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Glass-fission-track ages, composition, and origin of tephra beds in the Upper
Cretaceous Kanguk Formation, Banks Island, Arctic Canada

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Contributors' statement

JAW: Conceived project, fieldwork (1989), glass fission-track dating, major-element analysis of glass shards by microprobe, literature research, wrote paper.

CJB: Trace-element analyses by la-icp-ms – set up protocol, did all analyses, interpreted data, and wrote section on trace-element analyses in Methods section of paper.

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Abstract

More than 50 conspicuous tephra beds occur in the Kanguk Formation of SW Banks Island. Their glass shards are remarkably well preserved and permit comprehensive characterization offering the potential for reliable, precise correlation of Upper Cretaceous sedimentary rocks across the three major depocentres of the Arctic Archipelago and adjacent northern continental margin: Sverdrup, Banks, and the Beaufort-MacKenzie basins. Twenty-one tephra beds were analyzed; all have a high-K, peraluminous, rhyolitic composition with quartz, plagioclase, ilmenite, biotite, and zircon as the dominant minerals. Trace-element concentrations, especially low Nb and Ta, show that the parental magmas formed in a continental-margin subduction environment. Glass fission-track ages range from 100 Ma to younger than 60 Ma and indicate a very low sedimentation rate giving a very condensed sedimentary sequence in SW Banks Island – a sequence that may well contain the K-Pg transition. Source calderas are unknown but most likely are situated in east-central Alaska and the central and northern Kuskokwim volcanic belt, some 1000 to 1500 km distant from SW Banks Island. It is also possible that some of the very thin tephra beds come from the Okhotsk-Chukotka volcanogenic belt in NE Russia.

Keywords

Glass fission-track dating, glass composition, tephrochronology, Kanguk Formation, Late Cretaceous, Arctic Archipelago, stratigraphy.

Introduction

Tephra-fall beds are unique entities when their extrinsic and intrinsic attributes are taken into consideration. As such, each, in most cases, is readily recognizable. This reality, along with their commonly widespread distribution and ability to define their age by a variety of methods, make them extremely valuable stratigraphic markers. State of preservation is important in realizing the full potential of tephra beds in this respect. Late Cenozoic tephra beds typically have not suffered much, if any, alteration; in particular, they still have their glass shards, used widely to characterize tephra beds. In older tephra beds, however, the reactive glass has usually been broken down into clay minerals and/or other diagenetic phases. Some phenocrysts may also have suffered the same fate. As a result, their stratigraphic usefulness is diminished; correlations based on weathered tephra beds are more problematic.

Occasionally, old tephra beds are remarkably well preserved. A case in point is the sequence of tephra beds in the Upper Cretaceous Kanguk Formation of Banks Island in the southwestern Canadian Arctic Archipelago (Miall 1979) (Figs. 1 and 2). These tephra beds are interbedded with marine, organic-rich shales the basal part of which accumulated under anoxic bottom-water conditions. Penecontemporaneous mixing due to bioturbation is absent because of the lack of an infauna, although the uppermost part of some tephra units has been reworked by bottom currents (Fig. 3 c and d).

The Kanguk Formation and its correlative beds have a widespread distribution across the Canadian Arctic Archipelago and nearby MacKenzie Delta region so that its abundant tephra beds offer an opportunity for refinements in correlation and geochronology.

To this end, the current study, which is an outgrowth of the work by Kemp (1993), contains a description of the tephrostratigraphy at two sites in southwestern Banks Island, namely, Duck

Hawk Bluffs and the upper reaches of the Sachs River Valley (Fig. 1), where excellent exposures of the Kanguk Formation occur. The mineralogy, major- and trace-element composition of glass shards, and glass fission-track (ft) ages are presented for the more prominent tephra beds. At present, no definitive statement can be made on their sources, but several likely candidates are mentioned. The study concludes with comments on the stratigraphic significance of the tephra data. In short, characterization of the Kanguk Formation tephra beds will increase their utility for correlation of Upper Cretaceous-lower Paleocene strata of the several major depocentres in the Arctic Archipelago and northern continental margin.

Methods

Sample preparation involved sieving the bulk tephra to obtain the 0.25 – 0.125 mm size fraction for each sample followed by ultrasonically cleaning for 10 minutes, drying, and sieving again to concentrate the coarsest material. Minerals were separated from glass, and pumiceous glass from platy and bubble-wall glass shards using a Frantz Isodynamic Magnetic Separator. The platy and bubble-wall glass fraction were used for compositional analysis and age determination. Glass separates of all samples were then mounted in resin blocks and polished for major- and trace-element analyses.

Major-element concentrations in glass were determined using a JEOL JXA-8230 Electron Probe Micro-Analyzer with 5 WDS and 1 EDS at the University of Toronto. Operating conditions were 15 kV accelerating voltage, 6 nA current, and 10 μ m beam diameter. The MPI-DING ATHO-G reference glass (Jochum et al. 2006) was used to monitor accuracy of the glass analyses.

Trace elements were analyzed using the laser ablation inductively-coupled plasma mass spectrometry (la-icp-ms) system at the Department of Earth Sciences, University of Toronto.

99 This consisted of a New Wave UP-213 (solid state frequency quintupled Nd-YAG laser) laser
100 ablation microscope connected to a VG PQ-Excell quadrupole ICP-MS. Helium was used as the
101 transfer gas at a rate of 1000 cc/min and the plasma tuned to produce oxide production of less
102 than 2% monitoring ThO^+/Th^+ (masses 248/232) and U^+/Th^+ (masses 238/232) as close as
103 possible to unity. Samples were analyzed for 80 seconds of which the first 20 seconds consisted
104 of background. The sample cell was flushed for a minimum of 60 seconds between each
105 analysis. Up to 20 glass shards from each sample were analyzed in blocks at a time with
106 NIST610 being analyzed at the beginning and end of each block. ATHO-G was also analyzed in
107 each block as a reference standard. Laser conditions for NIST610 analysis were 10 Hz repetition
108 rate with a 55 μm spot in lines approximately 300 μm long. Glass shards and ATHO-G were
109 analyzed using 25 μm spots as lines 70 – 100 μm long with the same 10 Hz repetition rate and a
110 scan speed of 20 $\mu\text{m}/\text{sec}$. Energy and fluence values ranged from 0.036 – 0.093 mJ and 7.10 –
111 9.50 J/cm^3 within each run for UT912, 907, 928, and 923, respectively. Corresponding values for
112 UT929 and 934 are 0.047 – 0.061 mJ and 9.5 – 12.5 J/cm^3 and for UT915, 921, 942, 937, 931
113 and 941 are 0.055 – 0.069 mJ and 11.2 – 12.7 J/cm^3 . The resultant time resolved data were
114 reduced offline using the Glitter version 4.4.4 software package (MacQuarie Research Ltd.).
115 Elements were quantified using NIST610 (Pearce et al. 1997) and ablation yields were corrected
116 using SiO_2 (anhydrous) values obtained by electron microprobe analysis. This procedure gave a
117 bulk composition for each glass shard with fractionation effects being minimized, if present, by
118 the shallow penetration of the laser. Good agreement with ATHO-G glass was achieved apart
119 from Nb and Ta for some samples.

120 The glass fission-track method used to determine the age of several tephra samples from the
121 Kanguk Formation is the zeta calibration method, which is based on analysis of age standards

(Hurford and Green 1983; Wagner and Van den Haute 1992). The age standard used is the Moldavite tektite glass with a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 14.808 ± 0.021 Ma (2σ) (Schmieder et al. 2018). The population-subtraction variant was used (Westgate 2015) and correction for partial track fading was done using the diameter correction method (DCFT) (Sandhu and Westgate 1995) or the isothermal plateau technique (ITPFT) (Westgate 1989). Ages were calculated using $\lambda_D = 1.551 \times 10^{-10} \text{ yr}^{-1}$. Zeta value is 311 ± 4 based on 7 irradiations at the McMaster Nuclear Reactor, Hamilton, Ontario, using the NIST SRM 612 glass dosimeter and the Moldavite glass. Area was estimated using the point-counting technique (Naeser et al. 1982) or a calibrated eyepiece graticule. Internal age standards (Huckleberry Ridge tephra and Walcott Tuff) were dated to monitor the accuracy of the neutron fluence estimate and age determination for each sample.

Kanguk Formation

The Kanguk Formation was defined by Souther (1963) based on exposures on the Kanguk Peninsula, Axel Heiberg Island, where it consists of shale with minor sandstone along with tuffs and bentonite beds in its lower strata. It has a widespread distribution throughout the Arctic Islands being deposited in the Sverdrup Basin (Embry and Dixon 1990, Pugh et al. 2014), Banks Basin (Jutard and Plauchut 1973, Miall 1979, Dixon et al. 1992), (Figs. 4 and 5) with correlative beds in the Beaufort-MacKenzie Basin (Dixon et al. 1992, Young et al. 1976), Yukon Coastal Plain (Young 1975), and northern Alaska (Tappan 1960, Embry and Dixon 1990). Thicknesses on Banks Island range from 270 m to 463 m (Miall 1979). The Kanguk Formation disconformably overlies either the Hassel Formation or the Christopher Formation on Banks Island and has a gradational contact with the overlying Eureka Sound Formation (Fig. 5).

The black to dark-grey, organic-rich shales and siltstones of the lower Kanguk Formation accumulated in a distal offshore basin setting -- a low energy, low oxygen environment (Dixon et

al. 1992). Deep-water conditions were produced by a rapid transgression due to increased subsidence and eustatic sea-level rise (Pugh et al. 2014) that was contemporaneous with the continued opening or sea-floor spreading of the Canada Basin involving the counter clockwise rotation of northern Alaska and adjacent northern Siberia away from the Canadian Arctic Islands (Embry and Dixon 1990). Sandstones in the upper part of the Kanguk Formation point to a shallowing of the basin and shelf conditions marking the fourth transgressive – regressive cycle of Embry and Osadatz (1988).

Several estimates on the age of the Kanguk Formation are given in the lithostratigraphic chart (Fig. 5). More recent studies have added refinements. Palynological investigations on the underlying Hassel Formation at Hoodoo Dome, Ellef Ringnes Island, indicate a late Albian through mid-Cenomanian age providing a maximum stratigraphic age for the Kanguk Formation (Galloway et al. 2012). The $^{40}\text{Ar}/^{39}\text{Ar}$ age of lava flows immediately beneath the Kanguk Formation of 95.3 ± 0.2 Ma on Axel Heiberg Island provides another maximum age estimate (Tarduno et al. 1998). Ammonites suggest the basal Kanguk Formation on Amund Ringnes Island in the northern part of the Sverdrup Basin is late early Turonian (~ 92.0 to 91.0 Ma) (Balkwill 1978, mentioned in Tarduno et al. 1998).

At Axel Heiberg Island and the nearby Ellef Ringnes Island (Fig. 4), the lowermost Kanguk Formation is placed within the uppermost Cenomanian (Pugh et al. 2014, Davis et al. 2017). Evidence for this placement is the presence of an organic-rich zone with a positive $\delta^{13}\text{C}$ excursion, interpreted as the Oceanic Anoxic Event 2 (OAE2), known to have terminated at the Cenomanian – Turonian boundary (CTB) (Herrle et al. 2015), which is dated at 93.9 ± 0.15 Ma (Meyers et al. 2012). At the same two localities, bentonites in the Kanguk Formation, dated by the U – Pb method, give ages ranging from 92.99 ± 0.30 to 83.80 ± 0.21 Ma indicating a

168 Turonian to Santonian age (Davis et al. 2017). Deposition of the Kanguk Formation continued
169 into Campanian times in the eastern Sverdrup Basin based on pelecypods and foraminifera (Wall
170 1983). Additional, mostly earlier studies regarding the age of the Kanguk Formation include
171 Thorsteinsson and Tozer (1970), Balkwill et al. (1982), and Tapia and Harwood (2002).

172 Miall (1979) suggested that the Kanguk Formation on Banks Island probably ranges in age
173 from Turonian to Maastrichtian with a Turonian – Santonian age at the base of the formation in
174 the Big River Basin (Fig. 1). Evidence for a Maastrichtian age is largely based on palynological
175 studies by W.S. Hopkins, Jr., as reported by Miall (1979). Similar results were obtained by
176 Jutard and Plauchut (1973), as mentioned in Miall (1979). They also stated that the upper sand
177 member (Fig. 5) contains marine dinoflagellates that are known in Danian (early Paleocene)
178 strata in northern Europe.

179 **Tephrostratigraphy**

180 More than 35 tephra beds with thicknesses greater than 2 cm have been recognized in the
181 Kanguk Formation of southern Banks Island (Figs. S1 and S2). Many other distinct tephra beds
182 with thicknesses less than 2 cm exist but were not collected in this study. Typically, the tephra
183 beds, which were deposited in a marine environment, have a sharp, well-defined base but the
184 upper contacts are commonly more diffuse due to reworking (Fig. 3 c and d). Some beds are
185 partially to completely altered to a soapy yellow bentonite. However, most tephra beds contain
186 well-preserved, hydrated glass shards.

