

Widespread poly-metamorphosed Archean granitoid gneisses and supracrustal enclaves of the southern Inukjuak Domain, Québec (Canada)

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poly-metamorphosed Archean granitoid Widespread gneisses and 1 supracrustal enclaves of the southern Inukjuak Domain, Ouébec (Canada). 2 3 Jennika Greer^{1,2,3}, Guillaume Caro⁴, Nicole L. Cates^{1,5}, Peter Tropper⁶, Wouter Bleeker⁷, Nigel 4 M. Kelly^{1†} and Stephen J. Moizsis^{1,8*} 5 6 7 ¹. Department of Geological Sciences, University of Colorado, 2200 Colorado Avenue, Boulder, CO 80309-0399, USA mojzsis@colorado.edu 8 9 ². Department of the Geophysical Sciences, Chicago Center for Cosmochemistry, University of 10 Chicago, Chicago, IL, USA jennika@uchicago.edu 11 12 ^{3.} Robert A. Pritzker Center for Meteoritics and Polar Studies, Field Museum of Natural History, 13 Chicago, IL, USA 14 15 ^{4.} Centre de Recherches Pétrographiques et Géochimiques (CRPG), UMR 7358, Université de 16 Lorraine, CNRS, 54500 Vandoeuvre-lès-Nancy, France caro@crpg.cnrs-nancv.fr 17 18 ^{5.} Department of Geological Sciences, University of Manitoba, 240 Wallace Building, 125 Dysart 19 Road, Winnipeg, MB R3T 2N2, Canada nlcates@gmail.com 20 21 ^{6.} Institute of Mineralogy and Petrography, University of Innsbruck, Innrain 52, A-6020 22 Innsbruck, Austria peter.tropper@uibk.ac.at 23 24 ^{7.} Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada 25 wouter.bleeker@canada.ca 26 27 ^{8.} Institute for Geological and Geochemical Research, RCAES, Hungarian Academy of Sciences, 28 1112 Budapest, Budaörsi u. 45, Hungary 29 30 31 [†]Present address: Bruker Nano Analytics, Am Studio 2D, 12489 Berlin, Germany 32 nigel.kelly@bruker.com 33 34 * Corresponding author: mojzsis@colorado.edu 35 36 37 38 Abstract: 380 words Main Text: 8535 words 39 Figures: 14 40 Tables: 0 41 References: 58 42 Supplementary Information: 7 Figures, 4 Tables 43

44 Keywords

45 Archean; Inukjuak; supracrustal belt; granitoid gneisses; geochronology; metamorphic petrology

47 Highlights

- 1. The Inukjuak Domain comprises ~12,000 km² of Eo- to Neoarchean gneisses, (ultra)mafic
 schists and supracrustal enclaves within the Minto Block of northern Québec.
- 2. At least four generations of variably deformed Archean granite-granitoid gneisses aredocumented.
- 3. The oldest enclosing granodioritic and trondjemitic gneisses are ca. 3800 Ma; in some cases,
 these structurally transect supracrustal rocks and establish minimum ages.
- 4. Innuksuac Complex supracrustal enclaves range in size from $<1 \text{ m}^2$ to $\sim10 \text{ km}^2$ and show a variety of protolith compositions.
- 57 5. The terrane is metamorphosed to amphibolite facies with local retrogressions, reflecting a 58 protracted history that precludes preservation of primary fine-scale (microfossil) structures.

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Abstract. The ~12,000 km² Inukjuak Domain in northern Québec is part of the Archean Minto 79 Block in the northwestern Superior Province of Canada. Eoarchean (ca. >3800-3780 Ma) rocks 80 of the Nuvvuagittuq supracrustal belt (NSB) are the best known occurrence of otherwise 81 82 abundant <1 m to km-scale supracrustal enclaves dispersed throughout the Innuksuac Complex. The supracrustals are dominantly amphibolites, with subordinate intermediate-, mafic- and 83 ultramafic schists, quartzo-feldspathic (trondhjemitic and granodioritic) sills, dikes and sheets, 84 banded iron-formations and quartz-pyroxene±magnetite rocks, and (detrital) fuchsitic quartzites. 85 86 Supracrustal assemblages are in turn hosted by variably deformed granite-granitoid gneisses 87 metamorphosed to amphibolite facies. Locally, retrogression is expressed as pervasive 88 chloritization and development of jaspilite box veinings. This metamorphic history precludes 89 preservation of original fragile microfossil shapes. Despite its importance as one of the few 90 terranes to host Eoarchean supracrustal assemblages, limited geochronology was previously available for rocks beyond the ~8 km² NSB. Here, we report new major-, minor-, and trace-91 92 element geochemistry and metamorphic petrology coupled with U-Pb zircon geochronology, from rocks within and surrounding the NSB. These include the little-studied but volumetrically 93 significant Voizel suite gneisses. Results show that intra-NSB fold belt rocks of the Central 94 Tonalitic Gneiss (CTG) preserve mainly ca. 3650 Ma zircons. Beyond the NSB, the Voizel 95 gneisses – previously considered contemporaneous with the CTG – are instead about 100 Myr 96 97 younger (~3550 Ma). Tonalitic (ortho)gneisses at the margin of the NSB were previously 98 assigned a ca. 3650 Ma age, and the surrounding Boizard suite gneisses may be about 2700 Ma. We find the Boizard rocks contain inherited zircon cores up to ca. 3700 Ma, with younger 99 100 overgrowths dated at ca. 2700 Ma. A tonalitic gneiss that transects another highly deformed supracrustal enclave north of the NSB – dubbed the Ukaliq Supracrustal Belt – yields maximum 101

102 concordant zircon ages of 3653 ± 16 Ma (2 σ). Detrital zircons from Ukaliq and Nuvvuagittuq 103 quartzites and quartz-biotite schists define a maximum age of ca. 3780 Ma. No indication of U-104 Pb zircon ages older than about 3800 Ma exist in this terrane. Our reconnaissance sampling of 105 gneisses to the west of the NSB fold belt yielded more zircon-bearing rocks with ages of ca. 106 3760 Ma. Discovery of more pre-3700 Ma rocks beyond the NSB outcrops calls attention to the 107 existence of widespread scattered occurrences of Eoarchean and Paleoarchean rocks throughout 108 the region. (**380 words**)

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111 **1. Introduction**

The world's oldest rocks of demonstrably volcano-sedimentary origin comprise the Archean 112 "supracrustal belts"; these typically occur as irregularly deformed and metamorphosed enclaves 113 and rafts with broad spectrum of sizes captured in ancient granite-granitoid gneiss terranes that 114 are in turn separated unconformably from the surrounding felsic cratonic basement rocks (e.g., 115 116 de Wit and Ashwal, 1995). Although such bodies tend to be bounded by shear zones, examples also exist of Archean crustal enclaves that preserve weathering horizons and basal 117 conglomerates, and quartzites, which unconformably rest on old tonalite-trondhjemite-118 granodiorite (TTG) gneisses (e.g. Bleeker, 2002). Ranging in size from centimeter-scale to tens 119 of kilometers in outcrop area, the various Eoarchean (3850-3600 Ma) supracrustals thus far 120 121 documented are dominantly amphibolitic. Because of their widely documented poly-phase metamorphic histories, it is a misnomer to refer to these – either at the well-known Isua locality 122 in West Greenland (Nutman et al. 1996), the paragneisses of the Saglek Harbor rocks of 123 124 Labrador (Schiøtte et al., 1989), or for that matter in the Inukjuak region in northern Québec

described herein – as "greenstone belts" (cf. O'Neil et al. 2007). That is because without known 125 126 exception, all Eoarchean rocks experienced at least one (or more commonly, several) peak midto upper-amphibolite (or in some cases granulite facies) metamorphic events with associated 127 128 recrystallization(s) and several episodes of deformation before undergoing locally highly variable retrogression (e.g. Nutman et al. 2007; Cates and Mojzsis, 2006, 2009; Manning et al. 129 2006). It is owing to the intense structural juxtaposition of Eoarchean supracrustal rocks with 130 TTG gneisses in the Paleoarchean, followed by terrane assembly, that all such rocks are so 131 strongly modified. As such, none of these rocks are "greenstones" in the strict sense, nor do they 132 133 hold much potential for preservation of ultrafine-scale primary sedimentary features such as fragile microfossil shapes (Bridgwater et al. 1981; Whitehouse et al. 2019; cf. Dodd et al. 2017). 134 In spite of the fact that all of the oldest (>3.7 Ga) supracrustal rocks are undoubtedly modified 135 due to their long residence times in the crust, they nevertheless constitute the only direct sources 136 of evidence – albeit strongly debated – for the early biological evolution of our planet (e.g., 137 Schidlowski, 1988; Mojzsis et al. 1996; Rosing 1999; Nutman et al. 2016). We come back to 138 139 significance of this metamorphic history and what it means in the context of origin of life studies in Sections 4.1 & 4.5. 140

We emphasize that these rocks are so important to our understanding of the nature of the "Early Earth" as a terrane separate from the famous Itsaq Gneiss Complex in southern West Greenland (Nutman et al. 1996) that it makes sense to assess an ancient complex history through enhanced understanding of the gneisses that encompass them. For instance, exploration of surrounding granitoid gneisses can provide minimum ages for the supracrustals where unambiguous field relations exist on cross-cutting dikes, sheets and sills. Extensive surveys of the surrounding granitoids and their ages can also point to thermal peaks in the (poly148)metamorphic history endemic to these terranes that can be recapitulated in thermochronological149 investigations of the supracrustal rocks themselves.

