Further Evidence of Beryllium-10 Heterogeneity in the Early Solar System Inferred from Be-B Systematics of Refractory Inclusions in a Minimally Altered CR2 Chondrite. E. Dunham[1], M. Wadhwa[1], R. Hervig[1], S. Simon[2], L. Grossman[2] [1]School of Earth and Space Exploration, Arizona State University, Tempe AZ, 85287 (email: etdunham@asu.edu), [2]Dept. of the Geophysical Sciences, The Univ. of Chicago, Chicago IL, 60637.

Introduction: Determining the initial abundances and distributions of short-lived radionuclides in the solar protoplanetary disk is key to understanding the astrophysical birth environment of our Solar System ([1], and references therein). Beryllium-10, which decays to ^{10}B with a half-life of 1.4 Ma, is of particular interest since it is produced almost exclusively by irradiation reactions. Previous studies have demonstrated that this short-lived radionuclide was present in the early Solar System with an initial $^{10}Be/^{9}Be$ ratio in the range of ~10^{-4}-10^{-2} [2-8]. Although this wide range may in part be due to significant analytical uncertainties, the initial $^{10}Be/^{9}Be$ ratio inferred from these analyses is substantially higher than the value expected from the galactic background, ~10^{-5} [2].

There are two possible astrophysical settings in which the enhanced abundance of ^{10}Be in the early Solar System may have originated. One possible setting is the dense protosolar molecular cloud core where ^{10}Be may have been enhanced by trapping of galactic cosmic rays [9] or by spallogenesis during energetic particle irradiation [2]. An alternative setting is within the solar nebula, where irradiation of gas and/or refractory solids during an early active phase of the Sun may have produced ^{10}Be [2, 10, 11].

In this context, the prediction is that if the ^{10}Be enhancement occurred prior to Solar System formation, then processes involved in molecular cloud collapse and formation of the solar nebula would likely have resulted in a homogeneous ^{10}Be distribution. In contrast, local irradiation within the nebula could have produced significant temporal and spatial variations in ^{10}Be abundances in the early Solar System. The wide range in the initial $^{10}Be/^{9}Be$ ratio inferred from previous studies [2-8] is more consistent with the latter. However, with few exceptions (e.g., [6, 8]), the Be-B systematics reported thus far have been from refractory inclusions in CV3 chondrites [2-5, 7] that have experienced exposure to thermal and shock processes [12, 13]. Therefore, it is possible that some of the observed variation in the initial $^{10}Be/^{9}Be$ ratio could be due to disturbance by these processes. The CR2 chondrites are thought to be among the least altered based on petrological, geochemical and isotopic characteristics (e.g., [14]). In this study, we report for the first time the Be-B systematics in two calcium-aluminum-rich inclusions (CAIs) from a CR2 chondrite, Northwest Africa (NWA 5028). We additionally report the Be-B systematics of a CAI from the CV3 chondrite Allende, which allows us to compare our results with those of previous studies on CAIs from this same meteorite.

Analytical Methods: Sample characterization, including mapping of mineral phases and determination of mineral chemistries, was performed using electron microprobe techniques. The Allende CAI was analyzed with the Cameca SX-50 instrument at the University of Chicago [15], while the NWA 5028 CAIs were analyzed with the Cameca SX100 at the University of Arizona and the JEOL JXA-8520F at Arizona State University (ASU).

The samples were then thoroughly cleaned with mannitol (ultrasonication and soaking) to remove surface boron contamination; this allowed us to have confidence that the subsequent measurements were conducted under ideal conditions. Analyses of the B isotopic composition and the Be/B ratios were obtained with the Cameca IMS-6f secondary ion mass spectrometer at ASU using an $^{16}O^{-}$ primary beam. The primary accelerating voltage was 12.5 kV and the primary beam current ranged from 15 to 40 nA (resulting in a beam diameter of ~20-30 um). We chose to focus our Be-B analyses on melilite since it is the major carrier of Be in CAIs and typically has higher Be/B ratios than other phases in refractory inclusions [3,5]. Our analysis spots on the melilites in each inclusion were chosen based on backscattered electron images to avoid possible cracks and fine inclusions. We operated the mass spectrometer at a mass resolving power of ~1000 to resolve and avoid hydride and Al^{3+} interferences. We measured ^{9}Be (8s), ^{10}B (16s) and ^{11}B (4s) between 20 and 150 times for each measurement. At the end of each analysis, ^{28}Si was additionally measured; the (B or Be)/Si ratios were used, in addition to standard measurements, to determine B and Be concentrations. Because the standard (IMT-1 illite with known B content and isotope ratio) was placed as a suspension on the thin sections, analyses of unknowns and standards were obtained without the requirement to replace the sample with a standard block. Beryllium was calibrated against NIST 610, analyzed after (or before) the meteorite sections.