187 Investigations were focused on two sites, the Duck Hawk Bluffs and exposures near Swan
188 Lake along the upper reaches of the Sachs River (Fig. 1).

189 Duck Hawk Bluffs (DHB) is located on the southwestern coast of Banks Island facing the
190 Beaufort Sea at $71^{\circ} 57.9' \text{ N}$ and $125^{\circ} 38.0' \text{ W}$. A single tephra bed is exposed near the base of
191 the section, where sampled, and occurs in shales with thin sandy partings that belong to the
192 Kanguk Formation (Fig. 6). Fine-grained sandstone underlies the tephra, which is 8 cm thick,
193 poorly indurated, and dips 12° to the southeast so that the tephra bed gets higher above the beach
194 level to the west (Fig. 3a). It is capped by 25 cm of reworked tephra above which are 20 m of
195 interbedded shale and fine-grained sandstone of the Kanguk Formation. The uppermost part of
196 the section consists of sand and gravel of uncertain age.

197 The Swan Lake I section is located at $71^{\circ} 43.3' \text{ N}$ and $123^{\circ} 24.3' \text{ W}$ close to Swan Lake in
198 the upper Sachs River Valley. Three small trenches were dug into the hill. The 50 cm deep
199 uppermost trench, just below the contact with the overlying gravel and sand (Fig. 7), revealed
200 several thin, discontinuous, mostly altered and deformed tephra beds. Another trench in the
201 middle part of the section, about 7.5 m above the river, showed 7 thin and deformed tephra beds
202 (UT904 to UT910) (Fig. 3b), the upper part of some having been altered to bentonite. The
203 lowermost trench is just below the middle trench but several metres to the side. Here, a 50 cm
204 thick tephra (UT912) within bituminous shale is overlain by several thin tephra layers, some of
205 which may be correlatives of those seen in the middle trench.

206 Swan Lake II is located farther upstream along the upper Sachs Valley at $71^{\circ} 43.1' \text{ N}$ and
207 $123^{\circ} 23.0' \text{ W}$ where the Kanguk Formation consists of black bituminous shale and siltstone that
208 corresponds to the basal bituminous shale of Miall (1979) (Fig. 5). A 4 m thick, light brown,
209 thinly bedded shale is present at the top of this section. Tephra beds are confined to the
210 bituminous shale and more than 30 have thicknesses greater than 2 cm (Figs. S1 and S2). The
211 thicker beds occur in the lower part of the formation (Fig. 2). Tephra beds that were sampled are

indicated by their UT number (Fig. 8). They are laterally continuous and maintain a relatively uniform thickness (Fig. 2). As at the Swan Lake I section, tephra units near the top of the exposure have undergone more alteration than those lower in the section.

Composition of tephra beds

Vitric tephra-fall beds in the Kanguk Formation are high-K, peraluminous, almost aphyric rhyolites and high-silica rhyolites. The typical phenocryst assemblage is quartz, plagioclase, ilmenite, zircon, biotite, and apatite. Some tephra beds contain sanidine and rutile, and rarely, garnet and orthopyroxene.

The glass consists of mostly plate-like bubble-wall fragments, Y-shaped shards representing bubble junctions, and pumice pyroclasts, some equant in shape, others elongate with tube-like vesicles. All tephra beds contain colourless glass, but some also possess brown glass. Quartz grains are anhedral and commonly show embayments. Sodic plagioclase grains are the dominant feldspars although sanidine is present in some units. Ilmenite is the only Fe-Ti oxide present in the analyzed tephra beds; magnetite is conspicuous by its absence. Most ilmenites are subhedral to euhedral in shape with attached glass. They are homogeneous and possess inclusions of glass, feldspar and zircon. Some tephra beds (e.g. UT629) have multiple ilmenite populations. Zircon is ubiquitous. Grains are euhedral to subhedral, riddled with abundant inclusions and commonly encased in glass. Except for the very rare occurrence of orthopyroxene in the DHB tephra bed (UT629), biotite is the only ferromagnesian mineral recorded in the Kanguk Formation tephra units. The presence of euhedral hexagonal plates and attached glass speak to its primary origin. Garnet is present in UT629 at the DHB site and is believed to be xenocrystic due to its anhedral shape and absence of attached glass. Euhedral rutile with attached glass is also present in UT629.

234 Glass shards in all analyzed samples have calc-alkaline, peraluminous ($ASI = Al_2O_3 /$
235 $(CaO + Na_2O + K_2O) = 1.39 - 1.70$) rhyolitic to high-silica rhyolitic compositions (73-78 wt%
236 SiO_2) (Tables 1 and S1, Fig. 9). The cluster of high-silica rhyolite samples with their relatively
237 low Al_2O_3 , FeO_t and CaO is readily seen in Figure 9. Taking all the samples into consideration,
238 UT926 is distinctive in its high FeO_t , CaO , and Al_2O_3 . Samples UT921, UT933/34, and UT928
239 all have relatively high FeO_t and UT937/38 and UT942 have very low CaO contents (Table 1).
240 No firm correlation between the tephra beds at the 3 sampled sites can be identified with these
241 major-element data. Given the Late Cretaceous age of these tephra beds, it should be noted that
242 the consistency in the concentrations of Na_2O and K_2O from glass shard to shard in each sample
243 suggests that alkali exchange has not occurred or is very minor (Table S1).

244 The average trace-element content of glass shards belonging to 13 tephra beds, as determined
245 by the la-icp-ms method, is shown in Table 2. These values are based on several line analyses,
246 each line analysis giving the average composition of a glass shard. The individual glass shard
247 information is presented in Table S2. Three samples have two distinctive glass populations as
248 seen by their Ba content; they are UT907 and UT912 from Swan Lake I and UT934 from Swan
249 Lake II. Rare-earth element (REE) abundance curves show that UT629 from the DHB site also
250 contains two glass populations (Fig. 10). All REE profiles have a steep slope defined by the
251 LREEs, a moderate Eu anomaly, and a sub-horizontal slope defined by the MREEs and HREEs
252 (Fig. 10).

253 Compositional data show that no tephra bed occurs in more than one of the three studied
254 sections. Correlative beds will likely be identified as tephra beds from other sites are
255 characterized, especially those in northern Banks Island (Fig. 1). In addition, compositional

information is essential for provenance studies and is a necessary pre-requisite for evaluating the suitability of samples for glass fission-track dating.

Glass fission-track dating

Six tephra beds have been dated by the glass fission-track (ft) method, one from the DHB exposure and five from the Swan Lake II site. The results are shown in Table 3. Precision is generally about 10% when the fission-track area density is estimated by the point-counting method (Naeser et al. 1982). It is typically half that amount when the glass shards are large enough to allow for the use of a calibrated eye-piece graticule. Further reduction in the error associated with an age determination can be achieved by dating the sample several times under differing conditions and then calculating the weighted mean age and error. For example, using several separate irradiations, differing etch times, or correcting for partial track fading (PTF) by two different methods, the diameter correction method (DCFT) and/or the isothermal plateau correction method (ITPFT) (Westgate, 2015).

Five samples are judged to be suitable for ft dating because the restricted compositional range of their major and trace elements indicates the presence of a single glass population (Tables 1, 2, S1 and S2). The tephra bed at DHB (UT432, UT629) is an exception. Its CaO and FeO concentrations delineate a continuous compositional trend, most likely due to fractionation, but only one glass population exists (Fig. 11). However, the chondrite-normalized REE abundance curves show two glass populations but because they are co-magmatic and all the U concentrations cluster closely together (Fig. 11), a meaningful age can be determined.

Six age determinations were made on UT432/629 from the DHB. The fission-track area density was determined by the point-counting technique, correction for PTF was done by the

ITPFT method for all but one sample and the etch conditions for each sample were different (Table 3). The rounded weighted mean age and error is 66 ± 3 Ma (1σ). Two K-Ar ages on bulk glass separates were determined by R.C. Walter and G. Woldegabriel at J.L. Aronson's laboratory at Case Western University, Cleveland, Ohio. Analytical data are given in Westgate (1989). The results are 66.47 ± 3.09 Ma (1σ) and 66.45 ± 3.36 Ma (1σ), in good agreement with the glass ft age.

All remaining samples that were dated come from the Swan Lake II site. Details on procedures used and ages obtained are provided in Table 3. Mean ages range from 60 to 100 Ma and the associated errors from 3 to 7%. Internal age standards run during these analyses are within 1σ of their $^{40}\text{Ar}/^{39}\text{Ar}$ ages. The numerical ages are in their proper stratigraphic order, and, when they are plotted against height above the Sachs River, a linear regression analysis gives a correlation coefficient $r = 0.9961$ (Fig. 12).

Provenance considerations

Attempts to correlate distal tephra beds in the Kanguk Formation of southwestern Banks Island to other tephra-bearing exposures of the Kanguk Formation on the Island (Miall 1979) – a worthwhile project – should be straight-forward in that the methodologies to do this are well established and can be applied due to the excellent state of preservation of the tephra. In contrast, it is a more daunting task to identify the parent volcanic centre of distal, Upper Cretaceous tephra beds. Factors that militate against success of such a venture include extensive erosion of the volcanic pile at the source, especially the unconsolidated tephra-fall deposits, but perhaps leaving the more resistant welded ignimbrites. Glass would be devitrified and even some phenocrysts may have suffered alteration, particularly feldspars. Tectonism was rife during the Late Cretaceous – Paleocene period (Piepjohn et al. 2018). Opening of the Canada Basin resulted in

continental rift formation along the western, passive margin of the Arctic Platform (Fig. 4). Deformations and rotations of most of northern, central, and western Alaska occurred (Plafker and Berg 1994). Large-scale strike-slip movements along major faults took place in Alaska and the Yukon Territory. As a result, positions of some volcanic centres changed causing changes in distances between sources and their respective distal tephra occurrences.

Source – distal tephra correlations would have to be based on mineral assemblage, petrographic idiosyncrasies, whole-rock and mineral geochemistry of welded ignimbrites and tuffs, if present, and geochronology. Some of the distal tephra beds may well be of co-ignimbritic origin favouring the possibility of a firm correlation.

Davis et al. (2017) note that bentonite beds in the Kanguk Formation of northern Sverdrup Basin have alkaline characteristics indicating a within-plate tectonic setting. They point to volcanic centres on Alpha Ridge (Fig. 4), northern Ellesmere Island or northern Greenland as likely sources of the tephra. Thorarinsson et al. (2011, 2012) identified weakly peraluminous ($ASI = 1.05-1.20$) and peralkaline ($PI = 1.00-1.40$) welded, rhyolitic ignimbrites along the north coast of Greenland. These proximal volcanics erupted in a continental rift setting related to the opening of the Arctic Ocean in Late Cretaceous – Paleocene time. The composition of these bentonites and ignimbrites, however, denies a correlation with the tephra beds in the Kanguk Formation of southern Banks Island, as can be seen in Figures 13 and 14. The Banks Island samples plot in the “volcanic arc” field whereas the northern Greenland samples fall in the “within plate” field. The analyzed Banks Island tephra samples are peraluminous calc-alkaline rhyolites ($ASI=1.39 - 1.70$, and the peralkaline index, $PI=0.52 - 0.68$). Furthermore, the chondrite-normalized spidergrams for their glass shards show deep Nb-Ta troughs and enriched

323 large-ion lithophile elements and LREEs indicative of derivation from magmas produced in
324 subduction zones (Fig. 15).

325 Pointon et al. (2019) sampled bentonites in the Kanguk Formation in the northern part of the
326 Sverdrup Basin at the Sawtooth Range, central Ellesmere, and found two distinct types of
327 bentonite, a peralkaline rhyolitic to trachytic group and a subalkaline rhyolitic to dacitic group.
328 Tephra beds in the Kanguk Formation of Banks Island have a very similar composition to the
329 subalkaline bentonites of Pointon et al. (2019). They all plot in the same field on the
330 discrimination diagrams used by these authors, namely, that of the active continental margin.
331 Chondrite-normalized REE patterns and concentrations are also alike.

332 Several large calderas are present in the Yukon-Tanana terrane of east-central Alaska
333 (location 1, Fig. 16) (Bacon et al. 1990). Their intracaldera fill consists in part of welded
334 ignimbrites, which have a high K, peraluminous, rhyolitic composition (Table 4) like tephra beds
335 on southern Banks Island. The dominant minerals are quartz, plagioclase, and alkali feldspar;
336 mafic minerals are less abundant and consist of biotite, hornblende and Fe-Ti oxides (Bacon et
337 al. 1990). However, hornblende is absent in some of the volcanic rocks. For example, the lava
338 flow at Slate Creek (62 Ma; 64° 33' 23" N, 144° 10' 20" W) has quartz, plagioclase, sanidine,
339 biotite, and Fe-Ti oxides. These mineral assemblages are like those of the Banks Island tephra
340 beds, although hornblende has not been observed and sanidine is present in some but not all the
341 Banks Island tephra beds. Bacon et al. (1990) note that fiamme within the welded ignimbrites
342 have much smaller crystal contents than do their matrices. This observation points to generation
343 of large co-ignimbritic ash clouds during emplacement, caused by elutriation of the finer, lighter
344 vitric component during flow. Trace-element concentrations for sample 6D from the West Fork
345 caldera (Table 4) are like those of the suite of tephra beds from southern Banks Island (Table 2)

and indicate an origin in a continental magmatic arc, although it should be noted that the comparison is between whole rock and glass analyses. Furthermore, the two bivariate plots on Figure 17 show sample 6D plotting close to the Kanguk Formation tephra samples, including directly on the Sm-Nd linear compositional trend. Broad compositional similarities in the REE abundance curves of the Upper Cretaceous rhyolitic volcanics of east-central Alaska and the Banks Island tephra beds can also be seen in Figure 18a and the chondrite-normalized spidergrams of Figure 18b bear a strong resemblance to those of Banks Island tephra (Fig. 15). Potassium – argon ages on the caldera-fill welded ignimbrites range from ~94 Ma to 55 Ma (Bacon et al. 1990), which embraces the time interval defined by the glass fission-track ages of tephra beds at DHB and the Swan Lake II site.

