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A homogeneous liquid reference material for monitoring the quality and reproducibility of *in situ* cosmogenic ^{10}Be and ^{26}Al analyses

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Highlights: (max 85 characters, including spaces)

- Liquid reference material for quality control of cosmogenic ^{10}Be and ^{26}Al analyses
- Ratios similar to late glacial samples (^{10}Be/^{9}Be ~1.4x10^{-13}; ^{26}Al/^{27}Al ~4.4x10^{-13})
- Available free of charge to the community
- Initial analyses match suggested values for source material (CRONUS-A)

Key words: Cosmogenic Nuclides; Accelerator Mass Spectrometry; Isotopes; Geochronology; Geomorphology; Quaternary

Abstract

Analysis of the *in situ* produced cosmogenic nuclides ^{10}Be and ^{26}Al has been used for several decades to study Earth surface processes; yet, no reference material has been widely adopted and used by the community to ensure the quality and comparability of sample preparation and isotopic analyses. Such a reference material could facilitate inter-laboratory comparison and serve as a benchmark for quantifying the accuracy, precision, and long-term reproducibility of terrestrial cosmogenic nuclide analyses. Here, we describe a liquid reference material, UVM-A, which is freely available to the community. We created four liters of solution by dissolving CRONUS-A granular reference material [1], and spiking the solution with stable ^{9}Be and ^{27}Al, yielding a solution containing 236.7 ± 0.6 μg g^{-1} Be and 932.6 ± 1.6 μg g^{-1} Al (average, 1SD). Initial analyses of UVM-A indicate that the nuclide ratios of the reference material (^{10}Be/^{9}Be 1.43 ± 0.02 x10^{-13}; ^{26}Al/^{27}Al 4.44 ± 0.05 x10^{-13}; average, standard error) are similar to those of late-glacial exposure samples, are tightly clustered, and match the nuclide concentrations expected from the CRONUS-A quartz used to prepare the reference material. Use of this reference material will help to quantify uncertainty in cosmogenic exposure ages, burial ages, and erosion rates resulting from sample preparation and isotopic analysis.

1. Introduction

Analysis of the cosmogenic nuclides ^{10}Be and ^{26}Al ADDIN EN.CITE [2-6] involves several steps including isolation of a mineral phase (usually quartz), extraction and purification of Be and Al, and analysis of isotope ratios by accelerator mass spectrometry (AMS) ADDIN EN.CITE [7-9]. Secondary standards are used to control the quality of AMS analyses [10], while process blanks [8] are used to determine the integrity of sample processing [11]. However, until recently, there were no standard reference materials that the dozens of sample preparation laboratories [12] around the world could process to ensure the quality and reproducibility of chemical extraction. The lack of reference materials makes the comparison of data produced by different extraction and AMS laboratories uncertain. Although secondary standards quantify AMS performance of pure materials, they do not capture differences in chemical extraction and cathode preparation between laboratories.

The CRONUS-Earth Project [13] produced several reference materials, including three that were purified quartz [1]. Of these, CRONUS-N, reported as having $2.17 \pm 0.88 \times 10^5$ atoms g^{-1} ^{10}Be (average, 1SD, n = 23) and $1.05 \pm 0.11 \times 10^6$ atoms g^{-1} ^{26}Al (average, 1SD, n = 10) [1], has been the most widely analyzed. Repeated analysis of CRONUS-N over four years at the University of Vermont [14], as well as mineralogical investigations at the University of Washington (J. Stone and G. Balco, pers. comm.), demonstrate that the material is not homogeneous for ^{10}Be or for stable ^{27}Al. Aliquots (~10 g) of the CRONUS-N material, prepared in the University of Vermont laboratory as unknowns, have ^{10}Be concentrations of 1.93-2.55 x

10^5 atoms g^{-1} (n = 69) and stable ^{27}Al concentrations of 219-417 μg g^{-1} (n = 58) [14]. Isotopic and chemical analyses demonstrate that ^{10}Be and stable ^{27}Al are contained in dark grains that make up a small percentage of CRONUS-N material. Analyses of CRONUS-N material purified at University of Vermont by density separation give concentrations of ^{10}Be that are 5-15% lower than those of the CRONUS-N material prior to density separation [14]. Conversely, the dark grains, when prepared and measured separately, have a ^{10}Be concentration about 20 times higher than quartz isolated from the CRONUS-N material [14].

Here, we report on the creation and initial testing of a new, freely available, pre-spiked liquid reference material, termed UVM-A, for quality control of *in situ* cosmogenic ^{10}Be and ^{26}Al analyses. We created a liquid material because the potential inhomogeneity of a granular reference material such as CRONUS-N limits detection of variability due to laboratory techniques. In contrast, a liquid reference material such as we present here is not susceptible to such inhomogeneity and thus could be a more reliable indicator of reproducibility. However, evaporation would change the ^{10}Be and ^{26}Al concentrations of the reference material over long timescales, an issue avoided by spiking the reference material with ^{9}Be and ^{27}Al during creation. Accordingly, the pre-spiked reference material will not be sensitive to variations between stable isotope carriers used by different laboratories, thereby isolating variability introduced through sample processing procedures.

2. Background

The liquid reference material we describe here was created from pre-existing granular quartz reference material, CRONUS-A [1]. The sandstone used to create CRONUS-A was collected from exposed outcrops in Antarctica at 77.8830°S, 160.9431°E, and an elevation of 1612 m; the material was prepared following standard procedures [1]. Isotopic analysis of the CRONUS-A material prepared in 12 different laboratories and analyzed at several different AMS facilities [1] yielded an average ^{10}Be concentration of $3.42 \pm 0.10 \times 10^{7}$ atoms g^{-1} (n = 29, 1 SD) and an average ^{26}Al concentration of $1.43 \pm 0.07 \times 10^{8}$ atoms g^{-1} (n = 13, 1 SD). Although not directly reported, ^{26}Al/^{10}Be ratios average 4.23 ± 0.18 (n = 13, 1SD) [1].

