SHERGOTTITE NORTHWEST AFRICA (NWA) 6963 A PYROXENE-CUMULATE MARTIAN GABBRO: CONSTRAINTS ON THE MINERALOGY, PETROLOGY, AND PHYSICAL PROPERTIES OF THE MARTIAN CRUST AT DEPTH.

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Introduction: Shergottites represent the largest portion of the Martian meteorite collection and, with increasing finds from Antarctica and the Sahara, their diversity in textures and age is expanding [1-7] - including Northwest Africa (NWA) 6963 that represents a coarse intrusive sample [8]. Shergottites are generally classified based on mineralogy and textures into the sub-classes: basaltic, olivine-phyric (ol-phyric) [9], and poikilitic previously called lherzolitic [10]. Basaltic shergottites are the most common subclass and have been interpreted to represent samples of near surface lava flows on the Martian surface [11, 12]. However, the original investigations of basaltic shergottites compared them with terrestrial diabases [13], and a recent investigation into the textures of NWA 6963 and NWA 7320 (originally classified as basaltic shergottites) have suggested that some basaltic shergottites are, in fact, gabbroic in nature and represent intrusive magmas [8, 7 respectively]. Here, we combine mineralogy, petrology, quantitative textural, shape-preferred orientation (SPO) of the pyroxenes, and spectral properties of gabbroic shergottite NWA 6963 to constrain whether it formed in a near surface flow or crystallized at greater depth as a gabbroic intrusion. Interestingly, intrusive magmas in the Martian crust should dominate the volcanism, producing coarse grained gabbroic rocks [e.g., 14], but gabbros are rare in the meteorite collection. Therefore, studying gabbroic rocks, such as NWA 6963, can help fill an important gap in our knowledge about the Martian crust at depth.

Sample NWA 6963: NWA 6963 was found in 2011 in Guelmim-Es-Semara, Morocco [15]. Based on the bulk chemistry and oxygen isotopes, it was classified as a Martian meteorite [16]. Originally, NWA 6963 was classified as a basaltic shergottite, based on the similarities of the mineralogy, chemistry, and textures with Shergotty – the type specimen of basaltic shergottites. However, additional investigations into the textures of the rock led to reclassification of the rock as a gabbroic shergottite because of similarity of the textures and crystal sizes to those of terrestrial and lunar gabbros [8].

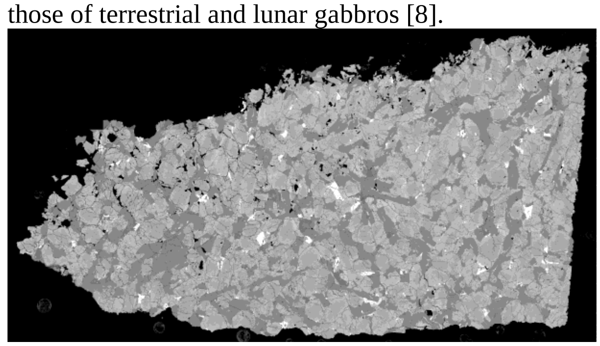

Figure 1. Backscattered electron image of a thick section of NWA 6963.

Methods: For this study we used the same 1.201 g slice of the meteorite from Martin Altmann and Stefan Ralew of "Chladni's Heirs" [8]. The same thick section from our previous study was used for the mineral chemical analyses, SPO, crystal size distribution, and Spatial Distribution Patterns (SDP) [8]. A second thick section and a thin section were made of the other half of the sample from our previous study (**Fig. 1**). These were used for mineral chemical analyses by electron microprobe (EMP), shock mineralogy analyses by petrography, microscopic Fourier transform infrared (μ-FTIR) spectroscopy, CSD, SDP, and microscopic X-ray fluorescence (μ-XRF). Further, parts of this other half were broken into chips and powders for major element (fused bead analyses by EMP), trace element (by La-ICPMS), and visible/near-infrared (VNIR) spectroscopy.

Results and Discussion: The bulk chemical composition of NWA 6963 is fairly typical of Martian meteorite basalts; it is low in Al and rich in Fe and Mg. NWA 6963 has lower Al_2O_3 than most of the basaltic shergottites and has the highest measured MnO content of ol-phyric and basaltic shergottites. It has a similar REE pattern to Los Angeles but is slightly more enriched in light REE and is significantly enriched in REE elements compared with Shergotty and Zagami –

the stones to which NWA 6963 was originally compared.

