SUBSOLIDUS MICROSTRUCTURES AND COOLING HISTORY OF PYROXENES IN THE ZAGAMI SHERGOTTITE Adrian J. Brearley, Institute of Meteoritics, Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131.

The Shergottite meteorites are a small, but extremely important group of achondritic meteorites, whose young crystallization ages set them apart from the eucrites and other basaltic achondrites. The two shergottite meteorites, Shergotty and Zagami are petrologically and chemically similar to terrestrial diabases and have both experienced moderate shock pressures (~30GPa) resulting in the formation of maskelynite glass from plagioclase. Petrogenetic studies of Zagami and Shergotty suggest that these two meteorites formed by igneous processes on a large, geologically active planet, such as Mars. Although a Martian origin for the shergottites (and other SNC meteorites) is currently favored [1,2,3] based on a variety of evidence, it is not yet proven. A fuller understanding of the mineralogical, chemical and isotopic characteristics of the shergottites may help constrain the possible sources of these meteorites more fully. The Zagami Consortium has been initiated to provide a comprehensive study of the petrography, mineralogy, chemistry and shock characteristics of this meteorite. The present studies are being carried out on two distinct lithologies of Zagami characterized by their different grain sizes, which were obtained by the Institute of Meteoritics, University of New Mexico in 1988.

Important constraints on the geological form (e.g. extrusive or intrusive) of the igneous body from which Zagami originates can potentially be obtained from microstructural studies of subsolidus textures in silicate minerals, e.g. pyroxenes. Specifically, such studies can help constrain the thermal regime under which cooling of the igneous body occurred. Additionally, information on the shock levels experienced by individual mineral phases can also be obtained from microstructural studies. The present study reports the first transmission electron microscope (TEM) observations of pyroxenes from Zagami, from both the coarse and finer grained lithologies mentioned above.

During crystallization of Zagami augite and pigeonite coprecipitated in approximately the proportions 50:50 according to [1]. Although exact modal proportions were not determined in this study the abundances of pigeonite and augite appear to be consistent with these values. Individual pyroxene grains in suitable crystallographic orientations were selected optically based on the presence of fine striations, indicative of either fine-scale exsolution or shock lamellae. These grains were subsequently studied by backscattered electron imaging and electron microprobe analysis. As found by [1], the pyroxenes are compositionally zoned with Mg-rich cores and Fe-rich rims. BSE images show that the Mg-rich cores constitute the bulk of individual grains and that they are highly irregular in shape. The width of the Fe-rich rim consequently varies significantly on any single grain from 10 to 100 μm. The morphology of the Mg-rich cores is additional evidence that they represent primary phenocrysts in the magma [1], which were subsequently resorbed or underwent reaction with an intercumulus liquid resulting in the formation of late Fe-rich overgrowths. Core to rim electron microprobe analyses of zoned pigeonite grains show that the cores are homogeneous with compositions of $En_{60}Fs_{32}Wo_8$ and the rims are zoned to iron-rich compositions of $En_{33}Fs_{51}Wo_{16}$.

After full characterization by electron microprobe, individual pyroxene grains were studied by TEM and analytical electron microscopy (AEM). A one to one correspondence between TEM observations, BSE images and microprobe analyses is thus possible. Initial observations have been carried out on pigeonites from the coarse-grained Zagami lithology and reveal a complex exsolution microstructure as well as localized shock effects. Two generations of augite lamellae have exsolved from pigeonite in both the Mg-rich cores and Fe-rich rims. The first set of lamellae exsolved parallel to (001) and are the thicker ranging from 20 to 300 nm in the cores and 50 to 120 nm in the rims. Mean lamellae widths are approximately 250 and 100 nm respectively, although lamellae are sometimes discontinuous and wedge out in the pigeonite host. Lamellae are typically spaced approximately 0.3 μm apart, but distances of up to 1 μm have been observed. In these extreme cases, very thin exsolution lamellae are present in between the thick lamellae and a precipitate-free zone ~250 nm wide is present adjacent to the augite lamellae. The second set of lamellae are significantly thinner and exsolved parallel to pigeonite

