TERRESTRIAL AGES AND PAIRING OF HOWARDITES, EUCRITES AND DIOGENITES FROM THE MILLER RANGE ICEFIELDS, ANTARCTICA.

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Introduction: In the past 45 years, the US Antarctic Meteorite (ANSMET) program has recovered more than 22,000 meteorites from more than 50 individual meteorite stranding areas. Although the Antarctic meteorite collection is dominated by ordinary chondrites which represent 80-90% of the recovered samples, it also contains many achondrites, including howardites, eucrites and diogenites, which are collectively known as HED meteorites. A challenge for the Antarctic meteorite collection is to identify paired fragments that belong to the same fall [1]. Eight ANSMET field seasons at the Miller Range Icefields (MIL), a series of blue ice fields about 40 km long and 10-20 km wide, have yielded more than 3000 meteorites including 56 HEDs. At least three possible pairing groups (with 3-10 members each) were initially identified among the MIL diogenites and one each among the howardites and eucrites. Since many HED meteorites are heterogeneous breccias [2], pairing identifications based on cm-sized samples is difficult and other independent evidence is needed to verify these proposed pairings, as was shown for several Antarctic howardite pairing-groups [3-5]. Here we re-examine pairings of HED's from the Miller Range Icefields, using multiple lines of evidence, including texture/petrography, chemical composition, cosmogenic radionuclides and find locations.

Due to the heterogeneous nature of HED meteorites, we will not only consider pairings strictly among the three HED groups, but will also consider pairing of howardites with brecciated eucrites or brecciated diogenites if the cosmogenic nuclides, texture and chemical compositions support this. The concentrations of cosmogenic radionuclides in meteorites are a function of the cosmic-ray exposure (CRE) age, shielding conditions (size and irradiation depth), chemical composition, as well the terrestrial age of the meteorite sample. Since the production rates of cosmogenic nuclides as a function of meteoroid size, depth and composition are well understood [6], their measured concentrations can be used to determine which meteorites belong to the same fall even if the chemical composition of the samples show significant variations. We selected 28 of the 56 HED samples from the MIL collection, including 12 diogenites, 8 howardites and 8 brecciated eucrites to investigate pairing relationships.

Experimental methods: We investigated polished thin sections of 22 HED meteorites, including those that were analyzed for cosmogenic radionuclides. For the cosmogenic radionuclide analysis, we dissolved between 50-200 mg of each sample in an HF/HNO_3 mixture along with 1 ml of a carrier solution containing a few mg of Be and Cl. After dissolution, a small aliquot of each sample was taken for chemical analysis (Mg, Al, K, Ca, Mn, Fe), mostly by atomic absorption spectroscopy. From the remaining solution, Be, Al and Cl were separated using procedures described previously; the $^{10}Be/Be$, $^{26}Al/Al$ and $^{36}Cl/Cl$ ratios were measured by accelerator mass spectrometry (AMS) at Purdue [7]. The measured $^{10}Be/Be$, $^{26}Al/Al$ and $^{36}Cl/Cl$ ratios were corrected for blanks and normalized to ^{10}Be, ^{26}Al and ^{36}Cl AMS standards [8-10]. The results are discussed below.

Petrography and chemical composition. Seventeen diogenites exhibit a coarse-grained brecciated texture, whereas MIL 03368 and MIL 090105 are more finely brecciated and distinct from the larger group. The chemical compositions of the individual samples show a more or less continuous mixing trend between the eucritic (low Mg, high Al, Ca) and diogenitic endmembers (high Mg, low Al, Ca). The POEM (percent of eucrite material) values of the HED meteorites, derived from the measured Al and Ca concentrations [2], show a bimodal distribution with 13 samples with POEM <25 and 12 samples with POEM >85. Only 3 of the 8 howardites show intermediate POEM values of 28-66. The compositions of four howardites (MIL 05062, 05085, 07009, 090159) with POEM values of 89-95 overlap with those of the eucrites. The composition of MIL 07665 overlaps with a group of 8 brecciated diogenites with POEM values ranging from 5-25; this together with its finely brecciated nature suggests it may be a diogenite, possibly associated with MIL 03368 and 090105. Due to the heterogeneous nature of HED breccias, the chemical compositions is only a suggestive indication of pairing [2].

Cosmogenic radionuclides. Cosmogenic ^{10}Be in HED meteorites is mainly produced from O, Mg, Al and Si, and is relatively independent of composition.

