Supplemental Data for Gosse et al., Muon Paleotopometry, GChron, 20250905

S1. Lab preparation, mineral separation, purification

The physical and chemical preparation of samples for µ-paleotopometry will likely be similar to routine TCN mineral separation and target preparation procedures, with the exception that (i) with greater depths (below 2000 g cm^{-2}) more quartz is needed to have sufficient µTCN atoms to count in the target mass; (ii) sample size may be restricted to core volume available, so extra care to obtain highest efficiency trumps throughput speed; and (iii) owing to the very low µTCN concentrations (<300 at/g) expected at great depth, it may be necessary to minimize the use of reagents and acids (e.g. heavy liquids, hexafluorosilicic acid, and pyrophosphoric acid) which may be sources of contamination, and use Type-1 water early in the mineral separation procedure, and optimum grade acids. In preparation for the low-level concentrations, we purified the acids with a Savillex sub-boiling distillation system, and installed fresh boron-free HEPA air filters for the lab, and new ion exchange tanks in the Elga CENTRA-R60 centralized water system, ion exchange tanks for the Type 1 system, and boron filter and ion exchange tank for the final Milli-Q Type1+ water system. We also conducted a thorough cleaning of the labs involved, and established protocols to minimize entrance to those labs until the samples were processed.

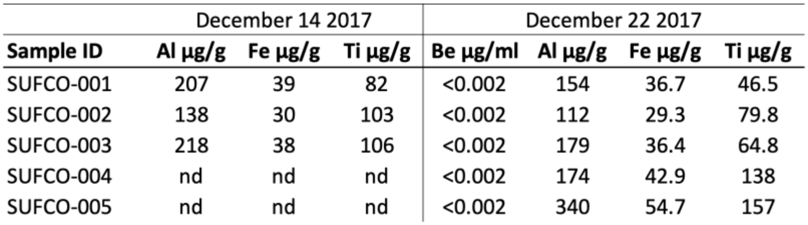
With this in mind, we present below the procedure modified from our usual mineral separation methods for the processing of the SUFCO Mine quartzite samples from Utah. We began with six samples that were approximately 1 kg mass (Table 1) and we aimed to produce BeO targets from 50 g of pure quartz.

Table S1. Initial mass and grain size of sieve sample material after crushing and grinding

Full Sample ID	Grain Size Fraction	Mass (g)	Main Contaminants
3513 16-SUFCO-3RWL-E1-C7-001	<150	891	Fe, K. Feldspar, Coal
	150-250	73	
3514 16-SUFCO-3RWL-E1-C10-002	<150	613	Fe-Hematite Cement, Coal
	150-250	221	
3515 16-SUFCO-3RWL-E2-C12-003	<150	389	Fe, K. Feldspar, Coal
	150-250	282	
3516 16-SUFCO-3RWL-E1-C14-004	<150	1015	Coal
	150-250	192	
3517 16-SUFCO-3RWL-E2-C15-005	<150	255	Fe, K. Feldspar, Coal
	150-250	1306	
3518 16-SUFCO-3RWL-E1-C17-006	<150	964	Fe, K. Feldspar, Coal
	150-250	155	

The six SUFCO samples consist of arenite sandstone material with the minor presence of Fe- garnet, hornblende, and potassium feldspar, as well as coal fragments. All samples were cemented by silica, some by iron-cement (Table S1). Generally, the quartz percentages ranged from 80% to 45% of the original samples, with coal particles being the greatest contaminant. The samples underwent partial physical processing (crushing, grinding, sieving, pre-rinsed and initial leaching in aqua regia) initially by A. J. Hidy at Lawrence Livermore National Laboratory and more mass was processed at CRISDal Lab, Dalhousie University (M. Soukup, G. Yang), yielding the grain size fractions <150 µm and 150-250 µm when dried (Table S1). Magnetic grains were isolated using a horseshoe-style magnet and then REE bar magnet (magnets were in small plastic bags to keep separated from the sample), followed by Frantz isomagnetic separation. Coal particles in the interstices between quartz grains that were enveloped in silica cement were visible with the naked eye. To remove the coal, we combusted dry 5-10 g aliquot distributed among multiple cleaned 20 ml alumina crucibles at 110°C in a muffle furnace overnight, then raised to 450°C for 5-6 hours. Crucibles were cleaned with diluted soap in Type 2 (reverse osmosis plus deionization) water, rinsed with Type 2 water, then soaked in a 2% HNO_3/Type1 water solution for one hour, thoroughly rinsed in Type 1 (18-MOhm with boron filter) water, oven dried, and placed in a desiccator. This HNO_3 and all other acids after this step were purchased at trace-level quality, then further processed with a sub-boiling distillation (HF, HCl, and HNO_3). We also tested a higher combustion temperature (550°C) but the quartz grains became more fragmented making the remaining sample purification steps less efficient, so we combusted at 450°C the majority of the sample masses. The coal content was reduced from up to 15% to 1-3% for the most coaliferous sample (SUFCO-006). Once the mineral separation was completed based on microscopy, the concentrations of Al, Ti, and Fe were analysed to test purity (Table S2) considering there was no longer any evidence of feldspar. However, more purification was needed to reduce the Al content to <100 µg/g, so additional 2:1 H_2O:HF digestion was continued for 1 week. The concentration of Al and Ti improved (reduced) after the additional week of partial digestion, however the Fe concentration did not improve. At this point, because we felt that a 30% mass removal for meteoric ^{10}Be removal was necessary, the amount of mass remaining would be below our desired sample mass to have sufficient ^{10}Be if we proceeded with more purification. In January 2018 we completed the 30% digestion (in one step; since 2018 we do this in three steps) followed by a 2:1 H_2O:HF rinsing then H_2O rinsing and drying.

