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Investigating the Paleozoic-Mesozoic low-temperature thermal history of the southwestern Canadian Arctic: insights from (U-Th)/He thermochronology

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ABSTRACT

The Arctic Amerasia Basin, located between the Canadian margin and Alaska, formed by purported Jurassic-Cretaceous rifting related to rotation of the Arctic Alaska-Chukotka microcontinent from northern Laurentia. Rifting may have been accompanied by rift shoulder uplift and cooling that is recorded in low-temperature thermochronometers. Furthermore, the southwestern Canadian Arctic has a widespread Devonian-Cretaceous unconformity with a poorly understood burial-unroofing history. We evaluate new zircon (U-Th)/He thermochronology (ZHe) and organic maturity (VRo) data from Neoproterozoic strata of the Amundsen Basin, Cambrian strata of the Arctic Platform, and Devonian strata of the Franklinian Basin to help resolve the sedimentary thickness deposited and eroded during the time represented by the regional unconformity. ZHe and VRo models identify the thermal maximum occurring between the late Paleozoic-Mesozoic interval. Proximal to the rifted Canadian margin, models estimate 3.7-4.5 km of deposition between the Devonian-Cretaceous, in marked contrast to <1 km towards the craton. Jurassic-Cretaceous exhumation is estimated at 2.3-3.5 km and is more uniform across the region. Whereas the magnitude of burial and erosion can be resolved from modeling, the timing of these events cannot be elucidated with confidence. The thermochronology models can be satisfied by either 1) late Paleozoic-early Mesozoic burial with a thermal maximum prior to Jurassic rifting followed by cooling; or 2) late Devonian maximum burial with gradual unroofing until Cretaceous sedimentation. Although continued deposition into the Mesozoic towards the craton interior seems unlikely, it remains a possibility that there was continued deposition proximal to the rifted Canadian margin.

Keywords: (U-Th)/He thermochronology, Arctic, Banks Island, Amerasia Basin

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49

50 INTRODUCTION

51 Understanding of the pre-Jurassic thermal history along the margins of the Canadian
52 Arctic Islands is limited, despite its importance in the geodynamic evolution of the Sverdrup
53 Basin and the northern Laurentian margin. A regional unconformity spanning Late Devonian to
54 Jurassic-Cretaceous time has been documented south of the Sverdrup Basin, over the Arctic
55 Platform and into the Mackenzie Corridor (**Fig. 1**; Miall, 1976; Jones et al. 1992; Wheeler et al.
56 1996). This unconformity shows a marked jump between higher thermal maturity Paleozoic
57 strata below the unconformity and lower thermal maturity Mesozoic strata above (Issler et al.
58 2012). Some studies indicate that the increase in maturity was a consequence of burial by (now
59 eroded) Upper Devonian strata, such as on Banks Island where Embry (1988) estimated ~5 km
60 of missing Upper Devonian-Lower Carboniferous strata, and Dewing and Obermajer (2009)
61 interpreted ~1.7-2.7 km of eroded Upper Devonian strata. Conversely, seismic and field data
62 from Banks Island has been used as evidence that the eroded strata were deposited during a more
63 protracted period through Devonian to Triassic time (Miall, 1976).

64 Elsewhere in the southwestern Canadian Arctic (**Fig. 2**), thermochronological studies on
65 either side of the unconformity have indicated deposition continued after the Devonian. On the
66 southwest margin of the Sverdrup Basin on Prince Patrick Island an estimated 4.2 km of strata is
67 missing between the Devonian-Jurassic unconformity, with an undetermined age for the eroded
68 strata (Harrison and Brent, 2005). In the Mackenzie-Beaufort Basin, there is an estimated 4 km
69 of missing Permian-Jurassic strata (Issler et al. 2012). Further south in the Mackenzie Corridor,

2.6-3.7 km of Carboniferous-Triassic strata was eroded prior to burial in the Cretaceous (Issler et al. 2005); however the timing of burial and uplift is not conclusive from thermal maturity and thermochronology data with estimated maximum burial in either the Triassic or Permian, before cooling in either Jurassic or Triassic times (Tr./Jr.: Issler et al. 2005; Perm./Tr.: Powell et al. 2016). Nearby sedimentary packages in the Mackenzie-Beaufort Basin and Anderson Plain have been studied using apatite fission track thermochronology (AFT; Issler et al. 2012), and indicate exhumation prior to deposition of Jurassic-Cretaceous sediment. To the south, progressive late Paleozoic-early Mesozoic unroofing of the Slave craton has been documented from apatite (U-Th)/He thermochronology (AHe) and was interpreted to be the result of dynamic topography (Fig. 2; Ault et al. 2009, 2013). More recently, detrital-zircon geochronology data indicates that rifting in the Amerasia Basin commenced in the earliest Jurassic (ca. 200-190 Ma; Midwinter et al. 2016), and therefore uplift and erosion associated with rifting should be recorded as cooling events along the flanks of the Sverdrup and Amerasia basins.

We report new (U-Th)/He zircon thermochronology results from Banks Island, Victoria Island and the Brock Inlier in an attempt to constrain the magnitude of Devonian to Cretaceous burial and unroofing events by testing two time-temperature histories, with either the thermal maximum occurring just prior to rifting in the proto-Amerasia Basin or immediately after deposition of the Devonian clastic wedge. The benefit of using zircon as the thermochronometer is its ubiquity, refractory nature, and typically high U-Th concentration, in addition to its ability to help resolve exhumation histories at shallow crustal conditions. Furthermore, the relationship between radiation damage and diffusion of helium from zircon (Guenther et al. 2013) helps explain significant dispersion in ZHe dates given a variety of pre-depositional histories experienced by each individual zircon in the study areas.

93

94 **GEOLOGICAL SETTING**

95 The bedrock geology from the Brock Inlier to Banks Island records multiple tectonic
96 events and preserves parts of a sedimentary history that encompasses the Neoproterozoic to the
97 Cenozoic. Meso- to Neoproterozoic strata ("Sequence B"; Young et al. 1979) of the Brock Inlier
98 post-date the Grenvillian orogeny (ca. 1200-1000 Ma) and pre-date the break-up of Rodinia (ca.
99 780-720 Ma). These represent sediment deposition in an intracratonic tectonic environment
100 (Amundsen Basin) considered to be an embayment of an epeiric sea that covered northwestern
101 Laurentia between the amalgamation and later break-up of Rodinia (Young, 1981; Rainbird et al.
102 1996). Sequence B strata exposed on the Brock, Minto (Victoria Island), and Cape Lambton
103 (Banks Island) inliers (**Fig. 1**; Rainbird et al. 1996) are part of the Neoproterozoic (Tonian-
104 Cryogenian) Shaler Supergroup, and have a maximum thickness of over 4 km. The units sampled
105 for (U-Th)/He dating in this study are the Nelson Head and Boot Inlet formations from the Brock
106 Inlier, which are overlain by >1 km of younger Neoproterozoic strata, and the Nelson Head
107 Formation in the Minto Inlier where it is overlain by 2-3 km of Neoproterozoic strata (Rainbird
108 et al. 1994). Along the northwestern Laurentian margin, ca. 723 Ma Natkusiak Formation flood
109 basalts and ca. 718 Ma sills on Victoria Island of the Franklin LIP (Ernst et al. 2016), mark the
110 onset of rifting along the margin of the Amundsen Basin (Heaman et al. 1992; Rainbird et al.
111 1998).

112 By the Cambrian, northwestern Laurentia was an established passive margin (Harrison,
113 1995; Durbano et al. 2015). Lower Cambrian sandstone, sampled for (U-Th)/He dating on both
114 Victoria Island and Brock Inlier (**Fig. 2**), unconformably overlie strata of Sequence B. Above
115 Lower Cambrian strata, an extensive carbonate platform developed and persisted through the

Silurian, although the shelf margin stepped back several times (de Freitas et al. 1999; Dewing et al. 2015). Lower Silurian to Lower Devonian sediment was deposited into the northeast part of the Arctic Islands from the Caledonian orogen, produced by the collision of Laurentia and Baltica. Late Silurian to Early Devonian north-south oriented folds, arches and reverse faults are likely related to this event (Miall, 1986). The Coppermine Arch was a regional high during Late Silurian times, and a NW trending thrust fault that parallels the arch axis, juxtaposes Proterozoic strata over Ordovician strata (Jones et al. 1992). This sequence of weakly to undeformed lower Paleozoic strata is termed the Arctic Platform.

