THE REGOLITH OF 4 VESTA – INFERENCES FROM HOWARDITES.

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Introduction: Asteroid 4 Vesta is quite likely the parent asteroid of the howardite, eucrite and diogenite meteorites - the HED clan [1]. Eucrites and diogenites are the products of igneous processes; the former are basaltic composition rocks from flows, and shallow and deep intrusive bodies, whilst the latter are cumulate orthopyroxenites thought to have formed deep in the crust [2]. Impact processes have excavated these materials and mixed them into a suite of polymict breccias. Howardites are polymict breccias composed mostly of clasts and mineral fragments of eucritic and diogenitic parentage, with neither end-member comprising more than 90% of the rock [3]. Early work interpreted howardites as representing the lithified regolith of their parent asteroid (e.g., see [4]). Recently, howardites have been divided into two subtypes; fragmental howardites, being a type of non-regolithic polymict breccia, and regolithic howardites, being lithified remnants of the active regolith of 4 Vesta [5].

We are in the thralls of a collaborative investigation of the record of impact mixing contained within howardites, which includes studies of their mineralogy, petrology, bulk rock compositions, and bulk rock and clast noble gas contents. One goal of our investigation is to test the hypothesis that some howardites represent breccias formed from an ancient, well-mixed regolith on Vesta [5]. Another is to use our results to further understand regolith processing on differentiated asteroids as compared to what has been learned from the Moon.

We have made petrographic observations and electron microprobe analyses on 21 howardites and 3 polymict eucrites. We have done bulk rock analyses using X-ray fluorescence spectrometry [6] and are completing inductively coupled plasma mass spectrometry analyses. Here, we discuss our petrologic and bulk compositional results in the context of regolith formation. Companion presentations describe the noble gas results and compositional studies of low-Ca pyroxene clasts [7-9].

Noble Gases: Noble gas contents of the lunar regolith and regolith breccias are high because surface exposure allows for solar wind (SW) and solar energetic particle (SEP) implantation into the upper few nm's of grains on the surface [10, 11]. Some howardites have noble gas contents indicating significant trapped components with isotopic characteristics resulting from a SW and/or SEP origin (e.g. high ^{20}Ne/^{22}Ne and low ^{21}Ne/^{22}Ne ratios) [12]. High ^{20}Ne content is one characteristic used to define the regolithic howardite subtype [5].

Petrology: We have initiated an evaluation of the extent of regolith gardening represented by the samples, through comparison of textural "regolithic" features. We have made semi-quantitative estimates of the abundances of glassy clasts and reworked clasts (breccia clasts, impact-melt matrix clasts), clast size and rounding, and we assume that these characteristics will correlate with the length of time being gardened in the regolith [9]. This assumption is in analogy with the lunar regolith, where maturation by meteoroid impacts causes diminution of particle sizes and the development of soil aggregates welded by impact glass (agglutinates) [e.g. 10]. The abundance of glass is a further characteristic used to define regolithic howardites [5].

Bulk Composition: The lunar regolith and regolith breccias are enriched in siderophile elements compared to the igneous precursors, due to meteoroid impacts adding chondritic debris to the regolith [10, 13]. This is clearly shown by elevated platinum group element abundances and to a lesser degree by Ni, due to the moderately high innate Ni contents of lunar igneous rocks [13]. Eucrites and diogenites contain much lower Ni, and the Ni contents of regolithic howardites are very elevated by inclusion of chondritic debris [5].

Discussion: Based on a concordance of high ^{20}Ne contents, elevated Ni contents, and glass abundance with a narrow range in Al contents, the suggestion was made that such regolithic howardites may represent lithified, ancient, well-mixed regolith [5].

It has long been appreciated that the analogy between howardites and lunar regolith and regolith breccias is imperfect [e.g. 4]. For example, even correcting for diminished solar wind flux at Vesta compared to the Moon, the ^{20}Ne content of regolithic howardites is lower than found for mature lunar regolith breccias [5].