Table S2. ICP and AAS measurements (Dalhousie University) on five SUFCO samples to test purity of quartz. (Be was below the detection limit in all samples).

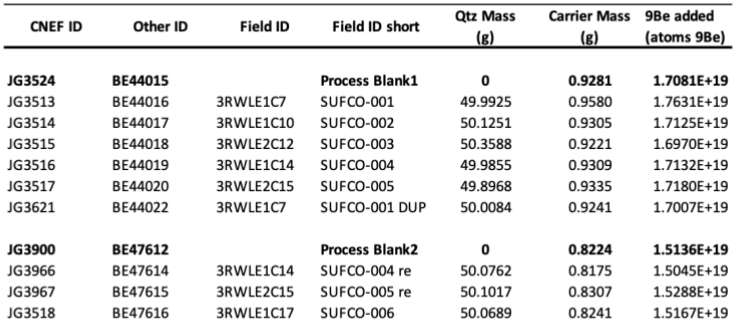


	December 14 2017			December 22 2017			
Sample ID	**Al µg/g**	**Fe µg/g**	**Ti µg/g**	**Be µg/ml**	**Al µg/g**	**Fe µg/g**	**Ti µg/g**
SUFCO-001	207	39	82	<0.002	154	36.7	46.5
SUFCO-002	138	30	103	<0.002	112	29.3	79.8
SUFCO-003	218	38	106	<0.002	179	36.4	64.8
SUFCO-004	nd	nd	nd	<0.002	174	42.9	138
SUFCO-005	nd	nd	nd	<0.002	340	54.7	157

S2. Target Chemistry Data

Target chemistry took place in November 2018 and November 2019. Details of the target chemistry procedure and carrier used at that time for BeO targets is provided in Kjaer et al. ((Kjær et al., 2022) *Supplementary Information*, *§3.2*). Table 3 provides details on the gravimetry. The carrier was BeCarrier-B31 (a phenacite carrier prepared by J. Gosse at CRISDal on 2012-Sep-28 with a monitored and reproduced concentration of 279 ± 8 µg/mL). The number of atoms subtracted from each sample was based on the process blanks analysed during the AMS experiments in 2018 and 2019 was 4.367 x 10^3 and 11.55 x 10^3 atoms ^{10}Be.

Table S3. Gravimetry data for the samples processed for two AMS experiments.



CNEF ID	Other ID	Field ID	Field ID short	Qtz Mass (g)	Carrier Mass (g)	9Be added (atoms 9Be)
JG3524	**BE44015**		**Process Blank1**	**0**	**0.9281**	**1.7081E+19**
JG3513	BE44016	3RWLE1C7	SUFCO-001	49.9925	0.9580	1.7631E+19
JG3514	BE44017	3RWLE1C10	SUFCO-002	50.1251	0.9305	1.7125E+19
JG3515	BE44018	3RWLE2C12	SUFCO-003	50.3588	0.9221	1.6970E+19
JG3516	BE44019	3RWLE1C14	SUFCO-004	49.9855	0.9309	1.7132E+19
JG3517	BE44020	3RWLE2C15	SUFCO-005	49.8968	0.9335	1.7180E+19
JG3621	BE44022	3RWLE1C7	SUFCO-001 DUP	50.0084	0.9241	1.7007E+19
JG3900	**BE47612**		**Process Blank2**	**0**	**0.8224**	**1.5136E+19**
JG3966	BE47614	3RWLE1C14	SUFCO-004 re	50.0762	0.8175	1.5045E+19
JG3967	BE47615	3RWLE2C15	SUFCO-005 re	50.1017	0.8307	1.5288E+19
JG3518	BE47616	3RWLE1C17	SUFCO-006	50.0689	0.8241	1.5167E+19

S3. Accelerator Mass Spectrometry measurements

All AMS measurements were completed at the Centre for AMS at Lawrence Livermore National Lab (CAMS-LLNL). The first AMS experiment on 2018-Jan-26 did not include a target for SUFCO-006 owing to the impurity of its quartz at the time of target chemistry. The second AMS run on 2019-Nov-22 included a target for SUFCO-006 after further purification, and included re-runs of samples SUFCO-004 and 005 owing to low currents during the 2018 AMS experiment. The AMS standard used for normalisation of the sample results was 07KNSTD3110 (Nishiizumi et al., 2007) with ^{10}Be/^{9}Be of 2.851 × 10^{-12} at/at. The average ^{10}Be/^{9}Be for the phenacite spike has been 1 to 20 × 10^{-16} at/at, with a higher ratio observed on samples with large quartz masses that require greater acid volumes for digestion and longer evaporation times. The final concentrations of ^{10}Be in quartz range from 296 ± 80 to 494 ± 90 atoms/g.