By the Middle Devonian, the onset of widespread clastic sedimentation began with the Ellesmerian orogeny, resulting from the collision of a northern landmass into northern Laurentia (Embry, 1988). The orogen produced a foreland basin (Franklinian Basin, **Fig. 1**) in front of the southwestern-directed propagating collisional zone. The Upper Devonian (Frasnian–Famennian) strata sampled for (U-Th)/He dating on Banks Island (**Fig. 2**), represents the uppermost unit in the Franklinian Basin and the youngest preserved succession of proximal Ellesmerian orogen foreland basin sedimentation (Embry, 1988). The thickness of preserved Middle-Upper Devonian clastic strata in the Franklinian Basin is estimated to be between 4 km (Embry, 1988) and 5 km (Embry and Klován, 1976; Harrison, 1995). Patchett et al. (2004) estimated that the Devonian clastic wedge blanketed the Arctic Platform and Canadian Shield with up to 2 km of sediment. Deformation related to the Ellesmerian orogeny is widespread across the Canadian Arctic Islands (Harrison, 1995).

Rifting in the early Carboniferous led to the development of the Sverdrup Basin (**Fig. 1**), accumulating sediment over the deformed lower Paleozoic strata of the Ellesmerian orogen, with rifting persisting until the early Permian followed by thermal subsidence to Jurassic time (Embry

and Beauchamp, 2008). The axial region of the Sverdrup Basin contains ~3 km of upper Paleozoic strata, up to 9 km of Mesozoic strata, and upwards of 3 km of Cenozoic strata (Trettin et al. 1991). Rifting of the proto-Amerasia Basin began in the Jurassic, with consequent seafloor spreading in the Cretaceous, separating the Arctic Alaska-Chukotka microcontinent (AACM) from Arctic Canada (Embry, 1990, 2000). Lastly, the basin was tectonically inverted by the Eurekan orogeny, which occurred from the Paleocene-Eocene due to the counter-clockwise rotation of Greenland into Ellesmere Island (e.g. Heron et al. 2015).

Using the rotational opening plate tectonic model of Grantz et al. (1979, 2011) and Embry (1990), the location of the AACM (**Fig. 1**) prior to its Jurassic-Cretaceous separation and rotation from the northern Laurentian margin places Arctic Alaska adjacent to Banks and Prince Patrick islands (**Fig. 2**). Initial rifting produced grabens on Banks and Prince Patrick islands, containing rocks as old as Middle and Early Jurassic, respectively (Miall, 1979; Harrison and Brent, 2005). Midwinter et al. (2016) proposed that initial rifting commenced as early as ca. 200 Ma, which may have fostered uplift and erosion in the southwestern Arctic, south of the Sverdrup Basin. New zircon (U-Th)/He thermochronological data can provide new estimates on the amount of burial and erosion prior to and following Early Jurassic rifting.

PREVIOUS THERMAL MODELLING STUDIES

For thermochronological modelling, it is essential to have an understanding of regional modern and paleo-geothermal conditions as these are critical data in evaluating the magnitude of burial and exhumation throughout time. There have been several studies estimating the modern and paleo-geothermal gradients in the Mackenzie Corridor and Arctic Islands (Feinstein et al. 1996; Majorowicz and Embry, 1998; Issler et al. 2005; Dewing and Obermajer, 2009; Chen et al.

2010; Hu et al. 2010; Issler et al. 2011, 2012). Bottom hole temperatures (BHT) from 156 wells within the Arctic Islands were used to determine the average modern temperature gradient of $31 \pm 7^\circ\text{C}/\text{km}$, and a Cretaceous-Tertiary gradient of $28 \pm 9^\circ\text{C}/\text{km}$ (Majorowicz and Embry, 1998). More recent work noted the current geothermal gradient to be $23 \pm 7^\circ\text{C}/\text{km}$ from 86 wells within the basin, although the scatter of BHT at depths greater than 2 km is $>40^\circ\text{C}$ (Chen et al. 2010). South of the Sverdrup Basin margin, Majorowicz and Embry (1998) and Dewing and Obermajer (2009) interpreted higher heat flow in the Franklinian Basin on Banks Island with the zone of high modern and paleo-heat flow perhaps attributed to the rifted margin of the Amerasia Basin.

Vitrinite reflectance (VRo) is an organic maturity parameter used for constraining maximum burial in sedimentary basins. Because vitrinite reflectance cannot retrograde, various techniques have been proposed to estimate erosion from VRo-depth relationships (Dow, 1977; Corcoran and Dore, 2005). Following the methodology of Dow (1977), Dewing and Obermajer (2009) interpreted a VRo-depth curve with a 0.6% VRo value at surface in the Muskox D-87 well on Banks Islands as indicating the removal of up to 2.7 km of sediment at this location.

In the Beaufort-Mackenzie Basin, the modern geothermal gradient is $25\text{-}30^\circ\text{C}/\text{km}$, whereas the southeast margin of the basin towards the Anderson Plain is marked by higher geothermal gradients ($30\text{-}50^\circ\text{C}/\text{km}$), which could reflect a higher contribution of heat production from less extended continental crust and possibly contributions from subsurface fluid flow (Issler et al. 2011). Thermal maturity data from the Kugpik O-13 well (**Fig. 2**), indicates a VRo step across the Jurassic-Permian unconformity of 0.2%, which is interpreted to represent up to 4 km of strata removed prior to Jurassic deposition (Issler et al. 2012). It is unknown if the higher paleo-temperature in the pre-rift Permian strata, as recorded by the VRo step, is due to deeper burial or elevated heat flow. AFT data from the Anderson Plain Kugaluk N-02 well suggests

Triassic exhumation with 1-2 km of Cretaceous-Cenozoic reburial that was subsequently removed by erosion (Issler et al. 2012).

Further south, from the East MacKay I-77 well in the Mackenzie Plain (**Fig. 2**), the modern geothermal gradient is measured at 33°C/km with a paleogeothermal gradient interpreted to be 41°C/km from the Carboniferous to Triassic (Issler et al. 2005). Whereas there are no preserved Carboniferous to Jurassic strata in the region, the maximum burial was modeled to be in the Late Triassic (213 ± 20 Ma) using AFT data integrated with shale compaction models, with an estimated missing thickness of 2.7-3.6 km of Carboniferous to Triassic strata (Issler et al. 2005).

On the Slave craton south of the Canadian Arctic Islands (**Fig. 2**), modelling of AHe data suggest that Paleozoic burial exceeded 3 km and reached maximum temperatures, ranging from 80-140°C, in Carboniferous to Middle Triassic time (Ault et al. 2009, 2013). Subsequent erosion occurred during the Paleozoic-Mesozoic, with a western migration of unroofing from ca. 340-225 Ma (Ault et al. 2013). The thermal histories of Ault et al. (2013) require near-surface conditions by the end of the Jurassic, indicative of nearly 3 km of exhumation, prior to 45-80°C of Cretaceous burial and reheating and subsequent erosion in the Cenozoic.

REGIONAL DETRITAL-ZIRCON GEOCHRONOLOGY STUDIES

The interpretation of zircon (U-Th)/He datasets can be complicated by the effects of pre-depositional thermal histories that the zircons have experienced. To assess this complexity, an understanding of the provenance ages for the sedimentary successions is vital prior to interpreting our data. The detrital-zircon ages discussed herein are from either $^{206}\text{Pb}/^{238}\text{U}$ or $^{207}\text{Pb}/^{206}\text{Pb}$ single crystal zircon dates analysed via secondary ion mass spectrometry or laser

ablation–multicollector–inductively coupled plasma–mass spectrometry, as summarized by Hadlari et al. (2012). The Devonian strata of Banks Island are part of the aurally expansive Devonian clastic wedge (Anfinson et al. 2012a, 2012b). U-Pb detrital-zircon age data from the Late Devonian Parry Islands Formation from northeastern Banks Island (**Fig. 3**), the youngest of the Franklinian Basin deposits (Embry and Klovan, 1976), identified two primary detrital-zircon sub-populations of ca. 700-380 Ma (44%) and ca. 2100-900 Ma (50%), with a secondary detrital-zircon population of 2700-2350 Ma (5%; sample PI-8 of Anfinson et al. 2012b).

