USING DUST FROM ASTEROIDS AS REGOLITH MICROSAMPLES.

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Introduction: Meteorite science is rich with compositional indicators by which we classify parent bodies, but few sample groups are definitively linked with asteroid spectra. More robust links need to be forged between meteorites and their parent bodies to understand the composition, diversity and distribution. A major link can be sample analysis of the parent body material and comparison with meteorite data.

Hayabusa, the first sample return mission of the Japanese Aerospace Exploration Agency (JAXA), was developed to rendezvous with and collect samples from asteroid Itokawa and return them to Earth. Thousands of sub-100 µm particles were recovered, apparently introduced during the spacecraft impact into the surface of the asteroid, linking the asteroid Itokawa to LL chondrites [1]. Upcoming missions Hayabusa 2 and OSIRIS-REx will collect more significant sample masses from asteroids. In all these cases, the samples are or will be a collection of regolith particles.

Sample return to earth is not the only method for regolith particle analysis. Dust is present around all airless bodies, generated by micrometeorite impact into their airless surfaces, which in turn lofts regolith particles into a "cloud" around the body. The composition, flux, and size-frequency distribution of dust particles can provide significant insight into the geological evolution of airless bodies [2]. For example, the Cassini Cosmic Dust Analyzer (CDA) detected salts in Enceladus' icy plume material, providing evidence for a subsurface ocean in contact with a silicate seafloor [3]. Similar instruments have flown on the Rosetta, LADEE, and Stardust missions. Such an instrument may be of great use in obtaining the elemental, isotopic and mineralogical composition measurement of dust particles originating from asteroids without returning the samples to terrestrial laboratories.

We investigated the ability of a limited sample analysis capability using a dust instrument to forge links between asteroid regolith particles and known meteorite groups. We further set limits on the number of individual particles statistically needed to robustly reproduce a bulk composition.

Meteorite composition: For the major meteorite groups, a combination of mineral abundance and mineral composition is required to classify the object. We used point-counts of multiple meteorites and types [4-13] as a proxy for regolith particles, examining the abundance of major and minor minerals (silicates, Fe-Ni metal, oxides, sulfides, and others) and the Fe content of the silicate component. Fig 1 shows one possible combination of parameters, the fraction of silicate particles vs the Fe content in the silicates.

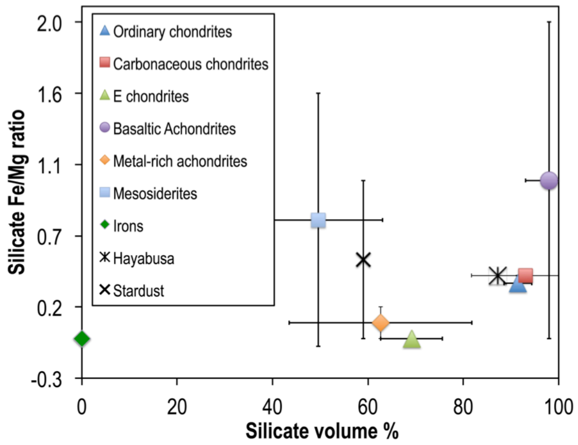

Fig. 1. Major meteorite classes grouped by silicate abundance (volume fraction) and Fe/Mg ratio in the silicates. The mean and spread are defined by point-counts of meteorites within each group. Some basaltic achondrites (HEDs, aubrites, angrites, ureilites) and metal-rich achondrites (pallasites, winonaites, acapulcoites, lodranites) are difficult to distinguish from one another using only this information. The composition derived from the Hayabusa and Stardust datasets is also shown for comparison.

In this phase space, major groups are distinguishable from each other. For example, given a particle abundance and Fe/Mg with 10% uncertainty, one could place the sample with reasonable confidence as a chondrite, basaltic achondrite, metal-rich achondrite, or iron. Several types of meteorites may be recognizable by the presence of unique minerals, for example, oldhamite in enstatite chondrites, or organic molecules and serpentines in carbonaceous chondrites. Some types have distinctive elemental ratios in their silicate fraction, for example, high-Mg pyroxene coupled with high Ca plagioclase (anorthite) in angrites.

Ordinary and carbonaceous chondrites overlap in Fig. 1, but the presence of carbon and organic species can be used to distinguish C chondrites. Ureilites and ordinary chondrites are distinguished by the presence of carbon in ureilites vs. metal in chondrites. However, not all combinations are distinct. For example, it may be difficult to distinguish basaltic meteorites, such as angrites and HEDs. The metal-rich pallasites, acapulcoites, and winonaites will also be difficult to distinguish, as they rely on the ratios of metal to sulfide and fine differences in Fe/Mg ratio in the silicates.