One such locality of ancient rocks is the ca. 3750-3780 Ma Nuvvuagittuq supracrustal belt 150 (NSB) in northern Québec (Figure 1) (O'Neil et al. 2007, 2019). These were discovered in 2001 151 during a regional geological and geochemical survey sponsored by the Provincial Government of 152 Québec (Simard et al. 2003; David et al. 2003; Stevenson et al. 2005). It should be emphasized 153 that the NSB is merely the best known of what are at least a dozen or so km-scale enclaves in the 154 southern part of the vast (~12,000 km²) Inukjuak Domain recognizable from aerial photographs 155 available from the offices of Natural Resources Canada and thus mappable at the regional scale 156 (Figure 2). Collectively, the assorted supracrustals in the Inukjuak Domain comprise what is 157 termed the Innuksuac Complex (Cates and Mojzsis, 2007, 2009 and references therein). 158

To enhance our understanding of this history, we present new field relations, metamorphic petrographic analysis, geochemical data, and U-Pb zircon geochronology for a selection of rocks within and beyond the NSB that include the little-studied TTG gneisses and associated supracrustal rocks from the nearby Ukaliq supracrustal belt (USB) that was introduced in Caro et al. (2016).

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165 **2. Geologic background**

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167 2.1 Innuksuac Complex supracrustal rocks – Nuvvuagittuq locality

Reviews of the geology of the Nuvvuagittuq supracrustal belt (NSB) are provided elsewhere (O'Neil et al. 2007, 2019 and references therein); a short summary is presented here. The NSB and neighboring supracrustals rocks that compose the Innuksuac Complex are found within the 171 Inukjuak Domain, which in turn is one of several large deformed belts (e.g., Tikkertuk/Bienville; 172 Minto Lake; Qalluviartuuq/Goudalie; Utsalik) that collectively make up the Minto Block in the northeast Superior province. The Inukjuak Domain is volumetrically dominated by Neoarchean 173 174 plutonic suites with subordinate rocks of Paleo- to Eoarchean age (Figure 3; Simard et al. 2003). The $\sim 8 \text{ km}^2$ outcrop area of the NSB has garnered much interest because of the verified 175 discovery of anomalous deficits in ¹⁴²Nd/¹⁴⁴Nd vs. Bulk Silicate Earth (O'Neil et al. 2008; Roth 176 177 et al. (2013)). Debate continues over the interpretation of these data (e.g. Cates et al. (2013); Roth et al. (2013); Guitreau et al. (2013); Caro et al. (2017), but there is broad agreement that the 178 anomalous ¹⁴²Nd/¹⁴⁴Nd values must represent evidence for an early (pre-4300 Ma) separation of 179 the terrestrial silicate reservoirs during the short (half-life = 103 Myr) activity of now-extinct 180 ¹⁴⁶Sm (Roth et al. 2013). One school of thought is that the ¹⁴²Nd/¹⁴⁴Nd vs. Sm/Nd data, in 181 182 conjunction with some ancient Sm-Nd model ages, indicate that formation times for certain protoliths to the NSB may be 4300-4400 Ma (O'Neil et al. 2008; 2012; 2019). This interpretation 183 has been challenged, however, by separate studies, and the topic is not discussed further here; 184 185 instead we refer the reader to Cates et al. (2013), Roth et al. (2013), Guitreau et al. (2013) and Caro et al. (2017). Despite their obvious importance, the NSB rocks specific to the "Porpoise 186 Cove" locality are the only ones mapped at the appropriate detail (i.e., 1:100 scale) to understand 187 a complex and protracted metamorphic history (Cates and Mojzsis, 2009; Cates et al. 2013; cf. 188 O'Neil et al., 2007; Darling et al. 2013). 189

As has been reviewed elsewhere (Cates and Mojzsis, 2007; O'Neil et al. 2019), the Nuvvuagittuq supracrustals are dominantly composed of (Ca-poor; cummingtonite-rich) basaltic amphibolites. Other rocks include layered ultramafic schists that comprise some rocks with geochemical signatures akin to komatiites (Frank et al. 2016; Touboul et al. 2014), finely194 banded quartz magnetite±pyroxene±amphibole rocks (s.s. banded iron-formations (BIF); Dauphas et al. 2007; Mloszewska et al. 2012), massive Ca-Fe-Mg silicate "quartzites" 195 (Mloszewska et al. 2013), and quartz-biotite schists of probable detrital origin (Simard et al. 196 2003; Cates and Mojzsis, 2007; O'Neil et al. 2007; David et al. 2009; Cates et al. 2013; Darling 197 198 et al. 2013; Bell et al. 2018). Cates et al. 2013 proposed that the cummingtonite amphibolite rocks owed their Ca-poor compositions to albitization of pyroclastic debris at time of formation 199 200 around 3.8 Ga. These authors further argued that the colloquial term "faux amphibolite" 201 endorsed by O'Neil et al. 2009 and others is an unfortunate obfuscation of geologic data. 202 Amphibolitic rocks of such composition are have been noted elsewhere in Eorchean terranes 203 including from southern West Greenland (e.g. sample GR00114 of Manning et al. 2006).

204 Furthermore, it has been detailed that detrital igneous zircons in fuchsitic (Cr-muscovite rich) 205 quartzites and quartz-biotite schists, along with ages for igneous zircons from trondhjemitic gneiss sheets – which in some places structurally transect the supracrustal sequences – show that 206 the NSB is probably not older than ca. 3800 Ma (Cates et al. 2007, 2009, 2013). Even after 207 208 nearly a thousand published U-Pb zircon ages, very few pre-3900 Ma ages have thus far been identified in the NSB (Bell et al. 2017, 2018). Yet, like many other aspects of the geology of the 209 Nuvvuagittuq rocks, the interpretation that these detrital zircons bracket the maximum age of the 210 NSB at ca. 3800 Ma has also been disputed (Darling et al. 2013; O'Neil et al. 2019). 211

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213 2.2 Innuksuac Complex supracrustal rocks beyond the NSB

A large number of scattered small pods and lenses (<1-10 m), as well as larger (>1 km) supracrustal rafts and enclaves have been provisionally noted within the Inukjuak Domain; the largest of these were tentatively mapped from aerial reconnaissance surveys supplemented by 217 field studies in the early 2000s (Berclaz et al. 2003). In several aspects, an emulsion-like 218 assortment of locally mappable supracrustal rocks locked within poly-phase granitoid gneisses is not unlike the outcrops of the so-called "Akilia association" found southwards of the Isua area 219 220 and throughout the Itsaq Gneiss Complex of southern West Greenland (McGregor and Mason, 1977), as well as the lesser-known "Manfred Complex" rocks of the Murchison region of 221 Western Australia (Kinny et al. 1988). Furthermore, much like the type-locality on Akilia 222 (island) for the Akilia association (Nutman et al. 2002; Manning et al. 2006) and other Akilia 223 rocks such as on Innersuartuut in the southern Faeringhavn terrane (Cates and Mojzsis, 2006 and 224 225 references therein), the Ukaliq rocks are the only other Innuksuac supracrustals in the area beyond Nuvvuagittuq that have mapped in the detail required to understand the field 226 relationships (Caro et al. 2017). Similarly, unlike the large (and arguably coherent) Isua and 227 Nuvvuagittuq belts, those of the Ukaliq, Akilia and Manfred supracrustal enclaves are mostly 228 present in outcrop as a scattered set of volumetrically small ($\leq 1 \text{ km}^2$) and dominantly mafic to 229 ultramafic enclaves, surrounded and broken up by strongly foliated plagiogranitoid gneisses. 230

231 Specific to the Inukjuak Domain, the ancient gneisses which host the supracrustals are attributed to the Voizel suite (Avoi; Simard et al. 2003). Field relations show that the Voizel suite 232 rocks are further enclosed and disrupted by a pinkish granitoid with only weakly developed 233 tectonic fabric, termed the Bozard suite (Aboz). The Bozard rocks were provisionally assigned an 234 age of 2750 ± 5 Ma in published reports from the Ministère des Ressources naturelles, de la 235 236 Faune et des Parcs (Provincial government of Québec). Evidence exists that the Bozard rocks intrude some supracrustal enclaves in places, for example a pegmatitic dike with the same age 237 was described previously described within the NSB (Simard et al. 2003). The large number of 238 239 metamorphic zircon growth ages at about 2700 Ma in the NSB imply that the emplacement of the Bozard suite led to regional metamorphism of the Innuksuac complex that variably
retrogressed the earlier (Paleoarchean) amphibolite facies metamorphism (Cates and Mojzsis,
2007, 2009; Cates et al. 2013; O'Neil et al. 2019).

