Stratigraphy of a Basaltic Planetoid - 4 Vesta and the HEDs.

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Introduction: The stratigraphy of a planet (or a planet-like body) is the sequence of layers in the crust of the body, but is more generally also the sequence of events starting with accretion and evolving through whole-body differentiation and global stratification to the present time. On the Earth, stratigraphy derives from the synthesis of field evidence, of the three dimensional structure of the crust, mantle and core, with spatial and temporal constraints from a variety of measurements that integrate all sub-disciplines of the planetary sciences. To determine the stratigraphy of Vesta, comparable data must be generated. The major processes responsible for the evolution of that planet-like body are: initial accretion, heating leading to the onset of whole body differentiation probably with segregation of core, mantle, crust and loss of volatile/hydrophilic components, later large scale impacts, continued accretion with impact driven erosion and deposition, continuing differentiation and metamorphism/homogenization of the near surface lithologies, sedimentary reworking on the surface at all stages and the role of space exposure in modifying surface breccias.

Prominent among the subdisciplines of stratigraphy are chronology, surface mapping and petrology. Radioisotope chronology is fundamental to the creation of a stratigraphic column, but is impractical for the entire gamut of samples. There are simply too many samples and many are unsuitable, often because of limited size. A complete stratigraphy incorporates many measurements of relative position of different lithologies *in sequences* that reflect both the times AND context of their formation. Contemporaneous events that occur in different spatial and environmental context, must be recognized and correlated if they are to be used to constrain the stratigraphy. Surface lithological mapping at all scales on the surface of the planet and matching those results with lithological characteristics of samples provide the first level of correlation among events.

Observations of Vesta: 'Field' evidence from direct observations of Vesta currently provides relatively coarse constraints on the stratigraphy of the planetoid. However, a dichotomy between lowland (S. polar basin) and highland (northern hemisphere) regions of the body represents a major stratigraphic event (the largest preserved impact on Vesta) equivalent to the lunar and Martian dichotomies between earlier highland and later lowland provinces. The Dawn mission to Vesta[1] will provide fairly detailed lithological mapping of the surface of the body in both these provinces that will show the surface diversity of the body at kilometer scales and provide more detail of lithological superposition. The cratering history of the body derived from the Vesta imagery will provide a relative chronology that hopefully can be calibrated from sample data.

Observations from Samples: To achieve finer spatial and sequence resolution, the best source of information available remains the petrology of the putative Vestan meteorites – the HED suite. As the Dawn mission to Vesta and Ceres becomes imminent[2], the role of the HED suite as samples of that body increase in importance. Of the three HED subgroups, howardites, eucrites and diogenites, the howardites provide by far the most diverse sampling of their parent planetoid and provide more context of the temporal and spatial lithologies on their parent body than any other group. The major difficulties in working with the howardites are first, that they are breccias and second, that the individual unbrecciated lithologies present as clasts are often occur as, possibly unrepresentative, tiny samples. However, using the HED meteorites as representative of Vesta, numerous significant events may be inferred and recognized.

Early A*ccretion:* Most oxygen isotopic signatures for HED samples are clustered about a distinct mass-fractionation line with $\Delta^{17}O$ = -0.2n [3] as is expected of a planetary body on which global differentiation has homogenized accreting oxygen reservoirs[3]. Those reservoirs are generally consistent with binary mixtures of preplanetary, i.e. ordinary and carbonaceous chondrite precursors. (Depending on the choice of specific components, ~70-80:~30-20 mixtures are compatible, though there is no unique solution.[4] Notably several meteorites and objects within meteorites are displaced from this iso-$\Delta^{17}O$ line suggesting they result from slightly different ratios of pre-planetary components. The deviations of $\Delta^{17}O$ may reflect the existence of multiple small parent bodies, each of which is assumed to have completely homogenized its oxygen isotope reservoirs, a property expected of planets. Alternatively, the $\Delta^{17}O$ deviations occur on a single body for which complete homogenization has not occurred – perhaps a body that has not fully achieved whole body differentiation and is planetoidal rather than fully planetary, perhaps like Vesta.[5]

Global Differentiation: The formation of surface basalts on celestial bodies suggests that the body has undergone differentiation leading to formation of a crust, mantle and core, perhaps in the presence of an atmosphere and hydrosphere, the classic signature of planet formation. The eucrites and mafic clasts in howardites are all basaltic. The diogenites easily fit within a scheme of basalt differentiation near the surface of a planet(oid). In a planetary context, formation of basalts by fractional crystallization or by partial melting mechanisms will depend on the local/regional context of magmatism more than on the global pattern of differentiation. Thus in addition to the timing of differentiation, the spatial context of melting within the body is important to stratigraphic correlation across the body. The recognition of correlated lithologies or, more usefully, suites of lithologies, in howarditic breccias is a fundamental goal.

