Roosevelt Formation sample location and the Pool Creek Syenite (Fig. 2; 650 to 640 Ma, Pigage and Mortensen, 2004), located 150 km north of the middle Mount Roosevelt sample locality. The older grain (669 ± 14 Ma) is intermediate in age while the younger (640 ± 10 Ma) detrital zircon grain is the same age as the Pool Creek Syenite. The erosion of volcanic
and/or plutonic rocks associated with the Gataga Volcanics and the Pool Creek Syenite intrusion form the likely sources. Occasional younger Neoproterozoic grains (690 to 640 Ma) are also found in samples from the lower Cambrian Vampire-Narchilla and Cambro-Ordovician Crow formations at the Coal River locality (Pigage 2009; Pigage et al. 2015). There was no detrital zircon record of Middle Cambrian volcanism in the middle member of the Mount Roosevelt Formation sample.

**Potential Sources 1610 to 1490 Ma “North American Magmatic Gap” Grains, lower Vizer formation**

The detrital zircon age profile presented here for the lower Vizer formation is are the first reported occurrence of NAMG detrital zircons (5% of accepted analyses) from the Cambrian Laurentian margin succession not associated with Grenville aged grains (Fig. 3). This absence of Grenville aged grains places serious doubt on the possibility that the NAMG zircons were derived from eastern Laurentia, despite the occurrence of 1520 and 1460 Ma magmatism in the Pinware terrane (Fig. 1 inset map) of the easternmost Grenville orogen (Gower and Krogh 2002; Heaman et al. 2004). The allochthonous Pinware terrane was accreted to the Archean and Paleoproterozoic core of Laurentia during the (1250 to 980 Ma) Grenville Orogeny. Consequently, any Pinwarian aged detrital zircon grains would be associated with younger (1350 to 1000 Ma) Grenville aged detrital zircon grains, as is found in the Shaler Group (Rayner and Rainbird 2013). The complete absence of Grenville aged detrital zircon grains combined with the older age range of the Vizer detrital zircon grains (1608 to 1532 Ma) as compared to the age of Pinwarian magmatism (1520 to 1460 Ma) rule out Laurentia as a potential ultimate source.
Aged detrital zircons derived from non-Laurentian sources have been found from northcentral Yukon to southern Arizona in Mesoproterozoic basins formed along the western margin of Laurentia (Medig et al. 2014 and references therein). The ultimate source of the 1610 to 1490 Ma detrital zircon grains is thought to be the Mawson and North Australia cratons (Stewart et al., 2010; Medig et al., 2014). Direct recycling from the three exposed Canadian Laurentian margin Mesoproterozoic successions into the Cambrian Vizer Formation is unlikely.

First, the PR1 basin (Fig. 1; basal Fifteen Mile Group) located 900 km northwest of the Liard area is characterized by a unimodal 1500 Ma detrital zircon population (Fig. 7D; Medig et al. 2014). These strata are directly overlain by younger Mesoproterozoic sediments of the Fifteen Mile Group and were not available to provide material directly to Cambrian strata (Medig et al. 2014). Second, the basal unit of the Pinguicula Group (unit A) in the Wernecke Mountains 700 km northwest of the Liard area contain a small component of NAMG grains not associated with younger grains (Fig. 7A-C; Medig et al. 2012). However, the Pinguicula Group in these areas is unconformably overlain by the Neoproterozoic Mackenzie Mountains Supergroup (Medig et al. 2012) and was not available to provide material directly to Cambrian strata. Finally, the Belt-Purcell basin, located 1200 km south of the Liard area (Fig. 1), is unconformably overlain by Early Cambrian strata in northeastern exposures and potentially a source. The rarity of NAMG grains in Ediacaran and Early Cambrian strata near the Belt-Purcell basin and to the north of this basin (Gehrels and Pecha 2014; Matthews 2016) suggests the NAMG grains in the Vizer formation were likely recycled from a more proximal source.

