COSMOGENIC RADIONUCLIDES IN UREILITES FROM FRONTIER MOUNTAIN, ANTARCTICA: EVIDENCE FOR A POLYMICT BRECCIA. K. C. Welten[1], K. Nishiizumi[1], M. W. Caffee[2] and D. J. Hillegonds[3], [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA, (kcwelten@berkeley.edu), [2]PRIME Lab, Purdue University, West Lafayette, IN 47907, USA, [3]Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA 94450, USA.

Introduction. The Frontier Mountain (FRO) meteorite collection includes 15 small ureilites with masses of 0.5-35 g. The relatively large number of ureilites (compared to only 2 HED meteorites) suggests that many of these specimens are probably part of a single fall. However, the FRO ureilites show several different lithologies with differences in olivine compositions, olivine/pyroxene ratios, shock stage and bulk carbon content [1-3]. Based on similar mineralogy, some of the FRO ureilites were recognized as pairs [1,2], whereas other specimens show two different lithologies. This could link many of the FRO ureilites together, as small fragments of a polymict breccia [2,3]. However, due to the different lithologies and the difficulty of recognizing brecciated textures in small samples, the extent of pairing among FRO ureilites is not very clear. In addition, ^{21}Ne cosmic-ray exposure (CRE) ages of 1.4 Myr (90228), 6.0 Myr (90036) and 12.8 Myr (90054) were reported for three FRO specimens [4-6].

Since a previous study has shown that cosmogenic radionuclides provide a powerful tool to identify paired specimens of a heterogeneous Antarctic meteorite shower [7], we measured concentrations of ^{10}Be ($t_{1/2}$=1.5 Myr), ^{26}Al ($t_{1/2}$=0.705 Myr) and ^{41}Ca ($t_{1/2}$=0.104 Myr) in 11 FRO ureilites. In this work, we constrain their exposure history and terrestrial age and evaluate whether they are small fragments of a heterogenous ureilite breccia.

Experimental. Ureilite samples of 100-170 mg were crushed and dissolved in HF/HNO_3. Small aliquots of the dissolved samples were taken for chemical analysis by atomic absorption spectrometry. We separated Be, Al, Cl and Ca from the dissolved samples for analysis by accelerator mass spectrometry. Concentrations of ^{10}Be and ^{26}Al were then measured at Purdue University, those of ^{41}Ca at LLNL.

Results and Discussion. Ten of 11 FRO ureilites show relatively constant ^{10}Be and ^{26}Al concentrations of 20±2 dpm/kg and 41±4 dpm/kg, respectively; whereas FRO 97013 shows much lower ^{10}Be and ^{26}Al concentrations and most likely represents a distinct fall. Based on the low ^{10}Be and ^{26}Al, we estimate a CRE age of 1.0-1.5 Myr for FRO 97013. The high ^{10}Be concentrations and low ^{26}Al/^{10}Be ratios of 2.0-2.5 in the remaining ureilites suggest that these were exposed in space long enough (>6 Myr) to reach saturation levels for ^{10}Be and ^{26}Al. For FRO 90036 and 90054 this is consistent with the ^{21}Ne CRE ages reported [5,6], but for FRO 90228 the radionuclide age is much higher than the ^{21}Ne age of ~1.4 Myr, which seems inexplicably low.

In the following discussion our null hypothesis states that all ureilites except FRO 97013 represent a single fall. We will test this hypothesis using our radionuclide results (Table 1). The variations in ^{10}Be and ^{26}Al are much larger than the experimental uncertainties of 2-5%, so they must be due to differences in shielding conditions and/or chemical composition. Since variations in ^{26}Al are not correlated with those in ^{10}Be (Fig. 1), they are not due to different shielding depths in a single object. Instead, the variations in ^{10}Be and ^{26}Al are probably due to differences in bulk compositions, as we found large variations in Al (0.1-0.6 wt%), Ca (0.5-3.6 wt%), Fe (9.8-16.9 wt%) and in undissolved C-rich material.

