Nature of five polymict eucrites from the Antarctic Yamato dense collecting area

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The howardite-eucrite-diogenite (HED) clan of meteorites represents the largest suite of achondrites in the current meteorite collections. They formed at surface and subsurface conditions or in igneous processes on their parent body, most likely the differentiated asteroid 4 Vesta - the second most massive body in the asteroid belt (e.g., Binzel and Xu, 1993). The HEDs do not only include magmatic rock types, but are typically metamorphosed and brecciated to varying degree caused by impact bombardment, and internal heating of the parent body, often obscuring their primary magmatic textures (e.g., Metzler, 1995). They consist of different lithic fragments, containing unusual lithologies, such as exogenous impactor materials (see review by Mittlefehldt et al., 2015 and refs. therein) and Fe-enriched veins crosscutting pyroxenes that might have formed during late-stage alteration events. Here we investigate the petrography and chemistry of rock-forming silicates, glasses and secondary phases in five, so-called polymict eucrites, including Yamato (Y-) 74159-114, Y-75011-114, Y-793548-66, Y-82210-101, and Y-74450-113 from the Antarctic Yamato collection at the National Institute of Polar Research to better constrain their complex formation environments and thermal evolution. Polymict eucrites are regolith breccias consisting of rock fragments that may contain coarse mineral and lithic clasts of basaltic and/or cumulate eucritic and less than 10% diogenitic material, embedded in a fine-grained clastic, or fragmented to glassy matrix, formed by impact comminution and localized mixing. Due to the great variety of textures and mineral compositions, they are of great importance for understanding crustal processes on differentiated asteroids. Sample textures were examined using a JEOL 6510-LA scanning electron microscope (SEM) and the chemical compositions of the rock-forming silicates, secondary phases and glasses were determined using a JEOL 8530F field emission electron microprobe (EPMA), both at the Institute for Mineralogy, University of Münster, Germany.

Lithologies: Four dominant textures are identified: ophitic to porphyritic, equigranular, subophitic, and quench-textures, present within several samples. Post-magmatic features occur in different intensities, varying from clast to clast, and even among coexisting mineral fragments. All five eucrites contain clasts and partly coexisting mineral fragments that show evidence of different metamorphic degrees, suggesting a complex evolution and probably repeating metamorphic overprint and mixing of lithologies. For instance, pyroxenes within subophitic lithologies are slightly zoned and/or equilibrated. Large, clearly zoned pyroxenes from quench-textured lithologies represent the least overprinted lithology among the analyzed samples. Except for Y-75011, all remaining eucrites (Y-82210, Y-74159, Y-793548 and Y-74450) contain large clasts with equigranular textures, covering at least one half of the thins sections and consisting of large angular, predominantly equilibrated pyroxene and plagioclase fragments in varying sizes (up to 0.5 mm), set in fine-grained silicate matrix. Yamato 74159 and Y-74450 are stronger metamorphosed, i.e., clouding of silicates and presence of several µm-sized augite-exsolution lamellae. Fragments of SiO_2 and ilmenite are essential part of observed mineral assemblages. Accessory phases, such as olivine, troilite, Ca-phosphates, chromite, impact melt-glasses, dark mesostasis, and iron metal are present. Some plagioclase crystals exhibit pyroxene inclusions.

Glasses: All five eucrites contain glasses within a variety of textures that either formed by impact melting and/or result from pyroclastic melts upon quench-cooling. As both types of melt can exhibit a wide range of structural characteristics, discrimination is difficult. However, pyroclastic melt mostly occurs as homogeneous, amorphous glasses without any crystalline phases and impact glasses with similar chemical compositions but different textures may have formed during the same event but at different cooling rates (Singerling et al., 2013). Thus, the intrasample chemical homogeneity may be a useful discriminant. Barrat et al. (2012) identified two main-groups of glasses: *high Fe/Mg* with >>10 and *low Fe/Mg* with <5, with the latter being subdivided into low-alkali, K-rich (K_2O >0,2 wt.%) and Na-rich (Na_2O >0,6 wt.%). Glass compositions of the studied eucrites indicate a relationship to the *low Fe/Mg*-type, and further sub-group of *low-alkali-melts*. In fact the chemical signatures of analyzed glasses range between pyroxene and plagioclase data and therefore can be due to mixing of both minerals, supporting that low-alkali-melts are melt-products of bulk rock material, as suggested by Singerling et al. (2013).