Variation in the reported CRONUS-A results (see Tables 3a and 3b in [1]) is likely driven by differences in sample processing procedures as well as uncertainty and differences in AMS analyses. Within individual laboratories (i.e., based on replicate samples), the coefficient of variation of ^{10}Be analyses was 0.3-2.0%. Comparing between laboratories, after correcting for different primary AMS normalization standards and different assumptions of the ^{10}Be half-life, the coefficient of variation in the overall ^{10}Be dataset (n = 23) was 2.9%. The overall ^{10}Be coefficient of variation (2.9%) exceeds the average analytic uncertainty (1.7 ± 0.9 %, average, 1SD), implying additional scatter beyond Poisson counting statistics. There were insufficient ^{26}Al replicates to assess intra-laboratory variation, but the coefficient of variation across the overall dataset (n = 10) was 4.8%. The overall ^{26}Al coefficient of variation (4.8%) exceeds the average analytic uncertainty (3.0 ± 1.4 %, average, 1SD), again implying additional scatter beyond counting statistics.

3. Methods

3.1. Creation of the liquid reference material

To create a homogeneous liquid reference material, we digested 267.60 g of CRONUS-A quartz [1] in 12 separate Teflon FEP plastic bottles using concentrated HF heated to 135◦ C gradually over the span of three days. Following digestion, we transferred the solution into a single bottle, rinsing each digestion bottle into the larger bottle three times with 1% HNO_3. To the resulting solution, we added 103.41 g SPEX 10,000 µg mL^{-1} Be standard (lot number AL16-192BEY, certified value 9988 ± 50 µg mL^{-1}) and 404.47 g SPEX 10,000 µg mL^{-1} Al standard (lot number AM17-16ALX, certified value 9989 ± 50 µg mL^{-1}), then homogenized the solution. We decanted the solution into 12 Teflon PFA plastic beakers and evaporated it to dryness. We then added 10 ml of $HClO_4$ to each beaker and evaporated it to dryness at 230°C, and repeated the acid addition and evaporation two additional times. We dissolved the resulting perchlorate precipitates in 1% HNO_3, quantitatively transferred the liquid, and brought the total volume to 4 L in a volumetric flask with additional 1% HNO_3.

Based on the method above, we calculated predicted $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios of the reference material. For these calculations, we used the reported ^{10}Be and ^{26}Al concentrations, as well as the reported ^{27}Al concentration (~110 µg g^{-1}, see Fig. 3A in [1]), of CRONUS-A quartz [1]. We assumed the concentrations of the SPEX standards described above, a density of 1.059 g mL^{-1} for the Be standard (in 5% HNO_3), and a density of 1.052 g mL^{-1} for the Al standard (in 5%

HCl); both of these density values are reported in the SPEX documentation. The predicted ^{10}Be/^{9}Be ratio for the homogeneous liquid is 1.40 x 10^{-13}, and the predicted ^{26}Al/^{27}Al ratio is 4.43 x 10^{-13}.

3.2. Quantification of stable ^{9}Be and ^{27}Al

We quantified total ^{9}Be and ^{27}Al in the UVM-A reference material using a similar procedure that we use in all samples processed in the laboratory [8]. We removed six 100µL aliquots and six 200µL aliquots of the liquid reference material (recording their mass), and diluted them by mass with 10 mL 0.5% H_2SO_4 spiked with an internal standard (10 ppm Y). We analyzed the 12 solutions with inductively-coupled plasma optical emission spectrometry (ICP-OES) using two emission lines for each element and the internal standard (Y), and corrected for the dilution of the internal standard by the initial aliquot mass. The measured ^{9}Be concentration of UVM-A is 236.7 ± 0.6 µg g^{-1} (average, n = 12, 1SD), reflecting ^{9}Be added through carrier and confirming that there is no detectable native ^{9}Be [15] in the CRONUS-A quartz. The measured ^{27}Al concentration of UVM-A is 932.6 ± 1.6 µg g^{-1} (average, n = 12, 1SD), reflecting a combination of native Al in quartz and Al added during the preparation of the material; we utilize this value of ^{27}Al for further ^{26}Al calculations.

3.3. Preparation of samples and AMS analysis

To determine the isotopic ratio of the reference material UVM-A, we removed 12 1-mL aliquots of the reference material, diluted it in 1% HNO_3, precipitated the Be and Al as a hydroxide gel, and performed cation column chromatography [8] to remove Ti and separate Be and Al. During the column procedure, we included an additional Mg-removal step [16] because ^{26}Mg creates an isobaric interference with ^{26}Al on the Purdue Rare Isotope Measurement (PRIME) Laboratory AMS. Following chemical separation, we precipitated the Be and Al independently as hydroxide gels, dried the gels, and burned the pellets to create oxides. We mixed the BeO and Al_2O_3 with Nb metal and packed the material into stainless steel cathodes.

AMS analysis for both isotopes was conducted at PRIME Laboratory. For ^{10}Be/^{9}Be, sample ratios were normalized to standard KNSTD Be 01-5-4 with an assumed ratio of 2.851 x 10^{-12} [17]; this dilution was prepared in 2001, has been checked against the original dilution series from 1983, and is equivalent to 07KNSTD in the CRONUS Earth online exposure age calculator. For ^{26}Al/^{27}Al, sample ratios were normalized to standard KNSTD with an assumed ratio of 1.818 x 10^{-12} [18].

Blanks (Table 1) were created by direct precipitation of the SPEX Be and Al standards that we added to the UVM-A solution; accordingly, we interpret blanks to represent the number of atoms of ^{10}Be or ^{26}Al added to the reference material by the SPEX solutions as well as any background AMS counts. Because the direct precipitation blanks were not fully processed, they do not include rare nuclides introduced by laboratory isolation of Be and Al. We chose to work only with direct precipitation blanks because sample preparation laboratories will analyze their own process blanks, and those process blanks will vary between laboratories and possibly between batches. To determine the ^{10}Be and ^{26}Al concentrations of the CRONUS-A quartz, we subtracted the average direct precipitation blank ratio from the sample ratios and propagated uncertainties in quadrature. We subtracted ratios (rather than atoms) because direct precipitation blanks and samples had the same mass of total Be and Al.

