NEW DATA ON THE CHEMICAL COMPOSITIONS OF SILICATES IN HED METEORITES: VARIETY IS THE SPICE. A. Patzer, Institute for Planetology, University of Muenster, 48149 Muenster, Germany (apatzer@uni-muenster.de).

Introduction: Howardites, eucrites, and diogenites (HEDs) are achondrites and can be linked to asteroid 4Vesta as their major source [e.g., 1]. Eucrites are mafic rocks essentially composed of plagioclase and pyroxene; diogenites include coarse-grained orthopyroxenites, harzburgites, and dunites; howardites are fragmental breccias predominantly consisting of eucrite and diogenite debris. To date, many different eucrites and diogenites, but clearly fewer howardites, have been studied [e.g., 2, 3 and references therein].

In the course of this study, 21 thin sections of 16 different, new Antarctic howardites were examined and more than 4500 spot analyses on major and minor silicates of HED provenance collected. Results show that the range of elemental compositions of pyroxene, plagioclase, and olivine in HED meteorites is significantly larger than previously recognized. In addition, they shed more light on the lithological variety inherent to their parent body. In conjunction with recent reports on late-stage assemblages and gabbroic eucrite clasts in howardites [4, 5], data strongly suggest that the formation of highly evolved magmas through extensive magmatic fractionation played a quantitatively minor, yet petrologically significant role on Vesta. In addition, the comprehensive set of new data was used to estimate a bulk composition of Vesta's upper crust.

Results: *Plagioclase.* The average composition is $An_{88\pm6}Ab_{12\pm6}Or_{0\pm1}$ (1340 analyses; total range: $An_{46-98}Ab_{2-52}Or_{0-9}$). Usually, anorthite contents scatter between ~75 and 95 % (Fig. 1a). Lower concentrations (An_{46-74}) are less common and appear to be restricted to gabbroic eucrites. The lowest anorthite contents were detected in a mm-sized feldspar clast, a small unusual feldspar-olivine fragment, and a few groundmass grains in howardite PCA 02066. Compositional data of these three components form a distinct cluster at $An_{46-52}Ab_{46-52}Or_{1-3}$ (Fig. 1a). Aside from relatively sodic compositions, feldspars in gabbroic eucrites may also be as calcic as An_{98}. Orthoclase contents are usually negligible (Or_{0-2}; in isolated cases: Or_{3-4}; also: rare localized concentrations of up to Or_9).

Pyroxene. The average composition is $En_{54\pm20}Fs_{36\pm13}Wo_{10\pm12}$ (2815 analyses; total range: $En_{1-88}Fs_{11-84}Wo_{0-46}$). In many samples, the majority of data points tend to show relatively MgO-rich compositions ($En_{\sim60-80}$; Fig. 1b). Regolith-like howardites LAP 04838 and MIL 05085 exhibit the largest variability, including distinctly FeO-rich species ($En_{1-77}Fs_{16-84}Wo_{2-46}$ and $En_{1-82}Fs_{17-84}Wo_{1-43}$, respectively).

Olivine. Olivine compositions vary over a range of Fo_{6-92} (369 analyses). The spectrum sampled is almost continuous, only showing a small gap at Fo_{38-40}.

Discussion: *Plagioclase.* Feldspars in eucrites (An_{75-96}) and diogenites (An_{83-96}) have been known to be calcic [3, 6, 7]. Among the eucrites, the basaltic and cumulate subtypes show diagnostically different abundances of anorthite (An_{75-90} and An_{90-96}, respectively).

Anorthite concentrations in plagioclases observed here mostly coincide with endmember compositions established before. The entire spectrum detected, however, is much larger ($An_{46-98}Ab_{2-52}Or_{0-9}$) and includes a more or less continuous trend from An_{63-98} (Fig. 1a).

Monomineralic feldspar debris yielding relatively low anorthite contents of 66-73 % is most likely derived from gabbroic eucrites. Gabbroic eucrites are medium-grained igneous rocks that include primitive and highly differentiated lithologies [4, 5]. Primitive (unequilibrated) members of this group contain chemically heterogeneous plagioclase with An_{70-98}. The most calcic feldspars (An_{93-98}), however, only account for trace or very minor amounts. They typically occur in olivine veinlets sometimes crisscrossing gabbroic pyroxene. Feldspars associated with three-phase symplectites, i.e., those in evolved gabbroic eucrites, show anorthite abundances of 66-88 %.