Detrital-zircon U-Pb data from the Cambrian passive margin of northern Laurentia show two unique age signatures (Hadlari et al. 2012). Hadlari et al. (2012) noted that samples from the Mackenzie Mountains are dominated by detrital-zircon ages reflecting provenance from the Archean craton and Paleoproterozoic terranes, whereas detrital-zircon ages from Victoria Island has minor age sub-population at ca. 1450-900 Ma (14%), a predominant sub-population in the Paleoproterozoic, ca. 2100-1600 Ma (59%), and an Archean sub-population at ca. 2850-2500 Ma (22%; **Fig. 3**). There is one grain with an U-Pb age of 749 ± 24 Ma, assumed to be either part of the Franklin LIP during the breakup of Rodinia (ca. 720 Ma) or the Gunbarrel LIP (ca. 780 Ma; Ernst and Bleeker, 2010); however, this Neoproterozoic age from Victoria Island makes up less than 0.25% of the dataset (Hadlari et al. 2012).

Detrital-zircon data from the Neoproterozoic Nelson Head Formation (Rayner and Rainbird, 2013) display an overwhelming component of Mesoproterozoic ages (ca. 1500-1000 Ma, 83%) with minor Paleoproterozoic (ca. 2100-1700 Ma, 9%) and Archean (ca. 2800-2500 Ma, 8%) components (**Fig. 3**). The (U-Th)/He samples collected as part of this study come from two Neoproterozoic units, the Nelson Head Formation and overlying Boot Inlet Formation, the latter of which yielded a 900 Ma depositional age based on Re-Os data (van Acken et al. 2013).

The youngest detrital grains in the units sampled from the Nelson Head Formation are 1000 Ma (Rayner and Rainbird, 2013); therefore, the inferred age of deposition for these two units is between ca. 1000-900 Ma. The broader provenance studies of Neoproterozoic strata from the Shaler and Mackenzie Mountain supergroups (**Fig. 3**) display a similar distribution of U-Pb ages with populations from ca. 1500-1000 Ma (67%), ca. 2100-1600 Ma (24%), and ca. 3000-2500 Ma (9%; Rainbird et al. 1992, 1996; Villeneuve et al. 1998).

(U-Th)/He THERMOCHRONOLOGY

We analyzed samples along a north-south transect between the Sverdrup Basin and Slave craton, divided into three areas: Banks Island, Victoria Island and the Brock Inlier (**Fig. 2**). The one sandstone sample collected on northern Banks Island is representative of the young part of the Late Devonian Franklinian Basin. Two sandstone samples collected on Victoria Island are representative of the basal Arctic Platform, which began accumulating sediment in the Early Cambrian on the passive margin of northern Laurentia. Three Neoproterozoic sandstone samples and one Cambrian sample were collected from the Brock Inlier. The Cambrian sandstone is similarly belonging to the Arctic Platform whereas the Neoproterozoic samples are representative of the Amundsen Basin.

Zircon (U-Th)/He thermochronology is based upon the retention of alpha particles (^4He), produced during ^{238}U , ^{235}U and ^{232}Th decay. Whereas radiogenic helium readily diffuses from the crystal structure at high temperatures, zircon becomes increasingly retentive of helium as temperature decreases. This temperature range between open and closed system behaviour is termed the partial retention zone (PRZ) and typically corresponds to $\sim 130\text{-}200^\circ\text{C}$ for helium in zircon (Reiners et al. 2004; Hourigan et al. 2005; Wolfe and Stockli, 2010). During burial and

reheating, zircon crystals that reside at high temperatures within or exceeding the PRZ for sufficient time may lose radiogenic helium through thermal diffusion, effectively resetting the (U-Th)/He system. Recent studies suggest that zircon crystals that have accumulated radiation damage in the crystal lattice over geologic timescales may be sensitive to a broader range of temperatures than previously reported (Guenther et al. 2013). Progressive radiation damage increases tortuosity of helium diffusion pathways, impeding thermal diffusion and resulting in a more retentive helium system. However, as radiation damage continues to increase past a certain threshold, fast-diffusion pathways are formed throughout the crystal lattice resulting in increased diffusivity of helium in zircon (Guenther et al. 2013). A useful proxy for radiation damage is the effective uranium (eU) concentration ($eU = U + 0.235 \cdot Th$). When integrated over the time that the zircon has resided at lower temperatures than required for thermal annealing of radiation damage, eU concentrations can be used to estimate zircon-specific diffusion kinetics (Guenther et al. 2013, 2014). ZHe date-eU trends may be negative or positive dependent on the sample's thermal history. Negative correlations, in which ZHe dates decrease with increasing eU, are commonly seen in rocks that have experienced long residence times at low temperatures in the uppermost crust (Guenther et al. 2014; Powell et al. 2016). Reiners et al. (2002) also noted that diffusivity scales with grain volume, suggesting that grain dimensions strongly influence helium diffusion.

Zircon sampled for ZHe thermochronology in this study have presumed different U-Pb ages based on the regional detrital studies (**Fig. 3**; Anfinson et al. 2012b; Hadlari et al. 2012; Rayner and Rainbird, 2013). The broad provenance expected in a single sample means that the pre-depositional history of zircon, including inherited helium and radiation damage, must be considered when assessing relationships between post-depositional thermal history and ZHe

date-eU trends. In an effort to account for variable and unknown pre-depositional histories, Guenther et al. (2015) introduced the concept of the 'inheritance envelope' for ZHe data from sedimentary samples. The inheritance envelope accounts for detrital histories that range from the oldest U-Pb date to the depositional age of the rock to investigate how well post-depositional thermal histories explain ZHe data. This concept is important, as the kinetics of helium diffusion in zircon with extensive pre-depositional histories will be significantly different than those with zero-inheritance due to the effects of long-term radiation damage accumulation in the crystal structure. A zero-inheritance grain is one that has experienced no pre-depositional radiation damage accumulation and has no inherited radiogenic helium, either because it is syn-depositional (i.e. a near-zero U-Pb age at time of deposition) or was fully reset and rapidly exhumed immediately prior to burial in the basin. For example, given a high eU concentration, helium diffusion will occur at lower temperatures in a zircon with an extensive pre-depositional history compared to a zircon with the equivalent eU concentration but zero-inheritance. Correspondingly, the more damaged zircon will have a younger ZHe date (Guenther et al. 2014). At low eU values, a zircon with inherited radiation damage will have lower helium diffusivity, and an older date than a zero-inheritance grain (Guenther et al. 2015). ZHe dates from a sample that is only partially thermally reset should be bound between the zero-inheritance (i.e. depositional age, youngest U-Pb detrital zircon age) and maximum-inheritance curves (Guenther et al. 2015). In this study, inheritance curves are used to represent probable detrital-zircon provenance with respect to the sample location and age. Furthermore, grain size has an impact on eU values (Reiners et al. 2002), so a "grain size envelope" can also be used to bound the curves from the minimum, average, and maximum equivalent spherical radius values.

ANALYTICAL METHODS

Thermochronology

Forty-four zircon grains from seven samples (**Table 1**) were selected for (U-Th)/He thermochronology, conducted at the Thermochronology Research and Instrumentation Laboratory (U-Th)/He facility at the University of Colorado at Boulder, USA. Samples were crushed, sieved (63-250 μm), washed and processed via methylene iodide (MI) heavy liquid techniques at the University of Ottawa, Canada. Despite careful processing, no apatite was recovered. Individual zircon grains are handpicked using a Leica M165 binocular microscope equipped with a calibrated digital camera and capable of both reflected and transmitted, polarized light. The grains are screened for quality, including crystal size, shape, and the presence of inclusions. After characterization, grains are placed into small Nb tubes that are then crimped on both ends. This Nb packet is then loaded into an ASI Alphachron He extraction and measurement line. The packet is placed in the UHV extraction line ($\sim 3 \times 10^{-8}$ torr) and heated with a diode laser to ~ 800 - 1100°C for 5 to 10 m to extract the radiogenic ^4He . The degassed ^4He is then spiked with approximately 13 ncc of pure ^3He , cleaned via interaction with two SAES getters, and analyzed on a Balzers PrismaPlus QME 220 quadrupole mass spectrometer. Degassed grains are then removed from the line, and taken to a Class 10 clean lab for dissolution. Apatite grains, still enclosed in the Nb tubes, are placed in 1.5 mL Cetac vials, spiked with a ^{235}U - ^{230}Th tracer in HNO_3 , capped, and baked in a lab oven at 80°C for 2 h. Zircon are dissolved using Parr large-capacity dissolution vessels in a multi-step acid-vapor dissolution process. Grains (including the Nb tube) are placed in Ludwig-style Savillex vials, spiked with a ^{235}U - ^{230}Th tracer, and mixed with 200 mL of Optima grade HF. The vials are then capped, stacked in a 125 mL Teflon liner, placed in a Parr dissolution vessel, and baked at 220°C for 72

h. After cooling, the vials are uncapped and dried down on a 90°C hot plate until dry. The vials then undergo a second round of acid-vapor dissolution, this time with 200 mL of Optima grade HCl in each vial that is baked at 200°C for 24 h. Vials are then dried down a second time on a hot plate. Once dry, 200 mL of a 7:1 HNO₃:HF mixture is added to each vial, the vial is capped, and cooked on the hot plate at 90°C for 4 h. Once the minerals are dissolved, regardless of the dissolution process, they are diluted with 1 to 3 mL of doubly-deionized water, and taken to the ICP-MS lab for analysis. Mineral standards of Durango apatite (31.5 Ma) and Fish Canyon Tuff zircon (28.2 Ma) are routinely analyzed (degassed and dissolved) in conjunction with the samples with each run to ensure data integrity. Sample solutions, along with standards and blanks, are analyzed for U, Th, and Sm content using a Thermo Element 2 magnetic sector mass spectrometer. Once the U, Th, and Sm contents have been measured, He dates and all associated data are calculated on a custom spreadsheet made by CU TRaIL staff.