Secondary ferroan phases in HED-meteorites are present as ferroan olivine veins with widths of up to 20 µm and Fe-enrichments along preexisting cracks in pyroxene crystals, often accompanied by small grains of troilite, chromite and secondary anorthitic plagioclase (e.g., Warren, 2002; Barrat et al., 2011; Roszjar et al., 2011; Pang et al., 2017) and likely formed by several different processes to explain all petrologic features observed. Two fundamentally different processes are discussed: influence (i) of a fluid phase, i.e., metasomatism (Warren, 2002; Barrat et al., 2011), and (ii) of a high temperature process due to re-melting of late crystallized phases (e.g., Warren, 2002) or incongruent in-situ melting induced by thermal annealing (Roszjar et al., 2011). Among the studied polymict eucrites, secondary phases are observed in both unequilibrated and equilibrated pyroxenes and along thermally or mechanically induced cracks within pyroxenes. They are more frequent within pyroxenes from granular lithologies and not restricted to large crystals. Therefore, the general degree of metamorphism seems to be insignificant, indicating a thermally independent post-magmatic process after- or during brecciation and/or thermal annealing, either induced by interaction with a fluid phase, in a high temperature event, or a combination of both.

Silicate chemistry: In general, rock-forming pyroxene and plagioclase crystals of all analyzed polymict eucrites show chemical compositions typical for basaltic material (e.g., Mayne et al., 2009; Barrat et al., 2011; Mittlefehldt et al., 2015; Pang et al., 2017). Pyroxenes in quenched and subophitic textures follow a continuous Mg-Fe-Ca-trend, whereas zoned pyroxenes of equigranular texture reflect an igneous Mg-Fe-trend, while equilibrated, homogeneous grains are even more enriched in Ca. Ophitic to porphyritic textures of Y-75011 follow a Mg-Fe-Ca-trend. In addition and according to Mayne et al. (2009) core data of some unequilibrated pyroxenes match cumulate composition, based on restricted molar Fe/Mn ratios. Plagioclases encompass values of An_{71-95}, again typical for basaltic eucrites, but with little variation in K, suggesting a slight K-depletion. Plagioclase compositions of distinct textures show a different extent in variation: equigranular or ophitic to porphyritic textures indicate a larger extent, resulting from different origins of single crystals. On the contrary, both the quench- and subophitic textures exhibit limited chemical variation, again underlining a common origin of the host rock.

Conclusions

A variety of lithic textures in five polymict eucrites are observed, indicating multiple shock-events, intense post-magmatic thermal annealing and alteration. Four dominant lithic textures are identified: ophitic to porphyritic, equigranular, subophitic, and quench-textured, present within several samples and indicative for a common origin of the investigated polymict eucrite and formation at equal conditions involving at least partially similar source materials. However, temporal evolution of variable lithologies is difficult to discern, as pre-and post brecciation processes have occurred. These post-magmatic features occur to different intensities, varying from clast to clast or among coexisting mineral fragments on a small spatial resolution. Regions of impact glasses are identified with a variety of textures and compositional affiliation to the main-group of *low Fe/Mg* and low-alkali-source melt. Secondary ferroan olivine and Fe-enriched veins along preexisting cracks in pyroxene crystals are observed in all types of clasts, sporadically accompanied by small grains of troilite, chromite and secondary anorthitic plagioclase, indicative for post-magmatic processes, which either require interaction with a fluid phase, or a high temperature event or both. The formation of secondary phases seems to be independent of the degree of metamorphism and may have happened during each stage of evolution. Various clast types show evidence of different thermal metamorphic degrees that indicate a complex evolution of formation and probably repeating metamorphic overprint on 4 Vesta and thus complex crustal processes.

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