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3. Sample collection and analytical methods

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246 **3.1 Field relationships**

Representative samples of the various rocks associated with the NSB, USB and surrounding terrane (**Figure 4**) were collected by us during the course of regional-scale studies in our 2005, 2012, and 2014 field seasons. A subset of these samples was chosen for geochemical analysis based on their apparent lack of weathering and homogeneity at the hand-specimen scale; a further subset was set aside based on perceived likelihood of producing abundant zircons for geochronology.

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254 **3.2 Petrography**

Four representative samples were prepared into thin sections and subsequently investigated using standard optical microscopy and backscatter electron (BSE) images to illustrate the textural relations, as well as by electron microprobe analysis. These samples were specifically chosen for thermobarometry work and provenance studies; see Sections 4.1, 4.5, 4.6).

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260 **3.3 Whole-rock geochemistry**

Samples for whole-rock geochemical analyses were crushed to fine powders at the RockPreparation Facility in the Department of Geological Sciences at the University of Colorado,

263 Boulder. Dedicated alumina mortars were pre-cleaned with washed quartz sand and conditioned with small amounts of sample before powders were made of the main sample masses. Care was 264 taken to avoid contact with metal hammers, saws, and other metal dividing apparatus that could 265 266 compromise future isotopic or trace metal analytical work. Splits from homogenized powders were subdivided for major-, minor-, and trace element geochemistry and approximately 40% by 267 mass for each was reserved for archival purposes. Whole-rock geochemical analyses were 268 performed at the CRPG SARM Facility in Nancy (France). Samples for which only geochemical 269 data are presented herein were also analyzed at this Facility. 270

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272 **3.4 Ion microprobe U-Pb zircon geochronology**

A fraction of those samples targeted for geochronology, based on visual inspection of 273 mineralogy, documented zirconium contents from the geochemical analyses as well as geologic 274 setting, was set aside for zircon extraction. Whole-rock samples were crushed and sieved to <350 275 µm to yield an appropriate size range of zircons. Sieved aliquots were then passed through two 276 277 stages of standard heavy liquid separations (tetrabromoethane and methylene iodide) with intermediate washings in in reagent-grade acetone by ultra-sonication before final washings in 278 acetone and DI water baths. After drying, strongly ferromagnetic minerals and metal filings 279 fractions were removed with a hand-magnet, followed by separations using a Franz magnetic 280 separator. Individual zircon grains from the least magnetic Franz fraction were then handpicked 281 under a binocular microscope, placed as oriented arrays (common long-axis directions) on 282 double-sided adhesive tape and cast in 2.52 cm-diameter molds with Buehler[©] epoxide resin 283 along with a halo of grain fragments from zircon standard AS-3 (Paces and Miller, 1993; Black 284 285 et al. 2003; Cates and Mojzsis, 2009). A variety of zircon sizes and morphologies from each

286 aliquot was chosen so as to diminish sampling bias. The mounts were cured in a 60°C oven for at least 48 hours prior to the first polishing step. The sample mounts were then polished to 287 brilliance in stages down to 0.25 µm alumina to expose approximate grain centers depending on 288 the grain sizes of the cast fraction. Transmitted and reflected optical micrograph mount maps 289 290 were produced to facilitate identification and navigation on the mounts. Paired BSE (backscattered electron) and CL (cathodoluminescence) images (e.g., Figure 5; see also 291 292 Supplementary Figures S1) were also acquired for all zircons analyzed for U-Pb to guide 293 primary ion beam position.

294 Immediately prior to ion microprobe analysis, the zircon mounts were ultrasonically bathed 295 in a 1N HCL solution for several minutes to reduce common Pb contamination, rinsed in 296 ultrapure water, air dried and then sputter-coated with ~100 Å of Au to facilitate conductivity. All U-Pb zircon ion microprobe data were acquired using the UCLA Cameca ims1270 high-297 resolution secondary ion mass spectrometer under standard operating conditions (e.g., Cates et 298 299 al. 2013). An abridged description of the methods is provided here: a ~ 8 nA O_2^- primary ion 300 beam was defocused to a $\sim 25 \,\mu m$ diameter spot, and the ion probe was operated at a mass resolving power of ~6000 to exclude molecular interferences. Oxygen flooding to a pressure of 301 3.2×10^{-5} torr in the analysis chamber was used to increase Pb ion yields (Schuhmacher et al. 302 1994). Prior to sample (unknown) analysis, a calibration curve was established using the zircon 303 304 standards 91500 (for set-up) and AS-3 (embedded with the unknowns). Ages for unknown zircons were determined by comparison with a working curve defined by multiple measurements 305 of zircon standard AS3 that yields concordant ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²³⁵U ages of 1099.1±0.5 Ma. 306 Raw machine data were reduced using the program ZIPS[©] (C. Coath, University of Bristol). 307 Geochronological data are presented using the Isoplot software package (Ludwig, 2003) by 308

309 generating Tera-Wasserburg plots (²⁰⁷Pb/²⁰⁶Pb vs. ²³⁸U/²⁰⁶Pb) that yield discordia, and weighted 310 average ages. Weighted average ²⁰⁷Pb/²⁰⁶Pb ages were calculated when a sample had a 311 population of zircons that overlaps concordia. We use Tera-Wasserburg plots for ancient zircons 312 to take advantage of the large differences in ²⁰⁷Pb/²⁰⁶Pb ratios that are not so well expressed in 313 the conventional Wetherill Concordia plot.

314

315 **3.5 Zircon trace-element geochemistry**

All zircon rare earth element ([REE]_{zirc}) analyses reported herein were measured on the 316 317 UCLA Cameca ims1270 ion microprobe following the approach described by Schmitt and Vazquez (2006). Analysis spots were $\sim 25 \mu m$ in diameter and carefully positioned to overlap 318 previous U-Pb geochronology analysis points to provide internally-consistent data sets. The REE 319 intensities were normalized to ³⁰Si⁺ and corrected for interfering oxides. The trace element 320 content of NIST standard glass 610 was used to determine the analytical sensitivity. Instrument 321 stability was monitored by regular and frequent bracketed measurements on standard zircon 322 323 91500.

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- 325 **4. Results**
- 326

327 **4.1 Petrographic analysis**

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329 4.1.1. Metamorphism of Innuksuac Complex supracrustals

A suite of characteristic NSB and USB samples were earmarked for petrographic analysis; compositional descriptions of these samples are provided in the next section (4.2). Ukaliq sample

IN14032A is provisionally interpreted by us as a (mafic) matrix-hosted "meta"-conglomerate 332 (Caro et al. 2016). Although quartz is subordinate in this rock, we interpreted it to have a 333 conglomerate protolith based on the mineralogy and association of strongly s-deformed quartz 334 335 "clasts" that are similar to samples described in the "Porpoise Cove" locality (e.g. Darling et al. 2016). Thin section studies also revealed the presence of rounded zircon grains interpreted by us 336 to be detrital. The main mineral assemblage of this sample is anthophyllite + muscovite + quartz 337 + rutile + zircon (Figure 6a). In retrogression, former biotite is now completely replaced by 338 stilpnomelane (a common phyllosilicate in ferruginous sediments such as metagreywackes), and 339 340 anthophyllite is replaced by chlorite + talc.

Sample IN12016 is a granite from the Boizard rocks. The mineral assemblage is chlorite +
epidote + albite + K-feldspar + muscovite + titanite + quartz (Figure 6b). Chlorite + epidote +
titanite replace former biotite. Muscovite + epidote also grow within albite porphyroblasts.
Epidote shows different contrast values in the BSE images indicative of variable REE contents.
The Ce-rich epidote (allanite) probably replaces former monazite grains (e.g. Finger et al. 1998).
Sample IN14036 is a grey gneiss collected to the west of the NSB and contains the mineral

assemblage biotite + plagioclase + muscovite + quartz + zircon (Figure 6c). Biotite shows
 retrogressive replacement by the assemblage chlorite + muscovite + titanite.

Sample IN12044 is a Voizel tonalite sample and contains the mineral assemblage biotite + Kfeldspar + plagioclase + quartz + apatite (**Figure 6d**). It is evident from this sample that retrogression led to the formation of the secondary assemblage chlorite + titanite + epidote replacing biotite and plagioclase. Calcite also occurs in small veins.