The absence of an exposed and therefore geologically viable source for the recycled NAMG detrital zircon grains in the Vizer formation indicates that these grains most likely came from a unit that has either been completely removed by lower Paleozoic erosion, is preserved only in the

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subsurface or has not yet been sampled. Unit Ps in the northwest Liard area provides evidence for such a unit. Pigage (2009) suggested Proterozoic strata of unit Ps (Fig. 2) most likely correlate with the Mesoproterozoic Pinguicula Group on the basis of a detrital zircon signature that 1) lacks 1490 to 1000 Ma Grenville-sourced detrital zircons characteristic of the Neoproterozoic Mackenzie Mountains and Shaler supergroups and eastern Windermere Supergroup successions and 2) contains a strong 2000 to 1900 Ma peak that is absent in the Paleoproterozoic Wernecke, Athabasca and Muskwa successions but present in some Pinguicula Group samples from the Wernecke Mountains (Fig. 6, 7). Although the exposed portion of unit Ps could not be a source of NAMG grains in the lower part of the Cambrian Vizer formation because it is overlain by Neoproterozoic strata, its presence does indicate that a Mesoproterozoic succession younger than the Muskwa assemblage (Paleoproterozoic) and older than the Mackenzie Mountain Supergroup (Neoproterozoic –Tonian) occurs in the subsurface of the northwest Liard area. By analogy with Mesoproterozoic successions exposed along the western edge of Laurentia, this succession probably contained a component of NAMG aged detrital zircons.

During deposition of the lower part of the Vizer formation the postulated Mesoproterozoic succession would have been progressively truncated eastward and available to provide detritus to the basal Cambrian sandstone as it was progressively overlapped. Erosion and overlap of the postulated Mesoproterozoic succession would also have happened in the southern part of the Liard area as Cambrian or Silurian strata directly overlie the Muskwa assemblage. Progressive removal of a Mesoproterozoic succession by sub-Cambrian erosion in the eastern and southern part of the Liard area forms the most geologically feasible source for the NAMG detrital zircon grains in the lower Vizer formation.
Paleogeographic implications

New detrital zircon results from the Vizer and Mount Roosevelt formations combined with previously published results show important changes in detrital zircon provenance occurred in the northern Canadian Cordilleran passive margin succession during the Early and Middle Cambrian. These changes are illustrated in Figure 9 using hypothetical drainage pathways for four time intervals corresponding to deposition of the Vampire-Narchilla and Vizer formations (Early Cambrian Terreneuvian series; Figure 9A); Sekwi Formation and correlatives (Early Cambrian, Series 2; Figure 9B); middle member of the Mount Roosevelt Formation (early Middle Cambrian; Figure 9C); and upper member of the Mount Roosevelt Formation (early Middle Cambrian; Figure 9D) in the Coal River and Liard areas.

In the Canadian Cordilleran passive margin succession the Early Cambrian Terreneuvian and Series 2 strata represent a major transgression that reached its maximum before the end of the Early Cambrian. This was followed by a major regression represented by a disconformity at the base of the Middle Cambrian and then a major Middle Cambrian transgression that progressively onlapped the Laurentian craton (Aitken 1989; Gabrielse 1991). South of 55° N most of the western Canadian Laurentian basement east of the passive margin was directly overlapped by Middle Cambrian strata, whereas north of the Liard Line the Cambrian overlapped large regions of Proterozoic sedimentary cover east of the passive margin (Fig. 1).

Detrital zircon age distributions for the basinal Vampire-Narchilla and the nearshore Vizer formations (Fig. 4 -6; Terreneuvian) indicate extensive recycling from Paleoproterozoic Athabasca-Muskwa sandstones exposed to the east and southeast, no recycling from the Neoproterozoic Mackenzie Mountain/Shaler and Windermere successions exposed to the northeast and no significant first cycle basement material. The Liard Line most likely impacted
the detrital zircon provenance of the Vizer formation indirectly by controlling the southward extent of the Mackenzie Mountains Supergroup (Aitken 1993). The minor component of NAMG aged detrital zircon in the lower part of the Vizer formation was most likely recycled from Mesoproterozoic strata exposed during the Terreneuvian in the eastern and southern Liard area (discussed above). Further north in the Mackenzie Mountains, detrital zircon age distributions for the lower and upper Backbone Ranges Formation (Fig. 4) indicate derivation mainly from cratonic basement sources to the east, including the Hottah terrane, Great Bear magmatic zone, Coronation Margin and the Slave craton (Fig. 9A; Leslie 2009; Lane and Gehrels 2014). The detrital zircon provenance of all three formations resulted from a westward paleoflow. The significant difference in detrital zircon signatures between the Vampire-Narchilla-Vizer and the Backbone Ranges successions most likely reflects the greater amount of basement exposure east of the Backbone Ranges localities in the Terreneuvian.