The source of small plagioclase grains as sodic as An_{63-65} remains ambiguous. The grains possibly formed in a fashion similar to a feldspar inclusion (An_{61}) observed in a high-Mg pyroxene clast (En_{75}) and, thus, may be of diogenitic origin.

Pyroxene. Principally, pyroxenes in diogenites are relatively MgO-rich (En_{71-77} [3]; En_{65-76} [7]), those in eucrites are more variable and more FeO-rich ($En_{<65}$). Among the eucrites, pyroxenes in the cumulate subtype are more magnesian (En_{46-65}) than those of basaltic samples ($En_{<46}$) [6]. Pyroxenes in gabbroic eucrites yield the broadest spectrum of endmember compositions: those in unequilibrated members tend to be relatively magnesian (up to En_{67} [5] and En_{69} [8 and references therein]), while those in evolved gabbroic eucrites may be as ferroan as Fs_{84} [4].

In accordance with endmember compositions reported for diogenites and the different groups of eucrites, those observed here are highly diverse and include many so-called forbidden types. A certain fraction of the more common, relatively MgO-rich compositions (En_{60-80}) are probably of diogenitic provenance (in particular fragments with En_{70-88}). Pyroxene debris

of $En_{\sim 60\text{-}70}$, however, may also be derived from cumulate and/or gabbroic eucrites.

On the opposite end of the spectrum stand distinctly FeO-rich pyroxene compositions. Many of them are metastable varieties that may have been associated with three-phase symplectites and can be linked to evolved gabbroic eucrites [4]. Six out of 16 howardite samples contain fragments of and/or clasts bearing three-phase symplectites (typical cases in ALH 09004, LAP 04838, MIL 05085, and PRA04402; anomalous cases in MIL 07007 and QUE 99033). This observation supports the conclusion drawn before that three-phase symplectites represent a minor, yet not unusual component of HED meteorites [4]. Thus, the presence of highly evolved magmas on Vesta may be more widespread than previously believed.

In terms of atomic Fe and Mn, the HED parent body has been reported to yield a ratio of about 30 [10]. On average, this value can be confirmed (31 ±3; total range: 14-69; typically 24-36; rare: <20). In general, pyroxenes from gabbroic eucrites tend to show slightly higher Fe/Mn whereas augites from basaltic eucrites tend to display lower values. Diogenites (as deduced from orthopyroxene debris of $En_{70+}Wo_{<3}$) yield ratios basically indistinguishable from those of eucrites (average: 30 ±2; typically 25-35).

Olivine. Olivine in diogenites is relatively magnesian (usually $Fo_{65\text{-}76}$ in harzburgites [3], up to $Fo_{92.5}$ in dunites [9]). Gabbroic eucrites often exhibit trace or minor amounts of fayalitic olivine ($Fo_{6\text{-}36}$) occurring in interstices and/or veins up to ~100 μm across [4, 5]).

The compositional gap at $Fo_{38\text{-}40}$ detected in the olivines examined here appears to reflect the dichotomy of sources: Olivine debris of $Fo_{6\text{-}36}$ – possibly including a couple of small grains with Fo_{37} – is likely derived from gabbroic rocks, and that of $Fo_{41\text{-}92}$ probably originates from diogenites. Grain sizes observed are consistent with this distinction. Olivine fragments exhibiting $Fo_{41\text{-}50}$ are rare, small, and could arguably come from gabbroic eucrites as well. Regardless of this uncertainty, however, different Fe/Mn trends emerge: Excluding a very small number of oddities, olivines from eucrites yield an average Fe/Mn of 45 ±3 (typically 40-50), those from diogenites an average ratio of 53 ±10 (typically 50-60).