353

4.1.2. Secondary jaspilite in the Nuvvuagittuq rocks

355	Later hydrothermal metamorphism in parts of the NSB – exemplified in the samples
356	described in Sec. 4.1.1. – also led to re-hydration and locally extensive formation of structurally
357	discordant (and locally as box work veinings) jaspilite (Supplementary Figures S2). This
358	process is described in detail elsewhere for other similarly metamorphosed banded iron
359	formations (e.g. Czaja et al. 2018). It is evident given the metamorphic history and the obvious
360	later (discordant, post-deformation) emplacement of the jaspilites, that the alleged microfossil
361	features claimed by Dodd et al. 2017 could not be primary to the rocks.

- **4.2. Whole-rock geochemistry**
- *4.2.1. Central Tonalitic Gneiss*

The largest outcrop of the Central Tonalitic Gneiss (CTG) is found near the geometric center of the NSB. Field observations show that rather than constituting a single mass of homogenous tonalitic gneiss, outcrops of the CTG instead comprise diverse interleaved granitoid gneisses and biotite-rich bodies (including possible paragneisses) with highly variable grains sizes; all are foliated in a general N-S direction (Supplementary Figure S3). Disrupted and strongly recrystallized enclaves of rocks that superficially resemble banded iron-formations (at least in mineralogy), which show evidence for extreme quartz mobility and schlieren are also found locally. Although difficult to assess, it is possible that this BIF was originally part of the Nuvvuagittuq supracrustal succession before becoming engulfed by these intrusive granitoids. Previous works (O'Neil et al. 2007, 2019) proposed that the CTG was genetically related to the

enclosing gneisses of the NSB (i.e. Voizel suite) but with no supportive evidence fromgeochronology.

The three CTG gneiss samples investigated (see sec. 4.3.1) here plot compositionally on the 380 border between tonalite and granodiorite on the conventional TTG classification diagram 381 (Figure 7; Barker, 1979). These have typical (felsic) granitoid REE patterns with chondrite-382 normalized LREE enrichments around 100, and HREE enrichment of about 10, although the 383 sample collected somewhat outside the main lobe of the NSB (IN14035) is less enriched in REEs 384 than the other more 'interior' samples (IN05001, IN12012). These latter two interior samples 385 have weak negative Eu anomalies (0.66 and 0.95) whereas sample -035 shows a weak positive 386 Eu anomaly (1.07; Figure 8). On a multi-element plot, all three show typical granitoid patterns 387 with strong negative Nb anomalies (all have Nb/Nb* = 0.13) and moderate Ti anomalies (0.48 to 388 0.67). Samples IN05001 and IN14035 also have positive Zr anomalies, with values of 1.92 and 389 1.45, respectively (all whole-rock geochemical data are reported in **Supplementary Table S1**). 390

391

392 *4.2.2. Voizel suite*

In outcrop, the coarse-grained Voizel (Avoi) rocks appear gray or white, depending on the 393 degree of weathering (Supplementary Figure S4). They have a pronounced gneissic texture 394 with a foliation trend that conforms to the structural outline of the NSB and USB as seen in 395 comparative field and aerial photographs, as well as regional-scale Google-Earth images. Unlike 396 397 at the NSB, the Avoi rocks disrupt and enclose the USB into 1-10 m-scale enclaves except for a few rare cases. For this study, eight Avoi samples were chosen for geochemical analysis. Three 398 come from the upper (northern) lobe of the Ukaliq locality and within the mass of Voizel 399 400 gneisses (IN12014, IN12026, and IN12027), and a further five samples come from the lower

(southern) USB lobe (IN12041, IN12044, IN12046, IN12050, and IN12056; Figure 3). These 401 rocks plot in the tonalite, trondhjemite, granodiorite, and quartz monzonite fields on the TTG 402 classification diagram (Figure 7). On an REE plot, the samples have typical TTG gneiss 403 patterns, as above with the CTG. Samples IN12050 and IN12027 fall in the quartz monzonite 404 field and have large positive Eu anomalies, with Eu/Eu* values of about 2. Samples IN12050 405 and IN12014 have relatively low concentrations of REE overall, and are depleted in HREE 406 relative to other samples. Overall, Avoi samples show typical Archean igneous felsic patterns 407 with strong negative Nb anomalies (Nb/Nb* values between 0.05 and 0.51) and moderate Ti 408 anomalies (Ti/Ti* values between 0.28 and 0.70). 409

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411 *4.2.3. Boizard suite*

Two samples of Boizard suite rocks were selected for analysis; the rocks are coarse grained, 412 pink, K-feldspar-bearing, have little to no fabric (Supplementary Figure S5), and plot in the 413 granite and quartz-monzonite fields (Figure 7). The HREE enrichments for these samples are 414 around 10 (normalized to chondrite) and both exhibit negative Eu anomalies (Eu/Eu* values 415 between 0.50 and 0.71). On a multi-element plot, the Aboi samples have typical Archean igneous 416 felsic patterns with strong Nb anomalies (Nb/Nb* values between 0.29 and 0.02) and moderate 417 Ti anomalies (Ti/Ti* values between 0.48 and 0.49). The Boizard suite dominates the landscape 418 of the Innuksuac Complex. Its rocks enclose the Voizel suite and these in turn envelope the 419 420 ancient gneisses hosting supracrustal rocks.

423 In places, rare, thin (0.1-1 m-scale) variably banded gray TTG gneisses can be seen to crosscut the various amphibolitic USB enclaves in the Ukaliq locality. Field relations suggest 424 that these gneisses pre-date the dismemberment of what was a previously a coherent supracrustal 425 426 belt or belts (sensu lato) via extensive intrusions of Avoi granitoids accompanied by deformation (Supplementary Figure S6). Three of these crosscutting gneissic sheets were sampled for 427 analysis, and all show typical Archean igneous felsic patterns with chondrite normalized LREE 428 enrichments similar to the other gneisses described above. These samples have positive and 429 negative Eu anomalies (Eu/Eu* values between 0.89 and 1.45). The three gneissic samples also 430 have strong negative Nb anomalies (Nb/Nb* values between 0.14 to 0.17) and moderate Ti 431 anomalies (Ti/Ti* values between 0.45 and 0.63). 432

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434 *4.2.5. Candidate volcano-sedimentary protoliths from Ukaliq*

The largest, best-preserved ~50-100m rafts of Ukaliq supracrustals comprise alternating 435 436 bands of variably recrystallized BIF and/or quartz±amphibole±pyroxene±magnetite rocks; 437 massive quartile with relict banding that may include faint cross-bedding structures, possible graded bedding and/or stretched clasts; fine grained, strongly banded amphibolitic gneisses; 438 massive to layered ultramafic schists; and sheets or dikes of trondhjemitic gneiss (Figure 9). The 439 440 northernmost extension of the Ukaliq supracrustal belt found in our field studies (Caro et al 441 2017) is represented here by a coarse-grained quartzite (sample IN14032A), the protolith of which is interpreted by us as a quartz-pebble metaconglomerate within a broad sequence of 442 quartzitic rocks of possible detrital origin as also found in the NSB (Cates and Mojzsis, 2007, 443 444 2009; Cates et al. 2013; Dauphas et al. 2007; Darling et al. 2013).

446 *4.2.6. Sample IN14036 – an orphaned member of the CTG?*

This grey gneiss is similar in appearance to the CTG gneisses but comes from the west of the main NSB outcrops (**Figure 3**; **Supplementary Figure S7**). The sample also has a positive Eu anomaly ($Eu/Eu^* = 1.08$), a strong negative anomaly (Nb/Nb* = 0.12), and a moderate Ti anomaly (Ti/Ti* = 0.68). We return to this sample later, owing to the fact that the geochronology revealed it to be older than the CTG gneisses.

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454 **4.3 U-Pb zircon geochronology**

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456	4.3.1.	Central	<i>Tonalitic</i>	Gneiss
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The three CTG samples with geochemical data were prepared for geochronological analysis. Following on the previous descriptions (see sec. 4.1.1), one of these was collected from the internal northwestern margin of the NSB (IN05001), another was collected from the internal westernmost limit of the NSB (IN12012), while the third was collected at the external western limit of the NSB (IN14035).

