THE PAIRING OF METEORITE FINDS. P.H. Benoit[1], J.M. Cunningham[1], P.A. Bland[2], F.J Berry[3], and C.T. Pillinger[2]. . [1]Cosmochemistry Group, Dept. Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701 USA. E-mail: COSMO@uafsysb.uark.edu. [2]Planetary Sciences Unit, [3]Department of Chemistry, The Open University, Milton Keynes MK7 6AA, UK.

The recognition of fragments of individual meteorites, or "pairing", has become especially important since the discovery of thousands of fragments on icefields in Antarctica and in hot deserts. Despite this, pairing has largely remained the provence of individual researchers and, to a large degree, individual analytical techniques. In this paper we summarize the main tools for meteorite pairing and we propose a system that expresses the degree of certainty for any given proposed pairing. We apply this scheme to reported pairings for Antarctic and hot desert meteorite finds.

Meteorites frequently fragment on reaching Earth, either during atmospheric passage, on impact, or due to subsequent weathering and erosion. About half of all modern falls have been documented to have broken into two or more fragments or "pairs" [*e.g.*, 1] and this is almost certainly an underestimate due to incomplete reporting and the vagaries of meteorite discovery and recognition. The presence of paired meteorites in desert concentrations such as those in Antarctica and the Sahara [2] is a virtual certainty, greatly complicating some studies of these meteorites [*e.g.*, 3]. The recognition of paired meteorites can be a difficult process. Individual researchers commonly apply their own set of criteria, that may vary widely in rigor and applicability. In this paper we propose a system for pairing that incorporates the various criteria used in the past. These criteria fall into three basic categories, including physical characteristics, geographic proximity, and recent space/terrestrial history.

Physical Characteristics. *Classification.* Classification is a pre-requisite for pairing. Breccias containing large clasts of >1 class are sufficiently rare that they can be ignored for this purpose.

Hand Specimen/Thin Section Description. In contrast to previous pairing studies [*e.g.*, 4] we regard petrographic similarity as supportive evidence but not a definitive guide for pairing. An exception is made for those very rare instances when fragments can be physically fitted together.

Shock Level. Uniform systems have been defined for characterization of shock stage in various meteorite classes [5]. We regard equivalence of shock stage as supportive of pairing, but, due to the known inhomogeneity of shock effects we do not invariably rule out pairings due to differences in shock stage.

Composition (mineral/bulk) and Rariety. Among many of the major meteorite classes (*e.g.*, equilibrated ordinary chondrites) the range of bulk and mineral compositions is so small as to be of very limited utility for pairing. Composition is, however, a vital pairing tool for unequilibrated ordinary chondrites, iron meteorites, basaltic meteorites, and other rare meteorite classes such as lunar meteorites [*e.g.*, 6]. Indirect measurements of mineral abundance or chemistry, such as induced thermoluminescence data, can also be used for some meteorite classes [7].

Geographic Proximity. Fragments of a meteorite can become widely separated during atmospheric passage or by terrestrial agents such as wind and water [8]. Proximity must thus be used with caution for pairing purposes. We regard find locations separated by no more than a few kilometers (the size of typical Antarctic icefields and hot desert blow outs) as supportive of pairing. However, strewn fields of modern meteorite showers suggest that fragments need to be separated by 50 km or more before distance is a valid argument against pairing.

Recent Space/Terrestrial History. *Cosmic Ray Exposure (CRE) Age.* Paired meteorites should have similar CRE ages [9]. However, the more common classes of meteorites often have preferred values of CRE ages, reflecting large break-up events [10]. Thus, we regard a match of CRE ages as supportive of pairing but not definitive; lack of a CRE age match is a strong argument against pairing.

Weathering. It can be argued that fragments of a meteorite can experience different weathering histories and that therefore the degree of weathering is not a valid tool for pairing. We suggest that the small separation of meteorite fragments during atmospheric passage compared to the size of climatic regions allows similarities in degree of weathering to be used to support proposed pairings but not to rule them out. Hand-specimen descriptions of degrees of weathering are generally too broad for pairing studies. Quantitative estimates can be obtained from induced thermoluminescence (TL) or from Mössbauer spectroscopy. Induced TL sensitivity is fairly constant in equilbrated meteorite classes but decreases as a function of weathering [11]. The range of TL sensitivity within meteorite finds is generally no more than a factor of 2, while differences between weathered meteorites of the same class range up to a factor of 20. Mössbauer spectroscopy measures the abundance of individual iron-bearing species [12]. The abundance of terrestrial-origin ferric oxides in individual weathered meteorite finds is fairly constant, with sample to sample variations generally <5% [13]. Differences between well-defined paired meteorite finds from both hot and cold deserts are generally <5%, while differences between unpaired meteorites may range up to a factor of three (Fig. 1).