For ^{10}Be/^{9}Be, the direct precipitation blanks had ~100-150 ^{10}Be counts per cathode (Table 1) implying a maximum precision of 8-10%; however, the relative standard deviation of the blank value (3.4%) is similar to but slightly smaller than allowed by Poisson counting statistics (3.6%) [10]. Therefore, we use the average blank value and assign an uncertainty based on the maximum precision allowed by counting statistics (the square root of the number of counts divided by the number of counts). This yields a direct precipitation blank ^{10}Be/^{9}Be of 4 .14 ± 0.15 x 10^{-15} (Table 1).

For ^{26}Al/^{27}Al direct precipitation blanks, four cathodes had no ^{26}Al counts (Table 1) and thus do not yield measurable ratios, which is not uncommon with ^{26}Al blanks at PRIME. Therefore, we recalculated the blank ratio assuming all counting cycles belonged to the same sample and summed the total ^{26}Al counts (n=4) and stable isotope current. To constrain the uncertainty, we use the maximum precision allowed by counting statistics, as described above. This yields a direct precipitation blank ^{26}Al/^{27}Al of 2.10 ± 1.05 x 10^{-16} (Table 1).

4. Results

For ^{10}Be/^{9}Be (Table 2, Fig. 1), measured ratios of UVM-A (not corrected for any ^{10}Be added with the ^{9}Be carrier) are 1.34-1.50 x 10^{-13} and average 1.43 ± 0.02 x 10^{-13} (n = 12, standard error). Using an error-weighted average yields the same result as the non-weighted average. Analytic uncertainties for the 12 cathodes are 2.7-6.0 %, with an average of 3.4 ± 0.9 % (n = 12, 1SD); the coefficient of variation of all 12 measurements is 3.7%. The measured ^{10}Be/^{9}Be ratios overlap with the predicted ^{10}Be/^{9}Be ratio based on stoichiometric calculations (1.40 x 10^{-13}).

Using the total masses of the CRONUS-A quartz and the SPEX Be carrier used to make the liquid reference material, and subtracting our best estimate of the blank as introduced with the ^{9}Be carrier we added (the SPEX standard), we infer that the ^{10}Be concentration of CRONUS-A is 3.38 ± 0.13 x 10^{7} atoms g^{-1} (average, n = 12, 1SD). This quantification of ^{10}Be in CRONUS-A yields a population of values indistinguishable from those of [1] (average 3.42 ± 0.10 x 10^{7} atoms g^{-1}, n = 29, 1SD) based on a two-tailed, unequal variance Student’s T-Test (p = 0.30).

For ^{26}Al/^{27}Al (Table 3, Fig. 2), measured ratios of UVM-A (not corrected for any ^{26}Al added with the ^{27}Al carrier) are 4.17-4.65 x 10^{-13} and average 4.44 ± 0.05 x 10^{-13} (n = 10, standard error). Using an error-weighted average yields the same result as the non-weighted average. Analytic uncertainties are 4.0-9.5 % and average 5.9 ± 1.6 % (n = 10, 1SD); the coefficient of variation of all 10 measurements is 3.9%. The measured ^{26}Al/^{27}Al ratios overlap with the predicted ^{26}Al/^{27}Al ratio based on stoichiometric calculations (4.43 x 10^{-13}).

Using the mass of the CRONUS-A quartz used to make the liquid reference material and the total ICP-quantified ^{27}Al, and subtracting our best estimate of the blank as introduced with the ^{27}Al carrier we added (the SPEX standard), we infer that the ^{26}Al concentration of CRONUS-A is 1.43 ± 0.06 x 10^8 atoms g^{-1} (average, n = 10, 1SD). This quantification of ^{26}Al in CRONUS-A yields a population of values indistinguishable from those of [1] (average 1.43 ± 0.07 x 10^8 atoms g^{-1}, n = 13, 1SD) based on a two-tailed, unequal variance Student's T-Test (p = 0.98).

Inferred ^{26}Al/^{10}Be ratios of CRONUS-A quartz are 3.96-4.73, averaging 4.22 ± 0.22 (n = 10 , 1SD, Table 4) and have a coefficient of variation of 5.3%. This population of values is indistinguishable from those of [1] (average 4.23 ± 0.18, n = 13, 1SD) based on a two-tailed, unequal variance Student's T-Test (p = 0.88).

5. Discussion

5.1. Utility of the liquid reference material

The liquid reference material we describe here, termed UVM-A, is available to the cosmogenic isotope community free of charge for tracking the accuracy and precision of ^{10}Be and ^{26}Al analyses. Because of the homogeneity of the liquid, variations in the measured ratios should indicate variability in sample processing techniques and AMS analysis (and excluding uncertainty introduced through the quantification of stable isotope carriers). Our results show that the 12 measurements of ^{10}Be/^{9}Be (coefficient of variation 3.8%) replicate at the level of counting statistics (analytic precisions 3.4 ± 0.9%, average, 1SD). Similarly, the 10 measurements of ^{26}Al/^{27}Al (coefficient of variation 3.9%) replicate to within counting statistics (analytic precisions 5.9 ± 1.6%, average, 1SD). Quantifying the variance of measured ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios over time, particularly when UVM-A is prepared with different sample batches, in different laboratories, and analyzed on different AMS instruments at different times , will allow for more realistic error budgets for exposure ages [2], burial ages [3], and erosion rates [5].

Utilization of a homogeneous reference material such as UVM-A will facilitate comparison of results from different preparation laboratories and different AMS facilities. Initial analyses of CRONUS-A indicated that the inter-laboratory variability exceeded the intra-laboratory variability [1], although a larger number of analyses at a greater range of laboratories will allow this finding to be evaluated more systematically. Such studies have been conducted by the radiocarbon dating community, and the creation of widely-used reference materials has facilitated intercomparison between laboratories for decades [19, 20]. Part of the variance between laboratories and between sample batches within a single laboratory may be due to inaccuracy in the quantification of stable isotope carriers, a problem that could be addressed by a systematic comparison study and/or by developing a set of stable isotope carriers that would be produced in large batches, robustly quantified, and widely adopted by the community.