The observed variations in ^{10}Be, which ranges from 14 to 25 dpm/kg, mostly reflect differences in shielding conditions and CRE history (for samples with CRE<7 Ma). The variations in ^{26}Al, which ranges from 47 to 99 dpm/kg, also reflect differences in the Al content of the samples (0.5 wt% in diogenites to 7 wt% in eucrites), and the terrestrial age. Finally, the variations in ^{36}Cl, which range from 2.3 to 20.3 dpm/kg, are mainly due to differences in composition (Ca content) as well as terrestrial age, since ^{36}Cl decreases ~20% every 100 kyr due to radioactive decay. Assuming an average normalized ^{36}Cl production rate of 24 ± 3 dpm/kg [Fe+8Ca], the measured ^{36}Cl concentrations yield terrestrial ages ranging from <50 kyr for some HED's to ~350 kyr for MIL 07009 and 11292.

Diogenite pairings. Twenty of the 22 diogenites from MIL were found on the Middle Icefields, so some of these are probably paired fragments of the same fall. Initial classification suggested 3 pairing groups accounting for 18 specimens, plus 4 unique falls. Instead, the cosmogenic radionuclide data suggest that 7 diogenites (07003, 07613, 090107, 090112, 090159, 11197 and 11201) that were initially assigned to 3 different pairing groups all belong to the same group. This pairing group represents a polymict diogenite with POEM values of 5-25, relatively constant ^{10}Be and ^{26}Al concentrations of 20±1 and 56±5 dpm/kg, and an average ^{36}Cl terrestrial age of 90 ± 20 kyr. Although the composition of MIL 090105 overlaps with this group, its ^{36}Cl age is much older (~230 ka), indicating it could be paired with MIL 03368. Finally, the radionuclide data confirm that MIL 07001 and MIL 090995 are two separate falls, while MIL 15309 is probably be a third independent fall, although the radionuclide data is still incomplete.

Howardite pairings. The radionuclide data in two howardites with intermediate POEM values, MIL 11100 and 11296, suggest that they are paired fragments of a small fall with a terrestrial age of ~120 kyr; they were found less than 2 km apart on the Northern edge of the Southern Icefield. MIL 05062 and 05085 are likely fragments of a small pairing group on the Northern Icefield with a terrestrial age of ~200 kyr that also includes MIL 05165. Although we analyzed 3 of the 6 howardites found on the Middle Icefield, none of these seem to be paired with each other. The MIL 07665 howardite could be a brecciated diogenite that is part of a group with MIL 03368 and MIL 090105, although it was found 15-20 km away from the other two fragments.

Eucrite pairing groups. The most likely eucrite pair is MIL 11191/15080, two fragments that were found a few km apart on the eastern edge of the Southern Icefield and have a young terrestrial age of <30 kyr. The radionuclide data of MIL 07004/07662 suggest that these two fragments may also be paired even though they were found more than 10 km apart. Finally, we suggest two possible pairings of eucrites with eucrite-rich howardites, including MIL 07009/11292 and MIL 090153/15380. The first pair stands out, as both fragments have a ^{36}Cl terrestrial age of ~350 kyr, the oldest among the MIL HED meteorites. The second pair has a terrestrial age of ~130 kyr. We note that this age overlaps with that of the howardite pair 11100/11296, which have similary low ^{10}Be concentrations of 14-15 dpm/kg, so we cannot exclude the possibility (although rather speculative due to large variations in composition, with POEM values ranging from 50 to 90) that all four fragments belong to a single heterogeneous pairing group extending ~15 km between Middle and Southern Icefields. Among the four fragments, MIL 090153 has a ~30% higher ^{26}Al concentration than the other 3 samples. This can either indicate that this sample contains a significant contribution of solar-cosmic-ray-produced ^{26}Al and thus was closer to the pre-atmospheric surface, or that it simply is a separate fall with a different CRE history, but this would require more detailed study to verify.

Conclusions. The chemical composition, cosmogenic radionuclide inventory, and find locations on the Middle Icefield indicate that at least 7 diogenites represent paired fragments of a brecciated diogenite with 5-25 wt% of eucritic material. Based on the textures, up to 10 additional diogenites may also belong to this large pairing group, which would account for ~75% (by number) or 50% (by mass) of all diogenites found at Miller Range. Among the howardites and eucrites no large pairing groups were identified, but the howardites include at least 2 probable pairs, while the eucrites include up to 4 pairs with some pairs representing both eucrites and eucrite-rich howardites.

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Table 1. Concentrations of major elements (Mg, Al, Ca, Fe) and cosmogenic radionuclides (in dpm/kg) in 28 HED meteorites from the Miller Range Icefields, Antarctica. Probable pairs or pairing groups are highlighted in red or blue, with speculative members highlighted in orange.