The South Fork Volcanics in south-central Yukon Territory contain thick caldera-fill deposits of welded, calc-alkaline, andesitic, dacitic, and rhyolitic ignimbrites similar to those of the Yukon Tanana terrane in Alaska (location 4 on Fig. 16) (Wood and Armstrong 1982). The mineral assemblage of the rhyolites is like that of the tephra beds of southern Banks Island apart from the presence of hornblende. Two whole rock, anhydrous, major-element analyses of the South Fork rhyolites indicate concentrations of FeO_t (2.66, 3.78 wt%), MgO (0.85, 1.17), CaO (3.08, 3.54), TiO₂ (0.28, 0.52) (Wood and Armstrong 1982) that are much higher than the glass analyses of the Banks Island tephra beds (Table 1), a difference that is likely too large to be explained fully by the different types of samples (whole rock versus glass shards). Two K-Ar ages on ignimbrites of 95.5 ± 3.3 Ma and 94.4 ± 3.3 Ma indicate emplacement was coeval with deposition of tephra beds in the basal Kanguk Formation.

High-silica rhyolitic tephra beds, interbedded with floodplain sediments, are exposed in bluffs along the Colville River near Ocean Point, Alaska (Conrad et al. 1989, Phillips 1988) (location 2

on Fig. 16). As many as 10 tephra beds occur in the 20 – 30 m section and range in thickness from 1 cm to 2 m. According to Bergman et al. (2006), they contain trace and minor amounts of biotite, sanidine, plagioclase, quartz, Fe-Ti oxides, zircon, and apatite, the same assemblage seen in the Banks Island tephra beds. The best estimate of their age is 69.1 ± 0.3 Ma based on several K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations. Although the age of these tephra beds is within the range of glass fission-track ages of the tephra beds at Banks Island and their mineral assemblage is the same, the glass composition of one of these beds is very different (Fig. 17, Table 4); Rb, Sm, Tb, Yb, Ta, and U are higher and Ca, Ba, and Eu much lower, casting doubt that one or more of these tephra beds correlate with those at Banks Island. Bergman et al. (2006) believe that the tephra deposits in northern Alaska sedimentary sequences are most likely derived from caldera eruptions in northeast Asia, namely, the Okhotsk-Chukotka volcanogenic belt (Fig. 16).

Fresh vitric tephra beds are present in 6 m long cores recovered from bottom sediments of the northeastern Chukchi Sea (Fig. 16) (Phillips et al. 1988). Reworked crystal-rich tephra in the lowermost sand unit contains quartz, plagioclase, glassy rock fragments, biotite, Fe-Ti oxides and hornblende – a familiar assemblage. Two K-Ar age determinations on the biotite are 92.1 ± 1.2 Ma and 95.2 ± 1.2 Ma, similar to ages obtained on the volcanic rocks in east-central Alaska and central Yukon. These tephra beds, like those at Ocean Point, may well have come from the Okhotsk-Chukotka volcanogenic belt.

The same source is invoked for the two 2-3 cm-thick subalkaline bentonites sampled by Pointon et al. (2019) at the Sawtooth Range in central Ellesmere Island – involving a transport distance of about 3000 km. Their U-Pb zircon age of 89 Ma is consonant with this source because this was a time when volcanism was most active in the Okhotsk-Chukotka volcanogenic belt (Pointon et al. 2019).

A couplet of tephra beds, known as the Giraffe tephra, is preserved in maar lake sediments above a kimberlite pipe on the Canadian Shield at Lac de Gras, NWT, more than 1000 km from the nearest Upper Cretaceous-Paleocene volcanic centre (location 3 on Fig. 16). A glass fission-track age of c. 38 Ma was noted in Wolfe et al. (2017), but U-Pb zircon dating suggested an age ~ 10 Ma older (Buryak 2017). Consequently, an additional glass fission-track age, using a longer etch time, was done giving an age of 54 ± 5 Ma (Table S4), consistent with the U-Pb zircon age. Given the location and thicknesses of 10 cm and 25 cm and an age of 54 ± 5 Ma (Table S4), these tephra beds must be related to very large eruptions with the potential of being preserved in the sedimentary rocks of Banks Island. They have several chemical affinities with the suite of tephra beds on Banks Island as well as some of the proximal volcanic rocks in east-central Alaska (Figs. 17 and 18), but none of the analyzed tephra beds on Banks Island correlates with the Giraffe tephra. The high Ba content of the Giraffe tephra beds of more than 2000 ppm makes them very distinctive (Tables 2 and 4).

Lower Paleogene welded ignimbrites are extensive in the Tanacross Quadrangle of east-central Alaska and relate to the last major phase of pluton emplacement, 60 -50 Ma (Foster et al. 1994). Moll-Stalcup (1994) gives a more restrictive age for shutdown of subduction of the Kula plate beneath southern Alaska at 56 Ma. A likely candidate for the parent caldera of these Giraffe tephra beds is an elongated mass (5 x 12 km) of felsic volcanic rock, including welded ignimbrite, more than 550 m thick in east-central Alaska (site EC, Bacon et al. 1990). It is the only thick volcanic pile of known Paleocene age (57.8 ± 1.7 Ma, K-Ar age on sanidine from a welded ignimbrite) in this region. The eastern point of this caldera is at $63^{\circ} 20' 28.71''$ N and $141^{\circ} 27' 49.0''$ W and is located about 1500 km west of Lac de Gras, NWT (Fig. 16). Phenocrysts in these rhyolitic welded ignimbrites are quartz, sanidine, plagioclase,

415 clinopyroxene, biotite, Fe-Ti oxides, and, in some cases, allanite. No chemical analyses of these
416 rocks have been found in the literature, but rocks of other calderas nearby have Ba contents
417 comparable to those of the Giraffe tephra (Table 4). Other K-Ar ages for this eruptive phase in
418 this region are 56.4 ± 4 Ma and 61.6 ± 2 Ma (Foster et al. 1994).

419 Extensive volcanic fields, calderas, volcano-plutonic complexes and plutons extend
420 northeastwards as a 400 km – wide arcuate belt greater than 1000 km long from the Bering Sea
421 to the Yukon-Tanana Upland in east-central Alaska (Bergman and Doherty 1986, Doherty and
422 Bergman 1987, Miller 1994, Moll-Stalcup 1994) (Fig. 19). The plutons are discordant and
423 surrounded by thermal aureoles. The volcano-plutonic complexes are circular to elliptical piles
424 of volcanic flows with intrusive cores (Miller 1994). These continental-margin arc rocks formed
425 during a rapid northward movement of the Kula plate, 74-50 Ma.

426 Volcanic centres in the northern part of the Kuskokwim Mountains belt are sufficiently close
427 to southwestern Banks Island for tephra from large-magnitude Plinian eruptions and co-
428 ignimbritic ash clouds to reach Banks Island to form thin, visible beds in the dark bituminous
429 shale of the Kanguk Formation, which, in places, has not been disturbed by bioturbation (Fig.
430 3c). Farther south along the Kuskokwim Mountains belt this prospect is less likely due to
431 increased distance. Rhyolites are the overwhelmingly dominant volcanic rock of the Kuskokwim
432 Mountains belt (Moll-Stalcup 1994). In the northern sector they are high-K, calc-alkaline rocks,
433 71-65 Ma. Typically, they are highly enriched in K, Rb, Ba, Th, and LREEs and depleted in Nb
434 and Ta relative to La. These are characteristics seen in the distal tephra beds on Banks Island
435 (Fig. 15) and a signal of subduction-related arc rocks.

436 Volcanic centres that may have contributed tephra to Banks Island include a large volcanic
437 field, more than 1500 m thick, in the Talkeetna Mountains at the eastern end of the Alaska Range

belt (Fig. 19). Thick, calc-alkalic pyroclastic rocks of Paleocene age occur in the basal part of the sequence (Moll-Stalcup 1994). Another candidate is the Sischu volcanic field in the central part of the Kuskokwim Mountains belt, about 1400 km southwest of Banks Island. It is at least 500 m thick and consists of rhyolite and dacite domes, flows, and tuffs that were emplaced between 71 to 66 Ma (Moll-Stalcup 1994). Volcanic rocks in the Sleetmute area of the central Kuskokwim Mountains belt are more than 1000 m thick but rhyolite vitric tuff is only a minor component. These rhyolites have REE patterns that are similar to those in the northern Kuskokwim Mountains belt with La at about 100 to 200, a moderate Eu anomaly, and HREE at about 10 to 30 x chondrites (see fig. 4C in Moll-Stalcup 1994). Again, these REE patterns closely resemble those seen in the tephra beds of the Kanguk Formation (Fig. 10). Volcanic rocks of Getmuna Creek, close to Sleetmute, are more than 150 m thick and consist mostly of rhyolitic tuffs, including welded ignimbrites, with quartz, biotite, sodic plagioclase, apatite, zircon, and garnet (Cady et al. 1955) – a mineral assemblage common to some tephra beds at Banks Island. The presence of xenocrystic metamorphic minerals in the volcanic rocks of the northern Kuskokwim Mountains belt is not surprising given that the magmas penetrated the underlying Precambrian schist and Paleozoic carbonate rocks. Furthermore, thermal aureoles surround many of the volcanic centres.

A list of the characteristics of possible volcanic sources for the tephra beds in the Kanguk Formation of SW Banks Island is given in Table 5.

Discussion

Any discussion on the compositional diversity of the tephra beds in the Kanguk Formation of southwestern Banks Island is currently incomplete because out of the 51 tephra beds recorded at the three studied sites (Figs. S1 and S2) only 21 of the more conspicuous beds were analyzed.

461 Although no tephra bed is present at more than one site, the suite of tephra beds has a broadly
462 similar composition, typified in Figure 17b where the Sm/Nd ratio values of 97 glass shard
463 analyses, representing all the sampled tephra beds, form a linear array with a correlation
464 coefficient, $r = 0.96$. The mineral assemblage is very similar and glass shards of all samples have
465 a high-K, peraluminous, calc-alkaline, rhyolitic composition. A factor influencing this overall
466 likeness is that the parental magmas of all tephra beds were generated in a subduction
467 environment at a continental margin, as demonstrated by their trace-element contents.

468 Six glass ft age determinations in the lower part of the Kanguk Formation, exposed at the
469 Swan Lake II site in the upper Sachs River Valley (Fig. 12), suggest that deposition rates were
470 very low. A thickness of 7.2 m of sediment was deposited over a 40-million-year interval, giving
471 a deposition rate of 18 cm Ma^{-1} . If the tephra component is removed, because each bed was
472 probably deposited in a few days, the deposition rate is further reduced to 13 cm Ma^{-1} . In
473 addition, the age data point to the average deposition rate not varying greatly over a long period
474 of time. These values are extremely low in the context of deposition rates calculated for the
475 Kanguk Formation in central Sverdrup Basin of 19 m Ma^{-1} and 26 m Ma^{-1} at the Glacier Fiord
476 section and 72 m Ma^{-1} and 21 m Ma^{-1} at the Ellef Ringnes section (Davis et al. 2017). Absence of
477 numerical age control in the upper part of the Kanguk Formation at the Swan Lake II site
478 prevents estimation of depositional rates.

479 Almost 20 m of the Kanguk Formation lies above the tephra bed (UT629) dated at 66 Ma.
480 Likewise, several metres of the Kanguk Formation at the Swan Lake II site are younger than
481 tephra bed UT921, dated at 60 Ma (Table 3). Therefore, the upper part of the Kanguk Formation
482 at these two sites is of Paleocene age, which agrees with the statement of Jutard and Plauchut
483 (1973) that marine dinoflagellates of Danian age occur in the upper sand member of the Kanguk

484 Formation. In other words, the Cretaceous-Paleogene (K-Pg) transition may be present in the
485 Kanguk Formation in SW Banks Island.