In essence: End member compositions observed for pyroxenes and plagioclases of HED provenance are $En_{1\text{-}88}Fs_{11\text{-}84}Wo_{0\text{-}46}$ and $An_{46\text{-}98}Ab_{2\text{-}52}Or_{0\text{-}9}$, respectively. Average compositions are $En_{54\pm20}Fs_{36\pm13}Wo_{10\pm12}$ and $An_{88\pm6}Ab_{12\pm6}Or_{0\pm1}$, respectively. The average Fe/Mn of pyroxenes is 31±3 (total range: 14-69, typically 24-36). Regarding olivine in howardites, two major sources can be distinguished: diogenites and gabbroic eucrites. Diogenitic olivine is more magnesian than that of gabbroic eucrites ($Fo_{\sim 43\text{-}92}$ vs. $Fo_{6\text{-}37}$). It also exhibits a relatively high average Fe/Mn (53±10 vs. 45±3).

Based on data from image processing, the average fractions of pyroxene and plagioclase in howardites are approximately 60 and 30 vol%, respectively. Olivine and silica contribute ~4 vol% each, and opaque phases sum up to ~2 vol%. Using average mineral data and assuming extensive gardening and mixing of upper rock layers on the HED parent body, a bulk composition for Vesta's upper crust can be derived. This upper crust contains approximately 50 wt% SiO_2, 18 % FeO, 13 % MgO, 9 % Al_2O_3, and 7 % CaO.

References: [1] De Sanctis et al. (2012) *Science*, *336*, 697-700. [2] BVSP (1981) *Basaltic Volcanism of the Terrestrial Planets*, Pergamon New York, pp. 214-35. [3] McSween et al. (2011) *SSR*, *163*, 141-74. [4] Patzer and McSween (2012) *MAPS*, *47*, 1475-90. [5] Patzer and McSween (forthcoming) *MAPS*. [6] Mayne et al. (2009) *GCA*, *73*, 794-819. [7] Beck and McSween (2010) *MAPS*, *45*, 850-72. [8] Barrat et al. (2011) *GCA*, *75*, 3839-52. [9] Beck et al. (2011) *MAPS*, *46*, 1133-51. [10] Papike et al. (2003) *AM*, *88*, 469-72. [11] Lindsley and Andersen (1983) *JGR*, *88*, A887-A906.

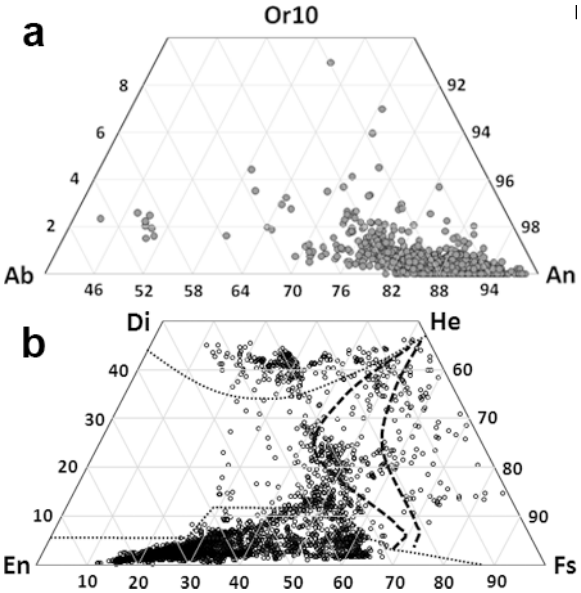

Fig. 1. a) Ternary diagram (cropped) displaying endmember compositions of plagioclase (Ab = albite, An = anorthite, Or = orthoclase). The majority of data points plot in the range established for eucrites and diogenites ($An_{\sim 75\text{-}95}$). The total spectrum observed, however, is clearly more diverse. b) Quadrilateral diagram displaying endmember abundances of pyroxene (En = enstatite, Fs = ferrosilite, He = hedenbergite, Di = diopside). Dashed lines define the boundary of "forbidden" compositions [11]. This zone retreats with increasing pressure (shown are the boundaries at 1 atm and 5 kb, respectively). Compositions exhibiting >70 % enstatite are most likely of diogenitic origin, those of approx. 60-70 % enstatite may also be derived from unequilibrated gabbroic eucrites.