THE DICHOTOMOUS HED METEORITE SUITE.
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Introduction: The howardite, eucrite and diogenite (HED) clan is the largest suite of crustal rocks available from a differentiated asteroid. Attempts to unravel the petrogenetic history of the HED parent body have tacitly assumed that the suite is representative of the crust, and thus can be used to understand the differentiation history of the entire parent body [1-3]. This assumption is a holdover from a time when we knew little about the HED parent body. Much has changed. Is this assumption still valid?

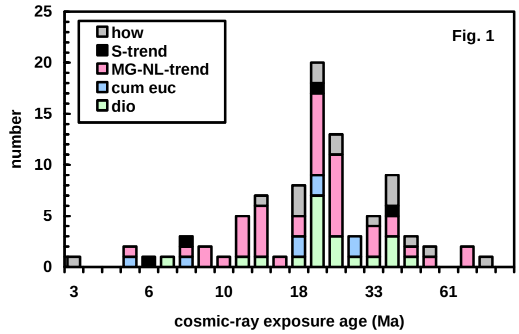
HED Geochemistry: The HED suite is composed of two main types of igneous materials: (i) diogenites, which are cumulate orthopyroxenites, and (ii) eucrites, which are mafic igneous rocks. The eucrites are divided into three compositional subgroups: (i) gabbroic cumulate eucrites, (ii) basaltic main group - Nuevo Laredo-trend eucrites, and (iii) basaltic Stannern-trend eucrites. Brecciated mixtures of these materials are the howardites, polymict eucrites, polymict cumulate eucrites and polymict diogenites. One model has the Stannern-trend, including the compositionally most primitive main group eucrites, representing a sequence of primary partial melts of the HED parent body [1]. The main group – Nuevo Laredo-trend is a series of residual melts formed by fractional crystallization of magmas compositionally like the most primitive of the main group eucrites [1]. Cumulate eucrites are gabbroic cumulates formed by this process [4, 5]. This scenario successfully explains the lithophile element contents of the eucrite suite [1, 4, 5].

This petrogenetic scheme seems incapable of explaining the siderophile element contents, however. For example, a model that successfully matches the Sc-La distribution of eucrites predicts Co abundances ~4.5 times those measured [5]. The high model Co contents result from metal in the model source regions buffering the siderophile element contents of the melts. Basaltic eucrites could not have been in equilibrium with metal, and thus, a core must have separated from silicates before eucrite formation [3]. Calculations indicate core separation requires that a large fraction of the parent body is molten [6]; much larger than indicated by lithophile trace element models. This has been taken to indicate complete melting of the HED parent body, and that the entire igneous suite (diogenites and all eucrites) were formed by crystallization of this molten asteroid [2, 3]. These models cannot explain the trace lithophile element contents of the Stannern-trend [3, 5].

Vesta and the Vestoids: Discovery that Vesta has a surface with reflective properties matching HED meteorites [7] led to the suggestion that Vesta is the HED parent body [8]. However, orbital-dynamics calculations indicated that Vesta ejecta does not match fall statistics and the cosmic-ray exposure age spectrum of HEDs [9]. Discovery of km-sized near Earth asteroids with spectra compatible with HED meteorites led to the suggestion that these asteroids, and the HED meteorites, are fragments of a totally disrupted differentiated asteroid [10]. It was suggested Vesta was <u>*not*</u> the parent body for the near-Earth basaltic asteroids because of the dynamical constraints, and because it was believed, based on geochemical arguments, that HEDs, main-group pallasites and IIIAB irons were from the same parent body. That parent body must have been totally disrupted to yield the irons [10]. Finally, recent work has identified a large number of 4-10 km-sized Vestoids with orbital parameters similar to those of Vesta, that are believed to be ejecta from it [11]. Potentially, one or more of these is the immediate source of HED meteorites.

Clustering of HED Meteorites: Two types of clustering in HED meteorite properties might indicate derivation from a limited region of their parent asteroid. Day of fall clustering could indicate delivery of relatively recent impact ejecta from a km-sized Vestoid in Earth-crossing/approaching orbit. A peaking of day of fall of HED meteorites occurs in June-August, but this is not correlated with orbital parameters of the basaltic near Earth asteroids [10]. Most observed HED falls are from the northern temperate/subtropical zone. The June-August peak likely simply reflects an anthropogenic effect – more people are out for longer periods of time in the summer, especially farm workers. (A smaller peak in April falls may reflect spring planting.) Regardless, a day of fall clustering would suggest recent formation of a "meteoroid stream" that is not indicated in the cosmic-ray exposure data (below).