486 Two candidates are strong contenders for the source of the distal tephra beds at southwestern
487 Banks Island based on composition and age data, although no firm correlations have been
488 established. They are the caldera-forming rhyolitic volcanism of the Yukon-Tanana region of
489 east-central Alaska that was active during the period 94 to 55 Ma, and the calderas of the
490 northern Kuskokwim Mountains belt in central Alaska that were active during the period 71 to
491 65 Ma. This chronology fully embraces the time interval during which the tephra beds at
492 southwestern Banks Island were deposited and the distance from these volcanic centres of 1000
493 to 1300 km is within the reach of large-magnitude eruptions – either Plinian eruptions or co-
494 ignimbritic ash clouds – given favourable wind conditions. The most likely source of the Giraffe
495 tephra beds in the Northwest Territories is some 1500 km to the west in the easternmost part of
496 the Yukon-Tanana Upland of east-central Alaska, an area that was volcanically active during the
497 Paleocene. However, it should be noted that given the recent studies of Pointon et al. (2019), the
498 Okhotsk-Chukotka volcanogenic belt can not be ruled out as a source for some of the distal
499 tephra beds in the Kanguk Formation of southern Banks Island.

500 **Conclusions**

501 The Kanguk Formation in southwestern Banks Island contains approximately 50 distal tephra
502 beds of which 21 were studied in detail. The latter group are high-K, peraluminous, almost
503 aphyric, rhyolites and high-silica rhyolites, and the dominant phenocrysts are quartz, plagioclase,
504 ilmenite, zircon, and biotite. Trace-element contents indicate derivation in a continental-margin
505 subduction environment. Six glass fission-track ages range from 100 ± 4 Ma to 60 ± 4 Ma
506 confirming a Late Cretaceous-Paleocene age but also indicating the presence of Paleocene strata

in the Kanguk Formation. The average sedimentation rate in the lower part of the Kanguk Formation in the upper Sachs River Valley is extremely low at 18 cm Ma^{-1} and did not vary much over a long period of time. In other words, the Kanguk Formation here is a condensed section that may well represent a continuous record of Late Cretaceous - Paleocene time. The source calderas of these distal tephra beds are unknown but the most likely source areas are the Yukon-Tanana region of east-central Alaska and the northern sector of the Kuskokwim Mountains belt in central Alaska. These conclusions need to be tested by the application of more precise dating methods, such as the $\text{Ar}^{40} / \text{Ar}^{39}$ and U-Pb methods.

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References

Bacon, C.R., Foster, H.L., and Smith, J.G. 1990. Rhyolitic calderas of the Yukon-Tanana Terrane, east central Alaska: volcanic remnants of a Mid-Cretaceous magmatic arc. *Journal of Geophysical Research*, **95**, B13, 21451-21461.

- 529 Balkwill, H.R. 1978. Evolution of Sverdrup Basin, Arctic Canada. American Association of
530 Petroleum Geologists Bulletin, **62**, 1004-1028.
- 531 Balkwill, H.R., and Hopkins, Jr., W.S., and Wall, J.H. 1982. Geology, Loughheed Island, District
532 of Franklin. Geological Survey of Canada, Memoir **388**, 1-48.
- 533 Bergman, S.C., Akinin, V.V., Decker, J., Miller, E., and Layer, P. 2006. North Alaska Upper
534 Cretaceous tephra: Eurasian or North American source calderas? Geological Society of
535 America, Abstracts with Programs, **38**, 90.
- 536 Bergman, S.C., and Doherty, D.J. 1986. Nature and origin of 50-75 Ma volcanism and plutonism
537 in W. and S. Alaska. Geological Society of America, Abstracts with Programs, **18**, 539.
- 538 Buryak, S. 2107. U-Pb zircon geochronology of the sedimentary fill of the Giraffe Pipe, Lac de
539 Gras, NWT. B.Sc. thesis, Department of Earth and Atmospheric Sciences, University of
540 Alberta, Edmonton, AB.
- 541 Cady, W.M., Wallace, R.E., Hoare, J.M., and Webber, E.J. 1955. The central Kuskokwim
542 region, Alaska. United States Geological Survey, Professional Paper 268, 132 pp.
- 543 Conrad, J.E., McKee, E.H., and Tuirrin, B.D. 1989. K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of tuff beds at
544 Ocean point on the Colville River, Alaska. *In* Geologic Studies in Alaska by the U.S.
545 Geological Survey, *Edited by* M.F. Diggles and J.P. Galloway. United States Geological
546 Survey, Geologic Notes, 77-82.
- 547 Davis, W.J., Schröder-Adams, C.J., Galloway, J.M., Herrle, J.O., and Pugh, A.T. 2017. U-Pb
548 geochronology of bentonites from the Upper Cretaceous Kanguk Formation, Sverdrup
549 Basin, Arctic Canada: constraints on sedimentation rates, biostratigraphic correlations and

- 550 the late magmatic history of the High Arctic Large Igneous Province. *Geological Magazine*,
551 **154**, 757-776.
- 552 Dixon, J., Dietrich, J.R., and McNeil, D.H. 1992. Upper Cretaceous to Pleistocene sequence
553 stratigraphy of the Beaufort-Mackenzie and Banks Island areas, Northwest Canada.
554 Geological Survey of Canada Bulletin, **407**, 90 pp.
- 555 Doherty, D.J., and Bergman, S.C. 1987. Late Cretaceous-Early Tertiary calderas in western
556 Alaska. *Geological Society of America, Abstracts with Programs*, **19**, 645.
- 557 Embry, A.F., and Dixon, J. 1990. The breakup unconformity of the Amerasia Basin, Arctic
558 Ocean: Evidence from Arctic Canada. *Geological Society of America Bulletin*, **102**, 1526-
559 1534.
- 560 Embry, A.F., and Osadetz, K.G. 1988. Stratigraphy and tectonic significance of Cretaceous
561 volcanism in the Queen Elizabeth Islands, Canadian Arctic Archipelago. *Canadian Journal*
562 *of Earth Sciences*, **25**, 1209-1219.
- 563 Foster, H.L., Keith, T.E.C., and Menzie, W.D. 1994. Geology of the Yukon-Tanana area of east-
564 central Alaska. *In The Geology of Alaska. Edited by G. Plafker and H.C. Berg. Geological*
565 *Society of America, The Geology of North America*, v. G-1, 205-240.
- 566 Gale, A.S., Mutterlose, J., Batenburg, S., with Gradstein, F.M., Agterberg, F.P., Ogg, J.G.,
567 Petrizzo, M.R. (contributors). 2020. Chapter 27: The Cretaceous Period. *In Gradstein, F.M.,*
568 *Ogg, J.G., Schmitz, M.D., Ogg, G.(eds.), The Geological Time Scale, Book Volume 2, Part*
569 *III. Geological Periods Phanerozoic*, pp. 1023-1086.

- 570 Galloway, J.M., Sweet, A.R., Pugh, A., Schröder-Adams, C.J., Swindles, G.T., Haggart, J.W.,
571 and Embry, A.F. 2012. Correlating mid-Cretaceous strata in the Canadian High Arctic using
572 palynology. *Palynology*, **36**, 277-302.
- 573 Gansecki, S.A., Mahood, G.A., and McWilliams, M. 1998. New ages for the climactic eruptions
574 of Yellowstone: Single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating identifies contamination. *Geology*, **26**: 343-
575 346.
- 576 Harris, N.B.W., Pearce, J.A., and Tindle, A.G. 1986. Geochemical characteristics of collision-
577 zone magmatism. *In* *Collision Tectonics. Edited by* M.P. Coward and A.C. Ries. Special
578 Publication of the Geological Society of London, **19**, 67-81.
- 579 Herrle, J.O., Schröder-Adams, C.J., Davis, W., Pugh, A.T., Galloway, J.M., and Fath, J. 2015.
580 Mid-Cretaceous High Arctic stratigraphy, climate, and Oceanic Anoxic Events. *Geology*,
581 **43**, 403-406.
- 582 Hurford, A.J., and Green, P.F. 1983. The zeta calibration of fission-track dating. *Isotope*
583 *Geoscience*, **1**: 285-317.
- 584 Jochum, K.P., et al. 2006. MPI-DING reference glasses for in situ microanalysis: New reference
585 values for element concentrations and isotope ratios. *Geochemistry, Geophysics,*
586 *Geosystems*, **7** (2).
- 587 Jutard, G., and Plauchut, B.P. 1973. Cretaceous and Tertiary stratigraphy northern Banks Island.
588 *In* *Geology of the Canadian Arctic. Edited by* J.D. Aitken and D.J. Glass, Geological
589 Association of Canada and Canadian Society of Petroleum Geologists, pp. 203-219.

- 590 Kemp, K.M. 1993. Tephrostratigraphy of the Late Cretaceous Kanguk Formation, Banks Island,
591 Arctic Canada. M.Sc. thesis, Department of Geology, University of Toronto, Toronto, ON.
- 592 Meyers, S.R., Siewert, S.E., Singer, B.S., Sageman, B.B., Condon, D.J., Obradovich, J.D., Jicha,
593 B.R., and Sawyer, D.A. 2012. Intercalibration of radioisotopic and astrochronologic time
594 scales for the Cenomanian – Turonian boundary interval, Western Interior Basin, USA.
595 *Geology*, **40**, 7-10.
- 596 Miall, A.D. 1979. Mesozoic and Tertiary geology of Banks Island, Arctic Canada: the history of
597 an unstable craton margin. Geological Survey of Canada, Memoir 387, 235 pp.
- 598 Miller, T.P. 1994. Pre-Cenozoic plutonic rocks in mainland Alaska. *In* The Geology of Alaska.
599 *Edited by* G. Plafker and H.C. Berg. Geological Society of America, The Geology of North
600 America, v. G-1, 535-554.
- 601 Moll-Stalcup, E.J. 1994. Latest Cretaceous and Cenozoic magmatism in mainland Alaska. *In* The
602 Geology of Alaska. *Edited by* G. Plafker and H.C. Berg. Geological Society of America,
603 The Geology of North America, v. G-1, 589-619.
- 604 Morgan, L.A., and McIntosh, W.C. 2005. Timing and development of the Heise volcanic field,
605 Snake River Plain, Idaho, western USA. *Geological Society of America Bulletin*, **117**, 288-
606 306.
- 607 Naeser, N.D., Westgate, J.A., Hughes, O.L., and Péwé, T.L. 1982. Fission-track ages of late
608 Cenozoic distal tephra beds in the Yukon and Alaska. *Canadian Journal of Earth Sciences*,
609 **19**: 2164-2178.

- 610 Pearce, J.A., Harris, N.B.W., and Tindle, A.G. 1984. Trace element discrimination diagrams for
611 the tectonic interpretation of granitic rocks. *Journal of Petrology*, **25**, 956-983.
- 612 Pearce, N.J.G., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R., Chernery,
613 S.P. 1997. A compilation of new and published major and trace element data for NIST SRM
614 610 and NIST SRM 612 glass reference materials. *Geostandards Newsletter*, **21**: 115-144.
- 615 Phillips, R.L. 1988. Measures sections, paleoenvironments, and sample locations near Ocean
616 Point, Alaska. United States Geological Survey Open-File Report 88-40.
- 617 Phillips, R.L., Pickthorn, L.G., and Rearic, D.M. 1988. Late Cretaceous sediments from the
618 northeast Chukchi Sea. *In* *Geologic Studies in Alaska by the U.S. Geological Survey during*
619 *1987. Edited by J.P. Galloway and T.D. Hamilton. United States Geological Survey,*
620 *Circular 1016, 187-189.*
- 621 Piepjohn, K., Atkinson, E., Dewing, K et al. 2018. Cenozoic structural evolution on northern
622 Banks Island, N.W.T. *Arktos*, **4**, 1-19.
- 623 Plafker, G., and Berg, H.C. 1994. Overview of the geology and tectonic evolution of Alaska. *In*
624 *The Geology of Alaska. Edited by G. Plafker and H.C. Berg. Geological Society of*
625 *America, The Geology of North America, v. G-1, 989-1021.*
- 626 Pointon, M.A., Flowerdew, M.J., Hülse, P., Schneider, S., and Whitehouse, M.J. 2019. Mixed
627 local and ultra-distal volcanic ash deposition within the Upper Cretaceous Kanguk
628 Formation, Sverdrup Basin, Canadian Arctic Islands. *Geological Magazine*, **156**, 2067-2084.
- 629 Pugh, A.T., Schröder-Adams, C.J., Carter, E.S., Herrle, J.O., Galloway, J., Haggart, J.W.,
630 Andrews, J.K.L., and Hatsukano, K. 2014. Cenomanian to Santonian radiolarian
631 biostratigraphy, carbon isotope stratigraphy and paleoenvironments of the Sverdrup Basin,

- 632 Ellef Ringnes Island, Nunavut, Canada. *Palaeogeography, Palaeoclimatology,*
633 *Palaeoecology*, **413**, 101-122.
- 634 Sandhu, A.S., and Westgate, J.A. 1995. The correlation between reduction in fission-track
635 diameter and areal track density in volcanic glass shards and its application in dating tephra
636 beds. *Earth and Planetary Science Letters*, **131**: 289-299.
- 637 Schmieder, M., Kennedy, T., Jourdan, F., Buchner, E., and Reimold, W.U. 2018. A high-
638 precision $^{40}\text{Ar}/^{39}\text{Ar}$ age for the Nördlinger Ries impact crater, Germany, and implications for
639 the accurate dating of terrestrial impact events. *Geochimica et Cosmochimica Acta*, **220**:
640 146-157.
- 641 Souther, J.G. 1963. Geological traverse across Axel Heiberg Island from Buchanan Lake to
642 Strand Fiord. *In* *Geology of the north-central part of the Arctic Archipelago, Northwest*
643 *Territories (Operation Franklin)*. Geological Survey of Canada Memoir **320**, 426-448.
- 644 Sun, S. –S., and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts:
645 implications for mantle composition and processes. *In* *Magmatism in the Ocean Basins*.
646 *Edited by* A.D. Sanders and M.J. Norry. Geological Society, London, Special Publication **42**:
647 pp. 313-345.
- 648 Tapia, P.M., and Harwood, D.M. 2002. Upper Cretaceous diatom biostratigraphy of the Arctic
649 Archipelago and northern continental margin, Canada. *Micropaleontology*, **48**, 303-342.
- 650 Tappan, H. 1960. Cretaceous biostratigraphy of northern Alaska. *American Association of*
651 *Petroleum Geology, Bulletin* **44**, 273-297.
- 652 Tarduno, J.A., Brinkman, D.F.B., Renne, R., Cottrello, R.D., Scher, H., and Castillo, P. 1998.
653 Evidence for extreme climate warmth from late Cretaceous arctic vertebrates. *Science* **282**,
654 2241-2244.