For sample IN12012 the weighted mean age (207 Pb/ 206 Pb) of the 11 most concordant grains (chosen grains are within 10% of concordia) is 3652 ± 14 Ma (**Figure 10**). These zircons tend to mostly be zoned cores surrounded by thin rims; the rims are too thin to measure by conventional ion microprobe techniques (**Supplementary Figure S1**). Retrospective imaging of younger age spots which do not plot within 10% of concordance show that they come from altered cores filled with fractures. For sample IN05001, the weighted mean age of the 14 grains that cluster on the concordia line is 3487 ± 15 Ma (**Figure 10**). Zircons extracted from this sample are considerably more fractured and filled with inclusions than those of sample IN12012, but some preserve oscillatory zoning around cores. For sample IN14035, a total of 24 spots were analyzed on 24 grains. The weighted mean age of the grains that cluster on the concordia line (within 10% concordance) is 3647 ± 10 Ma (all geochronological data are reported in **Supplementary Table S2**). It is evident that samples IN12012 and IN14035, although spatially separated, have wellconstrained ages that are essentially identical within error.

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477 *4.3.2. Voizel suite*

Seven samples from the Voizel suite with whole-rock geochemistry data were selected for 478 geochronology. Three samples are from the northern lobe of the USB (IN12014, IN12026, and 479 480 IN12027) whereas four samples are from its the southern lobe (IN12041, IN12044, IN12046, and IN12050). Sample IN12014 intercept of 481 gives upper age 3550 an +52 / -44 Ma (MSWD = 4.7) based on assessment of 10 analyses on 10 zircons. Two zircon 482 483 grains upon which there are four analyses that were not included in the collective age determination yield a weighted mean ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age of 1871 ± 86 Ma. These grains were highly 484 485 discordant but trace along a horizontal axis on the Tera-Wasserburg plot, suggestive of recent lead loss (Figure 11). Sample IN12026 gives an upper intercept age of 3481 ± 84 Ma (MSWD = 486 1.9) with a large scatter around the discordia. Sample IN12027 yields a weighted mean 487 207 Pb/ 206 Pb age from the four most concordant zircons of 3519 ± 16 Ma. The southern USB lobe 488 samples have ages that overlap these within error (with a skew towards slightly older ages). 489 Sample IN12041 has an upper intercept concordia age of 3550 ± 120 Ma (MSWD = 11.6). 490 491 IN12044 has an upper intercept age of 3554 ± 46 Ma (MSWD = 1.1) from analyses that plot on discordia. Sample IN12046 has an upper intercept concordia age of 3483 ± 140 Ma (MSWD = 11.6) from analyses that are spread around the discordia. A weighted average age of 3515 ± 140 Ma comes from analyses of the most concordant grains (within 3% of concordia) and are typically from larger grains.

Sample IN12050 comes from the easternmost margin of the Voizel suite, near the contact with the Boizard suite, and has an upper concordia intercept age of 3437 ± 170 Ma (MSWD = 17). Although there are multiple upper intercept ages of ca. 3550, no analyses from individual Voizel suite zircons are this old. Instead, the oldest individual spot ages (ca. 3530) are from the cores of euhedral to subhedral zircons with younger overgrowths, whereas the younger population ages are exclusively from zircon rims (**Supplementary Figures S1**).

502 With regards to the high degree of scatter in some of the upper concordia intercept ages 503 reported here (with high MSWD), such values are not uncommon in polycyclic metamorposed 504 early Precambrian terranes (e.g. Corfu 2013).

505

506 *4.3.3. Boizard suite*

Two samples from the Boizard suite with whole-rock geochemistry were selected for 507 508 geochronology. One was collected to the east of the northern lobe of the USB (IN12016), and one was taken to the south of the lower lobe (IN12054; Figure 3). Sample IN12016 has a 509 weighted mean ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age of 2706 ± 19 Ma from a total of 6 grains that cluster on or close 510 to concordia (Figure 12). Several old domains – as cores surrounded by zoned igneous 511 overgrowths – were recognized from zircons within this sample with ²⁰⁷Pb/²⁰⁶Pb dates up to ca. 512 3700 Ma; Supplementary Figures S1, Supplementary Table S1). Other zircons with dates 513 514 older than 3000 Ma also come from core regions of the grains, although in images some of these

515 appear altered and fractured. Young, highly discordant dates come from zircons with altered 516 cores that appear to be either metamict or filled with fractures and inclusions. Four highly discordant zircon grains give a weighted mean 207 Pb/ 206 Pb age of 1175 ± 340 Ma, but these trace 517 along a horizontal axis on the Tera-Wasserburg plot, suggestive of recent lead loss and should be 518 considered estimates. Sample IN12054 has a weighted mean 207 Pb/ 206 Pb age of 2720 ± 20 Ma 519 from a total of 8 analyses that cluster on or near concordia. The oldest date (and not, therefore 520 necessarily age) in this sample, 3431 ± 6 Ma, comes from a grain with a core surrounded by a 521 younger rim (2921 \pm 9 Ma). We find that the grains from the younger but still concordant 522 523 population have euhedral to anhedral habits.

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525 *4.3.4. Structurally intrusive gneisses to the Ukaliq supracrustal belt enclaves*

Four samples collected from structurally invasive gneisses transecting enclaves within the 526 various USB sites were selected for geochronology. Two of these were taken from the northern 527 lobe (IN12017 and IN12031) and two were taken from the southern lobe (IN12042 and 528 IN12053). Sample IN12017 gives a concordia upper intercept ²⁰⁷Pb/²⁰⁶Pb date (not necessarily 529 'age') of 3598 +44 / -37 Ma, owing to the fact that the majority of analyses come from 530 discordant zircons (Figure 13). Some of the younger, discordant zircons in this sample have 531 complex textures typical of hydrothermal growth or metamictization (Corfu et al. 2003) whereas 532 the oldest zircon in this sample $(3653 \pm 8 \text{ Ma})$ comes from a core with a thick, zoned overgrowth 533 (Supplementary Figures S1). Sample IN12031 has two populations, with the older population 534 more concordant which yields a weighted mean ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age of 3505 ± 5 Ma. The younger 535 population lies on the discordia with the older population with an upper intercept at 3496 ± 35 536 537 Ma. Sample IN12042 also gives an upper intercept at 3492 ± 190 Ma from a cluster of the most

concordant grains, but the oldest analysis in this sample comes from a 30% discordant grain with 538 a 207 Pb/ 206 Pb date of 3694 \pm 9 Ma. Sample IN12053 seems to have three populations, all of 539 which are discordant. The youngest, most discordant grains yield a weighted average ²⁰⁷Pb/²⁰⁶Pb 540 541 date of 2292 ± 120 Ma and come from either zircon rims or metamict cores (Supplementary Figures S1). One spot on a zircon with 25% concordance gave a weighted average 207 Pb/ 206 Pb 542 date of 3362 ± 19 Ma. The oldest population comprises two grains with 207 Pb/ 206 Pb ages of 3582 543 \pm 9 Ma and 3694 \pm 19 Ma (Supplementary Table S1). These grains are euhedral to subhedral, 544 and the oldest age domains correspond to zircon core surrounded by rims that have spongy 545 textures typical of hydrothermal alteration (e.g., Hoskin and Schaltegger, 2003). 546

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548 4.3.5. Igneous and sedimentary protoliths in the Ukaliq supracrustal belt enclaves

A quartz-biotite schist sample IN14032A interpreted to be a 'meta-conglomerate' based on 549 field relations, petrology (see sec. 4.2) and resemblance to other rocks from the Porpoise Cove 550 locality of the NSB (e.g., Cates et al. 2013), was discovered in the upper lobe of the Ukaliq belt. 551 552 This rock is within a succession of quartzites, amphibolites, and ultramafic rocks (Figure 8d; Caro et al. 2017) surrounded by Voizel gneisses. This sample has several different zircon 553 populations the oldest of which is interpreted here to be of detrital origin (see sec. 5.3); the oldest 554 of these clusters around a weighted average 207 Pb/ 206 Pb age of 3736 ± 5 Ma (Figure 13). 555 Younger, smaller, populations cluster around ca. 3650 Ma and ca. 2700 Ma. It is important to 556 note that these zircon U-Pb age populations are defined by spot analyses with less than 5% 557 discordance. This sample has a group of highly reversely discordant grains, with ages between 558 3185 ± 28 Ma and 3440 ± 29 Ma. 559

561 4.3.6. Granitoid gneiss sample IN14036 from outside the NSB

Gray gneiss sample -036 was collected to the west of the westernmost limb of the NSB (Supplementary Figure S7), approximately 150 m west of the outcrop of possible CTG-related sample IN14035 (Figure 3). Sample -036 is similar in appearance to other TTGs analyzed herein (in particular samples IN12012 and IN12044), but yields a much older age. It has an upper concordia intercept 207 Pb/ 206 Pb age of 3760 ± 17 Ma, with a weighted mean age, comprising only the least discordant grains, of 3750 ± 7 Ma. Zircons extracted from this sample generally plot on concordia, with only a few analyses defining the discordia (Figure 13).