Mineralogically, NWA 6963 is similar to basaltic shergottites Shergotty and Zagami with pigeonite and augite (25 ± 5 vol. % augite and 40 ± 5 vol. % pigeonite) with lesser amounts (30 ± 5 vol. %) of plagioclase (now shocked to maskelynite); however, texturally NWA 6963 is distinguishable from these other meteorites. The VNIR spectrum of powdered NWA 6963 and the TIR spectrum of a thick section of NWA 6963 are very similar to the spectra of other shergottites in these wavelength ranges, which is consistent with the mineralogy of NWA 6963 being dominated by pyroxene, as are all basaltic shergottites. The VNIR spectrum of the chip of NWA 6963 is distinguishable from the other Martian meteorites, which we suggest is due to the gabbroic texture of NWA 6963. Further, the CSD profile (**Fig. 2**) for pyroxenes in NWA 6963 is similar to that for pyroxenes from the olivine-phyric shergottites EET A79001A and DaG 476 [17]. This trend differs from those of Shergotty and Zagami, which show a two-step crystallization history with first crystallization of pyroxene cores at depth followed by crystallization of rims after magma eruption [12]. Textures alone point to a cumulate crystallization history either from crystals entrained at the base of flow from crystal settling, or within an intrusive body, but cannot be used to calculate the depth of crystallization. Instead, the Ti/Al ratio of pyroxenes has been previously used to calculate the crystallization depth for Martian meteorites [20]. Pyroxene Ti/Al compositions in NWA 6963 are consistent with experimentally crystallized pyroxenes >5 and <10 kbar [20, 21]. Based on the similarity and differences between NWA 6963 and other shergottites, we propose the following crystallization history.

The parent magma to NWA 6963 first intruded the Martian crust, ponding in a magma chamber around 5−10 kbar (~40−86 km). If the models connecting the olivine-phyric and basaltic shergottites are correct [6, 18, 19], then olivine began crystallizing from the magma (the ol-phyric shergottite parental magma), settling to the base of the chamber, and driving compositional evolution of the magma. Next pyroxene joined the crystallization sequence, again settling to the bottom of the magma chamber. At some point, the magma passed the peritectic and only pyroxene crystallized from the magma (now the basaltic shergottite parental magma). Some of this magma plus pyroxene cores then erupted to the surface possibly making some of the basaltic shergottites (all of those with fine-grained mesostasis). Because not all magma erupts to the surface, this leaves behind magma plus

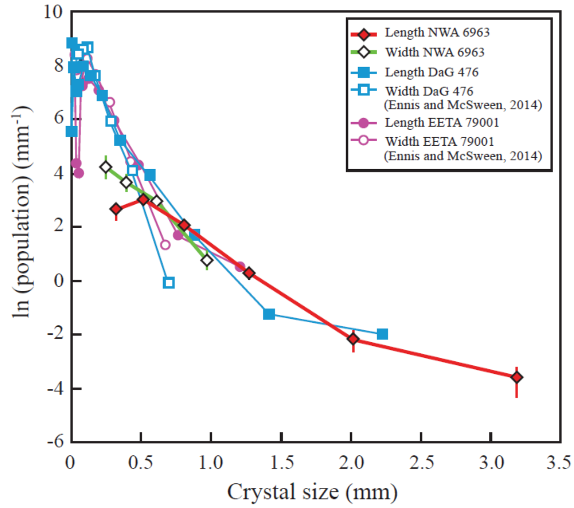

Figure 2. CSD patterns for lengths (solid symbols) and widths (open symbols) of pyroxene population in NWA 6963. DaG 476 and EET A79001 patterns from [17].

excess pyroxene in the case of NWA 6963 (or plagioclase in the case of NWA 7320 [7]). This magma−pyroxene crystal mush is then emplaced within the crust (at some pressure less than 7 kbar but higher than 1 bar) and finishes crystallizing to form NWA 6963. NWA 6963 represents a partial cumulate gabbro that is potentially associated with the basaltic shergottites, but the magma that formed NWA 6963 never made it to the surface of Mars. Therefore, NWA 6963 could represent the intrusive feeder dike system for the basaltic shergottites that erupted on the surface.

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