However, other environmental factors have also conspired to weaken the analogy between lunar and vestan regolith development, and the impact environment is probably the controlling factor. The cratering rate in the asteroid belt is higher, causing more rapid turn-over of the surface, and thus a shorter residence time in the environment affected by solar exposure [14]. The amount of regolith developed is also different: Over the same time period, it is estimated that a Vesta-sized body at 3 AU would develop a regolith that is 50 times thicker than a regolith developed on a similarly sized body at 1 AU [14]. The size of the body being impacted is also an important factor: It is estimated that a Vesta-sized body at 1 AU would develop a 4 times thicker regolith than does the Moon [14].

Another parameter is the collision speed for impactors on Vesta, compared to those on the Moon. The median impact speed for Vesta is 4.6 km s^{-1}, with 64% of impacts occurring at <5.5 km s^{-1} [15]. In contrast, the average impact speed for near-Earth objects on the Moon is calculated to be ~22 km s^{-1} [16].

At the high speed of impacts typical of the lunar environment, the impactors are essentially completely destroyed. This is evident from the almost total lack of identifiable chondritic debris in lunar soils and regolith breccias [17]. At the lower average speed of impacts on Vesta, a substantial fraction of the impactors survive and are incorporated into the regolith. Chondritic clasts, mostly CM and CR chondrites, are commonly found in howardites [e.g. 18, 19] and sometimes in polymict eucrites [20] and diogenites [21].

Because of the lower mean impact speed on Vesta compared to the Moon, interpretation of a polymict breccia of regolithic origin can be problematic if based too literally on the lunar experience. Low velocity collisions may result in locally-distributed, poorly-mixed, fragmental polymict breccias that contain abundant and intact chondritic debris. These breccias will have high siderophile element contents, without having spent much time in an active regolith. PRA 04401 is possibly an example of this. Our bulk rock sample (4.9 grams homogenized) contains 4440 µg g^{-1} Ni [6], which is equivalent to containing ~35% CM chondritic debris. Companion thin sections are dominated by ~60-70 vol% chondritic clasts [22]. (However, other petrologic characteristics of this howardite do suggest that it might be regolithic [7].) Several of the other howardite samples we prepared contained metal nuggets of 10-20 mg in mass, which might represent chondritic debris; investigations of these are planned.

As chondritic debris is not extensively heated during low velocity impact, such material may retain much of the original volatile element component. Thus, high ^{20}Ne contents could be due in part to trapped planetary gases, rather than SW implanted gases. This would be discovered during noble gas analyses typically done for meteorites [e.g. 12].

Because a much smaller fraction of impacts on Vesta are at speeds >5 km s^{-1} than is the case for the Moon, impact-melt production would be much less efficient (c.f. Fig. 5.3 of [23]). Petrographically, the abundance of rounded, reworked clasts (polymict breccia clasts, with or without impact-melt matrix) may be a better indicator of residence time in the vestan regolith. The proportion of impact glass should also increase with increasing time spent in the active regolith, though the abundance of impact glass may remain relatively low when compared to mature lunar regolith and breccias made from it.

Summary: The Dawn spacecraft will arrive at 4 Vesta in July to begin a year-long study from orbit [24]. The spacecraft will be mostly observing regolith, and thus an improved understanding of regolith development on Vesta will aid in interpreting the returned data. Although it has long been known that howardites differ in detail from lunar regolith breccias [e.g. 4], only recently has a distinction between regolithic and fragmental howardites been attempted [5]. The high impactor flux, lower mean impact speed and smaller size for Vesta compared to the Moon [14-16] combine to cause a distinctly different evolutionary path for regolith development on the former. Siderophile element contents need to be evaluated in concert with petrology to ensure that chondrite-rich fragmental breccias are excluded. Glass abundance might remain low even in mature vestan regolith; the abundance of reworked clasts may be a better petrologic marker of maturity.

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