- 655 Thompson, R.N., Dickin, A.P., Gibson, I.L., and Morrison, M.A. 1982. Elemental fingerprints of
656 isotopic contamination of Hebridean Palaeocene mantle-derived magmas by Archaean sial.
657 *Contributions to Mineralogy and Petrology*, **79**, 159-168.
- 658 Thorarinsson, S.B., Holm, P.M., Duprat, H, and Tegner, C. 2011. Silicic magmatism associated
659 with late Cretaceous rifting in the Arctic Basin – petrogenesis of the Kap Kane sequence, the
660 Kap Washington Group volcanics, North Greenland. *Lithos*, **125**, 65-85.
- 661 Thorarinsson, S.B., Holm, P.M., Duprat, H, and Tegner, C. 2012. Petrology and Sr-Nd-Pb
662 isotope geochemistry of Late Cretaceous continental rift ignimbrites, Kap Washington
663 peninsula, North Greenland. *Journal of Volcanology and Geothermal Research*, **219-220**,
- 664 Thorsteinsson, R., and Tozer, E.T. 1970. Geology of the Arctic Archipelago. *In* *Geology and*
665 *Economic Minerals of Canada. Edited by R.J.W. Douglas. Geological Survey of Canada,*
666 *Economic Geology Report No. 1, pp. 548-590.*
- 667 Tikhomirov, P.L., Kalinina, E.A., Kobayashi, K., and Nakamura, E. 2008. Late Mesozoic silicic
668 magmatism of the North Chukotka area (NE Russia): Age, magma sources, and geodynamic
669 implications. *Lithos*, **105**, 329-346.
- 670 Tikhomirov, P.L., Kalinina, E.A., Moriguti, T., Makishima, A., Kobayashi, K., Cherepanova,
671 I.Yu., and Nakamura, E. 2012. The Cretaceous Okhotsk-Chukotka volcanic belt (NE
672 Russia): Geology, geochronology, magma output rates, and implications on the genesis of
673 silicic LIPs. *Journal of Volcanology and Geothermal Research*, **221-222**, 14-32.
- 674 Wagner, G.A., and Van den Haute, P. 1992. *Fission-track Dating: Stuttgart, Kluwer.*

- 675 Wall, J.H. 1983. Jurassic and Cretaceous foraminiferal biostratigraphy in the eastern Sverdrup
676 Basin, Canadian Arctic Archipelago (Axel Heiberg Island, Ellesmere Island). *Bulletin of*
677 *Canadian Petroleum Geology*, **31**, 246-281.
- 678 Westgate, J.A. 1989. Isothermal plateau fission-track ages of hydrated glass shards from silicic
679 tephra beds. *Earth and Planetary Science Letters*, **95**: 226-234.
- 680 Westgate, J.A. 2015. Volcanic glass (fission track), *In Encyclopedia of Scientific Dating*
681 *Methods. Edited by W.J. Rink and J.W. Thompson. Springer, Dordrecht, The Netherlands,*
682 *pp. 941-946.*
- 683 Wolfe, A.P., Reyes, A.V., Royer, D.L., Greenwood, D.R., Doria, G., Gagen, M.H., Siver, P.A.,
684 and Westgate, J.A. 2017. Middle Eocene CO₂ and climate reconstructed from the sediment
685 fill of a subarctic kimberlite maar. *Geology*, **45**, 619-622.
- 686 Wood, D.H., and Armstrong, R.L. 1982. Geology, chemistry, and geochronometry of the
687 Cretaceous South Fork Volcanics, Yukon Territory. *In Current Research, Part A, Geological*
688 *Survey of Canada Paper 82-1A*, 309-316.
- 689 Young, F.G. 1975. Upper Cretaceous stratigraphy, Yukon Coastal Plain and northwestern
690 MacKenzie Delta. *Geological Survey of Canada, Bulletin 249.*
- 691 Young, F.G., Myhr, D.W., and Yorath, C.J. 1976. Geology of the Beaufort-MacKenzie Basin.
692 *Geological Survey of Canada, Paper 76-11.*

693

694 **Captions to Figures**

695 Fig. 1. Simplified map of Banks Island showing sites where the Kanguk Formation contains
696 tephra beds and bentonites (symbol "v"). Site 1 is Duck Hawk Bluffs and site 2 is the location of
697 the Swan Lake sections. Base map from Miall (1979, fig. 2) and index map from Map 1454A,
698 Geology, Banks Island, Geological Survey of Canada, in Miall (1979). This image was scanned
699 using Epson Perfection V850 Pro and then the required elements were copied in 2019 version of
700 CorelDraw followed by the addition of original material.

701 Fig. 2. Swan Lake II section showing the numerous white tephra beds intercalated with black
702 bituminous shale of the Kanguk Formation. The thick tephra bed beside the person is the 60-cm
703 thick UT937/938. The exposure is 17 m high above the Sachs River and is the same locality as
704 that recorded by Miall (1979; Station 74-MLA-28). There are more than 43 conspicuous tephra
705 beds exposed at this site.

706 Fig. 3. Tephra beds in the Kanguk Formation, Banks Island. (a) Duck Hawk Bluffs showing the
707 position of tephra bed UT629. The black patch on the beach is alluvium from the creek
708 occupying the gulley between the two bluffs. Note the two persons on the alluvial patch. The
709 stratigraphic column is shown in Fig.6. (b) Deformed tephra beds (UT904 at top to UT909 at
710 bottom) in the Swan Lake I section. The tephra bed in the middle of the image is UT907 and the
711 uppermost part of some tephra beds have been altered to bentonite. Scale in centimetres. (c)
712 Closely spaced, undeformed white and grey tephra beds in black bituminous shale of the Kanguk
713 Formation. The upper, relatively thick white tephra bed is UT926 and the grey tephra
714 immediately below the very thin white tephra is UT928 (Fig. 8). These tephra beds were
715 deposited in a marine environment and their excellent undisturbed preservation demonstrates
716 absence of an infauna. Scale is in centimetres. (d) A 60-cm thick white tephra bed (UT937,

717 UT938) showing sharp basal contact with the underlying bituminous shale. The uppermost 10
718 cm has been reworked. Scale is in centimetres.

719 Fig. 4. Simplified map showing the tectonic setting of the Sverdrup, Banks, and Beaufort-
720 MacKenzie sedimentary basins. Thick lines separate the different tectonic regions. ER is Ellef
721 Ringnes Island, AR is Amund Ringnes Island. Base map from Miall (1979, fig. 1) and tectonic
722 elements with their names added according to Dixon et al. (1992) and Embry and Osadetz
723 (1988). Base map scanned using Epson Perfection V850 Pro and then the required elements were
724 copied in 2019 version of CorelDraw followed by the addition of original material.

725 Fig. 5. Lithostratigraphic correlation chart. Numeric ages are in Ma and are taken from Gale et
726 al. (2020). Diagonal ruling, bounded by unconformities, indicates absence of units. Unit within
727 the Iceberg Bay Formation is the Strand Bay Shale. The Sverdrup Basin section is from the
728 Queen Elizabeth Islands.

729 Fig. 6. Stratigraphic section showing position of tephra UT629 in the Kanguk Formation along
730 the Duck Hawk Bluffs. See Fig.3a.

731 Fig. 7. Stratigraphic section of tephra beds in the Kanguk Formation at Swan Lake I section. The
732 dashed lines indicate a discontinuous tephra bed. The lowermost tephra bed (UT912) is 50 cm
733 thick. A few thin and discontinuous tephra beds occur in the uppermost part of the Kanguk
734 Formation at this site but were not sampled because of alteration to bentonite.

735 Fig. 8. Stratigraphic section through the Kanguk Formation at Swan Lake II section. UT913 and
736 UT914 are bentonites. The tephra bed UT937/38 is 60 cm thick. See illustration in Fig. 3d.

737 Fig. 9. Major-element compositional variability of tephra beds in the Kanguk Formation,
738 southwestern Banks Island.

739 Fig. 10. Chondrite-normalized REE abundance curves for tephra beds from the Kanguk
740 Formation, Banks Island. Each analysis is on a single glass shard. The shape of the curves is very
741 similar for all analyses. Each tephra bed contains a single population with respect to its REEs
742 except for the tephra bed from DHB. The variation seen is a result of the slight compositional
743 differences between the tephra beds. Normalization factors are from Sun and McDonough
744 (1989). DHB: 15 analyses on a single tephra bed; SLI: 14 analyses on two tephra beds; SLII: 67
745 analyses on 10 tephra beds.

746 Fig. 11. Compositional data on tephra samples relevant to their suitability for dating by the glass
747 fission-track method.

748 Fig. 12. Glass fission-track ages plotted against height above the Sachs River, Banks Island at the
749 Swan Lake II site. The horizontal bars about the mean age are at $\pm 1\sigma$; a simple linear regression
750 analysis indicates a coefficient of correlation, $r = 0.9961$.

751 Fig. 13. Discriminant diagram (after Pearce et al. 1984) showing whole rock analyses of
752 rhyolitic ignimbrites from Kap Washington and Kap Kane, North Greenland (cross symbol), plot
753 in the “within plate” tectonic setting whereas glass analyses of tephra beds from southwestern
754 Banks Island (dot symbol) fall in the “volcanic arc” field. North Greenland data from
755 Thorarinsson et al. (2011, 2012).

756 Fig. 14. A clear separation between the tectonic settings of volcanic rocks in North Greenland
757 and southwestern Banks Island is seen in this Ta – Nb bivariate plot (modified after Harris et al.
758 1986), in agreement with data shown in Fig. 13. Data sources and symbols as in Fig. 13.

759 Fig. 15. Chondrite-normalized spidergrams for glass shards from tephra beds in the Kanguk
760 Formation, Banks Island. Sharp, negative spikes at Sr and Ti suggest the tephra beds are highly

761 differentiated and have fractionated plagioclase and Fe-Ti oxides (ilmenite) and accessory rutile.
762 Normalization factors from Thompson et al. (1982).

763 Fig. 16. Sketch map showing possible source areas for tephra beds in the Kanguk Formation on
764 Banks Island and location of other tephra samples mentioned in the text. Explanation: (1)
765 Calderas in the Yukon – Tanana Terrane of east-central Alaska; 94 – 55 Ma (Bacon et al. 1990).
766 (2) Tuff beds in bluffs of the Colville River, North Slope near Ocean Point, Alaska, sample
767 UT712 (= 84Acr180B); 69 Ma (Conrad et al. 1989). (3) Location of Giraffe tephra beds near Lac
768 de Gras, Northwest Territories, Canada, samples UT2114 and UT2115; 54 Ma (Wolfe et al.
769 2017, this study). (4) South Fork Volcanics, Yukon Territory; ~ 95 Ma (62° 18' 13" N Lat. 131°
770 59' 10" W Long.) (Wood and Armstrong 1982). (5 and 6) Upper Cretaceous – Paleocene
771 volcanic and plutonic belts of mainland Alaska (Miller 1994, Moll-Stalcup 1994) consisting of:
772 Alaska Range Belt, 75 – 50 Ma and Kuskokwim Mountains Belt, 75 – 60 Ma. These two belts
773 are shown in detail in Figure 19. (7) The Okhotsk – Chukotka volcanogenic belt (OCVB) has
774 been suggested as a possible source of tephra beds in northern Alaska (Bergman et al. 2006) and
775 the northern Sverdrup Basin (Pointon et al. 2019). The most intensive volcanism at this source
776 was during the period 89 – 84 Ma (Tikhomirov et al. 2012). Sketch map based on Google Earth
777 Pro imagery, which was scanned using Epson Perfection V850 Pro and the required map
778 elements copied in 2019 version of CorelDraw.