We created sufficient UVM-A to last for years. The total volume of 4 L should provide 4000 separate 1-mL aliquots, enough for 4000 batches of samples assuming one quality control sample per batch. If the batch size is ten samples, as it is in the University of Vermont laboratory, then the total amount of UVM-A created is sufficient to accompany 40,000 cosmogenic samples. Because the ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios are fixed, the measured ratios will be immune to evaporative losses, which are possible (likely at very small scale) if the UVM-A material is stored for years.

5.2. Comparison between UVM-A and CRONUS-A

Our analyses of UVM-A (prepared at University of Vermont and analyzed at PRIME in a single batch) suggest that the nuclide concentrations of CRONUS-A calculated from the UVM-A liquid reference material match those expected from the source material [1] (Table 5). These are not analogous experiments because the initial values for CRONUS-A were determined based on results from 12 different preparation laboratories and measurements at numerous different AMS facilities [1]. The reproducibility of our measurements of UVM-A (3.7% for ^{10}Be and 3.9% for ^{26}Al) are similar to those determined for CRONUS-A (2.9% for ^{10}Be and 4.8% for ^{26}Al) by [1], even though the isotopic ratios we measured in UVM-A are two orders of magnitude lower than those in CRONUS-A.

6. Conclusions

The liquid reference material we describe here, termed UVM-A, is designed for tracking the accuracy, precision, and long-term reproducibility of *in situ* cosmogenic ^{10}Be/^{9}Be and ^{26}Al/^{27}

Al analyses over time. The homogeneity and fixed ratios of the reference material imply that any variability in the measured ratios is due to inconsistency in chemical preparation of Be and Al in the laboratory and/or variability during AMS analysis. Our initial analyses of UVM-A indicate reproducibility to within AMS counting statistics and inferred nuclide concentrations that match those of the CRONUS-A source material [1]. The UVM-A reference material is freely available by request from the cosmogenic laboratory at the University of Vermont (www.uvm.edu/cosmolab).

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Table Captions

Table 1. Isotopic data from the six $^{10}Be/^{9}Be$ blanks and six $^{26}Al/^{27}Al$ blanks used to correct for backgrounds.

Table 2. Laboratory preparation and AMS data from $^{10}Be/^{9}Be$ analyses of the UVM-A liquid reference material (n = 12).

Table 3. Laboratory preparation and AMS data from $^{26}Al/^{27}Al$ analyses of the UVM-A liquid reference material (n = 10).

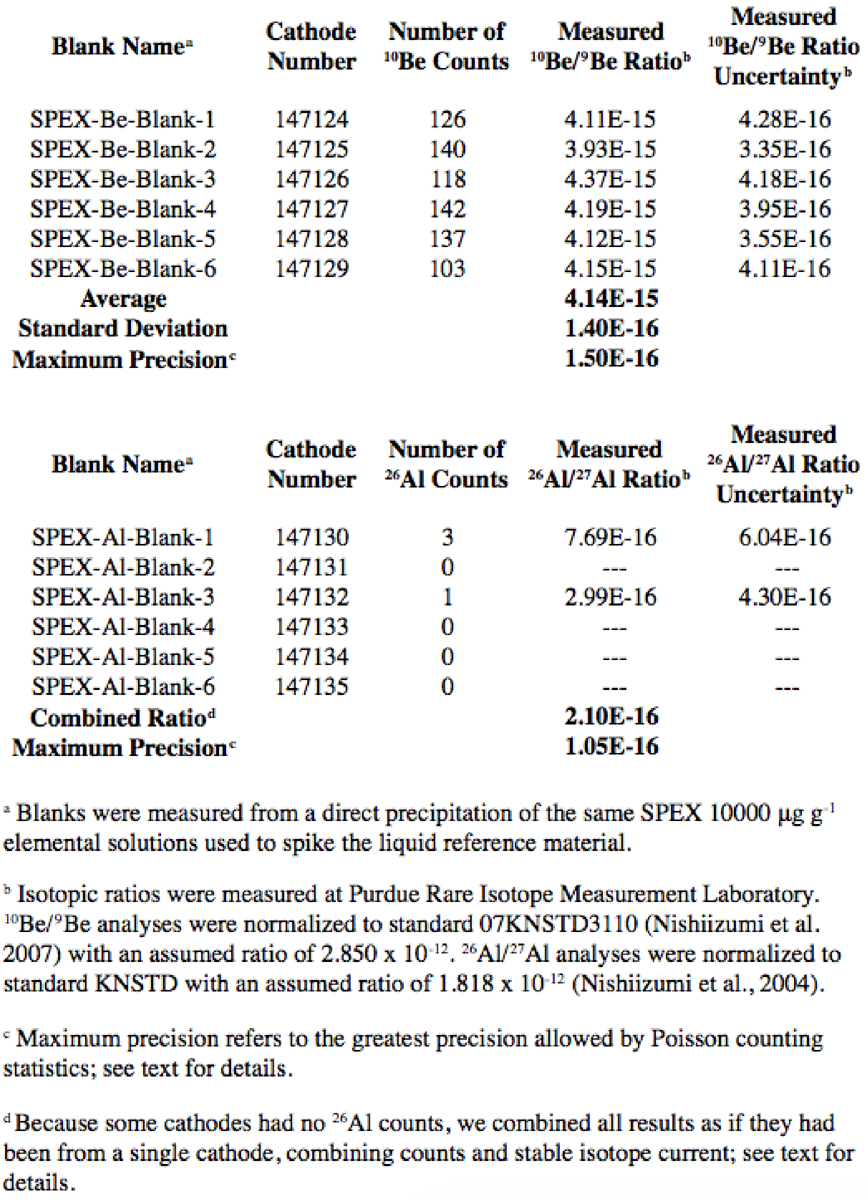
Table 4. Concentration and $^{26}Al/^{10}Be$ ratio data for CRONUS-A quartz [1], based on results from UVM-A.

Table 5. Summary data for isotopic ratios and concentrations.