The detrital zircon age distribution for the Lower Cambrian Series 2 Sekwi Formation in the Mackenzie Mountains indicates extensive recycling of ultimate Grenville orogeny sourced grains. These most likely came from the Mackenzie Mountain Supergroup exposed to their northeast in the Mackenzie Arch (Leslie 2009; Lane and Gehrels 2014). Northeastern source areas are also indicated by the detrital zircon age distribution for the Sekwi correlative unit in the Coal River area (Fig. 4, 9B), which has a broad spectrum of subdued peaks extending from 2800 to 1200 Ma that suggests derivation predominantly from the Mackenzie Mountain/Shaler supergroup (1500 to 1200 Ma grains) and cratonic sources including the Slave craton, Hottah terrane and Great Bear Magmatic zone (Pigage et al. 2015). Over most of the Liard area, Early Cambrian Series 2 time is represented by a disconformity and no detrital zircon data is available.
In the Liard area, Middle Cambrian strata are restricted to the syn-sedimentary Mount Roosevelt graben. No detrital zircon data is available for Middle Cambrian deposits elsewhere along the northern Canadian Cordilleran passive margin. The detrital zircon age distribution for the conglomeratic middle member of the Mount Roosevelt Formation indicates a local provenance consistent with the alluvial fan deposition model proposed by Post and Long (2008) with a minor contribution from 2500 to 2400 Ma basement sources. Most detrital zircon grains were recycled from the underlying Muskwa assemblage either directly or indirectly through Lower Cambrian sandstones, and their provenance was indirectly influenced by the Proterozoic stratigraphic changes associated with the Liard Line. The concordant 670 and 640 Ma detrital zircon grains strongly suggest that volcanic clasts in the conglomerate were also derived locally as the only magmatic rocks of this age near the Canadian Cordilleran passive margin are in the Liard area (discussed above; Fig. 9C).

In contrast, the detrital zircon age distribution for the sandstone-dominated upper member of the Mount Roosevelt Formation suggests derivation mainly from more distant first cycle cratonic sources to the east or southeast (Fig. 9D). The upper member of the Mount Roosevelt Formation contains a significant component of 2500 to 2300 Ma Laurentian basement sourced detrital zircon not present in any of the intermediate sources. Magmatism of this age has a limited distribution in western Canada (Figure 1, Canadian Geochronology Knowledgebase 2013). As discussed above the most likely potential source areas for the 2500 to 2390 Ma grains are in or near the western Trans-Hudson orogen (Fig. 1). The Buffalo Head, Thorsby or Wabamun terranes and western edge of the Rae Province form the most likely source areas for 2380 to 2300 Ma grains (Fig. 1; Gehrels and Ross 1998) (Fig. 1). The younger 1825 to 1770 Ma grains also indicate source areas to the east and southeast as intrusions of this age only occur southeast
of the Snowbird tectonic zone in the Hearne Province, Trans-Hudson orogen and intervening thrust-fold belt (Fig. 9D; Canadian Geochronology Knowledgebase 2013). The 2050 to 1830 Ma grains match well with plutons in several nearby arcs and terranes and Archean grains could have been derived from the Hearne, Slave or Rae provinces (Fig. 1; Gehrels and Ross 1998).

Both the Vizer and Vampire-Narchilla intervals and the upper member of the Mount Roosevelt Formation were sourced from the east or southeast. The dramatic change in detrital zircon provenance from recycled Paleoproterozoic blanket sandstone in the Terreneuvian to first cycle Laurentian basement in the early Middle Cambrian strongly suggests significant erosion of the Paleoproterozoic sedimentary cover and denudation of Laurentian basement occurred east of the Liard area during late Early Cambrian and Middle Cambrian regression. Further stratigraphic and detrital zircon provenance studies of Ediacaran and Cambrian strata along the northern Canadian Cordilleran passive margin should be able to refine the evolution of drainage divides and basement denudation.

CONCLUSIONS

The Vizer formation was derived primarily from Paleoproterozoic intermediate sources, with little or no first cycle Laurentian basement input. The conglomeratic middle member of the Mount Roosevelt Formation was derived primarily from Proterozoic and Lower Cambrian intermediate sources, possibly with a minor component of first cycle Laurentian basement material.

