PAIRING OF METEORITE FINDS: A PROBABILITY APPROACH.

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The recognition of fragments of meteorites from a single fall, "pairing" [1], is a significant problem in the utilization of meteorite find accumulations, notably those in Antarctica, Australia and the Sahara [2]. In the case of rare or unusual meteorites such as lunar meteorites, recognition of additional fragments results in greater availability of material for research and pairing is a factor in considering meteorite accumulation mechanisms and possible changes in the meteorite population over time [3,4]. We here present a probability approach to pairing.

The Philosophy of Pairing:

Pairing is guided by two principles: (1) It is easier to refute a pairing than prove one, (2) all pairings bear some degree of uncertainty. While many types of data may support a proposed pairing, a single data mismatch can be sufficient to refute a proposed pairing. Once refuted, a pairing is rarely reconstituted, as this requires significant changes in the data or in data interpretation. The certainty of a pairing can be increased by gathering independent supporting data, but virtually no proposed pairing can be considered completely certain.

We assess each piece of possible pairing data in relation to (a) how well the data match between the proposed paired fragments, and (b) how these data compare to other meteorites.

The Model:

The degree of certainty of a proposed pairing can be expressed by:

$$P_{pair} = (1-P_{rel})^n \qquad \text{(equation 1)}$$

where P_{rel} is the probability of match between two unrelated meteorites, and *n* is the number of meteorite fragments under consideration (e.g., falls in a given area). An expression for P_{rel} is:

$$P_{rel} = P_{abun} * P_{ss} * P_{brecc} * P_{cre} * P_{solar} * P_{3He} * P_{tage} * P_{weath} * P_{NatTL} \qquad \text{(equation 2)}$$

where the individual probabilities are described below.

We use the modern falls or subsets of the find collection for assessment of probabilities. Use of the modern falls for estimation of the data distribution for meteorite finds implicitly assumes that the two collections are the same, an questionable assumption for meteorite groups with large average terrestrial age (e.g., Antarctic finds) [4]. Data distributions for meteorite finds may themselves be influenced by pairing. The number of meteorites in the pairing area, *n*, can be estimated by the number of meteorite fragments at a collection site, corrected by iteration for possible pairings, but it is likely that meteorites have been lost to weathering [2,5]. In the present analysis, we concentrate on relative degrees of pairing certainty, setting *n* to a single number.

Assessment of relative pairing strength thus consists of gathering relevant data for the potentially paired fragments, finding a data match within analytical and other uncertainties and finding a P value using the proportion of modern falls (or subsets of finds for some terrestrial history criteria) that also give a data match. Supporting data are either not amenable to quantitation, or insufficient data are currently available to delineate data distributions. These data do not add to pairing certainty but can be used to refute pairings.

Pairing Criteria:

- *Classification/rarity(P_{abun})* . Paired fragments should belong to the same chemical class and petrologic type. A P value is estimated using the modern fall distribution.
- *Mineral/component composition and abundance (Supporting data).* Mineral compositions and abundances typically do not vary enough within major meteorite classes/types to allow their use as a quantitative pairing tool, although they can play an important role in subclassification [e.g., 6]. The abundance of minor or trace minerals, or abundance or size distribution of CAI, clasts, chondrule types etc., can be used as supporting data, but the degree of heterogeneity within meteorites is not well documented [7].
- *Secondary petrographic textures (P_{ss} and P_{brecc}).* Degree of shock metamorphism can be estimated from mineral textures. Although the degree of heterogeneity within typical meteorites has not been documented, we use the criteria that paired fragments should agree within one classification division. The shock level probability (P_{ss}) is then estimated from modern falls of the same major chemical class/type [8]. Brecciation is noted by the presence of clasts or from macrotextures. In the present system, we do not attempt to subdivide types of breccias, but assign a probability (P_{brecc}) for the presence of brecciation features based on modern falls of the same major chemical class. It is likely that estimated probabilities are underestimates due to many modern falls of common classes not being studied in any great detail.
- *Bulk composition and isotopic composition (Supporting data).* Within major chemical classes bulk compositions typically exhibit insufficient heterogeneity for quantitative pairing. Minor or trace elemental abundances can be used to support pairings in some cases [9]. Oxygen isotopic composition is also typically too homogeneous for pairing and insufficient data are currently available for other isotopic systems.
- *Cosmogenic noble gases (P_{cre}, P_{solar}, and P_{3He}, and supporting data).* Cosmic ray exposure ages of potentially paired fragments should match within analytical uncertainties, after corrections for shielding [10]. We use the modern falls subdivided by chemical group/type to determine probability (P_{cre}). Reflecting shielding, paired fragments should plot along trends with positive slopes on a plot of $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$, lack of such a trend refuting a proposed pairing. The presence of solar gases (e.g., ^{4}He) is evidence for pairing, probability being estimated for H and LL chondrites from modern falls (P_{solar}). Samples may also exhibit anomalously low values of $^{3}He/^{21}Ne$ compared to $^{22}Ne/^{21}Ne$. A probability of occurrence can be estimated from modern falls (P_{3He}).