Figure Captions

Figure 1. Probability density functions of measured $^{10}Be/^{9}Be$ ratios, showing the 12 individual analyses (thin gray lines) and the sum of all analyses (thick black line).

Figure 2. Probability density functions of measured $^{26}Al/^{27}Al$ ratios, showing 10 individual analyses (thin gray lines, after discarding two outliers) and the sum of all analyses (thick black line).



Blank Name[a]	Cathode Number	Number of ^{10}Be Counts	Measured ^{10}Be/^{9}Be Ratio[b]	Measured ^{10}Be/^{9}Be Ratio Uncertainty[b]
SPEX-Be-Blank-1	147124	126	4.11E-15	4.28E-16
SPEX-Be-Blank-2	147125	140	3.93E-15	3.35E-16
SPEX-Be-Blank-3	147126	118	4.37E-15	4.18E-16
SPEX-Be-Blank-4	147127	142	4.19E-15	3.95E-16
SPEX-Be-Blank-5	147128	137	4.12E-15	3.55E-16
SPEX-Be-Blank-6	147129	103	4.15E-15	4.11E-16
Average			**4.14E-15**	
Standard Deviation			**1.40E-16**	
Maximum Precision[c]			**1.50E-16**	

Blank Name[a]	Cathode Number	Number of ^{26}Al Counts	Measured ^{26}Al/^{27}Al Ratio[b]	Measured ^{26}Al/^{27}Al Ratio Uncertainty[b]
SPEX-Al-Blank-1	147130	3	7.69E-16	6.04E-16
SPEX-Al-Blank-2	147131	0	---	---
SPEX-Al-Blank-3	147132	1	2.99E-16	4.30E-16
SPEX-Al-Blank-4	147133	0	---	---
SPEX-Al-Blank-5	147134	0	---	---
SPEX-Al-Blank-6	147135	0	---	---
Combined Ratio[d]			**2.10E-16**	
Maximum Precision[c]			**1.05E-16**	

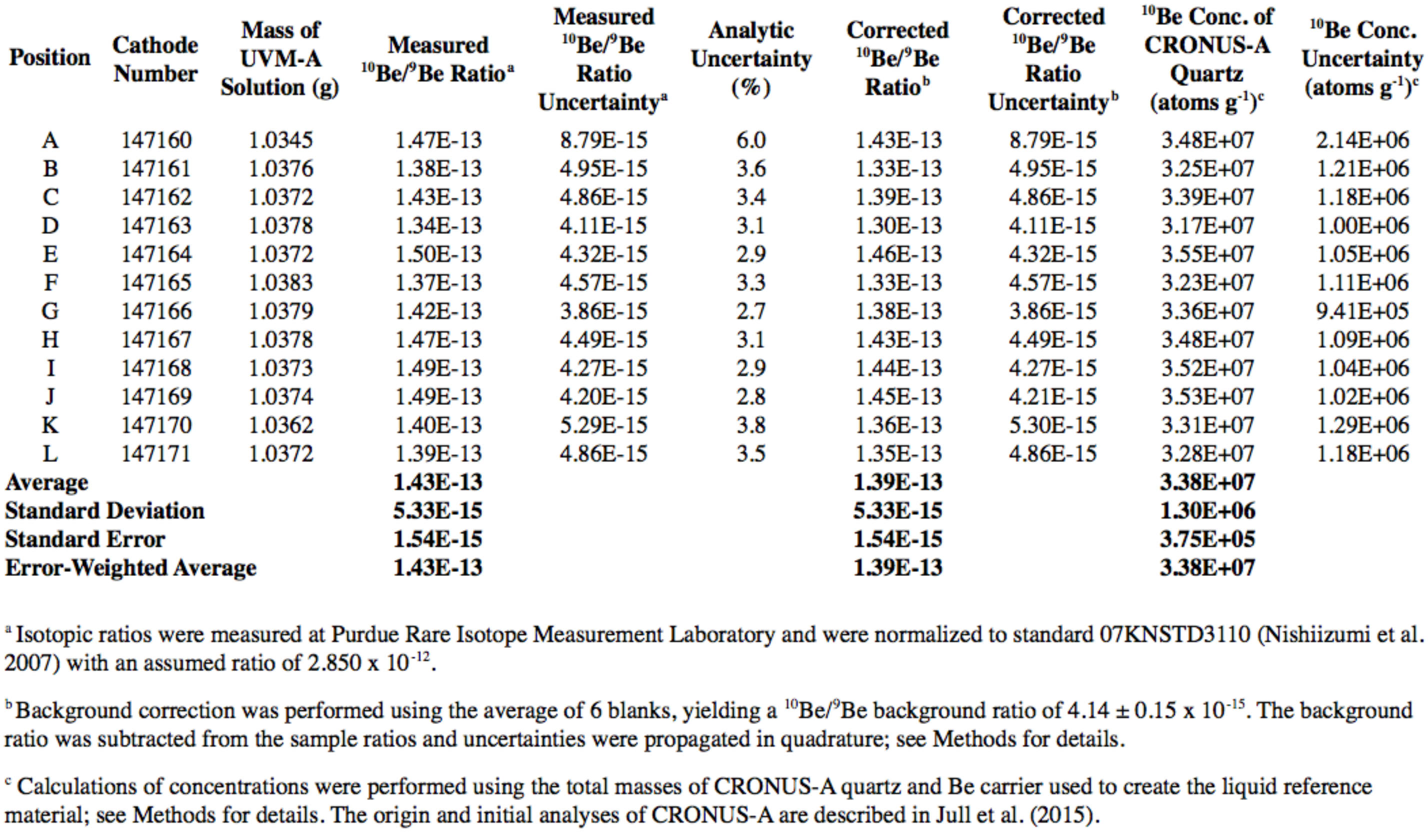
[a] Blanks were measured from a direct precipitation of the same SPEX 10000 µg g^{-1} elemental solutions used to spike the liquid reference material.