The North American Magmatic Gap aged detrital zircons in the lower part of the Vizer formation were likely derived from a local Mesoproterozoic succession that was completely removed by lower Paleozoic erosion or is preserved in the subsurface of the north central Liard area.
An Early Cambrian Terreneuvian age is suggested for the nearshore Vizer formation based on similar detrital zircon profiles with Terreneuvian transgressive sandstones to the south, the facies relationships of Terreneuvian strata in the Mackenzie Mountains and the similarity of the Vizer formation detrital zircon age distribution with that of the nearby basinal Vampire-Narchilla Formation.

Volcanic clasts in the middle member of the Mount Roosevelt Formation were likely locally sourced from the 689.1 ± 4.6 Ma Gataga volcanics (Ferri et al. 1999) and volcanic and/or intrusive rocks related to the 650 to 640 Ma Pool Creek Syenite (Pigage and Mortensen 2004), based on the presence of concordant 670 and 640 Ma detrital zircon grains. There is no detrital zircon evidence to support syn-extensional volcanism associated with the Middle Cambrian development of the Mount Roosevelt Graben.

The detrital zircon provenance of Early and Middle Cambrian strata deposited along the northern Canadian Cordilleran passive margin indicates major variations in source area and paleoflow occurred with time. Source areas were to the east when the Vizer, Vampire-Narchilla and Backbone Ranges formations were deposited (Early Cambrian, Terreneuvian series) and changed to the northeast as Sekwi Formation and Sekwi correlative strata formed (Early Cambrian, Series 2). The middle member of the Mount Roosevelt Formation (Middle Cambrian) in the Roosevelt graben was primarily locally sourced, whereas the detritus that formed the upper member was derived directly from Laurentian basement exposed over a large region to the east or southeast. The change from recycled Paleoproterozoic sedimentary cover to primary basement sources suggests that significant denudation of the cratonic basement occurred east of the Liard area in the Early Cambrian and Middle Cambrian.
Proterozoic stratigraphic changes associated with the Liard Line indirectly affected the provenance of the Vizer formation and middle member of the Mount Roosevelt Formation.

ACKNOWLEDGEMENTS

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McMechan et al Cambrian DZ Table 1

Table 1. References for detrital zircon age data used in Figures 4 - 6, 8. Fm. – formation, Grps. – Groups.
FIGURE CAPTIONS

Figure 1. Subcrop map at the base of the Paleozoic for northwest Laurentia showing distribution of Cambrian sandstone, and Cambrian and Proterozoic detrital zircon localities palinspastically restored for Cordilleran deformation. Numbers correspond to sections in Figure 2. Sources of information: Aitken 1993, Cook et al. 1999; Canadian Geochronology Knowledgebase 2013; Cook and MacLean 2004; McMechan 2002; Ootes et al. 2015. Pugh 1975; Ross et al. 2001; Slind et al. 1994; unpublished B.C. well logs. Palinspastic restoration based on: Campbell et al. 1982; K.M. Fallas, pers. comm. 2015; Fermor and Moffat 1992; Gabrielse and Taylor 1982; Gordey 2013; Mair 2006; McMechan 1994, 2000, 2013, unpublished; Pigage et al. 2015; Price and Fermor 1984. BP – Belt-Purcell basin; C – Coronation Margin; G – Great Bear magmatic zone; H – Hamill Formation and Horsethief Creek Group; HBB – Horby Bay Basin; HCI – Hart Creek Inlier; MM – Mackenzie Mountain Supergroup; Mn – McNaughton Formation; P – Pinware terrane (inset map); PR1 = PR1 Basin; S-l – upper Coppermine River Group and lower Shaler Supergroup; S-u – upper Shaler Supergroup; T – Thorsby terrane; W – Wabamun terrane; Yp – Yanks Peak Formation.

Figure 2. Proterozoic to Middle Ordovician stratigraphic correlations and tectonic events along the northern Canadian passive margin showing stratigraphic positions of detrital zircons samples from this study or used for comparison purposes in Figures 4 to 8. See Table 1 for sources of detrital zircon U-Pb age data. FO – Forward Orogeny; GB – Gunbarrel magmatic event; RO – Racklan Orogeny.

Figure 3. U-Pb zircon probability density distributions and histograms for Vizer and Mount Roosevelt formation samples.
Figure 4. Normalized U-Pb zircon age probability plots for Ediacaran to Cambro-Ordovician units in the Canadian Cordilleran passive margin succession. See Table 1 for sources of detrital zircon U-Pb age data from other studies. Grey bars highlight age range of ultimate Grenville Orogeny source area (Gren), NAMG (N) and 2500 to 2300 Ma. Edi – Ediacaran; eC2 – Early Cambrian – series 2; eCT – Early Cambrian – Terrenuevian; lC- eO – Late Cambrian to Early Ordovician; lC- mO – Late Cambrian to Middle Ordovician; mC – Middle Cambrian.