(100), cross cutting the thick (001) lamellae. This relationship is consistent with exsolution of the (100) lamellae at lower temperatures. The change of exsolution from the (001) orientation to (100) orientation during cooling is that reported by [4] in a lunar pigeonite. The thin (100) exsolution lamellae frequently terminate at the interfaces between the (001) augite lamellae and pigeonite host and probably nucleated heterogeneously at this interface. (100) lamellae are also frequently terminated within the pigeonite host like the (001) lamellae. The thicknesses of the (100) lamellae in both core and rim are comparable, ranging from 1.8 nm to 32 nm, although the majority of (100) lamellae are only 5-9 nm in width. The compositions of coexisting (001) augite exsolution lamellae and host pigeonite have been determined by analytical electron microscopy (Fig. 1). In the Mg-rich cores the host pigeonite is subcalcic (~$En_{64}Fs_{31}Wo_5$) and coexists with augite exsolution lamellae of composition $En_{40}Fs_{13}Wo_{47}$. In the Fe-rich rims the coexisting pigeonite and augite have compositions of ~$En_{43}Fs_{51}Wo_6$ and $En_{30}Fs_{23}Wo_{48}$. The compositions of the coexisting phases in both cores and rims record equilibration temperatures of ~950°C (±50°C) based on the experimentally determined 1 atm solvus of [5].

Based on microstructural studies of pigeonites from lunar samples [6,7,8,9] the relative cooling rates of the coarse Zagami pigeonites can be established. There is general agreement that the thickness of the exsolved augite lamellae in pigeonite is a function of cooling rate [8], provided that any comparison is between pigeonites of similar compositions. (001) exsolution lamellae in Zagami pigeonites are significantly thicker than those generally observed in lunar basalts. Lunar pigeonites typically contain augite lamellae ranging from 20 nm thickness to a maximum of 100 nm [6,7,8,9]. Zagami augite exsolution lamellae in the Mg-rich pigeonite cores reach thicknesses of 300 nm indicating a significantly slower cooling history than lunar basalts. Zagami also appears to have cooled more slowly than samples of Apollo 11 diabases and a terrestrial diabase studied by [6]. A slow cooling rate for Zagami is also indicated by the absence of a tweed microstructure in pigeonite, which is common in lunar basalts and results from spinodal decomposition during rapid cooling [8]. This process occurs at lower temperature after initial nucleation of (001) augite lamellae. In Zagami this second stage of exsolution is characterized by the nucleation of (100) augite lamellae below 950°C.

Conclusions: The exsolution microstructures in pigeonite from the coarse-grained Zagami lithology show that the cooling history of this rock was significantly slower than any lunar basalt so far studied. The microstructures are indicative of cooling at slow geological cooling rates [10], which by comparison with data from lunar basalts [11] must have been significantly less than 0.2°C/hr. Based on the schematic TTT diagram of [8] Zagami pigeonite may have cooled at least a factor of 10 slower (~0.02°C/hr) through the temperature interval 1100-950°C. These slow cooling rates suggest either that Zagami originates from a lava flow significantly thicker than 10 metrės or that comes from a shallow intrusive body such as a sill or dyke. The latter appears to be more likely and is consistent with the conclusions of [1]. Further studies of pyroxene microstructures in both coarse and fine-grained Zagami lithologies are currently in progress and should provide additional constraints on thermal histories.

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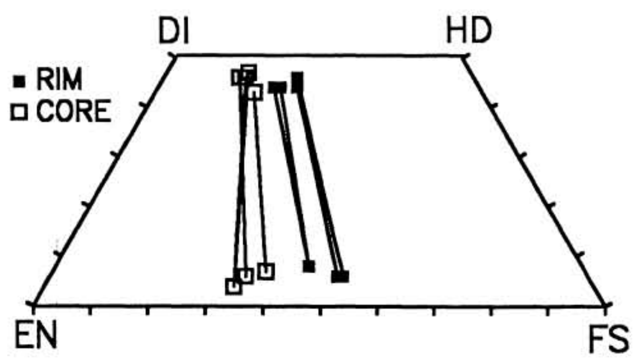

Fig. 1. Subsolidus phase relations of coexisting (001) augite exsolution lamellae and pigeonite host from Zagami determined by analytical electron microsopy.