779 Fig. 17. Ratios of incompatible elements as possible indicators of source. (a) Ratios of these
780 highly incompatible trace elements are not affected significantly by fractionation processes but
781 rather reflect the ratios of their source. The Giraffe tephra beds lie on the dominant
782 compositional trend defined by the tephra beds from the Kanguk Formation, the West Fork tuff
783 plots near UT907 samples, which is slightly away from the dominant trend, but the tephra

784 sample from the Colville River area of northern Alaska is distinct. (b) Ratios of adjacent REEs
785 are likewise more likely to reflect source. The samples from the Kanguk Formation show a
786 remarkable linearity – a regression analysis indicates a correlation coefficient, $r = 0.96$. Most of
787 the Giraffe tephra analyses lie on or close to this trend, but again the Colville River sample is
788 distinct. The welded tuff sample from the West Fork caldera, Alaska, is obscured by the other
789 data points; its Sm = 5.8 ppm and Nd = 29 ppm, which makes it lie within the compositional
790 trend of the Kanguk Formation samples.

791 Fig. 18. (a) Chondrite-normalized REE abundance curves for tephra beds of the Kanguk
792 Formation, Banks Island, compared to the rhyolitic volcanics of east-central Alaska and the
793 Giraffe tephra beds in the Northwest Territories. Normalization factors from Sun and
794 McDonough (1989). (b) Chondrite-normalized spidergrams using whole rock analyses of the
795 rhyolitic volcanics in east-central Alaska (Bacon et al. 1990) and glass shards of the Giraffe
796 tephra beds. Normalization factors from Thompson et al. (1982).

797 Fig. 19. Distribution of Upper Cretaceous and Paleocene plutons and volcano-plutonic
798 complexes in Alaska (modified after Miller 1994). T is Talkeetna, S is Sleepmute, SC is Sischu.
799 Modified after Miller (1994, fig. 5). This base map was scanned in Epson Perfection V850 Pro
800 and the required elements copied using 2019 version of CorelDraw.

Table 1. Average major-element composition of glass shards (wt%) in tephra beds of the Kanguk Formation, Banks Island, Canada

Site Sample	Duck Hawk Bluffs	Swan Lake I				Swan Lake II			
	UT629	UT904	UT907	UT910	UT912	UT915	UT921	UT922	UT923
SiO ₂	76.09 ± 0.74	74.78 ± 0.45	77.66 ± 0.53	78.03 ± 0.30	78.26 ± 0.13	77.37 ± 0.46	74.53 ± 0.32	76.02 ± 0.42	75.24 ± 0.33
TiO ₂	0.14 ± 0.04	0.19 ± 0.02	0.06 ± 0.02	0.09 ± 0.05	0.07 ± 0.03	0.09 ± 0.03	0.16 ± 0.02	0.12 ± 0.04	0.16 ± 0.03
Al ₂ O ₃	13.13 ± 0.30	14.67 ± 0.30	12.85 ± 0.29	12.63 ± 0.13	12.47 ± 0.09	12.77 ± 0.15	14.19 ± 0.13	13.64 ± 0.35	13.93 ± 0.15
FeO _t	1.19 ± 0.21	1.39 ± 0.11	1.02 ± 0.12	0.86 ± 0.05	0.81 ± 0.02	1.10 ± 0.12	1.74 ± 0.09	0.99 ± 0.14	1.10 ± 0.02
MnO	0.04 ± 0.03	0.06 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.05 ± 0.02	0.09 ± 0.01	0.09 ± 0.02
MgO	0.08 ± 0.02	0.19 ± 0.02	0.03 ± 0.01	0.06 ± 0.02	0.06 ± 0.02	0.05 ± 0.01	0.09 ± 0.02	0.07 ± 0.02	0.11 ± 0.02
CaO	0.67 ± 0.08	0.90 ± 0.05	0.58 ± 0.05	0.69 ± 0.07	0.66 ± 0.04	0.54 ± 0.06	0.80 ± 0.06	0.63 ± 0.05	0.63 ± 0.03
Na ₂ O	3.58 ± 0.31	3.00 ± 0.17	2.97 ± 0.15	2.89 ± 0.07	2.94 ± 0.15	2.84 ± 0.32	3.05 ± 0.24	2.94 ± 0.19	3.09 ± 0.26
K ₂ O	4.98 ± 0.22	4.74 ± 0.12	4.68 ± 0.23	4.63 ± 0.09	4.62 ± 0.09	5.11 ± 0.09	5.28 ± 0.19	5.42 ± 0.18	5.55 ± 0.09
Cl	0.11 ± 0.03	0.07 ± 0.02	0.10 ± 0.01	0.08 ± 0.03	0.08 ± 0.02	0.08 ± 0.02	0.11 ± 0.02	0.08 ± 0.02	0.10 ± 0.02
H ₂ O	6.03 ± 0.80	5.62 ± 0.36	5.02 ± 0.55	4.65 ± 0.42	4.86 ± 0.37	3.76 ± 0.56	7.11 ± 0.49	4.77 ± 0.58	4.57 ± 0.42
n	22	8	10	10	10	12	22	10	10

Site Sample	Swan Lake II							
	UT924	UT925	UT926	UT928	UT929	UT931	UT932	UT933
SiO ₂	77.60 ± 0.14	77.53 ± 0.17	73.24 ± 0.38	74.04 ± 0.6	77.38 ± 0.29	76.79 ± 0.22	77.83 ± 0.28	75.18 ± 1.04
TiO ₂	0.14 ± 0.02	0.14 ± 0.02	0.34 ± 0.06	0.19 ± 0.04	0.06 ± 0.04	0.14 ± 0.03	0.10 ± 0.03	0.13 ± 0.03
Al ₂ O ₃	12.73 ± 0.09	12.74 ± 0.09	15.09 ± 0.22	13.70 ± 0.19	12.72 ± 0.23	12.84 ± 0.08	12.59 ± 0.11	13.74 ± 0.43
FeO _t	0.72 ± 0.05	0.67 ± 0.02	1.96 ± 0.12	2.41 ± 0.25	1.08 ± 0.09	0.94 ± 0.04	0.83 ± 0.04	1.90 ± 0.30
MnO	0.05 ± 0.02	0.05 ± 0.01	0.07 ± 0.02	0.08 ± 0.02	0.03 ± 0.02	0.08 ± 0.02	0.04 ± 0.02	0.05 ± 0.02
MgO	0.07 ± 0.02	0.08 ± 0.02	0.31 ± 0.04	0.03 ± 0.02	0.03 ± 0.01	0.07 ± 0.01	0.08 ± 0.01	0.02 ± 0.02
CaO	0.72 ± 0.04	0.73 ± 0.02	1.21 ± 0.13	0.92 ± 0.09	0.51 ± 0.06	0.39 ± 0.03	0.60 ± 0.02	0.81 ± 0.17
Na ₂ O	2.81 ± 0.13	2.89 ± 0.13	2.79 ± 0.38	3.29 ± 0.4	2.93 ± 0.18	3.19 ± 0.22	2.86 ± 0.16	2.91 ± 0.36
K ₂ O	5.08 ± 0.08	5.10 ± 0.09	4.91 ± 0.33	5.22 ± 0.2	5.17 ± 0.13	5.44 ± 0.08	4.97 ± 0.12	5.15 ± 0.24
Cl	0.08 ± 0.02	0.07 ± 0.01	0.08 ± 0.01	0.11 ± 0.03	0.09 ± 0.02	0.12 ± 0.02	0.10 ± 0.03	0.12 ± 0.01
H ₂ O	6.38 ± 0.42	6.43 ± 0.42	5.5 ± 0.94	4.51 ± 0.69	4.36 ± 0.39	6.60 ± 0.46	4.17 ± 0.31	4.68 ± 0.69
n	10	10	7	20	10	10	10	10

Site Sample	Swan Lake II				ATHO-G	
	UT937	UT938	UT941	UT942	This Study	GeoRem
SiO ₂	77.28 ± 0.85	77.11 ± 0.6	76.40 ± 0.34	77.45 ± 0.30	75.09 ± 0.67	75.6
TiO ₂	0.14 ± 0.02	0.13 ± 0.03	0.09 ± 0	0.16 ± 0.03	0.24 ± 0.03	0.26
Al ₂ O ₃	12.62 ± 0.42	12.63 ± 0.33	12.84 ± 0.24	12.74 ± 0.11	12.06 ± 0.13	12.2
FeO _t	0.78 ± 0.06	0.77 ± 0.07	1.41 ± 0.09	0.80 ± 0.02	3.23 ± 0.06	3.27
MnO	0.09 ± 0.01	0.08 ± 0.02	0.03 ± 0.02	0.09 ± 0.02	0.11 ± 0.02	0.11
MgO	0.07 ± 0.02	0.08 ± 0.02	0.05 ± 0.02	0.08 ± 0.02	0.08 ± 0.02	0.1
CaO	0.43 ± 0.06	0.44 ± 0.07	0.73 ± 0.10	0.37 ± 0.04	1.67 ± 0.04	1.7
Na ₂ O	3.16 ± 0.29	3.24 ± 0.18	3.36 ± 0.16	2.91 ± 0.15	3.83 ± 0.34	3.75
K ₂ O	5.30 ± 0.14	5.38 ± 0.05	4.96 ± 0.09	5.28 ± 0.11	2.61 ± 0.06	2.64
Cl	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.02	0.12 ± 0.02	0.04 ± 0.02	0.04
H ₂ O _d	6.39 ± 0.45	6.03 ± 0.55	6.49 ± 0.46	3.91 ± 0.40		
n	9	10	10	10	17	

Notes: Operating conditions are specified in the "Methods" section of the text. Analyses recast to anhydrous values; H₂O_d is water by difference; one standard deviation is given; n is number of analyses. Accuracy monitored by analyses of ATHO-G glass and analyses of individual glass shards are given in Table S1.

UT924 and UT925 are from the same tephra bed; the same is true for UT933 and UT934, as well as UT937 and UT938. Location of the sites is shown in Fig. 1 and the stratigraphic positions of the samples are provided in Figs. 6, 7 and 8.

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Table 2. Average trace-element composition (ppm) of individual glass shards in tephra beds of the Kanguk Formation, Banks Island, Canada