Table S4. AMS data.

AMS ID	Field ID	10Be/9Be AMS boroncorr (10Be/9Be)	1s Error (10Be/9Be)	1s Error (%)	10Be atoms (atoms)	10Be atoms blnk corr (Be-10 atoms)	Total Analytical Error (Be-10 atoms)	1s Total Analytical Error %	Meas Concentration (Be-10 atoms/g)	Meas Conc Error (%)
AMS 2018-Jan-26										
BE44015	**Blank**	**2.556E-16**	**1.582E-16**							
BE44016	SUFCO-001	1.449E-15	2.180E-16	15%	2.554E+04	2.117E+04	3.92E+03	18.50%	423.6	19%
BE44017	SUFCO-002	1.336E-15	1.824E-16	14%	2.287E+04	1.850E+04	3.36E+03	18.17%	369.2	18%
BE44018	SUFCO-003	1.134E-15	2.613E-16	23%	1.925E+04	1.488E+04	4.03E+03	27.05%	295.5	27%
BE44019	SUFCO-004	2.306E-15	7.151E-16	31%	3.951E+04	3.514E+04	1.12E+04	31.81%	703.1	32%
BE44020	SUFCO-005	3.504E-15	1.042E-15	30%	6.020E+04	5.583E+04	1.68E+04	30.13%	1119	30%
BE44022	SUFCO-001 DI	1.255E-15	2.078E-16	17%	2.134E+04	1.697E+04	3.55E+03	20.94%	339.4	21%
AMS 2019-Nov-22										
BE47612	**Blank**	**7.629E-16**	**1.223E-16**							
BE47614	SUFCO-004 re	2.272E-15	3.600E-16	16%	3.418E+04	2.263E+04	3.82E+03	16.86%	451.9	17%
BE47615	SUFCO-005 re	2.374E-15	4.138E-16	17%	3.630E+04	2.475E+04	4.52E+03	18.27%	494.0	18%
BE47616	SUFCO-006	1.875E-15	3.682E-16	20%	2.843E+04	1.689E+04	3.51E+03	20.79%	337.3	21%

S4. Blank subtraction

Process blanks at CRISDal Lab during 2018 and 2019 ranged from 2x10^{-16} to 8x10^{-16} at/at. In 2018, process blank BE44015 yielded a ^{10}Be /^{9}Be ratio of 2.55x10^{-16} at/at, and using the same carrier, in 2019 the ratio was 7.63 x 10^{-16} at/at. The blank corrections ranged from 14% to 31% of the measured number of atoms (Fig. S1).

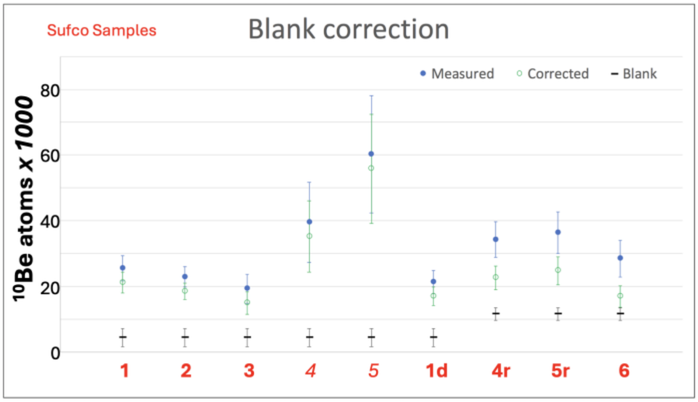


Figure S 1. Comparison of the ^{10}Be atoms measured in the process blanks with similar mass of carrier) and the number of ^{10}Be atoms in the measured and the blank-corrected values. Numbers on the bottom of the SUFCO-xxx sample IDs. The four bold samples on the right were analysed in 2019, the others in 2018. SUFCO-004 and 005 are italicized to emphasize their relatively high abundances and uncertainty. 1d: duplicate of SUFCO-001; 4r and 5r are reanalysis samples using new targets after further purification of the quartz.

References

Kjær, K. H., Winther Pedersen, M., De Sanctis, B., De Cahsan, B., Korneliussen, T. S., Michelsen, C. S., Sand, K. K., Jelavić, S., Ruter, A. H., and Schmidt, A. M.: A 2-million-year-old ecosystem in Greenland uncovered by environmental DNA, Nature, 612, 283-291, 2022.

Nishiizumi, K., Imamura, M., Caffee, M., Southon, J., Finkel, R., and McAninch, J.: Absolute calibration of Be-10 AMS standards, Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions With Materials and Atoms, 258, 403-413, 10.1016/j.nimb.2007.01.297, 2007.