[b] Isotopic ratios were measured at Purdue Rare Isotope Measurement Laboratory. ^{10}Be/^{9}Be analyses were normalized to standard 07KNSTD3110 (Nishiizumi et al. 2007) with an assumed ratio of 2.850 x 10^{-12}. ^{26}Al/^{27}Al analyses were normalized to standard KNSTD with an assumed ratio of 1.818 x 10^{-12} (Nishiizumi et al., 2004).

[c] Maximum precision refers to the greatest precision allowed by Poisson counting statistics; see text for details.

[d] Because some cathodes had no ^{26}Al counts, we combined all results as if they had been from a single cathode, combining counts and stable isotope current; see text for details.

Table 1.



Position	Cathode Number	Mass of UVM-A Solution (g)	Measured ^{10}Be/^{9}Be Ratio[a]	Measured ^{10}Be/^{9}Be Ratio Uncertainty[a]	Analytic Uncertainty (%)	Corrected ^{10}Be/^{9}Be Ratio[b]	Corrected ^{10}Be/^{9}Be Ratio Uncertainty[b]	^{10}Be Conc. of CRONUS-A Quartz (atoms g^{-1})[c]	^{10}Be Conc. Uncertainty (atoms g^{-1})[c]
A	147160	1.0345	1.47E-13	8.79E-15	6.0	1.43E-13	8.79E-15	3.48E+07	2.14E+06
B	147161	1.0376	1.38E-13	4.95E-15	3.6	1.33E-13	4.95E-15	3.25E+07	1.21E+06
C	147162	1.0372	1.43E-13	4.86E-15	3.4	1.39E-13	4.86E-15	3.39E+07	1.18E+06
D	147163	1.0378	1.34E-13	4.11E-15	3.1	1.30E-13	4.11E-15	3.17E+07	1.00E+06
E	147164	1.0372	1.50E-13	4.32E-15	2.9	1.46E-13	4.32E-15	3.55E+07	1.05E+06
F	147165	1.0383	1.37E-13	4.57E-15	3.3	1.33E-13	4.57E-15	3.23E+07	1.11E+06
G	147166	1.0379	1.42E-13	3.86E-15	2.7	1.38E-13	3.86E-15	3.36E+07	9.41E+05
H	147167	1.0378	1.47E-13	4.49E-15	3.1	1.43E-13	4.49E-15	3.48E+07	1.09E+06
I	147168	1.0373	1.49E-13	4.27E-15	2.9	1.44E-13	4.27E-15	3.52E+07	1.04E+06
J	147169	1.0374	1.49E-13	4.20E-15	2.8	1.45E-13	4.21E-15	3.53E+07	1.02E+06
K	147170	1.0362	1.40E-13	5.29E-15	3.8	1.36E-13	5.30E-15	3.31E+07	1.29E+06
L	147171	1.0372	1.39E-13	4.86E-15	3.5	1.35E-13	4.86E-15	3.28E+07	1.18E+06
Average			**1.43E-13**			**1.39E-13**		**3.38E+07**	
Standard Deviation			**5.33E-15**			**5.33E-15**		**1.30E+06**	
Standard Error			**1.54E-15**			**1.54E-15**		**3.75E+05**	
Error-Weighted Average			**1.43E-13**			**1.39E-13**		**3.38E+07**	

[a] Isotopic ratios were measured at Purdue Rare Isotope Measurement Laboratory and were normalized to standard 07KNSTD3110 (Nishiizumi et al. 2007) with an assumed ratio of 2.850 x 10^{-12}.

[b] Background correction was performed using the average of 6 blanks, yielding a ^{10}Be/^{9}Be background ratio of 4.14 ± 0.15 x 10^{-15}. The background ratio was subtracted from the sample ratios and uncertainties were propagated in quadrature; see Methods for details.

[c] Calculations of concentrations were performed using the total masses of CRONUS-A quartz and Be carrier used to create the liquid reference material; see Methods for details. The origin and initial analyses of CRONUS-A are described in Jull et al. (2015).

Table 2.

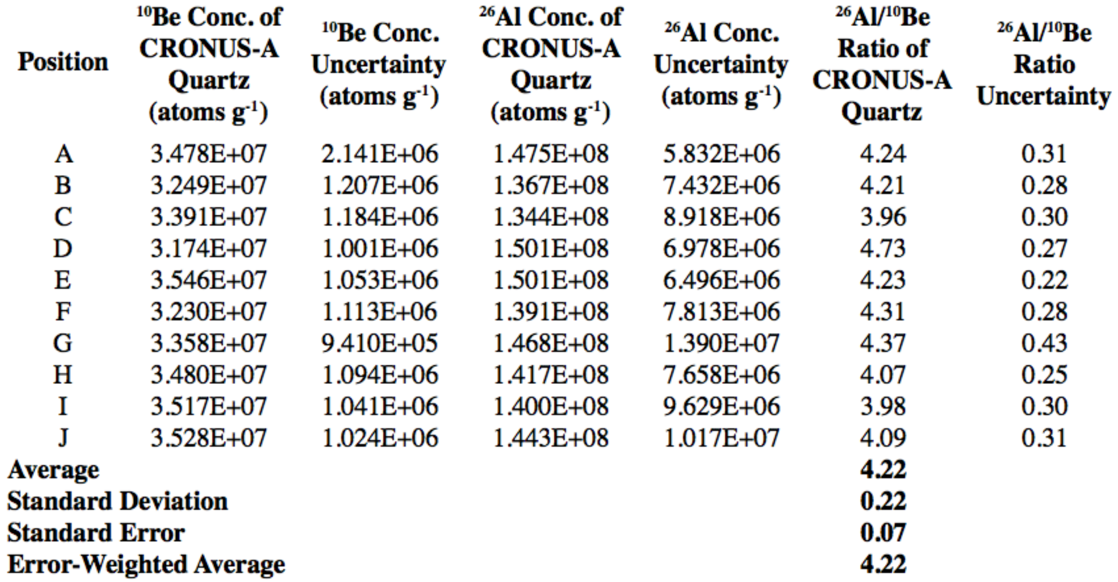
Position	Cathode Number	Mass of UVM-A Solution (g)	Measured ^{26}Al/^{27}Al Ratio[a]	Measured ^{26}Al/^{27}Al Ratio Uncertainty[a]	Analytic Uncertainty (%)	Corrected ^{26}Al/^{27}Al Ratio[b]	Corrected ^{26}Al/^{27}Al Ratio Uncertainty[b]	^{26}Al Conc. of CRONUS-A Quartz (atoms g^{-1})[c]	^{26}Al Conc. Uncertainty (atoms g^{-1})[c]
A	147160	1.0345	4.58E-13	1.81E-14	4.0	4.58E-13	1.81E-14	1.47E+08	5.83E+06
B	147161	1.0376	4.24E-13	2.30E-14	5.4	4.23E-13	2.30E-14	1.37E+08	7.43E+06
C	147162	1.0372	4.17E-13	2.76E-14	6.6	4.17E-13	2.76E-14	1.34E+08	8.92E+06
D	147163	1.0378	4.65E-13	2.16E-14	4.6	4.65E-13	2.16E-14	1.50E+08	6.98E+06
E	147164	1.0372	4.65E-13	2.01E-14	4.3	4.65E-13	2.01E-14	1.50E+08	6.50E+06
F	147165	1.0383	4.31E-13	2.42E-14	5.6	4.31E-13	2.42E-14	1.39E+08	7.81E+06
G	147166	1.0379	4.55E-13	4.31E-14	9.5	4.55E-13	4.31E-14	1.47E+08	1.39E+07
H	147167	1.0378	4.39E-13	2.37E-14	5.4	4.39E-13	2.37E-14	1.42E+08	7.66E+06
I	147168	1.0373	4.34E-13	2.98E-14	6.9	4.34E-13	2.98E-14	1.40E+08	9.63E+06
J	147169	1.0374	4.47E-13	3.15E-14	7.0	4.47E-13	3.15E-14	1.44E+08	1.02E+07
Average			**4.44E-13**			**4.43E-13**		**1.43E+08**	
Standard Deviation			**1.72E-14**			**1.72E-14**		**5.53E+06**	
Standard Error			**5.45E-15**			**5.45E-15**		**1.75E+06**	
Error-Weighted Average			**4.44E-13**			**4.44E-13**		**1.43E+08**	