Meteorite	Type	Mass (mg)	Mg (wt%)	Al (wt%)	Ca (wt%)	Fe (wt%)	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	^{36}Cl) (dpm/kg)	T(terr) kyr
MIL 07001	Dio-Ol	141.3	15.9	0.6	0.8	11.6	23.0±0.5	58.5±1.6	4.22±0.19	30 ± 70
MIL 15309	Dio	90.6	15.5	0.4	0.8	13.1	-	-	4.25±0.08	59 ± 66
MIL 03368	Dio	199.2	15.2	0.5	1.2	13.1	22.4±0.5	62.1±1.9	3.34±0.07	220 ± 70
MIL 07665	How	84.8	13.0	1.0	2.0	14.7	20.6±0.6	55.7±1.6	4.44±0.11	227 ± 78
MIL 090105	Dio	110.0	11.1	1.4	2.4	14.4	21.9±0.4	60.8±1.9	5.24±0.16	200 ± 80
MIL 07003	Dio	146.8	9.5	1.1	2.2	14.5	19.6±0.3	59.6±2.1	6.23±0.27	102 ± 82
MIL 07613	Dio	113.1	11.7	0.8	2.2	17.3	19.2±0.4	57.7±1.5	7.22±0.18	72 ± 77
MIL 090107	Dio	115.5	12.0	1.0	1.9	14.7	21.8±0.5	58.9±1.7	5.87±0.12	99 ± 77
MIL 090159	Dio	122.0	11.6	1.7	2.8	15.3	20.1±0.6	53.6±2.1	7.49±0.18	92 ± 84
MIL 090112	Dio	97.8	11.3	1.4	2.2	14.5	19.4±0.6	47.7±1.9	6.59±0.15	74 ± 80
MIL 11197	Dio	92.4	13.9	0.7	1.6	14.1	19.3±0.1	53.6±0.8	5.17±0.10	100 ± 74
MIL 11201	Dio	98.7	11.6	1.4	2.6	15.4	20.5±0.1	59.2±0.8	7.39±0.15	73 ± 82
MIL 09995	Dio	126.8	14.9	0.4	0.7	11.0	16.2±0.4	68.8±2.1	2.27±0.12	256 ± 70
MIL 07007	How	96.6	11.4	2.2	2.8	12.7	18.8±0.3	59.8±1.5	6.1±0.3	146 ± 90
MIL 11296	How	60.2	9.6	3.7	4.1	14.0	14.4±0.2	60.7±1.0	8.6±0.2	125 ± 93
MIL 11100	How	83.2	6.5	4.8	5.1	13.9	14.3±0.4	57.9±2.4	10.3±0.2	112±100
MIL 090153	How	82.1	5.2	6.3	6.7	14.4	15.0±0.4	82.0±3.3	12.5±0.3	121±100
MIL 15380	Euc-br	57.4	4.5	6.1	6.8	14.4	15.0±0.2	65.8±1.2	12.0±0.2	145±100
MIL 05062	How	76.8	5.2	6.5	7.1	14.2	19.2±0.6	79.6±2.6	10.9±0.4	196±100
MIL 05085	How	130.3	5.0	6.5	7.1	13.8	21.1±0.3	80.6±2.3	10.7±0.3	202±100
MIL 05041	Euc-br	90.8	3.6	6.7	7.9	15.0	17.2±0.7	86.6±3.0	15.2±0.3	96 ± 100
MIL 07004	Euc-br	81.8	3.7	6.0	7.1	14.2	21.4±0.3	69.3±2.7	10.1±0.4	228±100
MIL 07662	Euc-br	61.7	2.7	5.7	6.9	15.1	21.0±0.4	71.4±2.7	10.5±0.3	205±100
MIL 07016	Euc-br	89.6	3.0	6.3	8.1	15.2	16.4±0.6	52.2±1.7	9.6±0.2	300±100
MIL 11291	Euc-br	53.8	4.1	6.8	7.2	14.4	23.5±0.2	99.1±1.4	20.3±0.4	<35
MIL 15080	Euc-br	54.3	4.3	5.9	6.9	15.7	25.1±0.2	96.8±1.7	18.2±0.4	<75
MIL 07009	How	107.3	4.8	6.2	6.7	14.2	18.5±0.3	62.5±2.5	7.4±0.3	346±100
MIL 11292	Euc-br	68.2	4.0	6.5	7.1	14.6	17.9±0.1	60.8±0.9	7.7±0.2	350±100