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Introduction: Mapping and stratigraphic sequencing are goals of planetary exploration. The mapping of bodies that vary in size from Venus to Vesta has used terrestrial geologic principles, the idea that older surfaces accumulate more impact craters, high-resolution imagery, and remote spectroscopic techniques [1,2].

Another way of defining stratigraphic relationships is through age dating of rocks. Some systems, such as U-Pb, are not perturbed by thermal events thereby retaining crystallization/formation age information. Other systems, such as Ar-Ar, are more susceptible to open system behavior and can give ages of more recent thermal events and hence, the evolution of a given body.

Not all age dates are equally robust, however, nor do all lithologies give ages that can be associated with discrete events. By way of example, we consider the Ar/Ar ages of HEDs.

Suspect lithologies:

Breccias: Some eucrites and all howardites, which compositionally resemble much of Vesta's surface [3,4] are breccias - sedimentary rocks composed of angular fragments of rock and/or minerals cemented together by a matrix. The matrix may be compositionally similar to or different from the fragments (fig. 1). The fragments can also be of different ages. Consequently, a random sample of bulk breccia might yield a reliable age, a disturbed or highly uncertain age, or an averaged age that reflects a mixing between constituents. For these lithologies, it is desirable to separate the constituent clasts prior to dating in order to date the events experienced by each clast. In some cases, it is even necessary to separate a breccia clast from within a breccia clast!

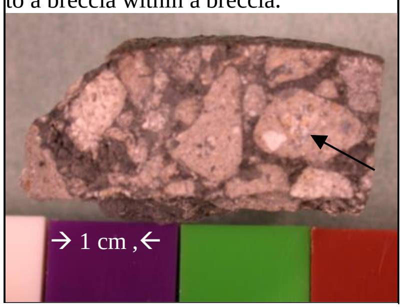


Figure 1. Photo showing the many rock fragments within the howardite, Kapoeta AMNH 4877. The arrow points to a breccia within a breccia.

For example, the distribution of Ar-Ar ages reported for eucrites [5-7] has a peak for unbrecciated eucrites at ~4.5 Ga; the ages of brecciated eucrites spread between 3.4 – 4.1 Ga. [6] points out that the plateaus taken to define these ages do not, in most cases, satisfy relatively modest criteria of plateau formation (≥ 50% ^{39}Ar release over 3 consecutive steps with ages that agree at a 95% confidence level). This suggests appreciable step-to-step variation of the measured ages and is not surprising for a breccia. Whereas all fragments *may* have experienced identical thermal histories prior to meteorite assembly, a common history cannot be assumed.

Ar/Ar ages vary on a scale of one hundred microns within the HED meteorites [8]. Thus, even samples as small as a few milligrams (1 mm^3) may give ambiguous ages if they include different lithologies. In conventional samples of mineral separates, the spatial and petrographic relationships of the grains that make up the sample are not normally constrained. In our view, the most convincing ages come from separated plagioclase crystals.

Impact melt clasts and veins: Impact melt clasts are not uncommon in meteoritic breccias and they have been targeted for dating impact events on Vesta [9]. The impact clasts are described as having a variety of textures with some containing relict clasts of a variety of minerals (fig. 2). The plagioclase within the samples (the main target for Ar-Ar dating), is reported to be heterogeneous in composition (An_{80-95}) [9]. Considering that plagioclase and pyroxene have different closure temperatures and that post shock heating is likely to be uneven, it is not surprising that the release plateau for QUE 94200 is disturbed. Although an age based on such a disturbed release pattern may place upper limits on the timing of an event, it does not give an unequivocal date of the event.

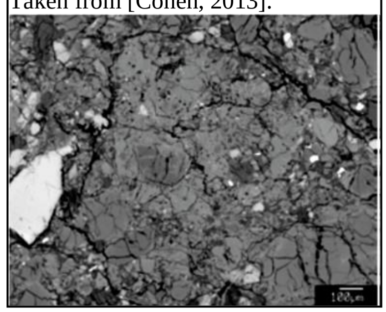
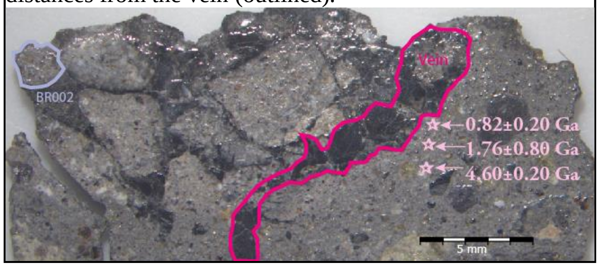


Figure 2. An impact melt clast from howardite QUE 94200 showing relict grains, some of which are zoned. Taken from [Cohen, 2013].