[a] Isotopic ratios were measured at Purdue Rare Isotope Measurement Laboratory and were normalized to standard KNSTD (Nishiizumi et al. 2004) with an assumed ratio of 1.818 x 10^{-12}.

[b] Background correction was performed using a combined blank, yielding a ^{26}Al/^{27}Al background ratio of 2.10 ± 1.05 x 10^{-16}. The background ratio was subtracted from the sample ratios and uncertainties were propagated in quadrature; see Methods for details.

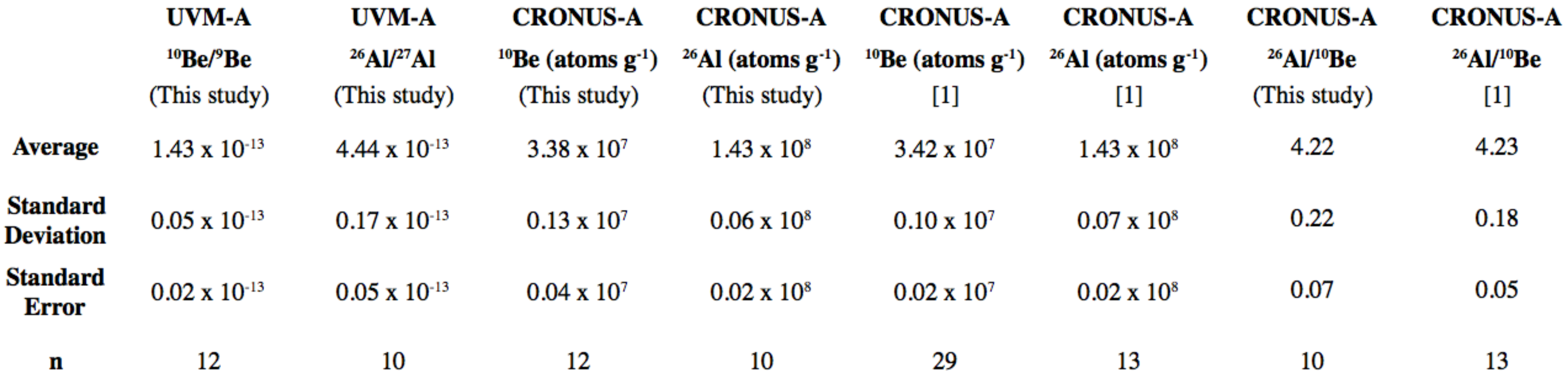
[c] Calculations of concentrations were performed using the total mass of CRONUS-A quartz used to create the liquid reference material and the ICP-quantified total ^{27}Al; see Methods for details. The origin and initial analyses of CRONUS-A are described in Jull et al. (2015).

Table 3.



Position	^{10}Be Conc. of CRONUS-A Quartz (atoms g^{-1})	^{10}Be Conc. Uncertainty (atoms g^{-1})	^{26}Al Conc. of CRONUS-A Quartz (atoms g^{-1})	^{26}Al Conc. Uncertainty (atoms g^{-1})	^{26}Al/^{10}Be Ratio of CRONUS-A Quartz	^{26}Al/^{10}Be Ratio Uncertainty
A	3.478E+07	2.141E+06	1.475E+08	5.832E+06	4.24	0.31
B	3.249E+07	1.207E+06	1.367E+08	7.432E+06	4.21	0.28
C	3.391E+07	1.184E+06	1.344E+08	8.918E+06	3.96	0.30
D	3.174E+07	1.001E+06	1.501E+08	6.978E+06	4.73	0.27
E	3.546E+07	1.053E+06	1.501E+08	6.496E+06	4.23	0.22
F	3.230E+07	1.113E+06	1.391E+08	7.813E+06	4.31	0.28
G	3.358E+07	9.410E+05	1.468E+08	1.390E+07	4.37	0.43
H	3.480E+07	1.094E+06	1.417E+08	7.658E+06	4.07	0.25
I	3.517E+07	1.041E+06	1.400E+08	9.629E+06	3.98	0.30
J	3.528E+07	1.024E+06	1.443E+08	1.017E+07	4.09	0.31
Average					**4.22**	
Standard Deviation					**0.22**	
Standard Error					**0.07**	
Error-Weighted Average					**4.22**	

Table 4.