- 569
- 570 4.4 Zircon Trace-element Geochemistry
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A routinely used means to determine whether a particular zircon age population is original to 572 its host rock (e.g. Manning et al. 2006; Cates and Mojzsis, 2009; Cates et al. 2013; Mojzsis et al. 573 2014; Reimink et al. 2014), is the lattice strain model for ionic compatibility between the 574 composition of a mineral (in this case, zircon) and a melt of the composition of the host rock 575 (Blundy and Wood, 1994; Taylor et al. 2015). In those rocks with multiple zircon age 576 populations, application of this model can help to determine the most likely age of the rock under 577 the assumption that the original melt and native, age-representative zircons, formed in 578 equilibrium. The assumption requires that the composition of the rock hosting the minerals in 579 question represents the last melt composition (Onuma et al. 1968). As described elsewhere 580 (Taylor et al. 2015) the model takes advantage of the chemical similarities of the trivalent rare 581 earth elements, where the main controlling factor for how easily these ions are incorporated into 582 583 growing minerals is the predictable change in ionic radius with increasing atomic number from

the lanthanide contraction. It has long been known that HREEs are more compatible in zircon than LREE because their ionic radii approach that of Zr^{4+} (0.84 Å in eight-fold coordination). Thus, the distribution of REEs in zircon is controlled by the composition of the melt, and the REE_{Zr}/REE_{rock} should plot as a parabola for a zircon that crystallized in a melt with the composition of the whole rock representative of that melt (e.g. Trail et al. 2007; Mojzsis et al. 2014 and references therein).

Partition coefficients were determined for each zircon in our database (REE_{zirc}/REE_{WR}) and 590 fitted using the Blundy and Wood (1994) lattice strain model. The best fit parabola (described by 591 its R^2 value) for the exponential function was then calculated iteratively over 1000 model fits to 592 the data. The higher the R^2 value, the better the model fit of the data to the lattice strain model 593 and consequently the more likely it is that the zircon REE chemistry comports with the whole-594 595 rock composition. In this work, we selected a subset of concordant zircons from the Voizel suite and CTG granite-granitoid gneisses for REE analysis (results in Figure 14a; data reported in 596 **Supplementary Table S3**) and lattice-strain modeling in order to refine our estimate(s) of the 597 598 most likely crystallization age(s) for these two units. Three concordant zircons from the Voizel rocks (IN12027 and IN12046) and four concordant zircons from CTG sample IN12012 and one 599 from IN05001 were set aside for REE analyses. The results of our analysis show that only the 600 oldest zircons in this particular analysis have statistically good fits ($R^2 \ge 0.9$) with their host-rock 601 REE compositions (Figure 14b), which we interpret to represent the crystallization age. 602

603

604 **4.5 Zr-in-rutile geothermometry**

606 The temperature dependence of Zr incorporation into rutile grown in equilibrium with quartz 607 and zircon yields a widely useful single-mineral geothermometer (Zack et al. 2004; Watson et al. 2006; Tomkins et al. 2007). Petrography of the four samples selected for Zr-in-rutile 608 609 geothermometry (Sec. 4.2) revealed an older high-grade mineral assemblage and a texturally later secondary mineral assemblage as previously shown in Figure 6. Owing to the pervasive 610 retrogression of the samples (complete replacement of biotite, plagioclase) it was not possible to 611 constrain P-T conditions using phase equilibrium calculations; instead this geothermometer 612 provides a constraint on temperature (T) by analyzing rutiles from the purported 613 614 metaconglomerate sample IN14032A. A total of 41 rutile analyses were performed by electron microprobe at the Institute of Mineralogy and Petrography, University of Innsbruck (Austria); Zr 615 contents range from 407 ppm to 914 ppm (Supplementary Table S4). No differences between 616 core and rim analyses were found. The calibration of Tomkins et al. (2007) yielded T of 660-617 730°C at 0.6 GPa and calculated mean T is 670°C \pm 40°C (2 σ). Due to the lack of precise 618 619 pressure (P) constraints an arbitrary P of 0.6 GPa was chosen, which is in agreement with the 620 observed mineral assemblage in sample IN14032A. The calculations also show that P has only minor influence on the estimates presented here since mean T varies only from 660°C at 0.4 GPa 621 to 680°C at 1 GPa (Triebold et al. 2012). We find that these results are in good agreement with 622 the earlier study of Cates and Mojzsis (2009) for the NSB rocks, which used the conventional 623 624 garnet-biotite and plagioclase-hornblende geothermometry.

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626 **4.6 Rutile crystal chemistry as provenance indicator**

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628 Geochemical discrimination studies of specific detrital minerals can be used in provenance

629 characterization. The widespread occurrence of rutile in medium to high-grade metamorphic 630 rocks as well as sedimentary rocks, and its high mechanical and chemical stability during weathering, transport and diagenesis make rutile a prime-candidate for such work (Triebold et al. 631 632 2012). It was shown that Cr and Nb abundances can effectively be used to distinguish between metamorphosed mafic and pelitic lithologies; Fe content also serves as an indicator of 633 metamorphic origin since metamorphic rutile contains generally >1000 ppm Fe (Zack et al. 634 2004). Rutiles investigated in this study have Cr contents ranging from 300 to 2400 ppm and Nb 635 contents ranging from 570 to 1900 ppm. It is also noteworthy that Fe contents range from 300 to 636 3900 ppm, and most analyses exceed 1000 ppm. According to the chemical classification of 637 Triebold et al. (2012) most of our rutile analyses suggest a metapelitic origin with only 7 rutile 638 analyses indicative of origin from metamorphism in the mafic rock. 639

640

641 5. Discussion

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5.1. Geology, age and origin of Voizel suite and Central Tonalitic gneisses

Although long considered part of the same suite, new evidence shows that the Voizel and 644 645 CTG instead belong to separate generations of TTG gneisses within the Inukjuak Domain. Their geochemical properties are similar: all the felsic gneisses analyzed here yield multi-element plot 646 patterns that conform with classic Archean continental crust signatures and have negative Nb and 647 648 Ti anomalies (Figure 8b; Rudnick, 1995). Both units are primarily tonalitic gneisses with about 70 wt.% SiO₂ and moderate concentrations of alkalis (NaO+CaO+K₂O ~ 9.0 wt.%). The Voizel 649 suite rocks, however, are more depleted in REEs (particularly the HREEs) than those from the 650 651 CTG, and two Voizel suite rocks that plot in the quartz monzonite field as opposed to the tonalite

652 field (Figure 7) also have positive Eu anomalies. Gneissic rocks with these types of features (low REE concentrations, positive Eu anomalies) in ancient (Hadean-Archean and younger) 653 metamorphic terranes have been interpreted as leucosomes during migmatite formation (e.g. 654 Sawyer, 2008; Cates et al. 2013; Mojzsis et al. 2014). Although these small geochemical 655 differences could be the result of internal variability, our preferred interpretation is that the 656 geochronological differences between these two suites point to two distinct emplacement events. 657 The Voizel suite is ca. 3550 Ma old based on upper concordia intercept ages, even if it has no 658 individual zircon analysis with an age above 3538 ± 6 Ma (IN12046). The zircon with the best fit 659 660 for the lattice strain model is among the oldest of the zircons (Sec. 4.4), with an age of 3530 Ma and 99% concordant (IN12027). In contrast to the Voizel suite samples, the CTG sample 661 IN12012 has abundant zircons with ages up to 3663 ± 5 Ma, and the zircon with the best fit for 662 663 the lattice strain model is 3661 ± 8 Ma. The ca. 3660 Ma cores are consistent with igneous growth and are interpreted as the maximum age of the CTG. Thus, the age of the CTG as 664 determined by the upper intercept of the discordia on the Tera-Wasserburg plot, is the age of 665 666 sample IN12012, which is 3652 ± 14 Ma. This age is about 100 million years older than the previously (albeit provisionally) assigned values for the Voizel suite (O'Neil et al. 2007, 2019 667 668 and references therein). Furthermore, David et al. (2009) presented geochronological data for a single mylonitized sample from the northwest of the margin of the NSB, which was resampled 669 by us as IN14035, and our data are in agreement. As IN14035 gives a weighted mean ²⁰⁷Pb/²⁰⁶Pb 670 671 zircon age of ca. 3650, this rock is most likely related to the CTG rather than to the more widely distributed and volumetrically more important Voizel suite. 672

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674 5.2. Nature of the Boizard suite gneisses

675 We find that the Boizard suite is both geochemically and geochronologically distinct from the other granitoid gneisses described within the Inukjuak Domain. It is a meta-granite and lacks 676 the foliation observed in the Voizel and CTG outcrops. Zircons from the Boizard suite cluster 677 678 mostly around ca. 2700 Ma, with some degree of inheritance. These older, inherited ages all come from grains with rounded cores, some of which are surrounded by igneous rims with strong 679 oscillatory zoning. The inherited cores of the Boizard suite zircons include ages previously seen 680 in the NSB (Cates et al. 2013), which suggests that the granites were extensively contaminated 681 by zircons from the supracrustals during emplacement. 682