The ages of melt veins are subject to the same ambiguities as those of melt clasts for the same reason, namely the presence of relict grains. However, veins can constrain crosscutting relationships with the lithologies around them. Additionally, melt veins can act as agents of contact metamorphism, resetting grains proportionally with distance from the vein. We have shown one example in Kapoeta where the ages of grains become older with increasing distance from a melt vein (fig.3). Over a span of 2 mm, single grains from within the breccia range from 0.82±0.20 Ga to 4.60±0.20 Ga. Unless analyzing a sample that is purely glass (which we have not yet found), the best one can expect is an averaged mixing age of the oldest preserved components with the youngest age of the vein-forming event.

Figure 3. Melt vein cross-cutting Kapoeta AMNH 4788 and the locations (stars) and ages of 3 grains that are at different distances from the vein (outlined).



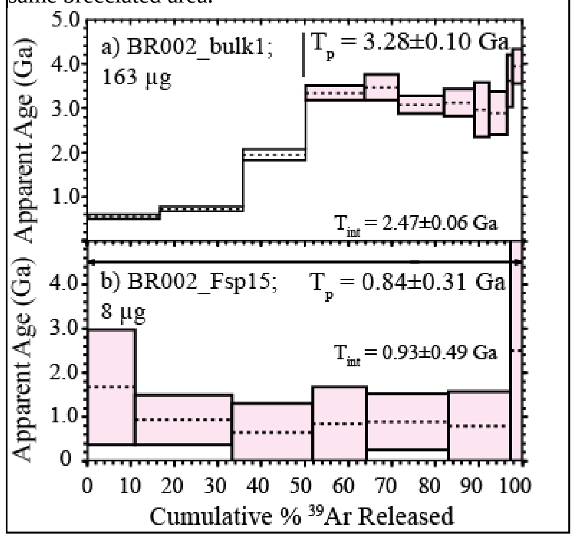
Exemplary lithologies:

Unbrecciated samples: Milligram sized samples that are unbrecciated, monolithologic, and crystalline often give robust release spectra. This explains the precision of the 4.48 Ga peak formed by unbrecciated eucrites [5]. Care must be taken, however, to ensure that such a sizable sample has not been brecciated, or there is the risk of clasts within the rock having different thermal histories, thereby giving perturbed spectra and ambiguous age data.

Single crystals: Single feldspar grains from any lithology are perhaps the ideal samples and, in our experience, give the most robust ages. For example, a random bulk sample from Kapoeta breccia BR002 (fig. 3) had a disturbed Ar release spectrum with a nominal plateau age and uncertainty (1σ) of 3.28±0.10 Ga (fig. 4a). The corresponding spectra of single plagioclase crystals from the same brecciated area had larger individual errors, but showed less overall dispersion and gave ages between 0.63±0.24 and 1.25±0.95 Ga, very different from that of the bulk sample (fig 4b; one of five measurements shown) [8]. We think it likely that other grains from the same area would have ages > 3.3 Ga, leading to the mixing age of 3.28 of the bulk breccia.

Even with single grains, however, there are caveats. These include: 1) a tradeoff between precision and accuracy. That is, due to the small sample size, errors are larger even when the age is more accurate; 2) insufficient mass. Sometimes it is not possible to use a single crystal for age dating because there is not enough mass to ensure gas measurements. In this case, several grains can be analyzed together. It makes most sense to combine those grains that are the most similar compositionally. However, consanguinity cannot be assumed for aggregates of grains unless they sample a monolithologic source rock; 3) heterogeneous crystals (i.e., zoned or exsolved). Compositional inconsistency makes for poor dating candidates; and 4) sub-micron inclusions of fluids or gases may exist that perturb the release spectrum.

Figure 4. a) release pattern of a breccia bulk sample; b) release pattern from a single feldspar crystal from the same brecciated area.



Conclusions: Ar/Ar ages from brecciated samples are potentially ambiguous and must be carefully scrutinized. The group that bears scrutiny includes the ages of HEDs as well as lunar samples that have been used to define a late heavy bombardment (LHB) period at ~ 3.9 Ga [7,9,10]. In fact, because the conception of a LHB period is based on the ages of bulk breccia samples, the concept itself becomes suspect and needs to be corroborated with single crystal ages before taken as true.

This does not mean that bulk samples from breccias give no valuable information. They may define upper limits of thermal events. However, as technology allows us to refine data analyses, we must also refine our interpretations.

References: [*] Pink Floyd, *"Careful with That Axe, Eugene"*. Waters, R. et al., Ummagumma, Harvest, 1969. Track 2. [1] Yingst, R.A. et al., 2014 *PSS* **103**:2-23. [2] McSween, H.Y. 2015 *Geol* **25**:4-9. [3] Binzel, R.P. 1997 *Icarus* **128**:95-103, [4] Gaffey, M.J., 1997 *Icarus* **127**:130-157. [5] Bogard, D.D., 2011. *Chem. Erde* **71**:207-226. [6] Kennedy, T. et al., 2013. *GCA* **115**:162-182. [7] Bogard, D.D. & Garrison,D., 2009 40th *LPSC* # 1131. [8] Lindsay, F.N. et al., 2015 *EPSL* **413**:208-213. [9] Cohen, B.A. 2013 *M&PS* **48**:771-785. [10] Tera, F. et al., 1974. *EPSL* **22**:1-21.