Sparse datasets: The Hayabusa mission provided an exercise in how many particles are required to link a parent body (Itokawa) to a meteorite group (ordinary chondrites). A dataset consisting of 1087 single-mineral particles [1] is composed of 83% silicates (olivine, pyroxene, and feldspar); the silicates have an Fe/Mg ratio of 0.43. Less than 1% of the particles are FeNi metal, and chromite and sulfides are also detected. This set of characteristics falls into ordinary chondrite group (Fig 1). This association was confirmed by laboratory-based analyses, including oxygen isotopes and trace-element analyses, but the simple mineralogy and major-element ratios are sufficient to link the 1087 particles from Itokawa with ordinary chondrites.

The Stardust mission returned particulate samples from the dust tail of comet Wild 2. Most of the particles are weakly constructed mixtures of nanometer-scale grains with occasional much larger (>1 mm) ferromagnesian silicates, Fe-Ni sulfides, and Fe-Ni metal. The characteristics of a set of 34 monomineralic particles [14], when examined in the same way, does not appear to link Wild 2 to any known meteorite group (Fig. 1). The presence of carbon particles might indicate carbonaceous chondrite-type materials, but in fact these samples are linked to IDPs by methods only available in the laboratory, including trace elements in olivine, amorphous silicates known as GEMS, and the morphologic presentation of pyroxene as platelets and whiskers [14-15].

Number of particles: We used a simple Monte Carlo-type model to understand whether smaller subsets of the 1087 Hayabusa particles would have yielded the link to ordinary chondrites with the same confidence. We created 100 sets each of randomly-selected sets of 20, 50, 100, 250, 500 and 750, 1000 particles. We computed the mineral abundance that would be derived with a sample set of that size (Fig. 2 for silicates, compared with the Hayabusa value of 87.2). This can be used to estimate the uncertainty in placing the computed composition onto Figure 1.

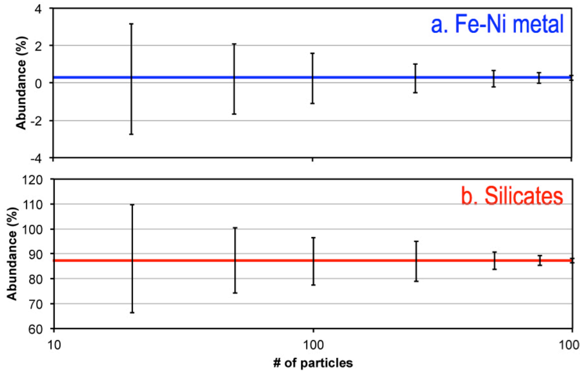

Fig. 2: Range (3σ, or 96% interval) of possible compositions for Itokawa using particle subsets. The colored lines show the actual composition and the range is an approximation of the statistical uncertainty associated with a composition derived from each subset. Sets of 20-50 particles yield ranges >10%, which exceeds the differences between meteorite groups in Fig. 1, and thus are too small to distinguish a parent body. At around 100-250 particles, the range decreases to 10%, which is sufficient to distinguish the parent body group using major components such as silicates (a) and possibly finer distinctions such as Fe-Ni metal content between ordinary chondrite subgroups (b).

The model sets have wider distributions with smaller set sizes, as expected, but the distributions decrease to about 10% (relative to the mean) around 100-250 particles. None of the result sets have too high an abundance of FeNi metal, or too different a metal/sulfide ratio, to place the Itokawa composition into the H chondrite field, and none contain carbon to confuse it with carbonaceous chondrites. Based on these results, we conclude that a sample set of 100-250 particles is sufficient to achieve the goal associating the parent body with a meteorite group.

This statistical analysis assumes that each grain is monomineralic. Many of the Hayabusa grains were monomineralic, but some were complex, consisting of multiple phases. Very small grain sizes are expected in an extended dust environment (much smaller than Hayabusa), increasing the chances that particles will be monomineralic. The elemental composition of each particle can also be used to confirm if this is likely.

Summary: The major meteorite groups can be distinguished from one another using basic indicators such as mineral abundance and Fe/Mg ratios in silicates. To accomplish the goal of linking mineral abundance and composition with known meteorite types, a statistically significant number of particles will need to be analyzed. In general, a sample size of 100-250 monomineralic particles, if randomly ejected and encountered, adequately distinguish major groups of meteorites. Firmer links may be made by increasing the number of particles to improve counting statistics of minor phases, identifying diagnostic minerals, and using contextual clues provided by other observations of the parent body, which will further narrow the possible interpretation space.

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