- *Terrestrial Age (P_{tage}).* Paired fragments should exhibit the same terrestrial age, within analytical uncertainties. Terrestrial age can be estimated from cosmogenic radionuclide abundance (^{14}C, ^{36}Cl, etc.), or from natural TL for ordinary chondrites from hot deserts [e.g., 11]. Estimation of a probability of random occurrence of a match (P_{tage}) must use databases for regional meteorite collections, and thus separate comparison distributions are needed for Antarctica, the Sahara, Australia, etc. Furthermore, the comparison distributions should be limited to petrographically similar meteorites (ordinary chondrites, achondrites, carbonaceous chondrites, etc.), as differences in mineral composition may result in significantly different weathering behavior, and thus different terrestrial age distributions. For this reason, application of terrestrial age as a pairing criteria is often limited to the most common meteorite classes, and is otherwise limited to serving as supporting data.
- *Weathering (P_{weath}).* The degree of weathering of a meteorite find can be estimated from hand-specimen description, thin-section modal mineralogy, Mössbauer spectroscopy, and TL sensitivity [12]. Profile samples through meteorite finds indicate that degree of oxidation as measured by Mössbauer spectroscopy exhibits a range of only about 10% within meteorites, and we thus adopt this criteria for pairing matches. Thermoluminescence (TL) sensitivity of ordinary chondrites decreases with increasing degrees of weathering, exhibiting a range of no more than a factor of two in profiles. Regardless of technique, P_{weath} must be estimated using distributions for meteorite finds from the same region. The four analytical techniques do not add cumulatively to pairing certainty. However, Mössbauer data and TL sensitivity exhibit a relatively wider range and smaller measurement uncertainty than the descriptive techniques, and thus tend to give better values of P_{weath}.
- *Natural Thermoluminescence (P_{NatTL}).* The natural TL of Antarctic ordinary chondrites exhibits a significant range which is not directly linked to terrestrial age and thus can be used as an independent pairing criterion [e.g., 3]. Natural TL levels in meteorite finds typically exhibit no more than a 10% range of natural TL at 250°C in the glow curve. Probabilities can be assigned using the total Antarctic natural TL distribution, corrected for known pairings.

Application:

We have applied this approach to over 2200 pairings reported in the literature. Unusual meteorites or meteorites with unusual features (very high or low levels of shock processing, etc.) have high relative pairing strengths. However, pairings of common meteorites (equilibrated ordinary chondrites) based on only a few pieces of data tend have low pairing strengths.

Conclusions:

A probability approach to pairing provides a quantitative way to evaluate pairing arguments, placing weights on data on the basis of degree of deviation from the norm. The procedure can be applied by non-specialists, and can provide guidance on data desirable to improve a pairing's certainty. The procedure is also amenable to computer-based analysis. The pairing criteria listed here are only those currently used or under current development. It is likely that additional criteria will be added in the future. For inclusion, a new analytic procedure must demonstrate two things: that the data range observed for profiles in meteorite finds is small, while the range exhibited within major meteorite classes is large. Computerized modal analysis of thin-sections is one such technique currently under development [13].

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