Impact Processes: Brecciation, comminution and mixing of lithologies by impact is both the greatest difficulty to interpreting the HEDs and Vesta and provides the best toolkit for creating a stratigraphy of the planetoid. The dichotomy producing event, that resulted in the southern basin province is the most visually striking division in the history of the body. Highland province breccias will contain evidence of *all* episodes in Vestan history possibly as discrete layers. Lithologies from the southern province may well be dominated by breccias whose ages post-date the dichotomy event because earlier events were obliterated in this region by the lowland basin forming processes. Impact melts from each province may provide the chronology of these events. The deep excavation of the southern basin, exposes buried lithologies not seen in the northern highlands. Large ejecta, from the southern lowlands, that are equated with Vestoids should be dominated by older lithologies and breccias from shallower sites on Vesta, (unless they contain relicts of older large scale impacts that were obliterated by the dichotomy event). Stratigraphically the provinces of Vesta and the Vestoids have the potential of sampling periods of Vestan history that may be petrographically and chronologically distinct. Impact melts generated at all ages can provide the chronology of impact.

Metamorphic Overprints on HED: Recrystrallization and homogenization of mineral grains are well known metamorphic effects in eucrites and are often associated with major impact events. Textures suggesting homogenization processes are common in lithic fragments in howardites. The fine grained matrix of most breccias generally shows relatively little evidence of homogenization. Implying that the breccias did not see as much metamorphism as the included clasts. Metamorphism therefore predates the formation of some howarditic breccias. Exceptions to this occur however, and metamorphosed polymict breccias have been recognized[6]. In addition assemblages similar to the metamorphic overprints seen in mesosiderites (reverse zoning in pyroxene, Fe/Mn/Mg indications of Fe mobility, olivine reaction rims or coronas) occur in a howardites like Winterhaven[7]. Metamorphism thus occurs pre- and post- brecciation, i.e. early and late in the history of many meteorite source regions prior to impact brecciation and transport and subsequent to brecciation.

Lithological Patterns on the surface of Vesta: Identifying clusters of meteorites with common magmatic, metamorphic and impact histories should provide guidance to their relative location on the surface of their planetoid. The variation of mafic clast compositions and diversity among the various eucrites and diogenites demonstrates that the basaltic planetoid had localized magmatism from its earliest history until late impact (sedimentation) gardening of the breccias. The identification of distinct fractionation patterns among lithic clasts, in addition to those seen in monomict eucrites (Stannern and Nuevo Laredo trends). If individual magmatic trends can be identified in two or more polymict breccias then localized magma sources on Vesta and their relative timing may be accessible.

Ejection from Vesta: Cosmogenic isotope ages of the HEDs require several ejection events from Vesta, or from the Vestoids. These events provide a potential correlation mechanism among individual meteorites that were ejected from the same source craters. The ejection events are also the last events seen in the meteorites that reflect events on the parent body. Whether these events occurred on Vesta itself or on individual Vestoids is an issue that remains to be resolved.

Stratigraphy on a Basaltic Planetoid: Evidence for events, and sequences of events is present in the HED meteorites and particularly in the polymict continuum from polymict diogenites through howardites to polymict eucrites. Early accretionary processes suggested by stable isotope results, early magmatism, the onset of planetary differentiation, and continued magmatism from both petrographic observations and radioisotope chronology give way to later impact events. Impact and metamorphic overprints punctuate the stratigraphic record and provide markers to be exploited for defining the evolution of provinces on Vesta and the Vestoids.

While the detailed stratigraphic column for HED meteorites and by extension Vesta does not yet exist, by focusing on the relationships of lithic and mineral clasts to one another, chronologically, petrographically, and chemically, the stratigraphic units and sequences that define the evolution of a planetoid to a fully differentiated and homogenized planet.

References: [1] McSween et al. 2010, *SSR;* [2] Russell et al. 2007 *EMP* **101;** [3] Greenwood et al., 2005, *Nature*, **435**, 918; [4] Boesenberg & Delaney 1997, *GCA* **61**, 3205; [5]Delaney, J. S., 2010, **LPSC XLI,;** [6]Delaney et al 1982 *JGR* **87;** [7] Boesenberg this meeting.