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685 5.3. Candidate Innuksuac Complex supracrustal rocks beyond the NSB

In contrast with the Nuvvuagittuq outcrops, the Ukaliq rocks are more strongly deformed into 686 a set of relatively small disconnected mafic to ultramafic enclaves with very minor (<1% of total 687 outcrop) metasedimentary components. The three TTG gneisses sampled for this study were 688 689 selected because they were mapped to cross-cut USB amphibolites. Results of our U-Pb zircon geochronology show that they are generally younger than those found in the ca. 3780 Ma 690 691 Nuvvuagituq outcrops further to the southwest (Cates and Mojzsis, 2007). Zircons from the oldest Ukaliq supracrustal belt enclave samples mostly yield an upper intercept age of ca. 3600 692 Ma (sample IN12017, Figure 13), although the oldest and still highly concordant individual 693 694 grain in this particular sample is ca. 3650 Ma. These ages might be interpreted as evidence that modification and dismemberment of the USB was contemporaneous with the emplacement of the 695 CTG. Associated granitoid gneisses, which preserve the oldest age in this sample is tonalitic with 696 697 less than 200 ppm Zr (Supplementary Table S1), thus making inheritance an unlikely source of

698 the oldest grains. The other two supracrustal gneiss samples are granodioritic. Sample IN12053, 699 with a zircon population of ca. 3360 Ma also has two older grains at ca. 3700 Ma and ca. 3580 Ma, but these grains are discordant (~30%). This sample has low Zr concentration (111 ppm), 700 701 again arguing against inheritance, and all of these analyses come from zircon cores with oscillatory zoning. Thus an absolute age of this unit cannot be established, though the older 702 analyses likely best represent the sample. Sample IN12053 also has a population of ca. 2700 Ma 703 704 zircons, which is unsurprising due to the proximity of the enclave to the contact between the Voizel suite and Boizard suite. This age has not been observed in any of the other enclave 705 706 samples analyzed in this study.

The quartz-biotite schist we provisionally assigned as a quartz-pebble "metaconglomerate" 707 sample IN14032A has a minimum age of formation of 3550 Ma, as determined by field 708 709 relationships with the surrounding Voizel suite. If the different disrupted USB rafts are related to 710 one another, then the oldest age of the felsic enclaves sets the minimum age at 3600 Ma. The oldest zircon in this sample, at 3771 Ma, if interpreted as such gives a minimum age of the 711 712 detrital source material (Supplementary Table S2; Figure 13). A small zircon population in this sample the same age of the CTG further supports the idea that the dismemberment of the USB 713 714 commenced at 3650 Ma, which led to partial re-setting of the ca. 3770 Ma zircons (Cates and Mojzsis, 2009; Cates et al. 2013). This could also suggest that the USB incorporated detritus 715 after the emplacement of the CTG, but not since that time, and instead the quartz-biotite schist 716 717 has a maximum age of 3650 Ma

Sample IN14036 was collected outside of the limits of the NSB. However, since its age of ca.
3760 is the same as other samples collected from the NSB (Cates and Mojzsis, 2007; Cates et al.
2013), it is likely related to the supracrustals in some way. This particular sample could represent

an enclave of the NSB within the surrounding TTGs, suggesting that the NSB is not as cohesive as previously thought, or that the section of CTG that separates this sample from the rest of the belt is intruding the NSB, which extends further west than previously thought. It is also possible that the USB exists as a set of enclaves within the Voizel, and this sample represents the westernmost expression of the USB as well as a maximum age for the supracrustals. Further field studies to document further Eoarchean rocks in the northern Inukjuak Domain are needed to distinguish between these possibilities.

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729

730 **6.** Conclusions

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732 Poly-metamorphosed TTG gneisses of the Inukjuak domain were emplaced over multiple generations spanning a billion years. Our results from detailed U-Pb zircon geochronology of 733 samples from both the Nuvvuagittuq and Ukaliq supracrustal belts reveal multiple generations of 734 735 zircon growth, spanning from ca. 3780 to 2700 Ma. These intrusive events, distributed over space and time, disrupted, deformed and metamorphosed the various supracrustal enclaves of the 736 Innuksuac Complex and are recorded as episodes of metamorphic zircon growth from samples 737 collected from within the enclaves as well as in the oldest TTG gneisses (Cates and Mojzsis, 738 2007; Cates et al. 2013; cf. Darling et al. 2013). 739

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The results of our study can be summarized as follows:

743 1. Lattice strain partition modeling differentiates between different zircon age populations based on compositional parameters, and suggests both crystallization ages and neoform 744 zircon growth events for many of the studied units. Based on this combined approach, the 745 746 age of the CTG can now be resolved to ca. 3650 Ma. The previously undated Voizel suite is about 100 million years younger, with a maximum age of approximately 3550 Ma. The 747 Boizard suite, emplaced at ca. 2700 Ma, experienced widespread xenocrystic 748 contamination during its emplacement and carries inherited zircons from all older suites 749 in the terrane, including those from the NSB. Disruption and partial structural 750 dismemberment of the Ukaliq supracrustal belt (with a maximum age of ca. 3770 Ma) 751 may be contemporaneous to the timing of the formation of the CTG. This age 752 relationship may provide a link to the neighboring ca. 3750-3780 Ma NSB (Cates and 753 754 Mojzsis, 2007; Cates et al. 2013). Sample IN14036 represents a new expression of an old TTG gneiss to the north and west, but further field study is needed to determine whether 755 it represents an outcrop of the NSB or USB, or something else entirely. 756

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Petrological investigations of select samples show pervasive retrograde metamorphism of
the mineral assemblages. Our new Zr-in-rutile thermobarometry results underscore the
history of amphibolite to greenschist facies metamorphism that accompanied polyphase
deformation events throughout the southern Inukjuak region. It is apparent that none of
the Eoarchean Innuksuac supracrustal rocks escaped a variable history of retrograde
metamorphism and deformation.

765 3. No confirmed microfossils older than about 3500 Ma exist, probably because all known 766 Eoarchean rocks of sedimentary protolith – including those of the Inukjuak Domain – are both metamorphosed, deformed and variably recrystallized. In our view, the claims of 767 Dodd et al. 2017 that microfossil shapes including "hematite tubes and filaments" are 768 found in secondary jaspilite veins from Nuvvuagittuq are no exception. Indeed, many of 769 the structures they describe including associations of hematite, quartz and magnetite are 770 771 documented as non-biological features (e.g. Figueiredo et al. 2008). The geologic history described herein precludes preservation of any fine-scale primary structural features, 772 either "stromatolites" or purported fragile microfossil shapes hosted in jaspilite box-work 773 veinings (Taylor 2011). Despite such shortcomings, the Inukjuak Domain supracrustal 774 rocks are a unique complementary repository to the only other large (~3000 km²) domain 775 776 of Eoarchean rocks known, those of the Itsaq Gneiss Complex in West Greenland. Investigations of the Innukjuak Domain have only scratched the surface of a region that 777 was nots recognized for its enormous antiquity until recently (2001-2002). To date, the 778 779 most exciting rocks reported from the Inukjuak region are those that are also easily accessible by boat, but otherwise the vast inland localities can only be spot-checked here 780 and there, with many more apparent from aerial photographs and satellite images. 781

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4. That some rocks from the area indeed include paragneisses with protoliths ascribable to
detrital "quartzites" and "conglomerates" means that they could preserve one of the
oldest if not the oldest unconformities thus far recognized. For instance, quartz-rich
sedimentary rocks appear to overly ca. 3650 Ma TTG basement in several places in the
Nuvvuagittuq and Ukaliq outcrops. Also, although data reported herein are largely of a

788		reconnaissance nature on a rather extensive and well-selected suite of "reconnaissance
789		samples" it is striking to note that there are no zircon grains older than about 3800 Ma
790		despite thousands of zircon analyses since 2005. This result in of itself casts serious
791		doubts on the interpretation that the Inukjuak Domain, including the Nuvvuagittuq
792		Supracrustal Belt, preserves a formational history that goes back half a billion years older
793		(to ca. 4300 Ma; cf. O'Neil et al. 2007, 2019).
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796	5.	The ca. 3.8 Ga Innuksuac Complex provides a hitherto unexpected windfall in the study
797		of early Earth materials by providing a new, more global perspective beyond that of the
798		Isua, Akilia, Manfred and Saglek Harbor rocks. The ~12,000 km ² Inukjuak Domain is
799		unquestionably an important resource that adds to our understanding of the physical,
800		chemical, (proto-)biological and geodynamical state of the Earth's surface at the Hadean-
801		Eoarchean transition around 3850-3800 million years ago.
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803	(8	535 words)
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1071	FIGURE CAPTIONS
1072	Figure 1. Simplified map of the northwestern Superior Province, with the location of the town of
1073	Inukjuak (gray dot) and the study area (yellow star) highlighted. (For interpretation of the
1074	references to color in this figure legend, the reader is referred to the web version of this article.)
1075	