Figure 5. MDS plots (Vermeesh 2017) showing relative statistical similarity of detrital zircon age distributions (based on the Kolmogorov-Smirnov test D value) for Ediacaran and Cambro-Ordovician units in the Canadian Cordilleran passive margin succession. See Table 1 for sources of detrital zircon U-Pb age data. BBl – lower Backbone Ranges Formation, BBu – upper Backbone Ranges Formation. The thick pale grey dashed line separates samples with ultimate Grenville sourced grains (to the right of the line) from those lacking or having very few Grenville sourced zircons (to the left of the line).

Figure 6. Normalized U-Pb zircon age probability plots for potential sources of zircons found in Mount Roosevelt and Vizer formation samples. See Table 1 for sources of detrital zircon U-Pb age data. Grey bars highlight age range of ultimate Grenville Orogeny source area (Gren), NAMG (N) and 2500 to 2300 Ma. eCT – Early Cambrian – Terrenuevian; mC – Middle Cambrian; mP – Mesoproterozoic; nP – Neoproterozoic; pP – Paleoproterozoic. MM – Mackenzie Mountain Supergroup; l Shaler – upper Coppermine River Group and lower Shaler Supergroup; L – Leslie (2009); LG – Lane and Gehrels (2014).
Figure 7. U-Pb zircon age probability density distributions from samples of the basal Pinguicula Group (unit A) exposed in the Wernecke Inlier, Wernecke Mountains, Yukon (A – C; Medig et al. 2012) and the PRI basin (D; Medig et al. 2014). Grey bar indicates age range of NAMG.

Figure 8. MDS plots (Versmeech, 2017) showing relative statistical similarity of detrital zircon age distributions (based on the Kolmogorov-Smirnov test D value) for potential intermediate sources of detrital zircons found in the Vizer and Mount Roosevelt formation. Samples from this study are labelled in italics. See Table 1 for sources of detrital zircon U-Pb age data. HTC – Horsethief Creek Group; L – Leslie (2009); LG – Lane and Gehrels (2014); MM – Mackenzie Mountain Supergroup; Shaler- l – upper Coppermine River Group and lower Shaler Supergroup; Shaler- u – Shaler Supergroup, upper part. Note: the lower part of the Shaler Supergroup includes one sample from sandstone at top of Coppermine River Group.

Figure 9. Hypothetical drainage pathways suggested by observed detrital zircon signatures superimposed on sub-Paleozoic subcrop map (see Figure 1 for details). A) Vampire-Narchilla (VN), Vizer (V) and Backbone Ranges (BR) formations (Early Cambrian – Terreneuvian); B) Sekwi Formation (S) and Sekwi correlative unit (SC) (Early Cambrian – Series 2); C) middle member Mount Roosevelt Formation (Middle Cambrian – Series 3); D) upper member Mount Roosevelt Formation (Middle Cambrian – Series 3). BHT – Buffalo Hills terrane; C – Coronation Margin; G – Great Bear magmatic zone; H – Hottah terrane; LR – La Ronge arc; MA – Mackenzie arch; MM- Mackenzie Mountains Supergroup; PRA – Peace River Arch; STZ – Snowbird Tectonic zone; T – Thorsby terrane; TA – Taltson magmatic belt; W – Wabamun terrane.
2.1-1.85 Ga

2.32-1.99 Ga

2.3-1.91 Ga

2.32 Ga

<2.3 Ga

1.96-1.90 Ga

1.85-1.78 Ga

2.00-1.92 Ga

2.0-1.78 Ga continental magmatic arcs

1.9-1.80 Ga thrust-fold belts

2.3 Ga magmatic crust

Eastern limit Cordilleran deformation

300 km

Cordilleran Passive Margin and Lower Cambrian sandstones

Neoproterozoic - Earliest Cambrian Windermere Supergroup, Hyland Group

Neoproterozoic Tonian Mackenzie Mountains/ Shaler Supergroups

Mesoproterozoic Sedimentary Sequences

Paleoproterozoic 1760 - 1600 Ma Sedimentary Sequences

1.9-1.8 Ga juvenile crust with ‘basement’ inliers

2.0-1.78 Ga continental magmatic arcs

1.9-1.80 Ga thrust-fold belts

2.3 Ga magmatic crust

Magmatism: 2.4 to 2.3 Ga, 2.5 to 2.4 Ga

Archean (>2.5 Ga) crust

Cambrian detrital zircon sample locality, this study; other studies

Proterozoic detrital zircon sample locality other studies

Liard Area

Laurentia

Arctic Islands

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| Crow Formation            | n=194|
| NW Liard loc. (3A)        |      |
| **THIS STUDY**            |      |