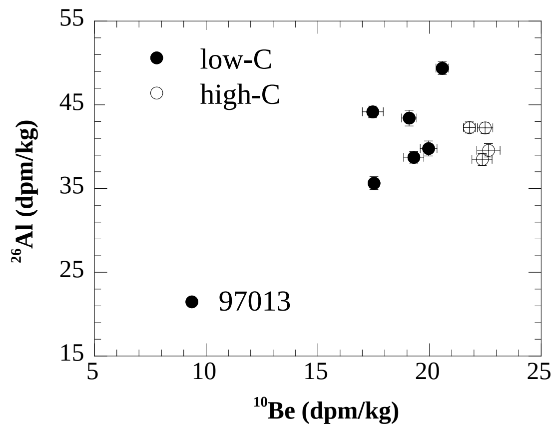

Fig. 1. Concentrations of ^{26}Al and ^{10}Be in FRO ureilites.

Since oxygen is relatively constant, the variations in ^{10}Be are most likely due to variations in bulk carbon, which is one of the main target elements for the production of ^{10}Be in ureilites. Based on an elemental production rate of ~100 atom/min/kgC [8], the variations in ^{10}Be among ten FRO ureilites can be explained by variations in C content of ~5 wt%. Very low bulk C contents (<0.5 wt%) were reported for FRO 90054, 90228 and 93008 [1,6,9], whereas ~13 vol% graphite was reported for FRO 95028. Since the highest ^{10}Be concentrations were found in the C-rich ureilites, FRO 90036, 90168, 90233 and 95028, we conclude that the variations in ^{10}Be are mainly due to variations in bulk C from 0-5 wt%.

Si is the main target element for the production rate of ^{26}Al in ureilites. Since ureilites are mixtures of olivine (37-40 wt% SiO_2) and pyroxene (53-57 wt% SiO_2), the bulk SiO_2 content depends on the relative abundance of pyroxene, which varies from 0 to 90%. Although we did not measure Si, the ^{26}Al concentrations in nine ureilites show positive correlations with

Al (R=0.94) and Ca (R=0.92) and a negative correlation with Fe (R=0.89). These strong correlations indicate that (i) the observed variations in ^{26}Al are mainly due to differences in bulk composition, and (ii) the samples were irradiated under very similar shielding conditions, most likely in the same meteoroid. The ^{26}Al concentration in FRO 01030 falls significantly below these correlations, suggesting that FRO 01030 is a distinct fall.

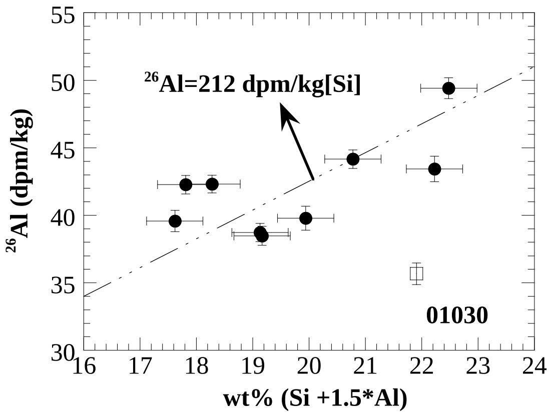

Fig. 2. Concentration of ^{26}Al vs. bulk (Si+1.5*Al) in FRO ureilites. The dashed line is a linear fit through the origin and the solid points, excluding FRO 01030.

The small variations in Al (0.1-0.6%) can only account for variations in ^{26}Al of 1-2 dpm/kg, so a large part of the variations in ^{26}Al must result from variations in Si. We estimated the Si concentration in each sample from the measured Mg, Al, Ca, Mn and Fe concentrations by assuming that the remaining fraction is SiO_2+Cr_2O_3+C. With an average Cr_2O_3 content of 0.7 wt% and C contents of 0-5 wt% derived from the ^{10}Be data, we estimate Si contents of 17.4-22.4 wt% for the FRO ureilites. Fig. 2 shows that the ^{26}Al concentrations in nine FRO ureilites are consistent with irradiation of these samples in a single, but heterogeneous object. The low ^{26}Al concentrations indicate an elemental production rate of ~212 dpm/kg[Si], which constrains the pre-atmospheric radius to 10-15 cm [10]. This small size is consistent with the ^{22}Ne/^{21}Ne ratio of 1.23 in FRO 90054 [5] and agrees with the total recovered mass of <200 g.

