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Exposure History of Separated Phases from the Kapoeta Meteorite

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EXPOSURE HISTORY OF SEPARATED PHASES FROM THE KAPOETA METEORITE. M. W. Caffee[1], K. Nishiizumi[2], and J. Mazarik[2], [1]Center for Accelerator Mass Spectrometry and Geosciences and Environmental Technologies Division, Lawrence Livermore National Laboratory, Livermore, CA 94550. (caffee1@llnl.gov), [2]Space Sciences Laboratory, University of California, Berkeley, CA94720-7450. (kuni@ssl.berkeley.edu).

Abstract: The cosmogenic radionuclides, ^{10}Be (1.5 Ma), ^{26}Al (0.705 Ma), ^{36}Cl (0.301 Ma), and ^{53}Mn (3.7 Ma) were measured in selected clasts and matrix samples from the howardite Kapoeta. This work is an extension of that based on ^{10}Be and ^{26}Al [1]. Recent work based on measurements of cosmogenic ^{21}Ne suggest the possibility of a complex recent exposure history for Kapoeta. The measurement of these radionuclides, in conjunction with production rates based on Monte Carlo calculations, can constrain exposure conditions and durations. Taken together, the radionuclide data are entirely consistent with a single stage 4π exposure lasting ~ 3 Ma.

Introduction: Meteorites have been exposed to energetic particles at various stages of their evolution. All meteorites share a recent exposure to galactic cosmic rays (GCR) and solar cosmic rays (SCR) as meter-sized-bodies while in Earth-crossing orbits. The simplest irradiation scenario is one in which the meteoroid was excavated from deeper than several meters from within a large body and subsequently exposed to cosmic rays as a meter-sized body. Although this scenario applies to a large number of meteorites it is not universally true. Some meteorites show evidence of a complex recent exposure [e.g. 2, 3, 4]. Additionally, many meteorites were exposed to energetic particles during an earlier epoch. For example, while it is known that gas-rich meteorites were exposed before their final consolidation it is not known precisely when this exposure occurred. Caffee *et al.* [5] hypothesized that this exposure to energetic particles occurred during a period when the solar energetic particle flux was enhanced relative to present-day particle fluxes. Accordingly, the demonstration of a recent complex exposure for Kapoeta is directly relevant to the hypothesis of Caffee et al [5].

Cosmogenic ^{21}Ne: Caffee *et al.* [6] determined an exposure age of 3.5 Ma for Kapoeta feldspars containing no solar-flare tracks, an age in good agreement with that determined from previous measurements based on bulk samples. However, a pyroxene separate yielded an exposure age of ~0.5 Ma. Measurements by Pedroni *et al*. [7] verified the existence of components within Kapoeta having cosmogenic ^{21}Ne exposure ages < 3.5 Ma. Pun et al. [8] extended and verified these measurements. Pun et al. [8] also proposed a modified cosmogenic ^{21}Ne production rate for the samples of Pedroni which results exposure ages of ~2.1 Ma for the carbonaceous clasts. Accordingly, Pun et al. [8] proposed that Kapoeta has been exposed in a 4π geometry as a small body for 2.1 Ma.

Experiment: The hypothesis of Pun et al. [8] has two essential elements that can be tested using cosmogenic radionuclides. The first element is an integrated exposure consisting of both 4π and 2π exposures. The second element is that while all constituents share the most recent 4π exposure, the duration of exposure in the 2π geometry varies between the different constituents. Both of these elements are testable using cosmogenic radionuclides. If some constituents of Kapoeta were exposed only in a 4π geometry for ~2.1 Ma, while others have in addition to this exposure a 2π exposure while resident in a parent body regolith immediately prior to its fragmentation, there would be readily detectable variations in the activities of some of the cosmogenic radionuclides, specifically ^{10}Be and ^{53}Mn.

Procedure and Results: The sample choice was made with the goal of selecting those samples which, on the basis of noble gas and petrographic considerations, would be most likely to exemplify any complex exposure. In a previous work [1] we reported cosmogenic ^{10}Be and ^{26}Al results. Table 1 summarizes the cosmogenic radionuclides from both the earlier work [1] and the work reported herein. The details of the sample preparation are given in Nishiizumi [1] and are only summarized herein. The ^{10}Be, ^{26}Al, and ^{36}Cl concentrations were measured using AMS techniques at the Lawrence Livermore National Laboratory [9]. The errors in Table 1 include a ± 1σ AMS measurement and sample weight errors but do not reflect errors in the chemical analysis (1.5 - 2 %) or the uncertainty in the absolute activities of the standards. The ^{53}Mn activities in the dark and light bulk portions of Kapoeta were measured by neutron activation [10]. The neutron activation was performed at JRR-3 reactor, Ibaraki, Japan. The ^{10}Be concentration in the dark and light bulk portions was measured using AMS at the University of Tokyo. These samples were split from a ~1 cm piece of Kapoeta: a different specimen from those prepared by Pedroni.