| Crow Formation Coal       | n=264|
| River loc. n = 271        |      |
| Franklin Mtn. Fm.         | n=45 |
| Mt. Roosevelt Formation (upper) | n = 201 |
| Sekwi Formation           | n=80 |
| Sekwi Correlative         | n=74 |
| upper Backbone Range Fm.  | n=57 |
| lower Backbone Range Fm.  | n=48 |
| Vampire - Narchilla unit  | n = 230 |
| McNaughton Fm.            | n=222|
| Hamill Group              | n=192|
| Yanks Peak Formation      | n=112|
| UNIT                      |      |
Unlikely correlatives of Vizer and Mount Roosevelt formations: units contain abundant Grenville age zircons.
Potential intermediate source

Cambrian unit

This Study

Likely Sources

Unlikely Sources: units contain abundant Grenville age zircons

Mt. Roosevelt (upper)

Mt. Roosevelt (middle)

Viser

Yusezyu

Muskwa

Ps

Athabasca

Keele (L)

Keele (LG)

Rapitan

Pa

Toobally

MM
A Neoproterozoic - Earliest Cambrian
Windermere Supergroup, Hyland Group

B Neoproterozoic Tonian
Mackenzie Mountains/ Shaler Supergroups

C Mesoproterozoic Sedimentary Sequences

D Paleoproterozoic 1760 - 1600 Ma Sedimentary Sequences

Inferred extent of Paleoproterozoic sedimentary cover

Magmatism: 2.4 to 2.3 Ga, 2.5 to 2.4 Ga
Detrital zircon sample
Zircon U-Pb Dating Methodology

Published Methods

Detailed descriptions of the methods followed by Geosep Services to produce and process their ZrnUPb data have been presented in numerous peer-reviewed manuscripts. These include Bradley et al. (2009), Hults et al. (2013), and Moore et al. (2015).

Sample Preparation

Zircon grains were isolated and prepared for LA-ICP-MS analysis using standard procedures combined with specific customized procedures described by Donelick et al. (2005). These customized procedures were designed to maximize recovery of: 1) all possible grain sizes present within a sample by minimizing the potential loss of smaller grain sizes through the use of water-table devices, and 2) complete grains with as close to full terminations by minimizing grain breakage and/or fracturing inherent with the standard procedures typically used to separate individual grains from the original rock material. Use of these procedures results in a significantly greater range of recovered grain sizes, as well as a higher percentage of “complete” grains being retained during the mineral separation process (Fig. 1).

Fig. 1. Example zircon separate from GSS Project 025, showing a wide range in grain-shapes and grain-sizes after sample processing by GSS mineral separation procedures. Importantly, a significant number of tiny grains, as well as complete grains were recovered.

Whole rock samples were first run multiple (minimum = 3) times through a Chipmunk brand jaw crusher with the minimum jaw separation set to 2-3 mm. The crushed material was then sieved through 300 µm nylon mesh, and the <300 µm size fraction washed with tap water and allowed to dry at room temperature. Zircon grains were separated from other mineral species using a combination of lithium metatungstate (density ~2.9 g/cm³), Frantz magnetic separator,
diiodomethane (density ~3.3 g/cm$^3$), and hand-panning separation procedures. Epoxy wafers (~1 cm x 1 cm) containing zircon grains for LA-ICP-MS were polished manually using 3.0 µm and 0.3 µm Al$_2$O$_3$ slurries to expose internal zircon grain surfaces. The polished zircon grain surfaces were washed in 5.5 M HNO$_3$ for 20 s at 21°C in order to clean the grain surfaces prior to introduction into the laser system sample cell.