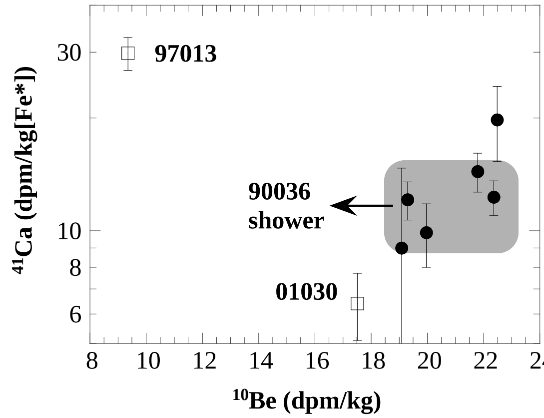

Fig. 3. Cosmogenic ^{41}Ca (normalized to effective Fe* = Fe+1.2*Mn+1.4*Cr+0.2*Ca) vs. ^{10}Be in FRO ureilites.

Due to the short half-life of ^{41}Ca, measured ^{41}Ca concentrations in the FRO ureilites are mainly a function of terrestrial age. The ^{41}Ca results confirm three distinct falls, with terrestrial ages of <20 kyr (97013), ~110 kyr (90036 shower) and ~200 kyr (01030). The old age of FRO 01030 is consistent with its find location in the Meteorite Valley Moraine, where most old FRO meteorites were found.

Based on the cosmogenic radionuclides in 11 FRO ureilites, we conclude that they represent three distinct falls, including FRO 97013, FRO 01030 and the FRO 90036 shower, which represents a polymict ureilite breccia with at least 9 members.

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References: [1] Fioretti A.M. and Molin G. (1996) *MAPS* 31, A43. [2] Smith C.L. et al. (2000) *MAPS* 35, A150. [3] Fioretti A.M. and Goodrich C.A. (2001) *MAPS* 36, A58. [4] Smith C.L. et al. (1999) *MAPS* 34, A110. [5] Rai V.K. et al. (2002) *MAPS* 37, A120. [6] Rai V.K. et al. (2004) *LPSC* 35, #1180. [7] Welten K.C. et al. (2005) *MAPS* 40, A100. [8] Nagai H. et al. (1993) *GCA* 57, 3705-3723. [9] Grady M.M. and Pillinger C.T. (1993) *LPSC* 24, 551-552. [10] Leya I. et al. (2000) *MAPS* 35, 259-286.

Table 1. Concentrations of major elements (in wt%) and cosmogenic radionuclides (in dpm/kg) in FRO ureilites.

FRO	C	Mg	Al	Ca	Mn	Fe	^{10}Be	^{26}Al	^{41}Ca	^{41}Ca/(Fe*)	CRE age
90036	high	21.1	0.16	0.51	0.26	16.2	22.6±0.5	39.6±0.8	-	-	6 [6]
90054	low	19.4	0.46	2.59	0.31	14.6	17.5±0.5	44.2±0.9	-	-	12.8 [5]
90168	high	20.6	0.27	1.01	0.26	16.1	22.5±0.4	42.3±0.8	3.4±0.8	20±5	
90228	low	19.6	0.59	3.56	0.33	9.8	20.6±0.4	49.4±1.0	-	-	1.4 [4]
90233	high	20.8	0.25	1.09	0.27	15.5	21.8±0.4	42.3±0.8	2.4±0.3	14.4±1.7	
93008	low	18.9	0.33	2.18	0.31	12.1	19.1±0.4	43.4±1.0	1.2±0.8	9±6	
95028	high	20.6	0.13	0.94	0.26	14.1	22.4±0.5	38.5±0.8	1.9±0.2	12.3±1.3	
01012	low	19.4	0.28	0.84	0.25	16.0	20.0±0.4	39.8±0.9	1.7±0.3	9.9±1.9	
01088	medium	20.0	0.19	0.93	0.26	16.9	19.3±0.5	38.7±0.8	2.2±0.3	12.1±1.4	
97013	low	20.4	0.07	0.63	0.27	14.4	9.4±0.2	21.5±0.5	4.6±0.5	30±3	
01030	low	21.9	0.18	1.24	0.29	10.5	17.5±0.4	35.7±0.8	0.8±0.2	6.4±1.3	