Results: *Sample Description.* One inclusion, TS68, is a lightly altered, compact type A CAI from Allende previously studied by [15]. The two other CAIs (designated 5028_1 and 5028_2) are from the CR2 chondrite NWA 5028. Both have irregular shapes. Inclusion 5028_1 is ~5 mm across, and is dominated by aluminous diopside that encloses patches of melilite (<100 µm across; $Åk_{1-85}$) and anhedral spinel. There are minimal alteration products in CAI 5028_1. Inclusion CAI 5028_2 is ~1 mm across and contains anhedral spinel, typically 10 µm across, enclosed in melilite ($Åk_{4-18}$). The inclusion is surrounded by a pyroxene rim ~40 um thick. There is a small area of secondary anorthite in this inclusion, but it was avoided during analyses.

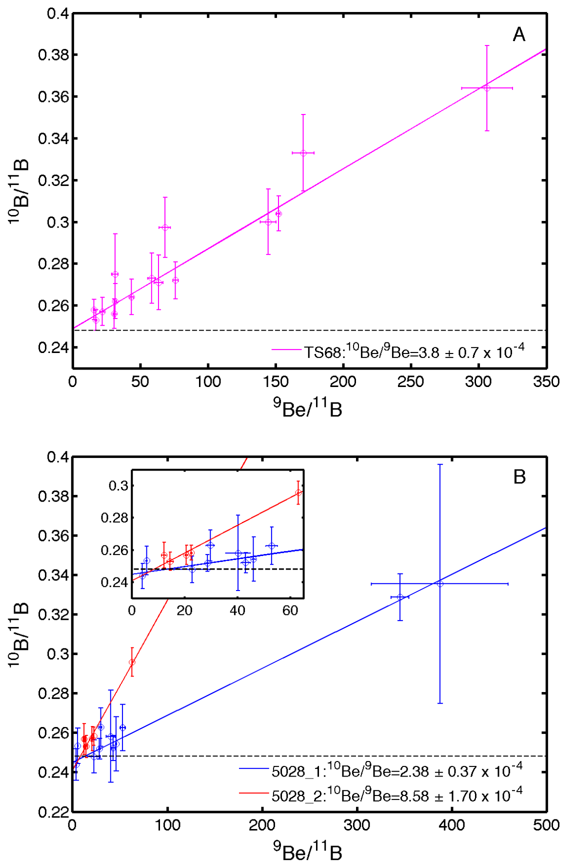

Figure 1: Be-B isochron diagrams for melilite in (A) a CAI (TS68) from Allende; and (B) two CAIs (5028_1 and 5028_2) from the CR2 chondrite NWA 5028. The inset in (B) shows the lower left portion of the figure in greater detail. The horizontal dashed line in each figure represents the chondritic value of $^{10}B/^{11}B$ (=0.2481; [16]). The error bars are 2 sigma, calculated from counting statistics.

Be-B Systematics. Figure 1 shows the Be-B isochron plots for the three CAIs that were analyzed here. The data for the Allende CAI TS68 (Fig. 1A) define a slope corresponding to a $^{10}Be/^{9}Be$ ratio of (3.8 ± 0.7) × 10^{-4} (mean square weighted deviation, MSWD = 1.8) and an initial $^{10}B/^{11}B$ ratio of 0.249 ± 0.004. The data for the NWA 5028 CAI 5028_1 yield a $^{10}Be/^{9}Be$ ratio of (2.4 ± 0.4) × 10^{-4} (MSWD = 1.07) and an initial $^{10}B/^{11}B$ ratio of 0.246 ± 0.003; those for the CAI 5028_2 yield an isochron with a slope corresponding to a $^{10}Be/^{9}Be$ ratio of (8.6 ± 1.7) × 10^{-4} (MSWD = 0.97) and an initial $^{10}B/^{11}B$ ratio of 0.241 ± 0.005.

Discussion: In previous studies of Allende CAIs, the inferred initial $^{10}Be/^{9}Be$ ratio ranged from 4.8 to 9.5 × 10^{-4} [2-5]. The $^{10}Be/^{9}Be$ ratio that we have obtained for TS68 falls towards the lower end, but is still within the range of these previously reported values when analytical uncertainties are considered. We note that the Be-B systematics in the Allende CAI TS68 show slightly greater scatter (MSWD = 1.8; Fig. 1A) than those in the two NWA 5028 CAIs (MSWD ~1) and may reflect a slight disturbance by secondary processes (involving fluid-rock interactions and thermal effects) on the Allende parent body [13].

The data for the two CAIs from the CR2 chondrite NWA 5028 define good isochrons (MSWDs close to ~1; Fig. 1B). This is also consistent with our petrographic and mineralogic characterization, which indicates a minimal degree of alteration of these two CAIs. In this context, it is interesting to note that CAI 5028_2 has a $^{10}Be/^{9}Be$ ratio (8.6 × 10^{-4}) that is a factor of ~3 higher than that of CAI 5028_1. Since CR2 chondrites are thought to have largely escaped alteration and reheating on their parent body, we believe that the variation in the $^{10}Be/^{9}Be$ ratio observed here for the two NWA 5028 CAIs cannot be attributed to secondary processes and is indicative of gross heterogeneity in the distribution of ^{10}Be in the solar nebula. This, in turn, presents a strong argument in support of ^{10}Be production by local irradiation of nebular gas or dust.

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