**LA-ICP-MS Session Details**

LA-ICP-MS data collection was performed at the Geoanalytical Laboratory, Washington State University, Pullman, Washington, U.S.A following conditions and parameters presented in Table 1. Individual zircon grains were targeted for data collection using a New Wave YP213 213 nm solid state laser ablation system using a 20 µm diameter laser spot size, 5 Hz laser firing rate, and ultra high purity He as the carrier gas. Isotopic analyses of the ablated zircon material were performed using a ThermoScientific Element2 magnetic sector mass spectrometer using high purity Ar as the plasma gas. The following masses (in amu) were monitored for 0.005 s each in pulse detection mode(Pb, Th, and U isotopes): 202, 204, 206, 207, 208, 232, 235, and 238.

Table 1. ICP-MS and laser ablations system operating conditions and data acquisition parameters

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<table>
<thead>
<tr>
<th><strong>Laser ablation system: operating conditions</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>New Wave Neodymium: YAG</td>
</tr>
<tr>
<td>Wavelength</td>
<td>213 nm</td>
</tr>
<tr>
<td>Laser mode</td>
<td>Q switched</td>
</tr>
<tr>
<td>Laser output power</td>
<td>10 J/cm$^2$</td>
</tr>
<tr>
<td>Laser warm up time</td>
<td>6 sec</td>
</tr>
<tr>
<td>Shot repetition rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Sampling scheme</td>
<td>spot (20 µm)</td>
</tr>
</tbody>
</table>

At time = 0.0 s, the mass spectrometer began monitoring signal intensities; at time = 6.0 s, the laser began ablating zircon material; at time = 30.0 s, the laser was turned off and the mass
spectrometer stopped monitoring signal intensities. A total of 200 data scans were collected for each zircon spot analyzed comprising: approximately 55 background scans; approximately 20 transitions scans between background and background+signal, approximately 125 background+signal scans. A scheme was developed to check whether mass 238 experienced a switch from pulse to analog mode during data collection and a correction procedure was employed to ensure the use of good quality intensity data for masses 235 and 238 when such a switch was observed.

**UPb Data Analysis**

Previous LA-ICP-MS studies of UPb zircon dating used the so-called intercept method, which assumes that isotopic ratio varies linearly with scan number due solely to linearly varying isotopic fractionation (Chang et al., 2006; Gerhels et al., 2008). The data modeling approach favored here was the modeling of background-corrected signal intensities for each isotope at each scan. Background intensity for each isotope was calculated using a fitted line (for decreasing background intensity) or using the arithmetic mean (for non-decreasing background intensity) at the global minimum of selected isotopes (\(^{206}\)Pb, \(^{232}\)Th, and \(^{238}\)U) for the spot. Background+signal intensity for each isotope at each scan was calculated using the median of fitted (2nd-order polynomial) intensity values for a moving window (7 scans wide here) that includes the scan. The precision of each background-corrected signal intensity value was calculated from the precision of background intensity value and the precision of the background+signal intensity value.

Zircon UPb age standards used during analysis are summarized in Table 2, including the 1099±0.6 Ma FC zircon (FC-1 of Paces and Miller, 1993) used here as the primary age standard. Isotopic data for FC were used to calculate Pb/U fractionation factors and their absolute errors for each FC data scan at each FC spot; these fractionation factors were smoothed session-wide for each data scan using the median of fitted (1st-order polynomial) fractionation factor values for a moving window that includes the current FC spot and scan.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Standard U-Pb age (±2σ)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>1099.0 ± 0.6 Ma</td>
<td>Paces and Miller, 1993</td>
</tr>
<tr>
<td>F5</td>
<td>1099.0 ± 0.6 Ma (assumed equal to FC-1)</td>
<td>Paces and Miller, 1993</td>
</tr>
<tr>
<td>IF</td>
<td>28.201 ± 0.012 Ma</td>
<td>Lanphere et al., 2001; Kuiper et al., 2008</td>
</tr>
<tr>
<td>MD</td>
<td>99.12 ± 0.14 Ma</td>
<td>Renne et al., 1998</td>
</tr>
<tr>
<td>T2</td>
<td>416.78 ± 0.33 Ma</td>
<td>Black et al., 2004</td>
</tr>
<tr>
<td>TR</td>
<td>61.23 ± 0.11 Ma</td>
<td>Dave Chew, personal communication</td>
</tr>
</tbody>
</table>