Vitrinite Reflectance

Vitrinite reflectance (VRo) measures the amount of light returned from woody organic particles in the rock (e.g. Hartkopf-Fröder et al. 2015). Another method to obtain maturity data is Rock-Eval pyrolysis experiments which produce a thermal maturity parameter (Tmax) that can be converted to a vitrinite reflectance equivalent (Behar et al. 2001; Jarvie, 2001). These parameters record the maximum thermal stress of the rock, and do not retrograde. Converted Tmax and VRo data can be used to validate 1D burial history models using Basin Mod 5.4 software (published by Platte River Associates). Model input data are formation thickness, lithology and age of the rock formations. Crustal heat flow through time and the amount of section that was deposited and subsequently eroded are estimated and entered into the model.

Using these input parameters, a depth versus thermal maturity curve is produced. These modeled depth versus maturity curves are compared to the measured thermal maturity values. The crustal heat flow over time and the amount of sediment deposition and subsequent erosion are varied until a reasonable fit is generated by the software between the modeled maturity and the measured maturity values. Model output is a time-temperature curve that can be compared to those used in the ZHe forward models.

ANALYTICAL RESULTS AND NUMERICAL MODELLING

Zircon (U-Th)/He dating

We report 44 (U-Th)/He zircon ages from seven samples of the southwestern Arctic's lower stratigraphy (**Table 1**). Results are plotted in **Figure 4** as individual zircon (U-Th)/He dates versus eU concentration and equivalent spherical radius (ESR). ZHe ages have a significant degree of dispersion, with a range of 1300 m.y. between the clusters of ages within the Neoproterozoic, Devonian, and Triassic-Cretaceous (**Table 2**). Similarly, the samples have a broad distribution of eU values varying by 1000s of ppm. A few zircon with anomalously young ZHe dates (<15 Ma) and correspondingly high eU concentrations (2415-4235 ppm), are viewed as outliers and are not considered in our modelling or discussion.

Based on our new ZHe ages and available independent geological constraints, we use thermal history modelling in an attempt to constrain the magnitude of burial and exhumation and the maximum temperatures reached for each sample. Furthermore, we try to resolve if either of the following two hypotheses for lower Paleozoic-early Mesozoic thermal histories are viable with the ZHe data: A) sedimentation continued after deposition of the Devonian clastic wedge with maximum burial in the Triassic prior to rapid cooling in Jurassic-Cretaceous as a result of

uplift along the rifted margin of the Amerasia Basin (Miall, 1976; Hadlari et al. 2016; Midwinter et al. 2016); or B) maximum burial occurred in the latest Devonian with protracted cooling until the Cretaceous. We assume the following for each model: 1) the mean surface temperature is 0°C, 2) a geothermal gradient between 25-40°C/km, and 3) the thermal maximum is defined by the onset of rifting in Model A (ca. 200 Ma), or the end of the Devonian in Model B (ca. 355 Ma).

To assess the hypothesis of continued burial during the Carboniferous to Triassic and subsequent cooling in the Jurassic against the previous model of maximum burial in the Devonian, plausible t-T histories were modeled using the HeFTy software program (version 1.8.3; Ketcham, 2005). Commonly, inverse modelling of age data evaluates many more t-T histories to find the path that is statistically consistent with the analytical data; however, this is somewhat complicated by the diverse pre-depositional thermal history experienced by each zircon in a detrital population. This can be circumvented through a forward modelling approach (Guenther et al. 2014; Powell et al. 2016), which can incorporate the possible pre- and post-depositional thermal histories observed in our ZHe date-eU trends. Below, thermal models from the three regions are discussed with respect to our analytical data and incorporate available independent geologic constraints.

Zircon (U-Th)/He modelling

Banks Island

One sample was collected from Upper Devonian strata, either the upper part of the Weatherall Formation or the lowest part of the Parry Islands Formation. The five ages from our sample range from 443 ± 75 Ma to 150 ± 40 Ma. The Banks Island sample generally has lower

eU values than samples from Brock Inlier and Victoria Island with a bimodal population of ZHe dates in the Silurian-Devonian and the Jurassic. Although a negative date-eU correlation exists, it is not as pronounced as the date-eU trends of Victoria Island and Brock Inlier samples. No trends were observed between ZHe date and ESR (**Fig. 4**). The zircon grains from the sample have a smaller average grain size than the other samples, with an average ESR of 36 μm .

Palynological reports from northern Banks Island provide a Frasnian age (383-372 Ma) for the sampled unit (Sweet, 1973; Norris, 1974). The sample is located on the western side of the Banks graben (**Fig. 2**), which preserved Mesozoic strata as old as the Middle Jurassic Awingak Formation (ca. 165 Ma); however outside of the graben, the oldest Mesozoic sediment preserved is the Lower Cretaceous Isachsen Formation (ca. 135 Ma; Miall, 1979). There are variable pre-depositional U-Pb ages with the majority of the U-Pb zircon ages ranging from ca. 700-380 Ma to ca. 2100-900 Ma (Anfinson et al. 2012b). Zircon (U-Th)/He dates from the Middle to Upper Devonian samples of the Franklinian Basin north of Banks Island were reported by Anfinson et al. (2013). Although their results were not modeled, the majority of the reported ZHe ages are older than the depositional ages of the sampled units indicating the zircon have not been thermally reset.

The two different thermal histories are tested with three forward models produced for each scenario: heating from the Devonian to Triassic with subsequent rapid cooling from Jurassic rifting (**Fig. 5A**), and rapid heating in the Devonian followed by protracted cooling until the Cretaceous (**Fig. 5B**). The time of deposition is chosen at 380 Ma. Subsequent to a post-200 Ma cooling episode inferred from the initiation of rifting in the proto-Amerasia Basin (Midwinter et al. 2016), reheating is assumed to have commenced in the Early Cretaceous rather than the Middle Jurassic due to the sample's location outside of the Jurassic graben. Additional

assumptions are that maximum reheating occurs at 55 Ma, which coincides with the youngest part of the Eureka Sound Formation in this area (Miall, 1979). Cretaceous to Cenozoic temperatures are constrained to 80°C on the basis of preserved Cretaceous stratigraphy (Miall et al. 1979). In **Figure 5**, we present t-T models defined by maximum heating at 100°C, 140°C, and 180°C (paths 1, 2, 3, respectively), with each forward model showing inheritance date-eU curves for 380 Ma (zero-inheritance), 700 Ma, 900 Ma and 2100 Ma to highlight the difference in date-eU trends for the end-members of the detrital zircon U-Pb age sub-populations. The ZHe models fail to explain the analytical data at 180°C for both scenarios, but it cannot resolve between the two candidate t-T paths at 100°C and 140°C (paths 1, 2: **Fig. 5**).

Victoria Island

The two Victoria Island samples were collected from Cambrian sandstone near Minto Inlet (Quyuk formation; Durbano et al. 2015). The two samples yielded twelve single ZHe zircon dates with significant dispersion, ranging from 1302 ± 91 Ma to 40 ± 12 Ma. Six of the ZHe ages retain an age older than that of deposition. The date-eU comparison exhibits a strongly negative correlation. The Victoria Island sample has bimodal population of ZHe ages, with dates in the Neoproterozoic and in the Mesozoic; however, there is variance within these broad groupings. There are two sub-populations of grain dimensions identified, (**Fig. 4**) displaying a positive correlation in ZHe date-ESR diagram. The zircon from the two samples have an average ESR of 45 μm .