Figure. 2. Regional geologic map (after Simard, 2003) showing the geological context of the ancient supracrustal remnants of the Innuksuac Complex. The study area is outlined by the rectangle (see Figure 3). Rock suites that have not been substantially characterized are shown in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Figure 3. Local geologic map showing the main lithologies discussed herein. Samples described in this work are represented by large black dots, additional samples with geochemical data are represented by small white dots, and samples from other studies are represented by small gray points (see Supplementary Information in Cates et al. 2013 for reported data tables). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Figure 4. Field photographs of the main lithologies discussed in this work. The Voizel suite is represented by sample IN12041 (hammer for scale, ~30 cm); Ukaliq enclaves are exemplified by sample IN12042 (as a white gneiss that cross-cuts amphibolite; 1 m hammer for scale); an example of the Central Tonalitic Gneiss is from sample IN12012 (hammer for scale); and the Boizard suite is represented by IN12054 (pen for scale, 10 cm). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

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Figure 5. Back-scatter electron and cathodoluminescence paired images of representative zircon
grains reported in this work (a-f). (a) Example of a euhedral, igneous zircon; note rim with bright
CL response. (b) Example of an igneous core with an overgrown metamorphic rim. (c) Example

1099 of a rounded, inherited core surrounded by an igneous overgrowth. (d) Example of a zircon with 1100 a texture typical of metamictization. (e) Zircon with a geochronology spot that has overlapped a 1101 fracture. (f) Zircon with a texture that suggests intense metamictization and/or hydrothermal 1102 alteration. Please see **Supplementary Figures S1** for the complete documentation of these 1103 samples.

1104 Figure 6. Back-scatter electron images illustrating the textural relationships in four 1105 representative samples discussed in the text. (a) Meta-conglomerate sample *IN14032A* shows the mineral assemblage anthophyllite (Anth) + muscovite (Ms) + stilpnomelane (Stp) + quartz (Qz) 1106 + rutile (Rt). Anthophyllite is replaced by the assemblage chlorite + talc (Chl + Tc). (b) Boizard 1107 1108 suite granite sample IN12016 contains the mineral assemblage chlorite (Chl) + epidote (Epi) + 1109 titanite (Ttn) + albite (Ab) + quartz (Qz). (c) The grey gneiss sample IN14036 shows the mineral assemblage biotite (Bt) + muscovite (Ms) + plagioclase (Pl) + quartz (Qz). Biotite is replaced by 1110 chlorite + titanite (Chl + Ttn). (d) The Voizel tonalite sample IN12044 contains the mineral 1111 1112 assemblage biotite (Bt) + K-feldspar (Kfs) + plagioclase (Pl) + quartz (Qz) + apatite (Ap). 1113 Biotite is replaced by chlorite + titanite (Chl + Ttn) and albite contains small zoisite (Zo) grains.

Figure 7. Classification of samples based on normative anorthite, albite, and orthoclase compositions. Fields from Barker (1979). CTG samples are red, Voizel samples are green, Boizard samples are blue, and supracrustals and USB enclaves are purple. Numbers refer to the last two-digits of the sample identifiers in **Supplementary Table S1**. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 8. (top) Chondrite-normalized (Anders and Grevesse, 1989) REE plot; (bottom) Primitive
Mantle-normalized (McDonough, 1992) multi-element plot. Color coding of the samples as in

Figure 7 (Supplementary Table S1). (For interpretation of the references to color in this figure
legend, the reader is referred to the web version of this article.)

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1125 Figure 9. (a) Light-colored quartz-rich rocks below the belt of ultramafic boudins in the northern Ukaliq supracrustal belt. Significantly, the quartz-rich rocks appear to show a progression from 1126 1127 detrital quartzites to meta-cherts with magnetite-bearing laminae higher up. Sample location of IN14032A is annotated in the figure. (b) Close-up view of the quartz-rich rocks of probable 1128 detrital origin (i.e. quartzite proper). Note subtle aspects of the relict layering suggesting both 1129 1130 grading and truncations. The greenish color is probably due to calc-silicates. (c) Mesoscopic view of highly deformed amphibolites and supracrustal gneiss, with strong boudinage of the 1131 more competent layers. Gneissosity has been pulled into the boudin necks and folded, whereas 1132 1133 quartz-feldspar veins and pods fill discontinuities and areas of strong local extension. (d) Quartzbiotite schist at the base of the ultramafic body (IN14032A; labelled) for which detrital zircon U-1134 Pb geochronology was attempted. These various outcrop-scale structures illustrate the structural 1135 1136 style of the Ukaliq supracrustal belt, with the boudins being analogous to the larger ultramafic bodies in the wider area, and the quartz veins representing late Neoarchean granitic pegmatites 1137 1138 that intruded late during the boudinage forming deformation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.) 1139

Figure 10. U-Pb zircon geochronology expressed in Tera-Wasserburg plots for Central Tonalitic
Gneiss samples (IN05001, IN12012, IN14035); gray ellipses not included in the weighted
average ²⁰⁷Pb/²⁰⁶Pb age.

Figure 11. U-Pb zircon geochronology for Voizel suite samples investigated in this work; grayellipses not included in weighted mean or upper intercept age calculations.

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Figure 12. Boizard suite U-Pb zircon geochronology; gray ellipses not included in weighted
 mean ²⁰⁷Pb/²⁰⁶Pb age.

Figure 13. U-Pb zircon geochronology for various supracrustal (NSB and USB) and USB intrusion samples; gray ellipses not included in weighted mean or upper intercept age calculations.

Figure 14. (a.) REE data plotted for zircons used in the lattice-strain partitioning modeling work described herein. (b) Onuma diagrams of selected zircons from TTG and Voizel samples showing R^2 fitting values (see Mojzsis et al. 2014 and references therein). Colors correspond to the calculated partition values for a particular grain using its host rock, and the model best-fit line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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1160 SUPPLEMENTARY ONLINE INFORMATION

1161 SUPPLEMENTARY FIGURES

1162	Figures S1. Back-scatter electron and cathodoluminescence paired images of zircon grains used
1163	in geochronological and trace-element analysis, labeled with ion microprobe spot and $^{207}\text{Pb}/^{206}\text{Pb}$
1164	age. Please see Supplementary Data Table S2 for specific assignments of age spots to zircons.
1165	Figure S2. Field photos of the CTG: above, sample IN05001 (person and backpack for scale);
1166	below, sample IN12012 (hammer 30 cm for scale).
1167	
1168	Figure S3. Field photos of the CTG: above, sample IN05001 (person and backpack for scale);
1169	below, sample IN12012 (hammer 30 cm for scale).
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1171	Figure S4a. Field photos of the Voizel suite: both pictures sample IN12014 (above: hammer and
1172	person for scale; below: field of view at bottom of photo approximately 4m).
1173	
1174	Figure S4b. Field photos of the Voizel suite: above, sample IN12027 (hammer for scale); below,
1175	sample IN12041 (hammer for scale).
1176	
1177	Figure S4c. Field photos of the Voizel suite: sample IN12046 (field of view at bottom of photo
1178	approximately 1.5m).
1179	
1180	Figure S4d. Field photos of the Voizel suite: both pictures sample IN12050 (hammers 30 cm for
1181	scale).
1182	
1183	Figure S5a. Field photos of the Boizard suite: sample IN12016 (knife 8 cm for scale).
1184	

1185	Figure S5b. Field photos of the Boizard suite: both pictures sample IN12054 (pens for scale).
1186	
1187	Figure S6. Field photos of USB enclaves: above, sample IN12042 (as white gneiss cross-cutting
1188	amphibolite and A_{voi} ; sledgehammer for scale); below, sample IN12053 (clipboard and
1189	sledgehammer ~1m for scale).
1190	
1191	Figure S7. Field location of TTG mylonitic gneiss sample IN14036
1192	
1193	SUPPLEMENTARY TABLES
1194	Table S1. Data used for geochemical analysis; oxides reported in weight percentages and trace
1195	elements in ppm; CTG = red, Voizel = green, Boizard = blue, USB enclaves = purple.
1196	
1197	Table S2. Data used for geochronological analysis; CTG = red, Voizel = green, Boizard = blue,
1198	USB enclaves = purple.
1199	
1200	Table S3. Data used for zircon trace-element analysis; CTG = red, Voizel = green.
1201	

Table S4. Results of Zr-in-rutile analyses.





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Figure 10 Click here to download high resolution image



Figure 11 Click here to download high resolution image







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Figure 14 Click here to download high resolution image