**Pb/U Fractionation Factor**

Under the operating conditions of LA-ICP-MS sessions, fractionation factors are occasionally found to vary strongly with scan number, decreasing with increasing scan number (presumably
due to increasing ablation pit depth and the effect this has on fractionation; e.g., Paton et al., 2010). The zircon crystal lattice is widely known to accumulate α-radiation damage (e.g., Zhang et al., 2009 and references therein). It is assumed that increased α-damage in a zircon leads to a decrease in the hardness of the zircon; this in turn leads to a faster rate of laser penetration into the zircon during ablation leading to dependence of isotopic fractionation on the degree of zircon lattice radiation damage. Ages calculated for all zircon age standards, when those standards were treated as unknowns, were used to construct a fractionation factor correction curve (exponential form) in terms of accumulated radiation damage. The notion of matrix-matched zircon standard and zircon unknown has been proposed largely on the basis of trace element chemistry (e.g., Black et al., 2004). In this study, time and lattice damage, parameters invisible to instruments used to characterize trace element chemistry, were introduced and applied based on measured U and Th chemistries to effectively matrix-match standard and unknown zircons.

*Common Pb Correction*

Common Pb was subtracted out using the Stacey and Kramer (1975) common Pb model for Earth. Ages and common Pb ratio were determined iteratively using a pre-set, session-wide minimum common Pb age value (default for each session was the age of the oldest age standard which for both Ap and Zrn was 1099 Ma FC-1 and/or FC-5z).

*Preferred Age*

Uranium decay constants and the $^{238}\text{U}/^{235}\text{U}$ isotopic ratio reported in Steiger and Yäger (1977) were used in this study. $^{207}\text{Pb}/^{235}\text{U}_c$ ($^{235}\text{U}_c = 137.88^{238}\text{U}$), $^{206}\text{Pb}/^{238}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages were calculated for each data scan and checked for concordance; concordance here was defined as overlap of all three ages at the 1σ level (the use of 2σ level was found to skew the results to include scans with significant common Pb). The background-corrected isotopic sums of each isotope were calculated for all concordant scans. The precision of each isotopic ratio was calculated by using the background and signal errors for both isotopes. The fractionation factor for each data scan, corrected for the effect of accumulated α-damage, was weighted according to the $^{238}\text{U}$ or $^{232}\text{Th}$ signal value for that data scan; an overall weighted mean fractionation factor for all concordant data scans was used for final age calculation.

Ages and common Pb ratio were determined iteratively using a pre-set, session-wide minimum common Pb age value (default for each session was the age of the oldest age standard which for both Ap and Zrn was 1099 Ma FC-1 and/or FC-5z).

If the number of concordant data scans for a spot was greater than zero, then for grains that yield ages older than ca. 1000 Ma, the $^{207}\text{Pb}/^{206}\text{Pb}$ age is used. For younger grains, the $^{206}\text{Pb}/^{238}\text{U}$ age is used.

Analyses were filtered following the criteria of Gehrels and Pecha (2014). Analyses with >10% uncertainty (1σ) in $^{206}\text{Pb}/^{238}\text{U}$ or the $^{206}\text{Pb}/^{207}\text{Pb}$ age are not included in our analysis. Concordance is based on $^{206}\text{Pb}/^{238}\text{U}$ age/$^{206}\text{Pb}/^{207}\text{Pb}$ age, with 100% = concordant. Analyses with >20% discordance (<80% concordance) or >5% reverse discordance (>105% concordance) are not included.
Preferred Age Precision

Errors for the isotopic ratios $^{207}\text{Pb}/^{235}\text{U}_c$ ($^{235}\text{U}_c = 137.88^{238}\text{U}$), $^{206}\text{Pb}/^{238}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ at each scan included errors from the background-corrected signal values for each isotope, the fractionation factor error, and an additional relative error term required to force 95% of the FC ages to be concordant. Errors for the isotopic ratios $^{207}\text{Pb}/^{235}\text{U}_c$ ($^{235}\text{U}_c = 137.88^{238}\text{U}$), $^{206}\text{Pb}/^{238}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ at each scan included errors from the background-corrected signal values for each isotope, the fractionation factor error, and an additional relative error term required to force 95% of the FC ages to be concordant. Asymmetrical negative-direction and positive-direction age errors were calculated by subtracting and adding, respectively, the isotopic ratio errors in the appropriate age equation (Chew and Donelick, 2012).

References Cited


Lanphere, M.A. and Baadsraard, H., 2001. Precise K-Ar, \(^{40}\text{Ar}/^{39}\text{Ar}\), Rb-Sr and U-Pb mineral ages from the 27.5 Ma Fish Canyon Tuff reference standard. Chemical Geology, v. 175, p. 653-671.