The sandstone unit contains trilobites belonging to the late Early Cambrian (or Late Cambrian series 2; Hadlari et al. 2012). The majority of the detrital-zircon U-Pb ages are from a range of 2100-1500 Ma. The passive margin of the Arctic Platform developed an approximately

2 km thick succession from the Cambrian to Silurian (Dewing et al. 2013). Subsequent deposition of the Devonian clastic wedge placed another ~2 km of sediment over the region. The only comparable temperature data are VRo values from the Victoria Island F-36 well, which has ~1.2% VRo (~150°C) in Silurian strata (Dewing et al. 2007) and Rock-Eval Tmax of 477°C (~170°C) from Lower Devonian shale on the northern part of the island (unpublished data, Geological Survey of Canada). The VRo at the base of the Lower Cretaceous-Eocene Eureka Sound Group is nearly consistent across the Arctic to produce a ~0.4% VRo indicative of a uniform sedimentary blanket across the central and western Canadian Arctic Islands (Bustin, 1986), so it is assumed there was reheating during the Cretaceous-Cenozoic boundary near our sample locations, but less than that on Banks Island.

The burial history of Victoria Island is assumed to reflect that of Banks Island; however, with the absence of post-Devonian strata on Victoria Island, the late Paleozoic-Mesozoic burial history is more challenging to elucidate. The t-T models assess the thermal history for both continued Carboniferous to Triassic heating, or maximum burial in the Devonian with protracted cooling until the Cretaceous (**Fig. 6A**) with each forward model showing inheritance date-eU curves for 520 Ma (zero-inheritance), 900 Ma, 1500 Ma, 2100 Ma and 3000 Ma to demonstrate the difference in date-eU trends for the predominant detrital zircon U-Pb sub-populations. The depositional age is assumed to be 520 Ma. Using a cooler paleo-thermal gradient of 25°C/km with the Cambrian-Silurian passive margin succession, heating is to 50°C, compared to 60°C in the Devonian using a 30°C/km paleo-thermal gradient with the convergent margin succession. Because our ZHe data are unable to resolve the lower temperature history from Jurassic to present, forward models follow stratigraphic constraints that suggest Jurassic cooling to 40°C, and Cretaceous reheating to 60°C. In **Figure 6A**, the model cannot resolve between the timing of

maximum burial, however the inheritance curves which fit the data provide candidate t-T paths when less than or equal to an additional 30°C is invoked with a thermal maximum of 140°C.

Brock Inlier

Three samples were collected from Neoproterozoic strata of the Brock Inlier. Two samples are from the Nelson Head Formation, and a third sample is from the lower part of the overlying Boot Inlet Formation. The three samples yielded 24 ZHe dates on Neoproterozoic to Cambrian strata. The Cambrian sandstone is assumed to be of similar age and detrital-zircon provenance as the Early Cambrian samples collected from Victoria Island, with five single ZHe dates ranging from 1085 ± 76 Ma to 107 ± 8 Ma. The Neoproterozoic samples, from the Nelson Head and Boot Inlet formations, yielded 19 ages with significant dispersion, ranging from 1118 ± 78 Ma to 57 ± 5 Ma with four of the ages greater than the assumed depositional age of 900 Ma (**Fig. 6B**). Similar to the Victoria Island samples, there is a negative date-eU correlation. Whereas no correlation exists between ZHe date and ESR, there are two sub-populations of grain dimensions identified (**Fig. 4**). Zircons from the three Neoproterozoic samples have an average ESR of 43 μm .

The Brock Inlier preserves about ~1 km of Neoproterozoic strata above the Nelson Head Formation (Rainbird et al. 2016), whereas elsewhere in the Amundsen Basin another ~2-3 km of younger Neoproterozoic strata is preserved on Victoria Island (Rainbird et al. 1994). Above the Neoproterozoic strata is the unconformity with Cambrian strata of the Arctic Platform. The predominant zircon provenance ages for the Nelson Head Formation are between 1500-1000 Ma, which defines >90% of the data. The Brock Inlier preserves ~0.3 km of Cambrian-Ordovician strata (Rainbird et al. 2016), but possesses minimal Devonian strata even though 2 km of

Devonian siliciclastics were interpreted to have blanketed the region (Patchett et al. 2004). Above the regional Devonian-Cretaceous unconformity, at the base of the Lower Cretaceous Langton Bay Formation, Yorath and Cook (1981) identified incised valleys, and interpreted the valley fill to be Jurassic in age; there are, however, no paleontological reports confirming this. The earliest deposition over the region is assumed to have commenced with the early Albian Langton Bay Formation (ca. 110 Ma) and terminated with the late Albian Horton Bay Formation (ca. 100 Ma), confirmed by paleontological data (Jeletzky, 1966). Cretaceous sediment has been measured as up to 0.6 km thick on the Brock Inlier (Jones et al. 1992), and 2 km on the Anderson Plain (Issler et al. 2012). Furthermore, the Slave craton has an estimated Cretaceous burial of ≤ 1.4 km from vitrinite reflectance of sedimentary xenoliths (Stasiuk et al. 2006), or ≤ 1.6 km from thermochronometry modelling (Ault et al. 2013). Thermal models from the Anderson Plain (Issler et al. 2012) and the Slave craton (Ault et al. 2009, 2013) suggest minimal Late Cretaceous reheating from ~ 20 – 80°C .

The t-T models are used to identify plausible burial temperatures and to evaluate our data against proposed heating of the Neoproterozoic strata during the Devonian to Triassic, or maximum burial in the Devonian with protracted cooling until the Cretaceous (**Fig. 7B**). Each forward model shows inheritance date-eU curves for 1000 Ma (youngest U-Pb age), 1500 Ma, 2100 Ma and 3000 Ma to highlight the difference in date-eU trends for the predominant detrital-zircon U-Pb age sub-populations. The depositional age is presumed to be 900 Ma (van Acken et al. 2013). The forward models assume maximum burial of 3 km by 720 Ma, when rifting of Rodinia resulted in cooling, preserving 1 km of Neoproterozoic strata prior to Cambrian deposition. We invoke limited (10°C) Cambrian-Ordovician heating, with 60°C of heating occurring from deposition of the Devonian clastic wedge. Forward models reach 40°C during

Jurassic cooling and 60°C during Cretaceous reheating. **Figure 6B** shows a candidate t-T path attaining maximum heating at 120°C, however the data cannot resolve the timing of the thermal maximum. Therefore, similar to Victoria Island, when we invoke additional heating equal to or less than 20°C, the models are acceptable.

VRo modelling

In order to resolve between the two plausible thermal maximums on Banks Island, the acceptable t-T pathways from the ZHe forward models were checked against 1D burial history models of the Musko D-87 well from VRo data (**Fig. 7A**). The burial history model using maximum burial at 200 Ma obtained a fit between the model and the measured thermal maturity values using: 1) heat flow of 45 mW/m² up to 210 Ma, rising to 60 mW/m² at time of rifting (200 Ma), then decreasing to 45 mW/m² at 140 Ma; 2) deposition of 2 km of Late Devonian strata on top of the existing 1.8 km of Devonian strata, erosion of 0.3 km during earliest Carboniferous time, followed by deposition of 1.7 km of upper Paleozoic and Mesozoic strata (using the relative stratigraphic thicknesses preserved in the Jameson Bay C-31 well on Prince Patrick Island), erosion of 2.3 km between 200-132 Ma, 1.7 km of Cretaceous burial and 2.8 km of Tertiary erosion. The resulting t-T curve (**Fig. 7B**) shows a maximum temperature of 106°C at around 210 Ma, similar to ZHe forward model shown in path 1 (**Fig. 5A**). Acceptable fits could not be obtained for higher temperature curves shown in paths 2 or 3; therefore, path 1 is the favourable thermal history.