Clustering of HED cosmic-ray exposure ages, which date the liberation of m-sized meteoroids from their immediate parent object, was first demonstrated by [12], who noted that two major peaks at ~21 and ~38 Ma contain representatives of all three major types – howardites, eucrites and diogenites - and thus, these rocks are closely associated on the HED parent body. They also suggested there are minor peaks at ~6, ~12 and ~73 Ma, with the ~12 Ma peak being the most pronounced of these. (However, [13] concluded that only the two major peaks are statistically significant.) Fig. 1 is a histogram of HED cosmic-ray exposure ages similar to those of [12-15], but eucrites have been divided into cumulate eucrites, main group – Nuevo Laredo-trend and Stannern-trend. The major clusters at ~21 and ~38 Ma and the minor peak at ~12 Ma each contain diogenites, main group – Nuevo Laredo-trend eucrites and howardites, and the ~21 Ma peak also contains cumulate eucrites.



The anomalous Stannern-trend eucrite Pomozdino falls in the ~21 Ma age peak [15], and Stannern falls in the ~38 Ma age peak. The two impacts that delivered ~50% of HEDs to Earth, apparently liberated all known types of igneous materials. Thus there is no compelling reason to believe that Stannern-trend rocks are from a distinct location on the HED parent body (or a different parent body) from the main group – Nuevo Laredo-trend eucrites. Unfortunately, because there are so few cosmic-ray exposure ages for Stannern-trend eucrites, one cannot conclude *with certainty* that Stannern-trend materials are from the same limited regions sampled by the two cratering events - one needs to demonstrate a clustering of Stannern-trend ages within the main HED age clusters.

Discussion: Two scenarios can explain the cosmic-ray exposure age distribution of HEDs: (i) the peaks reflect cratering events on their parent asteroid [12-16], or (ii) they represent later fragmentation of spalls from their parent asteroid [16]. In the former case, the HED suite may be representative of the parent body *if* they were ejected by a large impact that sampled a wide region of the parent body crust. This would then suggest that main group – Nuevo Laredo-trend eucrites are the dominant basalt types on the parent body. (This is also inferred from mass balance constraints derived from howardite compositions [17].) However, [13] concluded that the cosmic-ray exposure age spectrum of HEDs was compatible with impacts by objects 2-4 km in size. Such impacts would sample much more limited regions of the HED parent body.

If the second scenario – derivation from spalls - is correct, then no conclusion can be reached regarding the dominant type of basalt on the parent body. The spalls are small; observation and modeling indicate <10 km [11, 18]. Small chips excavated from a large basin may not fully represent the geology of the region of impact. The typical spall sizes are 20-50% that of the thickness estimated for the Vestan crust [2, 3]. If the monomict and unbrecciated eucrites and diogenites were liberated from one or more of these spalls, then they more likely represent m-sized blocks in a megabreccia, rather than bedrock.

Models of HED petrogenesis have presumed global significance, but this need not be the case. One major problem for crystallization models is that there is no straightforward means to explain the incompatible lithophile element trends of both the main group – Nuevo Laredo-trend and the Stannern-trend [1, 3, 5]. Crystallization models have presumed that the parent asteroid was entirely molten, or nearly so [2, 3]. As an alternative, the main group – Nuevo Laredo-trend eucrites might simply represent one large igneous province in which high-temperature primary melts were emplaced as plutons and underwent extensive fractionation in the crust. This can potentially explain the very low siderophile element contents of main group – Nuevo Laredo-trend eucrites. Stannern-trend eucrites could represent a separate province where low-temperature primary melts were extruded. However, this leaves the low siderophile element contents of Stannern-trend eucrites unexplained.

Only four of 9 Stannern-trend eucrites so far identified have had cosmic-ray exposure ages done. This makes it difficult to arrive at firm conclusions regarding their positional association with main group – Nuevo Laredo-trend eucrites on the HED parent body. Additional ages on Stannern-trend eucrites would help resolve this issue, and provide constraints on HED parent body evolution. If Stannern-trend eucrites are from the same region of the HED parent body, their exposure ages should show the same clustering.

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