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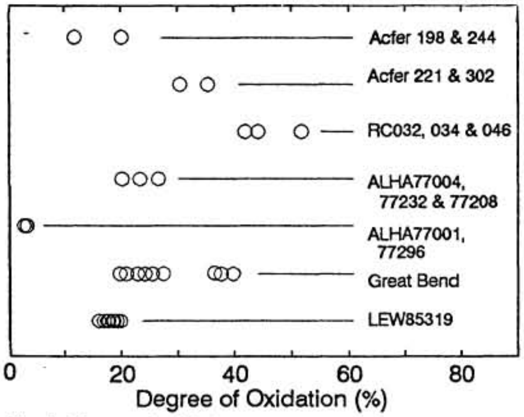

Fig. 1. Range of oxidation from Mössbauer spectroscopy for paired meteorite finds and within large finds.

Surface Exposure Age. Natural thermoluminescence (TL) of meteorite finds reflects their terrestrial thermal history. For hot desert finds, natural TL reflects terrestrial age (below). For cold desert finds, however, natural TL levels are largely determined by the duration of exposure on the relatively warm ice surface [14]. In analogy to weathering indicators, we suggest that similarity in natural TL level is suggestive of pairing but, in light of possible terrestrial history differences, lack of a match does not rule out a potential pairing. We suggest natural TL differences of no more than 10% for pairing purposes, although at very low TL levels (<50 gray) we suggest a criteria of ±10 gray.

Terrestrial Age. Terrestrial ages of meteorite finds can be estimated from natural TL (for hot desert finds) and from the abundance of cosmogenic radionuclides such as ^{36}Cl, ^{81}Kr, and ^{14}C [15]. The terrestrial ages of paired fragments should agree within uncertainties, with the caveat that these uncertainties are often poorly constrained and a topic of ongoing research [16]. The long halflives of ^{26}Al and ^{10}Be limit their utility for terrestrial age estimation but Welten *et al.* [17] have suggested that paired fragments should have ^{26}Al or ^{10}Be activities within 25% of each other, or ^{26}Al/^{10}Be activity ratios with 10%. We suggest that these criteria are supportive of pairing, but should be used only if more definitive terrestrial age data are not available.

A pairing synthesis. We propose a ten level scale to describe the certainty of proposed pairings (Table 1). All meteorites start at the "<0" (unpaired) level. Meteorites that share a common classification are automatically raised to "0" level. A set of criteria are then applied (Table 2), each criteria adding or subtracting from the pairing level. Redundant data within a criteria (*e.g.*, induced TL and Mössbauer spectroscopy for an equilibrated ordinary chondrite) do *not* double the score for a given criteria. The cumulative score is the pairing level. When applied to proposed pairing groups a running average of each criteria should be used. The contribution of each sample's data to the averages should be weighted according to the pairing level.

Comparison to previous pairing systems. Although pairing criteria have varied widely from researcher to researcher, in general our proposed system is more demanding than previous systems in terms of the amount of data needed to claim a definitive pairing (Level V+). We place less emphasis of field observations and petrographic descriptions and more weight on laboratory data. However, in accord with previous useage, our proposed system allows fairly high level pairings to be made for meteorites in rare classes using only field observations, petrography and mineral or bulk chemistry.

The pairing database. We have applied our system to many previously proposed pairings of hot and cold desert meteorites. A listing will be available from the senior authors.

Table 1. Levels of meteorite pairing and qualitative descriptions.

X \	(highest certainty)
IX	
VIII	Definitely
VII	paired
VI. /	
V. /	
IV.	Likely paired
III	Probably paired
II.	Possibly paired
I.	Potentially paired
0.	Unlikely paired <-- Shared Classification
<0	Not paired

Table 2. Pairing tools and their influence on pairing level.

	Matched	Not Matched
Physical Characteristics		
Classification	Pre-requisite	Not Paired
Hand specimen/thin section description	+3, +1+	None
Shock level	+1	-1
Chemistry (mineral/bulk, rare classes only)	+2	-2
Geographic Proximity.	+1	Variable†
Recent Space/Terrestrial history.		
Cosmic Ray Exposure Age	+1	-2
Weathering (Induced TL/Mossbauer)	+1	None
Surface Exposure Age (Natural TL)	+1	-1
Terrestrial Age (^{26}Al, ^{36}Cl, ^{14}C).	+1	-2

+ +1 for similarity in petrographic characteristics aside from classification; +3 if fragments can be physically fit together, for a maximum of +4 in this catagory.

† No modifier if <50 km, -2 if >50 km.

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