The burial history model using maximum burial at the end of Devonian clastic wedge deposition (360 Ma) obtained a fit between the model and the measured thermal maturity values using: 1) heat flow of 55 mW/m² up to 210 Ma, rising to 60 mW/m² at time of rifting (200 Ma),

then decreasing to 45 mW/m² at 140 Ma; 2) deposition of 4.5 km of Late Devonian sandstone above the 1.4 km of existing Devonian clastic wedge (total Devonian clastic wedge thickness of 6.3 km), 3.5 km of erosion between 355-132 Ma, deposition of 1.7 km of Cretaceous strata and 2.7 km of Tertiary erosion. The resulting t-T curve (**Fig. 7C**) shows a maximum temperature of 107°C at about 355 Ma, similar to zircon forward model shown in path 1 (**Fig. 7B**). Acceptable fits could not be obtained for higher temperature curves shown in paths 2 or 3. VRo models were able to constrain the thermal maximum for each scenario, but like the ZHe models, could not resolve between the timing of maximum burial.

DISCUSSION

The ZHe dates examined in this investigation exhibit a significant degree of dispersion which likely is a consequence of protracted thermal histories with eU concentrations varying by 1000s ppm. The date-eU plots (**Fig. 4**) reveal a strongly negative correlation for all the samples that may be a result of a reheating episode or a sustained period through the zircon PRZ (Guenther et al. 2014, 2015). The candidate t-T paths from the forward models (path 1: **Fig. 5**; **Fig. 6**) illustrate that the maximum burial temperatures from Banks Island to Brock Inlier do not exceed 140°C. Temperatures higher than this are not supported by our analytical data as the inheritance curves match nearly none of the data points. Burial history models of one well from Banks Island also support the lower end of the t-T models, with maximum temperature of about 105-110°C (**Fig. 7B, C**). There are two notable grouping in the date-eU trends: 1) zircon with relatively low eU values (100s ppm) and a ZHe date often greater than the age of deposition, possibly due to low radiation damage and higher closure temperatures, and 2) younger ZHe ages with generally higher eU values (1000s ppm), probably due to increased radiation damage and

increased diffusivity. These two groups reflect the broad range of pre-depositional histories and associated radiation damage within each sample, contributing to significant dispersion in ZHe dates and eU concentrations.

The t-T paths based on ZHe forward models and VRo inverse models assess the magnitude of burial and uplift between the Devonian-Cretaceous unconformity, for either of the two end-member thermal histories: (1) protracted heating continuing from the Devonian to the Triassic, with rapid cooling as a result of Jurassic rifting, or (2) rapid heating in the latest Devonian with protracted cooling until the Cretaceous. The models from Banks Island identify either 3.7 km (2.0 km in the latest Devonian and 1.7 km in the Carboniferous-Triassic) or 4.5 km (latest Devonian) of missing thickness with a thermal maximum of 105-110°C. The model for continued burial into the Triassic suggests a thinner stratigraphic package due to high heat flow as a result of rifting in the proto-Amerasia Basin. On both Victoria Island and Brock Inlier, the modelled maximum temperatures are 140°C and 120°C respectively, which represents less than 1 km of additional burial between the Devonian-Cretaceous unconformity.

These thickness results are similar to previous studies that quantify the preserved thickness of late Paleozoic-early Mesozoic strata in the Canadian Arctic and Arctic Alaska. North of Banks Island is Prince Patrick Island (**Fig. 2**) where preserved Carboniferous to Triassic strata of the Sverdrup Basin is estimated to be ~4.5 km thick, determined from field mapping, well data and seismic profiles from the SW to NE of the island (Harrison and Brent, 2005). This is in marked contrast to the 9 km of Mississippian to Lower Jurassic strata in the axis of the Sverdrup Basin (5 km of upper Paleozoic strata and up to 4 km of Triassic siliciclastic sediments; (Embry and Beauchamp, 2008). The Mississippian to Early Jurassic sequence in Arctic Alaska has a typical thickness of 2 km (Moore et al. 1994) and reaches up to 6 km in parts of the Arctic

Alaska Basin axis (Hubbard et al. 1987). Along the Alaska (Beaufort) Rift shoulder, this sequence is ~1 km in the Kuparuk 3-11-11 well (**Fig. 2**). Towards the axis of the Hanna Trough, this sequence thickens dramatically to 9.5 km (6 km of Upper Devonian-Permian and 3.5 km of Permian-Early Jurassic; Sherwood et al. 2002). Previous investigations of the thickness of missing strata between the Devonian and Cretaceous unconformity in the southwestern Canadian Arctic provide a scatter of values. Data from the Mackenzie Delta suggests up to 4 km of missing Permian to Jurassic strata (Issler et al. 2012). Embry (1988) suggested that Banks Island was missing up to 5 km of post-Devonian strata, whereas Anfinson et al. (2013) interpret that their Franklinian Basin Devonian samples were not buried to depths greater than 7 km.

When quantifying the erosion, whether the result of rapid uplift associated to Jurassic rifting, or protracted late Paleozoic-Mesozoic exhumation, the thicknesses are similar across the southwestern Canadian Arctic. From the ZHe and VRo models, Banks Island is interpreted to have either 2.3 km of erosion if the thermal maximum is at 200 Ma, or 3.5 km if the thermal maximum is at 355 Ma. Victoria Island and Brock Inlier experience a similar temperature decrease of 70-100°C and 60-80°C respectively, corresponding to ~2.3-3.3 km and 2-2.7 km of sediment erosion, respectively, assuming a paleo-geothermal gradient of 30°C/km. These results are similar to previous studies investigating the amount of late Paleozoic-early Mesozoic erosion in northern Laurentia. On Prince Patrick Island, near the Intrepid H-49 well, sub-Jurassic erosion is interpreted to have removed ~4.2 km of strata, and on nearby Eglinton Island, Middle Jurassic strata overlie Middle-Upper Devonian strata, as regional mapping suggests >4.2 km of section was removed by pre-Middle Jurassic erosion (Harrison and Brent, 2005). Further south in the Mackenzie Corridor 2.6-3.7 km of exhumation was estimated prior to Cretaceous deposition (Issler et al. 2005).

One of the goals of this study was to assess how plausible both hypotheses are with regards to the new ZHe data. The t-T thermal models cannot discount either maximum burial in the Triassic or the Devonian. The scenario with the maximum burial in the Devonian is the generally accepted thermal history followed by gradual uplift, erosion and recycling of material into the Sverdrup Basin (e.g. Embry and Beauchamp, 2008), but there is support for the alternative thermal history of continued deposition into the early Mesozoic (Lerand, 1973; Miall, 1976). Since the ZHe data cannot resolve between the two, we will review the evidence of continued deposition into the Triassic to test the plausibility of this thermal history. Burial from southerly-derived sediment in the late Paleozoic-early Mesozoic is consistent with further inboard unroofing to the south over the Mackenzie Platform (Powell et al. 2016) and Slave craton (Ault et al. 2013) which had migrating western unroofing from ca. 340-225 Ma. Miall (1976) provided indirect evidence to postulate that upper Paleozoic and Mesozoic rocks may have been deposited over Banks Island, specifically a wedge of possible upper Paleozoic strata imaged on seismic data from offshore Banks Island (Lerand, 1973) and the observation that sandstone of the Lower Cretaceous Isachsen Formation is coarser than the Devonian siliciclastics in the region indicating that the Isachsen Formation was derived from another source. Furthermore, sandstone from the Upper Cretaceous Kanguk Formation on northern Banks Island contains pebble-sized coral fragments of Early Permian age (Miall, 1979).

The Early Jurassic extensional period, marked by the rift onset unconformity of the Sverdrup Basin (ca. 200-190 Ma; Hadlari et al. 2016; Midwinter et al. 2016), provides a mechanism for uplift and exhumation on the rift shoulders from the Jurassic to Early Cretaceous, the syn-rift phase of the Amerasia Basin. It was not until after the breakup unconformity (ca. 130 Ma; cf. Embry and Beauchamp, 2008), which marks the end of uplift prior to Cretaceous

deposition (**Fig. 8**), that seafloor spreading and the creation of oceanic crust allowed for the counter-clockwise rotation of the AACM from northern Laurentia (Embry, 1990, 2000). Outside of the Sverdrup and Arctic Alaska basins, the syn-rift strata are only preserved in these extensional features.