Site	DHB	Swan Lake I				Swan Lake II					
Sample	UT629	UT907		UT912		UT915	UT921	UT923	UT928	UT929	UT931
		High Ba	Low Ba	High Ba	Low Ba						
Rb	111 ± 8	195	212 ± 10	201 ± 5	234 ± 2	132 ± 5	162 ± 4	161 ± 4	146 ± 7	130 ± 4	153 ± 4
Sr	63.7 ± 6.0	41.6	17.4 ± 1.7	96.5 ± 1.9	64.9 ± 1.6	34.4 ± 9.2	78.2 ± 3.2	80.9 ± 1.5	62.8 ± 18.9	30.6 ± 7.4	16.6 ± 2.6
Y	24.7 ± 5.9	27.5	26.1 ± 1.2	19.0 ± 0.4	21.8 ± 0.2	27.3 ± 1.6	34.6 ± 0.8	30.3 ± 0.7	40.8 ± 2.0	26.4 ± 0.7	34.6 ± 1.5
Zr	147 ± 22	146	94 ± 6	95 ± 1	93 ± 2	114 ± 9	268 ± 6	204 ± 4	332 ± 9	113 ± 13	139 ± 6
Nb	10.1 ± 1.2	10.0	10.3 ± 0.3	7.4 ± 0.1	8.0 ± 0.3	9.3 ± 2.4	9.9 ± 0.2	11.0 ± 0.2	11.6 ± 0.9	8.0 ± 0.3	10.9 ± 0.4
Cs	3.16 ± 0.68	6.18	6.83 ± 0.38	10.19 ± 0.30	12.87 ± 0.37	5.91 ± 0.23	7.50 ± 0.29	5.97 ± 0.21	4.89 ± 0.31	5.56 ± 0.34	6.38 ± 0.15
Ba	950 ± 28	674	165 ± 24	869 ± 19	429 ± 23	1018 ± 49	1389 ± 20	938 ± 28	1134 ± 123	1018 ± 78	254 ± 24
La	33.5 ± 4.5	48.1	24.6 ± 2.2	41.7 ± 0.7	38.2 ± 0.5	38.8 ± 5.8	45.0 ± 0.7	42.0 ± 1.0	43.8 ± 1.3	36.5 ± 1.0	38.9 ± 1.8
Ce	65.3 ± 10.0	88.5	51.5 ± 3.6	72.7 ± 1.8	69.0 ± 1.3	74.9 ± 8.3	82.1 ± 1.0	79.5 ± 1.5	86.2 ± 3.0	71.3 ± 1.3	77.6 ± 2.3
Pr	7.10 ± 1.26	9.21	5.83 ± 0.24	7.00 ± 0.17	6.79 ± 0.17	8.08 ± 0.67	9.40 ± 0.18	8.80 ± 0.13	9.90 ± 0.23	7.76 ± 0.22	8.78 ± 0.29
Nd	26.0 ± 5.4	33.7	22.2 ± 1.5	23.3 ± 0.1	22.7 ± 0.4	30.5 ± 2.8	37.4 ± 0.7	33.8 ± 0.7	40.1 ± 1.0	29.3 ± 0.5	34.8 ± 1.3
Sm	4.86 ± 1.17	6.41	5.09 ± 0.28	3.85 ± 0.12	3.94 ± 0.18	5.74 ± 0.43	7.38 ± 0.35	6.52 ± 0.17	8.23 ± 0.59	5.78 ± 0.32	6.83 ± 0.25
Eu	0.43 ± 0.08	0.37	0.23 ± 0.04	0.49 ± 0.02	0.37 ± 0.03	0.35 ± 0.05	0.84 ± 0.07	0.99 ± 0.07	1.03 ± 0.23	0.34 ± 0.07	0.47 ± 0.07
Gd	3.73 ± 0.95	4.75	3.99 ± 0.21	2.70 ± 0.34	2.59 ± 0.12	4.53 ± 0.28	5.95 ± 0.27	5.04 ± 0.37	6.91 ± 0.28	4.39 ± 0.32	5.28 ± 0.28
Tb	0.64 ± 0.18	0.76	0.70 ± 0.04	0.46 ± 0.02	0.49 ± 0.03	0.76 ± 0.05	0.96 ± 0.03	0.82 ± 0.02	1.15 ± 0.05	0.70 ± 0.04	0.90 ± 0.04
Dy	4.03 ± 1.05	4.63	4.30 ± 0.17	2.83 ± 0.06	3.16 ± 0.18	4.80 ± 0.33	5.95 ± 0.15	5.04 ± 0.18	7.08 ± 0.31	4.61 ± 0.32	5.45 ± 0.32
Ho	0.87 ± 0.22	1.03	0.93 ± 0.06	0.58 ± 0.03	0.72 ± 0.02	0.99 ± 0.06	1.25 ± 0.03	1.07 ± 0.04	1.50 ± 0.09	0.95 ± 0.03	1.15 ± 0.07
Er	2.60 ± 0.68	2.66	2.60 ± 0.22	1.88 ± 0.16	2.13 ± 0.07	2.64 ± 0.19	3.56 ± 0.19	3.06 ± 0.08	4.20 ± 0.22	2.65 ± 0.14	3.46 ± 0.20
Tm	0.41 ± 0.10	0.45	0.41 ± 0.05	0.32 ± 0.03	0.35 ± 0.04	0.44 ± 0.04	0.55 ± 0.04	0.47 ± 0.03	0.65 ± 0.05	0.41 ± 0.01	0.51 ± 0.04
Yb	3.12 ± 0.69	2.90	2.90 ± 0.21	2.38 ± 0.04	2.77 ± 0.16	2.97 ± 0.18	4.00 ± 0.21	3.60 ± 0.14	4.62 ± 0.27	2.86 ± 0.15	3.84 ± 0.25
Lu	0.46 ± 0.10	0.43	0.43 ± 0.05	0.38 ± 0.04	0.40 ± 0.02	0.46 ± 0.05	0.58 ± 0.04	0.55 ± 0.03	0.66 ± 0.02	0.44 ± 0.03	0.57 ± 0.03
Hf	4.66 ± 0.75	5.07	3.92 ± 0.17	3.37 ± 0.16	3.47 ± 0.15	4.13 ± 0.17	7.42 ± 0.09	5.97 ± 0.14	8.79 ± 0.29	3.94 ± 0.31	4.43 ± 0.20
Ta	0.71 ± 0.05	0.71	0.75 ± 0.01	0.70 ± 0.01	0.88 ± 0.03	0.55 ± 0.06	0.67 ± 0.02	0.69 ± 0.05	0.64 ± 0.05	0.54 ± 0.03	0.65 ± 0.05
Pb	17.71 ± 2.26	30.10	28.34 ± 0.66	27.58 ± 1.70	30.10 ± 1.36	27.51 ± 3.59	27.80 ± 2.79	24.73 ± 2.07	24.54 ± 1.28	25.77 ± 1.08	22.22 ± 2.58
Th	6.8 ± 0.6	19.3	19.2 ± 0.6	20.8 ± 0.4	24.5 ± 0.5	10.7 ± 0.9	14.7 ± 0.5	13.4 ± 0.5	10.9 ± 1.2	10.0 ± 0.6	12.1 ± 0.8
U	2.43 ± 0.13	4.20	4.84 ± 0.51	5.96 ± 0.44	8.34 ± 0.85	4.04 ± 0.72	5.01 ± 0.62	4.25 ± 0.32	3.09 ± 0.45	3.30 ± 0.46	3.69 ± 0.70
n	15	1	6	3	4	5	6	7	7	7	7

Site	Swan Lake II			
Sample	UT934	UT937	UT941	UT942
	High Ba	Low Ba		
Rb	151 ± 4	174	148 ± 6	98 ± 3
Sr	47.3 ± 1.2	20.3	31.9 ± 9.4	38.7 ± 7.1
Y	39.5 ± 0.9	38.1	24.3 ± 1.1	34.0 ± 0.7
Zr	321 ± 6	146	101 ± 12	139 ± 11
Nb	11.8 ± 0.3	11.6	10.3 ± 0.7	5.9 ± 0.2
Cs	4.72 ± 0.34	5.41	6.05 ± 0.45	3.08 ± 0.11
Ba	1203 ± 25	287	395 ± 151	798 ± 32
La	50.2 ± 1.5	42.3	31.0 ± 1.8	29.1 ± 0.9
Ce	96.2 ± 2.5	85.6	61.4 ± 3.0	60.1 ± 1.1
Pr	10.86 ± 0.39	9.60	6.53 ± 0.39	6.72 ± 0.15
Nd	43.0 ± 1.1	37.0	24.7 ± 1.6	26.7 ± 0.8
Sm	8.57 ± 0.24	7.40	4.60 ± 0.53	5.63 ± 0.18
Eu	0.94 ± 0.08	0.37	0.46 ± 0.08	0.41 ± 0.07
Gd	7.07 ± 0.24	5.84	3.56 ± 0.31	5.04 ± 0.37
Tb	1.13 ± 0.05	1.02	0.63 ± 0.05	0.86 ± 0.05
Dy	6.89 ± 0.42	6.69	3.84 ± 0.26	5.56 ± 0.16
Ho	1.44 ± 0.04	1.38	0.85 ± 0.06	1.20 ± 0.05
Er	4.13 ± 0.22	3.95	2.46 ± 0.14	3.31 ± 0.10
Tm	0.61 ± 0.03	0.61	0.40 ± 0.03	0.51 ± 0.03
Yb	4.49 ± 0.41	4.25	3.07 ± 0.31	3.78 ± 0.15
Lu	0.66 ± 0.03	0.63	0.44 ± 0.03	0.52 ± 0.04
Hf	8.58 ± 0.43	5.01	3.48 ± 0.23	4.43 ± 0.39
Ta	0.62 ± 0.03	0.74	0.70 ± 0.06	0.39 ± 0.03
Pb	24.97 ± 1.05	26.00	21.46 ± 1.01	17.36 ± 0.63
Th	11.7 ± 0.6	14.4	12.3 ± 1.6	7.2 ± 0.4

Notes: Analyses by the laser ablation ICP-MS method. Operating conditions are specified in the "Methods" section of the text. One standard deviation is given; n is the number of analyses. Location of sites is shown in Fig. 1 and the stratigraphic positions of the samples are given in Figs. 6, 7 and 8. Table S2 shows the individual trace-element analyses and provides information on accuracy by reference to analyses of the ATHO-G glass standard run during the course of the sample analyses. DHB is Duck Hawk Bluffs.

U	3.15 ± 0.39	3.11	4.11 ± 0.82	2.57 ± 0.41	3.70 ± 0.59
n	6	1	7	7	7

Draft

Table 3. Glass fission-track ages of tephra beds in the Kanguk Formation, Banks Island, Canada

Sample number	Method for determination of area track density	Method for correction of partial track fading	Spontaneous track density (10 ⁴ t/cm ²)	Corrected spontaneous track density (10 ⁴ t/cm ²)	Induced track density (10 ⁴ t/cm ²)	Track density on muscovite detector over dosimeter glass (10 ⁵ t/cm ²)	Etching conditions HF:temp:time (%: °C: s)	D _s (µm)	D _i (µm)	D _s /D _i or D _i /D _s [#]	Age ± 1σ (Ma)	Rounded weighted mean age and error ± 1σ (Ma)
Duck Hawk Bluffs												
UT432	Point-counting	ITPFT	3.62 ± 0.08 (2233)		12.30 ± 0.15 (6890)	7.09 ± 0.05 (16842)	26: 24: 110	nr	nr	nr	64.43 ± 9.17	
UT629	Point-counting	ITPFT	2.75 ± 0.06 (2147)		9.56 ± 0.14 (4999)	7.53 ± 0.06 (14081)	26: 25: 90	nr	nr	nr	67.04 ± 9.24	
UT629	Point-counting	ITPFT	2.78 ± 0.05 (3115)		9.62 ± 0.11 (7544)	7.43 ± 0.05 (19818)	26: 23: 177	nr	nr	nr	66.48 ± 7.64	
UT629	Point-counting	ITPFT	2.73 ± 0.06 (1964)		9.61 ± 0.17 (3170)	7.53 ± 0.06 (16824)	24: 23: 145	nr	nr	nr	66.23 ± 10.95	
UT629	Point-counting	DCFT	3.63 ± 0.05 (6495)	4.43 ± 0.06 (6495)	11.50 ± 0.07 (29965)	5.21 ± 0.04 (19559)	24: 20: 155	6.09 ± 0.12 [203]	7.45 ± 0.11 [513]	1.22 ± 0.03 [#]	62.42 ± 4.65	
UT629	Point-counting	ITPFT	2.95 ± 0.04 (5855)		6.53 ± 0.04 (21537)	4.93 ± 0.04 (19559)	24: 20: 200	6.60 ± 0.12 [205]	6.63 ± 0.08 [509]	1.00 ± 0.02	68.94 ± 4.82	66 ± 3
Swan Lake II												
UT921	Point-counting	DCFT	6.18 ± 0.10 (3654)	8.16 ± 0.14 (3654)	36.70 ± 0.24 (24452)	7.60 ± 0.05 (19449)	24: 20: 120	6.62 ± 0.11 [233]	8.74 ± 0.14 [522]	1.32 ± 0.03 [#]	52.33 ± 7.05	
UT921	Graticule	DCFT	8.02 ± 0.56 (206)	10.59 ± 0.74 (206)	39.50 ± 0.93 (1808)	7.60 ± 0.05 (19449)	24: 20: 120	6.62 ± 0.11 [233]	8.74 ± 0.14 [522]	1.32 ± 0.03 [#]	63.15 ± 4.67	60 ± 4
UT924	Point-counting	DCFT	11.59 ± 0.13 (7682)	17.08 ± 0.20 (7682)	52.70 ± 0.26 (41959)	7.60 ± 0.05 (19449)	24: 19: 145	5.32 ± 0.10 [233]	7.84 ± 0.11 [532]	1.47 ± 0.03 [#]	76.17 ± 9.66	
UT924	Graticule	DCFT	12.90 ± 0.45 (814)	19.00 ± 0.67 (814)	63.20 ± 1.14 (3066)	7.60 ± 0.05 (19449)	24: 19: 145	5.32 ± 0.10 [233]	7.84 ± 0.11 [532]	1.47 ± 0.03 [#]	70.77 ± 2.84	
UT925	Point-counting	DCFT	11.30 ± 0.13 (7902)	16.17 ± 0.18 (7902)	57.60 ± 0.23 (48313)	7.60 ± 0.05 (19449)	24: 19: 160	5.97 ± 0.09 [327]	8.54 ± 0.11 [649]	1.43 ± 0.03 [#]	66.02 ± 7.59	71 ± 3
UT931	Point-counting	ITPFT	5.75 ± 0.06 (7895)		12.20 ± 0.07 (27147)	5.19 ± 0.04 (19559)	24: 20: 255	6.54 ± 0.13 [218]	6.44 ± 0.11 [351]	1.02 ± 0.03	75.55 ± 6.39	
UT931	Graticule	DCFT	9.36 ± 0.28 (1085)	11.88 ± 0.37 (1085)	24.2 ± 0.74 (1023)	5.21 ± 0.04 (19559)	24: 19: 200	7.17 ± 0.13 [309]	9.11 ± 0.14 [605]	1.27 ± 0.03 [#]	79.04 ± 3.49	
UT931	Graticule	ITPFT	5.96 ± 0.30 (405)		11.40 ± 0.28 (1712)	5.19 ± 0.04 (19559)	24: 20: 255	6.54 ± 0.13 [218]	6.44 ± 0.11 [351]	1.02 ± 0.03	83.60 ± 4.66	80 ± 3
UT938	Point-counting	ITPFT	6.95 ± 0.05 (16348)		12.80 ± 0.09 (20731)	5.27 ± 0.04 (19559)	24: 24: 240	6.76 ± 0.11 [306]	6.63 ± 0.12 [366]	1.02 ± 0.02	88.21 ± 7.26	
UT938	Graticule	ITPFT	8.24 ± 0.24 (1226)		14.00 ± 0.27 (2600)	5.27 ± 0.04 (19559)	24: 24: 240	6.76 ± 0.11 [306]	6.63 ± 0.12 [366]	1.02 ± 0.02	96.87 ± 3.43	
UT937	Point-counting	ITPFT	8.97 ± 0.43 (435)		26.80 ± 0.60 (2032)	7.60 ± 0.05 (19449)	24: 20: 260	8.35 ± 0.19 [210]	8.08 ± 0.15 [359]	1.03 ± 0.03	78.59 ± 4.19	89 ± 3
UT941	Point-counting	ITPFT	4.85 ± 0.05 (10729)		74.50 ± 0.05 (19594)	5.29 ± 0.04 (19559)	24: 21: 200	6.34 ± 0.12 [202]	6.46 ± 0.10 [353]	0.98 ± 0.02	106.29 ± 7.92	
UT941	Graticule	ITPFT	5.28 ± 0.23 (1034)		14.10 ± 0.20 (1901)	5.29 ± 0.04 (19559)	24: 21: 200	6.34 ± 0.12 [202]	6.46 ± 0.10 [353]	0.98 ± 0.02	97.89 ± 4.93	100 ± 4