	UVM-A **^{10}Be/^{9}Be** (This study)	**UVM-A** **^{26}Al/^{27}Al** (This study)	**CRONUS-A** **^{10}Be (atoms g^{-1})** (This study)	**CRONUS-A** **^{26}Al (atoms g^{-1})** (This study)	**CRONUS-A** **^{10}Be (atoms g^{-1})** [1]	**CRONUS-A** **^{26}Al (atoms g^{-1})** [1]	**CRONUS-A** **^{26}Al/^{10}Be** (This study)	**CRONUS-A** **^{26}Al/^{10}Be** [1]
Average	1.43×10^{-13}	4.44×10^{-13}	3.38×10^{7}	1.43×10^{8}	3.42×10^{7}	1.43×10^{8}	4.22	4.23
Standard Deviation	0.05×10^{-13}	0.17×10^{-13}	0.13×10^{7}	0.06×10^{8}	0.10×10^{7}	0.07×10^{8}	0.22	0.18
Standard Error	0.02×10^{-13}	0.05×10^{-13}	0.04×10^{7}	0.02×10^{8}	0.02×10^{7}	0.02×10^{8}	0.07	0.05
n	12	10	12	10	29	13	10	13

Table 5.

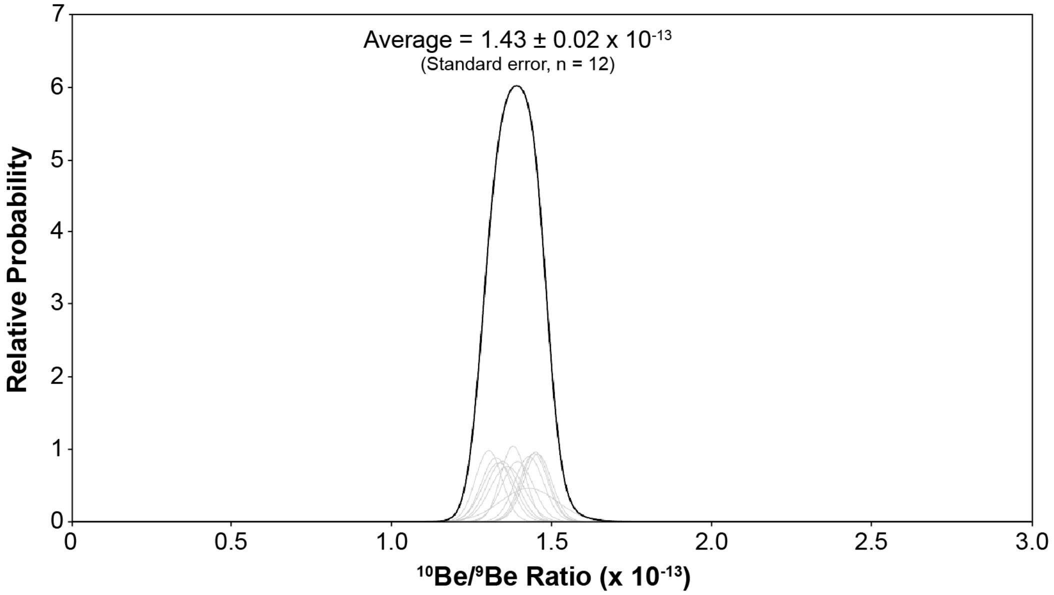


Figure 1.
(width = 140 mm, 1.5 columns)

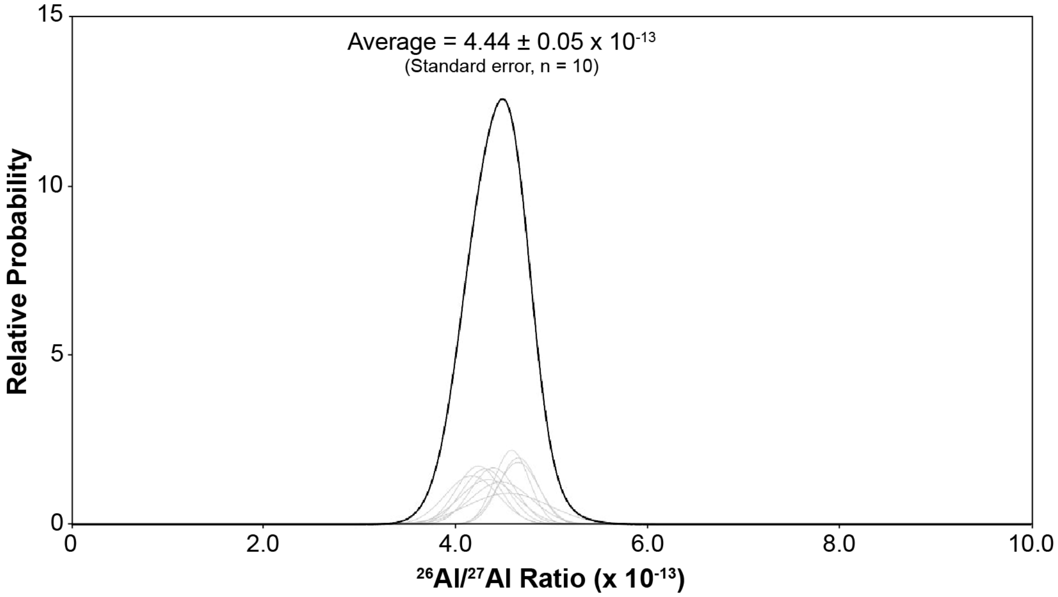

Average = 4.44 ± 0.05 x 10^{-13}
(Standard error, n = 10)
Relative Probability
15
10
5
0
0
2.0
4.0
6.0
8.0
10.0
$^{26}Al/^{27}Al$ Ratio (x 10^{-13})

Figure 2.