On central Banks Island, ~0.4 km of Lower Jurassic (?) to Lower Cretaceous strata was intersected by a well (Castel Bay C-68) that are inferred to have been deposited in a narrow graben (Miall, 1979), and the small grabens and half-grabens on Prince Patrick Island preserve Lower Jurassic strata (Harrison and Brent, 2005). The Mackenzie-Beaufort Basin preserves ~1 km of Jurassic-Lower Cretaceous syn-rift sediment (Issler et al. 2012), whereas in Arctic Alaska, the Dinkum Graben and related half grabens contain more than 3 km of Jurassic-Lower Cretaceous strata (Hubbard et al. 1987). While Carboniferous-Triassic pre-rift strata are clearly not preserved in the southwestern Canadian Arctic, recent analysis of seismic data from the Dinkum Graben (Houseknecht and Connors, 2016) identified a thin Mississippian-Triassic succession overlying Devonian strata. From these lines of evidence, it is challenging to conclusively determine whether Banks Island had continued deposition into the Mesozoic. It is less likely that the regions of Victoria Island and Brock Inlier had burial into the Triassic given the low amount of additional heating after the Devonian from the ZHe models and the late Paleozoic-early Mesozoic unroofing in the cratonic interior. Yet on Banks Island, proximal to the rifted margin, the ZHe and VRo models, the comparison of syn-rift strata preserved or missing in the southwestern Arctic, and the geologic evidence from Miall (1976, 1979), it remains plausible for deposition to have persisted after the Late Devonian with Jurassic-Cretaceous uplift linked to the opening of the Amerasia Basin. If there was continued sedimentation into the Triassic, Banks

Island could represent a continuation of the margins of either the Sverdrup or Arctic Alaska basins.

CONCLUSIONS

The intra-sample zircon (U-Th)/He age dispersion from Banks Island, Victoria Island and the Brock Inlier and strongly negative date-eU correlations indicate a protracted residence in the zircon helium partial retention zone. Using ZHe date, eU values, and grain size, we are able to evaluate several temperature-time models of late Paleozoic-Mesozoic basin evolution in order to constrain the thermal maximum and magnitude of burial and exhumation. The models also assess two different thermal histories, the scenario of continued late Paleozoic-early Mesozoic deposition with the thermal maximum prior to Jurassic rifting, and the scenario of maximum burial in the Devonian. Whereas the ZHe and VRo models can constrain the maximum temperature, the models cannot resolve the timing of maximum burial; therefore the data cannot exclude either scenario. When evaluating the magnitude of burial between the Devonian-Cretaceous unconformity, the north-south transect of our study reveals variable amounts of missing strata, decreasing south towards the craton (≤ 1 km), with substantial sedimentary accumulation on Banks Island (~ 3.7 - 4.5 km). The amount of exhumation along the transect is less variable with a similar amount on Banks Island (2.3 - 3.5 km), Victoria Island (2.0 - 2.7 km) and Brock Inlier (2.3 - 3.3 km) indicative of potentially more uniform uplift. ZHe thermochronology, in conjunction with VRo modelling, is able to discern the thermal maximum of each sampled region with its broad pre-depositional history of the detrital zircons, but in this case is unable to resolve the timing of the thermal maximum.

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Tables

1. Sample coordinates and stratigraphic position of samples from southwestern Arctic

2. Single zircon (U-Th)/He data from samples of the southwestern Arctic

Figure Captions

Figure 1: Map of the Arctic depicting the basins and regions mentioned in the text. AA: Arctic Alaska; AACM: Arctic Alaska-Chukotka microcontinent; CH: Chukotka; PE: Pearya. Outline of AACM (black line) from Drachev (2011). Rotation of AACM away from the Canadian margin illustrated by the black arrows (from Embry, 2000). Sverdrup Basin from Embry and Beauchamp (2008); Franklinian Basin from Anfinson et al. (2013); Arctic Platform from Dewing and Obermajer (2009); Amundsen Basin from Rainbird et al. (1996). Red dashed polygon denotes the location of Figure 2.

Figure 2: Simplified tectonic map of south Arctic Islands and northwestern Laurentia (adapted from Ault et al. 2013) showing locations of (U-Th)/He samples dated in this study, sample locations of Ault et al. (2009, 2013) within the Slave craton, and sample locations of Anfinson et al. (2013) within the Franklinian Basin. Outline of Arctic Alaska represents the restored position prior to the opening of proto-Amerasia Basin, based on Nokleberg et al. (2000). Large black arrow represents direction of progressive late Paleozoic-early Mesozoic cooling/unroofing of the Slave craton, interpreted by Ault et al. (2013). Select wells (x) referenced from Issler et al. (2005, 2012), Dewing et al. (2007), Dewing and Obermajer (2009), and Bird and Houseknecht (2011). The Banks graben (Dewing and Obermajer, 2009) and Dinkum Graben (Houseknecht and Connors, 2016) are Jurassic rift structures. Sverdrup Basin outline from Embry and

943 Beauchamp (2008). Generalized basin axes of the Sverdrup Basin, Arctic Alaska Basin and
944 Hanna Trough from Gottlieb et al. (2014). AP: Anderson Plain; DG: Dinkum Graben; EI:
945 Eglinton Island; PP: Prince Patrick Island; WCSB: Western Canada Sedimentary Basin.

946
947 Figure 3: Published U-Pb detrital zircon age spectra as a reference for zircon inheritance for (U-
948 Th)/He samples dated in this study. Banks Island: Devonian Parry Islands Formation (PI-8:
949 Anfinson et al. 2012b); Victoria Island: Lower Cambrian sandstone (Sample C-E; Hadlari et al.
950 2012); Brock Inlier: Neoproterozoic Nelson Head Formation on Victoria Island (Rayner and
951 Rainbird, 2013), and Neoproterozoic strata of the Shaler/Mackenzie Mountain Supergroup
952 (Rainbird et al. 1992, 1996, 1997; Villeneuve et al. 1998).

953
954 Figure 4: (U-Th)/He zircon date versus eU diagram, and (U-Th)/He zircon date versus equivalent
955 spherical radius (ESR) diagram, divided into the three study areas. Major tectonic events of
956 northern Laurentia are highlighted in the timeline on the right. The three different deposition
957 ages for the sample locations are indicated by a horizontal dotted black line. The coloured
958 horizontal boxes correspond to the duration of sediment accumulation within the basin (same
959 colour scheme as Figure 1).

960
961 Figure 5: Forward thermal history models from Devonian strata of Banks Island using zircon (U-
962 Th)/He data. Single zircon date and eU shown on each graph as square symbol with associated
963 error. The timing of the inheritance curves is derived from the U-Pb detrital studies (Figure 3).
964 Thermal model A has peak burial ca. 200 Ma; thermal model B has peak burial ca. 355 Ma.
965 Cretaceous burial of 2 km based on Dewing and Obermajer (2009). Time-temperature plot shows

thermal pathways 1-3; forward models illustrate the expected ZHe inheritance date-eU curves for: (1) maximum temperature at 100°C; (2) maximum temperature at 140°C; (3) maximum temperature at 180°C. Inheritance curves correspond to date-eU trends for zircon between 26-46 μm ESR, and describe the effect of the pre-depositional history and accumulated damage on ZHe dates. The solid line in each inheritance curve represents the projected date-eU trend for a zircon with a 36 μm ESR (mean value).

Figure 6: Forward thermal history models using zircon (U-Th)/He data. Single zircon date and eU value shown on each graph as square symbol with associated error; time-temperature plot shows peak burial at 200 Ma (black line), and 355 Ma (dashed black line), with the corresponding date-eU plot for each scenario. Inheritance curves describe the effect of the pre-depositional history and accumulated damage on ZHe dates, which are derived from the U-Pb detrital-zircon studies (Figure 3) and the solid line in each inheritance curve represents the projected date-eU trend for a zircon with the mean ESR value. (A) Cambrian strata of Victoria Island. For time-temperature plots, passive margin sedimentation of 2 km based on Dewing et al. (2013); Devonian clastic thickness of 2 km based on Patchett et al. (2004); Cretaceous burial is interpreted; date-eU plot is for a maximum temperature at 140°C. See Supplementary Material for more date-eU plots at 110°C and 170°C. Inheritance curves correspond to date-eU trends for zircon between 31-67 μm ESR with the solid line representing the projected date-eU curve for 45 μm ESR (mean value). (B) Neoproterozoic strata of the Brock Inlier. For time-temperature plots, Amundsen Basin accumulation (3 km) and preservation (1 km), and passive margin sedimentation of 0.3 km based on Rainbird et al. (2016); Devonian clastic thickness of 2 km based on Patchett et al. (2004); Cretaceous burial is based on Jones et al. (1992); date-eU plot is

for a maximum temperature at 120°C. See Supplementary Material for more date-eU plots at 100°C and 160°C. Inheritance curves correspond to date-eU trends for zircon between 31-59 µm ESR with the solid line representing the projected date-eU curve for 43 µm ESR (mean value).