Table 1. Cosmogenic Radionuclides in Kapoeta

Sample	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	^{36}Cl (dpm/kg)	^{53}Mn (dpm/kg Fe)
Clast 3/C1	18.10±1.03	36±11	6.91±0.55	
Clast 3/C2	17.02±0.28	45.6±3.1	6.89±0.51	
Clast 3/_	16.97±0.36	78.6±4.5	18.01±0.47	
Mtx 3/C1/3	16.55±0.17	66.2±2.4	9.49±0.17	
Mtx 3/_3,4	16.90±0.25	68.8±1.4	12.05±0.30	
Dark	16.47±0.51*			182±10
Light	16.91±0.69*			180±11

Discussion: Given the possible complexity of the Kapoeta irradiation, and the inhomogenous distribution of spallation targets the measurement of numerous nuclides is essential. Each of the cosmogenic nuclides measured in theis work contains specific clues needed to reconstruct the irradiation conditions. The ^{10}Be activity in the five splits from Pedroni are essentially identical at 17 ± 1 dpm/kg (Table 1). In addition to this work, we measured ^{10}Be with the University of Tokyo AMS group [11] in dark and light portions of Kapoeta. The ^{10}Be concentrations are 16.5 ± .5 dpm/kg for the dark phase and 16.9 ± .7 dpm/kg for the light phase, identical to the separated phases. Based on the ^{10}Be activities alone it can be supposed that all the diverse constituents of Kapoeta represented in this study have the same exposure history within the time frame accessible by ^{10}Be. This conclusion is at odds with the observations based on cosmogenic ^{21}Ne. Thus far our conclusions are based exclusively on activity data; they are independent of production rates and exposure conditions. To address the issue of how long the exposure durations are and in what geometry they occurred it is necessary to have more information regarding the specific conditions under which the irradiation occurred. Toward that end we have determined ^{36}Cl activities and performed Monte Carol calculations to model the expected ^{36}Cl concentrations for a variety of shielding conditions. Since the halflife of ^{36}Cl is much shorter than the hypothesized 4π exposure time of 2.1 Ma [8] we expect the ^{36}Cl activity for all samples to be equal to the saturation value appropriate for their respective target chemistries. This value though is a function of both the diameter of the meteoroid and the depth at which the constituents were buried. Our calculations indicate that the ^{36}Cl activities in all the samples are consistent with exposure in a 4π geometry on a meteoroid having a pre-atmospheric radius of ~20 cm. Additionally, the calculations predict a burial depth of several cm. The ^{26}Al measurements serve two purposes: verification of the ^{36}Cl results and as a tracer for exposure to SCRs. For all five aliquots, after target chemistries were taken into account, the ^{26}Al activities were consistent with the saturation activity expected for those exposure conditions required by the ^{36}Cl activities. More significant though is the observation that the ^{26}Al activities were not higher than those predicted for GCR production. Cosmogenic ^{26}Al is produced prodigiously by SCRs. Many constituents within Kapoeta contain solar-wind-implanted noble gases. Of those samples analyzed in this work the two matrix samples were exposed at some point in their history to the solar wind, as evidenced by the presence of large amounts of ^{20}Ne. During this exposure SCR ^{26}Al must have been produced. The lack of any detectable vestige of this ^{26}Al evinces a burial period, lasting at least several Ma, of these constituents between Kapoeta's 4π exposure and its 2π regolith exposure. Building on the knowledge provided by the shorter-lived cosmogenic radionuclides, it is possible to use the ^{10}Be activities to calculate an exposure age. The ^{10}Be saturation activity for small bodies having a minimal of shielding is estimated 23 dpm/kg. This yields 4π exposure ages for the various constituents of Kapoeta of ~2.9 Ma. The ^{10}Be activity data alone are not necessarily at variance with some of the noble gas data. For example, a two-stage irradiation could be accommodated in which a 4π exposure of ~2.1 Ma immediately followed a longer 2π exposure. Again, based on the ^{10}Be data, all constituents would have experienced the same exposure history. However, the lack SCR ^{26}Al indicates that some time elapsed between the 4π and 2π exposures. During this time period the ^{10}Be activity would decrease, which in turn requires a longer 4π exposure to reach the measured activity levels. Moreover, since the duration of the 2π exposure is such that the ^{10}Be activity is at or near saturation, any intermediate burial period makes it increasing difficult to accumulate significant quantities of ^{10}Be in the 2π exposure. This argument is further reinforced by the measured activity of ^{53}Mn in the light and dark fractions. The ^{53}Mn exposure ages are 3.1 Ma, indistinguishable from the ^{10}Be exposure ages.

Summary: Cosmogenic ^{10}Be, ^{26}Al, ^{36}Cl, and ^{53}Mn were measured in a variety of samples from Kapoeta. All these radionuclides are consistent with a 4π exposure on a small body having a duration of ~ 3 Ma. The noble gases, specifically cosmogenic ^{21}Ne, attest to irradiation periods in excess of this. Constituents of Kapoeta undoubtedly underwent exposure to energetic particles while resident in a parent body regolith. However, the timing of this exposure is unconstrained. The radionuclide data are consistent with a regolith exposure occurring before the time period addressable by the longest-lived radionuclide, ^{53}Mn.

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