Age reference standards

UT1366	Point-counting	DCFT	0.41 ± 0.01 (1648)	0.47 ± 0.01 (1648)	38.00 ± 0.16 (53783)	4.95 ± 0.04 (19559)	24: 24: 145	5.95 ± 0.08 [205]	6.93 ± 0.08 [528]	1.16 ± 0.02 [#]	1.91 ± 0.14
UT1366	Point-counting	DCFT	0.27 ± 0.01 (520)	0.29 ± 0.01 (520)	22.10 ± 0.18 (14722)	4.93 ± 0.04 (19559)	24: 22: 160	5.89 ± 0.10 [212]	6.26 ± 0.07 [597]	1.06 ± 0.02 [#]	2.02 ± 0.22
UT2354	Graticule	DCFT	1.85 ± 0.05 (2085)	2.17 ± 0.05 (2085)	78.50 ± 0.86 (8301)	7.30 ± 0.06 (14017)	24: 19: 260	7.60 ± 0.11 [224]	8.92 ± 0.11 [615]	1.17 ± 0.02 [#]	6.27 ± 0.16

Notes: The population-subtraction method was used (Westgate, 2015). Ages calculated using the zeta approach and $\lambda_D = 1.551 \times 10^{-10} \text{ yr}^{-1}$. Zeta value is 311 ± 4 based and 7 irradiations at the McMaster Nuclear Reactor, Hamilton, Ontario, using the NIST SRM 612 glass dosimeter and the Moldavite tektite glass with an $^{40}\text{Ar}/^{39}\text{Ar}$ age of $14.808 \pm 0.021 \text{ Ma}$ (2σ) (Schmieder et al., 2018). Number of tracks counted is given in parentheses; number of tracks measured is given in square brackets. The fluence is obtained by multiplying the muscovite track density by 0.53×10^{10} based on 9 determinations. Age determinations are corrected for partial track fading using the isothermal plateau method (ITPFT) (Westgate, 1989) or the diameter correction (DCFT) method (Sandhu and Westgate 1995). Ds = mean long-axis of spontaneous tracks; Di = mean long-axis of induced tracks; nr = not recorded. The $^{40}\text{Ar}/^{39}\text{Ar}$ age of Walcott Tuff (UT2354) is $6.27 \pm 0.04 \text{ Ma}$ (2σ) (Morgan and McIntosh, 2005) and that of Huckleberry Ridge Tuff (UT1366) is $2.003 \pm 0.014 \text{ Ma}$ (2σ) (Gansecki et al., 1998).

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Table 4. Rhyolitic whole rock and glass compositional data relevant to source and correlatives of tephra beds in the Kanguk Fo

Sample	6D	31	60	32A	UT712	UT2114
Locality	West Fork caldera, AK	Sixtymile Butte caldera, AK	Sixtymile Butte caldera, AK	Dennison Fork caldera, Alaska	Ocean Point Colville River, AK	Lac de Gras NWT
Age, Ma	93.6 ± 2.0	92	92	unknown	69.1 ± 0.3	53.5 ± 5.3
Rock type	welded ign.	lava flow	lava flow	welded ign.	tephra-fall	tephra-fall
Analyzed material	whole rock	whole rock	whole rock	whole rock	glass shards	glass shards
Latitude, N	63° 45' 37"	63° 31' 07"	63° 32' 15"	63° 33' 29"	70° 03' 49"	64° 48'
Longitude, W	142° 16' 24"	143° 03' 42"	143° 09' 40"	142° 12' 10"	151° 34' 30"	110° 06'
Number on Fig. 16	1	1	1	1	2	3
wt %						
SiO ₂	76.88	72.31	73.51	72.03	77.27 ± 0.52	77.58 ± 0.40
TiO ₂	0.09	0.09	0.29	0.31	0.09 ± 0.04	0.10 ± 0.08
Al ₂ O ₃	12.98	14.95	14.52	15.12	12.40 ± 0.15	12.58 ± 0.11
FeO _t	1.28	1.87	1.76	2.23	1.30 ± 0.06	1.10 ± 0.07
MnO	0.07	0.06	0.05	0.06	0.02 ± 0.01	0.07 ± 0.05
MgO	0.12	0.53	0.4	0.74	0.01 ± 0.01	0.09 ± 0.03
CaO	0.76	1.65	1.46	2.26	0.32 ± 0.03	0.84 ± 0.09
Na ₂ O	2.79	3.89	3.45	2.88	2.56 ± 0.17	2.60 ± 0.60
K ₂ O	5.03	4.49	4.53	4.38	5.87 ± 0.50	4.84 ± 0.31
Cl	nd	nd	nd	nd	0.19 ± 0.03	0.21 ± 0.04
H ₂ O _d or (LOI)	(1.51)	(0.96)	(1.27)	(1.14)	6.57 ± 0.51	6.37 ± 0.80
n	1	1	1	1	4	20
ppm						
Rb	204	173	160	193	263	158.2 ± 8.2
Sr	93	307	253	356	nd	114.4 ± 9.2
Y	29	24	24	25	nd	21.5 ± 2.1
Zr	116	150	150	179	nd	157 ± 13
Nb	15	14	13	12.0	nd	5.6 ± 0.5
Cs	7.7	5.2	4.6	6.1	11.2	6.39 ± 0.47
Ba	659	2160	2170	2160	21	2203 ± 162
La	37	53	46	54	35	27.8 ± 2.4
Ce	65	90	78	91	88.3	45.4 ± 3.7
Pr	nd	nd	nd	nd	nd	5.01 ± 0.63
Nd	29	33	28	33	38	18.6 ± 2.3
Sm	5.8	5.2	4.8	5	11.85	4.32 ± 0.83
Eu	0.59	0.94	0.87	1.05	0.05	0.40 ± 0.21
Gd	6.2	4.9	2.4	5.1	nd	4.02 ± 1.10
Tb	0.70	0.56	2.1	0.52	2.1	0.51 ± 0.15
Dy	nd	nd	nd	nd	nd	3.63 ± 0.63
Ho	nd	nd	nd	nd	nd	0.83 ± 0.15
Er	nd	nd	nd	nd	nd	2.35 ± 0.51
Tm	nd	nd	nd	nd	nd	0.38 ± 0.10
Yb	2.0	1.6	2.0	2.0	7.94	2.65 ± 0.41
Lu	0.37	0.32	0.29	0.32	1.17	0.46 ± 0.10
Hf	4.1	4.6	4.5	4.9	9.44	4.65 ± 0.85
Ta	1.34	1.23	1.19	1.15	2.42	0.74 ± 0.16
Pb	nd	nd	nd	nd	nd	32.9 ± 1.73
Th	25.8	25.0	23.8	24.3	29.97	17.2 ± 1.5
U	4.4	5.2	5.1	5.6	8.61	6.34 ± 0.43
n	1	1	1	1	1	17
ASI	1.51	1.47	1.54	1.59	1.42	1.52
PI	0.60	0.56	0.55	0.48	0.68	0.59

Notes: Data on calderas in east-central Alaska (location 1) is from Bacon et al. (1990); analyses recast to anhydrous values. Age on tephra at Ocean Point, Alaska, is from Conrad et al. (1989). USGS sample number for UT712 is 84Acr180B (Phillips 1988). The two tephra beds from Lac de Gras locality are known as the Giraffe tephra beds (Wolfe et al. 2017); data on the glass fission age are given in Table S4. Abbreviations as follows: H₂O_d is water by difference; LOI = loss on ignition; AK = Alaska; nd = not determined; n = number of analyses; mean ± 1σ given for samples with multiple analyses; ign. = ignimbrite; ASI is the Aluminum Saturation Index and PI is the Peralkaline Index; NWT = Northwest Territories.

Information

UT2115
Lac de Gras
NWT
53.5 ± 5.3
tephra-fall
glass shards
64° 48'
110° 06'
3
77.41 ± 0.35
0.13 ± 0.05
12.55 ± 0.16
1.17 ± 0.14
0.04 ± 0.04
0.10 ± 0.02
0.86 ± 0.05
2.94 ± 0.24
4.59 ± 0.20
0.22 ± 0.03
5.88 ± 0.53
19
152.4 ± 8.6
124.2 ± 14.8
24.1 ± 2.3
173 ± 17
6.0 ± 0.6
6.48 ± 0.63
2332 ± 139
30.6 ± 2.6
48.0 ± 3.9
5.49 ± 0.69
20.0 ± 4.4
4.47 ± 1.45
0.50 ± 0.31
4.73 ± 2.61
0.68 ± 0.22
4.08 ± 1.37
0.87 ± 0.33
2.79 ± 0.88
0.53 ± 0.23
3.48 ± 1.01
0.56 ± 0.32
5.94 ± 1.28
0.86 ± 0.43
33.41 ± 5.78
19.9 ± 1.8
6.66 ± 0.68
17
1.50
0.60

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Table 5. Characteristics of possible volcanic sources for tephra beds in the Kanguk Formation, SW Banks Island

Characteristics	Banks Island	Northern Greenland	East-central Alaska	South-central Yukon	NE Alaska Range	Central Kuskokwim Mts	Northern OCVB
Map number on Fig. 16			1	4	5	6	7
Rock type	tephra-fall	welded igm	welded igm	welded igm	welded igm	welded igm	welded igm
Composition	CA, LSR, HSR	PA, LSR, T, C	LSR, HSR	rhyodacite	R, D	R	LSR, HSR, D
Glass (G) or whole rock (WR)	G	WR	WR	WR			WR
Mineralogy	q+pg+bi+il+z+a ±f±r±ga	pg+f+q+ox±am±px ±z ±a	q+pg+f+bi+ox±am	q+f+pg+bi+am (ox likely present)		q+pg+bi+a+z+ga+ox?	pg+f+q+bi+am+opx+ tmg+il+a+z+al+ga
Age of volcanic activity, Ma	100 - ~50	71 - 61	94 - 55	102 - 94	56.5 - 50.4	75 - 60	106 - 79
Distance to SW Banks Island (km)	0	2000	1100	1000	1600	1500-1800	2000-2500
References	this study	Thorarinsson et al. 2011, 2012	Bacon et al. 1990	Wood and Armstrong 1982	Moll-Stalcup 1994	Moll-Stalcup 1994 Cady et al. 1955	Tikhomirov et al. 2008, 2012
Likelihood of being a source	not applicable	none	probable	unlikely	possible	probable	possible

Notes: Multiple volcanic centres occur in each of the source areas and so these data do not capture fully the compositional variability. The list of minerals is presented in the order of decreasing abundance. Information on the NE Alaska Range refers to the Talkeetna Mountains. Abbreviations: igm=ignimbrite, CA=calc-alkaline, LSR=low silica rhyolite, HSR=high silica rhyolite, PA=peralkaline, T=trachyte, C=comendite, D=dacite, G=glass, WR=whole rock, q=quartz, pg=plagioclase(mostly sodic), bi=biotite, il=ilmenite, z=zircon, a=apatite, f=alkali feldspar, r=rutile, ga=garnet, ox=FeTi oxides, am=amphibole, px=pyroxene, opx=orthopyroxene, tmg=Ti-magnetite, al=allanite. OCVB= Okhotsk-Chukotka volcanic belt.

			BANKS ISLAND	BANKS ISLAND	SVERDRUP BASIN
			Formations Miall 1979	Formations Dixon et al. 1992	Formations Embry and Dixon 1990
CRETACEOUS	Paleo- gene	Eocene 56.0	Eureka Cyclic Member	Eureka Cyclic Member	Iceberg Bay sandstone
		Paleocene 66.0	Sound Shale Member	Sound Shale Member	Shale
	Upper	Maastrichtian 72.1	Upper Sand	upper sand	Expedition sandstone
		Campanian 83.65	Lower Sand	shale member	
		Santonian 85.7	Bituminous Shale	bituminous shale	
		Coniacian 89.39	KANGUK Shale	KANGUK	KANGUK
		Turonian 93.9			Shale and siltstone
		Cenomanian 100.5			Hassel sandstone
		Albian 113.2	Christopher Hassel	Christopher Shale	Christopher