Figure 7: (A) Vitrinite reflectance and RockEval Tmax data for Musko D-87 well on Banks Island (Dewing et al. 2007). Blue diamonds are RockEval Tmax values (converted) and green squares are vitrinite reflectance (VRO); EasyRo calibration used from Sweeney and Burnham (1990). Forward models of (B) peak burial at 200 Ma and (C) peak burial at 355 Ma; corresponding acceptable-fit curves (green line) using Basin Mod 5.4 software compared against time-temperature path 1 from Figure 5A and B (black line).

Figure 8: (A) Plausible time-temperature pathways for each region from ZHe (black) and VRO models (green) for two thermal histories: thermal maximum in the Triassic (solid line) and thermal maximum in the Devonian (dashed line). Synoptic north-south cross section of southwestern Canadian Arctic for the scenario of maximum burial at 200 Ma showing (B) Triassic pre-rift and (C) Jurassic syn-rift phase of the Amerasia Basin, with subsequent uplift until deposition commenced in the Cretaceous (ca. 135 Ma). Location of cross section on Figure 2, and note vertical scale change between (B) and (C). Thickness constraints for cross section sourced from Bird and Houseknecht (2011) for Kugparuk 3-11-11 well; from Hubbard et al. (1987) for Dinkum Graben; from Dewing and Embry (2007) for E-76, C-68, D-16, F-36 wells; from Ault et al. (2013) for the Slave craton. For discussion on other Victoria Island and Brock Inlier constraints, see Results section.

Table 1

Sample coordinates and stratigraphic position of samples from southwestern Arctic

Sample Name	Location	Unit	Age	Latitude (N)	Longitude (W)
C-033289	Banks Island	Parry Islands Formation /Weatherall Formation	latest Devonian (Famennian- Frasnian)	74.134	-118.670
C-457858	Victoria Island	unnamed Cambrian Sandstone	Early Cambrian (Series 2)	71.433	-115.435
C-542504		unnamed Cambrian Sandstone	Early Cambrian (Series 2)	71.499	-114.993
Brock	Brock Inlier	Mount Clark Formation	Early Cambrian	69.150	-121.883
14RAT514A1		Boot Inlet Formation	Neoproterozoic (Tonian)	69.006	-122.664
14RAT518C1		Nelson Head Formation	Neoproterozoic (Tonian)	69.348	-122.918
14RATA1004B1		Nelson Head Formation	Neoproterozoic (Tonian)	69.342	-122.945

Table 2

Single zircon (U-Th)/He data from samples of the southwestern Arctic

Sample Name	ESR ¹ (μm)	Mass (μg)	U (ppm)	Th (ppm)	Th/U	He (nmol/g)	eU (ppm)	Ft ¹	Corr. Age ¹ (Ma)	Full Unc. ¹ (Ma)
Banks Island (Devonian)										
C33289zr01	36.5	2.12	703.4	90.8	0.129	1088.5	725	0.70	390.3	75.6
C33289zr02	45.7	4.35	1084.7	716.8	0.661	891.1	1253	0.75	174.0	20.1
C33289zr03	26.5	0.93	803.9	215.2	0.268	1117.9	854	0.60	397.1	145.9
C33289zr05	31.7	1.44	1252.9	1040.5	0.831	796.1	1497	0.65	150.1	39.8
C33289zr06	41.6	3.92	508.0	274.6	0.541	1022.3	573	0.73	442.6	75.0
Victoria Island (Cambrian)										
C524504zr02	59.6	5.27	116.5	295.1	2.532	597.6	186	0.79	713.0	49.9
C524504zr03	56.3	6.59	168.6	430.2	2.552	1631.1	270	0.78	1302.0	91.1
C524504zr04	36.3	1.49	2596.8	2814.1	1.084	2841.1	3258	0.67	236.2	16.5
C524504zr05	57.6	6.06	447.9	432.3	0.965	1898.6	549	0.79	759.1	53.1
C524504zr06	66.9	6.85	231.1	452.3	1.957	1342.7	337	0.82	846.5	59.3
C524504zr07	46.4	2.60	233.0	370.6	1.590	1340.5	320	0.74	971.3	68.0
C457858zr01	37.2	2.69	450.6	599.3	1.330	475.8	591	0.70	211.8	45.0
C457858zr02	44.2	3.90	223.6	414.0	1.851	1037.3	321	0.74	778.1	97.4
C457858zr04	36.1	2.30	1660.7	3750.7	2.258	427.8	2542	0.68	45.5	9.9
C457858zr05	31.3	1.53	1224.6	2589.7	2.115	257.2	1833	0.64	40.4	11.5
C457858zr06	44.5	3.84	2952.7	5456.6	1.848	77.3	4235	0.74	4.6	0.5
C457858zr07	34.0	1.95	696.7	1194.8	1.715	501.4	978	0.67	141.2	35.1
C457858zr08	36.0	1.95	966.3	1171.1	1.212	690.5	1242	0.69	148.8	28.1
Brock Inlier (Cambrian)										
Brock.zr01	36.3	1.25	4251.9	3293.6	0.775	2105.5	5026	0.67	114.3	8.0
Brock.zr03	35.2	1.36	2659.7	1691.9	0.636	1187.2	3057	0.66	107.2	7.5
Brock.zr04	35.7	1.10	749.3	209.8	0.280	2247.6	799	0.67	724.7	50.7
Brock.zr06	45.3	2.33	360.5	159.8	0.443	1114.7	398	0.74	661.8	46.3
Brock.zr08	42.6	2.24	196.7	215.5	1.095	1142.1	247	0.72	1085.2	76.0
Brock Inlier (Neoproterozoic)										
14RAT514zr01	34.9	1.35	1896.3	1359.1	0.717	1342.0	2216	0.66	167.4	11.7
14RAT514zr02	32.0	0.76	2405.5	1396.5	0.581	72.5	2734	0.63	7.8	0.6
14RAT514zr03	34.8	1.05	416.8	340.0	0.816	2181.1	497	0.66	1118.1	78.3
14RAT514zr04	43.2	1.88	734.6	415.8	0.566	1879.1	832	0.73	549.5	61.1
14RAT514zr05	38.4	1.84	6967.7	4352.2	0.625	2038.1	7990	0.69	67.9	11.5
14RAT514zr06	36.5	1.14	691.3	1133.9	1.640	2337.3	958	0.67	642.8	45.0
14RAT514zr07	31.4	0.91	177.2	222.7	1.257	595.2	230	0.64	703.3	56.3
14RAT518C1zr01	46.9	6.11	1710.0	542.3	0.317	522.1	1837	0.76	69.3	9.0
14RAT518C1zr02	42.2	3.75	276.7	203.4	0.735	859.7	324	0.73	646.5	100.8
14RAT518C1zr04	43.2	1.88	235.5	281.5	1.195	1178.3	302	0.72	928.3	65.0
14RAT518C1zr05	38.4	1.84	386.8	237.0	0.613	1686.5	443	0.69	937.7	65.6
14RAT518C1zr06	32.0	1.89	1121.7	357.9	0.319	310.9	1206	0.66	72.5	21.2
14RAT518C1zr07	46.3	4.75	748.3	259.4	0.347	772.7	809	0.75	231.4	27.0
14RAT518C1zr08	43.8	4.48	1987.8	1819.9	0.916	139.9	2415	0.74	14.5	2.1
14RATA1004B1zr01	45.4	2.70	1143.3	1071.6	0.937	5167.6	1395	0.74	865.6	87.2
14RATA1004B1zr03	45.9	3.98	1374.9	1482.2	1.078	872.3	1723	0.75	123.8	16.1
14RATA1004B1zr04	38.8	2.23	359.6	430.1	1.196	1228.8	461	0.71	661.7	128.7
14RATA1004B1zr05	55.1	4.48	283.4	413.1	1.458	1692.9	380	0.78	976.9	69.0
14RATA1004B1zr06	59.1	4.69	417.1	370.8	0.889	1590.6	504	0.80	691.7	48.9
14RATA1004B1zr07	47.1	2.68	3828.1	4531.3	1.184	1131.9	4893	0.74	57.3	5.0
14RATA1004B1zr09	59.4	6.75	339.7	297.7	0.876	1701.4	410	0.80	892.8	62.5

¹ Abbreviations as followed: ESR - equivalent spherical radius; Ft - alpha ejection correction, calculated using the method of Farley (2002); Cor. Age - corrected age; Full Unc. - uncertainty including the estimate for the uncertainty in the alpha ejection correction

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig.8

Victoria Island

Brock Inlier