NAKHLITE NORTHWEST AFRICA (NWA) 5790: DISCUSSIONS ON COOLING RATE, OXIDATION STATE AND LACK OF ALTERATION.

C.M. Corrigan[1], M.A. Velbel[1,2]. [1]National Museum of Natural History, Department of Mineral Sciences, MRC 119, Smithsonian Institution, 10th St. and Constitution Ave. NW, Washington, DC USA (corriganc@si.edu), [2]Michigan State University, Department of Geological Sciences, East Lansing, MI, USA.

Introduction: The group of martian meteorites known as the nakhlites currently consists of eight meteorites (each individual often consisting of >1 paired stones). The nakhlites are thought to represent a coherent clinopyroxenite thick flow, dike or sill intrusion that was emplaced at or near the martian surface and subsequently disrupted by impact [1]. The nakhlite group as a whole shows internal variation between samples consistent with different formation depths within the nakhlite stack [2, 3]. The meteorites also show variation within individual paired samples [1].

The nakhlite Northwest Africa (NWA) 5790 (and its likely pair, NWA 6148) were found in Mauritania in 2009. [4] reported that the mineralogy of this meteorite is consistent with the rest of the nakhlites; it is a clinopyroxenite and modal analyses of their samples contained 51% pyroxene (augite), 9% olivine and accessory titanomagnetite (<1%). Olivines and pyroxenes retain primary zoning. In the description of NWA 5790 by [4], a complicated mesostasis containing feldspars, silica, merrilite, apatite, olivine, pyroxene, oxides and glass makes up the other 40% of the sample.

Methods: In the initial stages of this study [5], three sections of NWA 5790 were obtained from the Monnig Collection at Texas Christian University. Modal mineralogy was calculated from all three sections using mineral mapping techniques on the FEI NanoSEM at the Smithsonian Institution (Fig. 1), which is equipped with a THERMO-NORAN energy dispersive X-ray analytical system. This system was recently fitted with a Si-drift detector that has enabled more detailed elemental mapping. Refined modal mineralogy is being obtained using both methods utilized by [5] for the Miller Range (MIL) nakhlites.

Discussion: *How NWA 5790 stacks up:* [6] proposed a stacking order for the nakhlites based on Al_2O_3 values in the cores of pyroxenes. In this respect, NWA 5790 would have been the most exterior sample in the stack. [4] suggested that such high mesostasis abundance would indicate that NWA 5790 represents the chilled top of the nakhlite stack. Based on mineral chemistry and modal mineralogy (particularly the high abundance of mesostasis), [7] agreed that NWA 5790 would likely have formed at the edges of the nakhlite igneous body, but whether the top of the pile or the bottom is undetermined. Solidification fronts may have extended from both the top and the bottom of the nakhlite igneous body, as cooling progressed toward the center, similar to that discussed by [8].

Theo's Flow has been suggested as an analog to the nakhlite igneous body [9 and therein]. However, the distribution of zoned olivines and the inferred cooling histories of the nakhlites weaken the analogy. The top of the Theo's Flow peridotite layer is near the stratigraphic middle of the body - ~50 m below the cooling surface and ~70 m above the bottom of the body. Such mid-level material would cool slowly, and would have equilibrium compositions throughout each crystal rather than compositional zoning preserved by rapid cooling (as is observed in NWA 5790 and the MIL nakhlites; [10]). The compositional zoning of olivine in some nakhlites, and the inference that it results from proximity to a cooling surface of the nakhlite body [10], are inconsistent with the top of the nakhlite stack being in a mid-flow stratigraphic position similar to the top of the Theo's Flow peridotite interval. Consequently, (1) the nakhlite stack is not a cumulus layer like the Theo's Flow peridotite, and (2) there is no reason to expect that there exists an unsampled supra-nakhlite igneous lithology (as proposed by [9]).

Skeletal olivine and implications for cooling rate: To interpret the skeletal growth of the last olivine to crystallize in NWA 5790 (Fig. 2), the composition of the late-stage melt from which it crystallized must be constrained. NWA 5790 mesostasis (from which late-stage ferroan zoned olivine crystallized) most closely resembles [11]'s Nazca plate DSDP Site 332B ocean ridge tholeiite charge in SiO_2 and Al_2O_3 abundances, and his three experimental basalt charges (synthetic glasses of Apollo 12 olivine basalt, Apollo 15 quartz-normative basalt, and Apollo 11 high-Ti-basalt compositions) in FeO abundance. NWA 5790 mesostasis is almost devoid of MgO, likely reflecting previous crystallization of olivine and clinopyroxene.

Small skeletal olivine projections from the corners and edges of otherwise polyhedral large olivines in NWA 5790 conform to [11]'s "hopper" category. [11]'s anhydrous cooling-rate experiments produced hopper olivine at cooling rates between ~2-60°C/hr in charges of Apollo 12 & Apollo 15 basalt bulk compositions, but produced only polyhedral olivine at cooling rates as high as ~15°C/hr in an experimental charge of DSDP Leg 34 basalt composition [11 Table 3a]. Edge growth appears at slightly higher cooling rates (e.g.,

~15-40°C/hr) for Apollo 12 basalt composition. [11]'s anhydrous isothermal crystallization experiments produced hopper olivine at supercoolings (ΔT) of 35-75°C [11, Table 3b] depending on the bulk composition of the experimental charge. Textures broadly similar to NWA 5790 olivine late-growth textures were produced at a cooling rate of 7°C/hr and ΔT of 20°C in experiments with Apollo 12 basalt compositions [11, Figs. 8 & 9b]. Hydrous crystallization experiments produced hopper crystals in a variety of peridotitic and olivine bytownite gabbro experimental charges at ΔT of up to ~30-40°C [11, Table 4a] and cooling rates of 3-20°C/hr [11, Table 4b] and as high as ~100°C/hr; however, experiments over the high-temperature part of this range produced a variety of other textures not observed in NWA 5790.

The observed NWA 5790 edge-growth textures conform most closely to textures produced at experimental cooling rates of ~15-40°C/hr in charges of Apollo 12 basalt composition [11]. The cooling rates inferred from Fe-Mg and Ca zoning in NWA 5790 olivine and diffusion-profile modeling yield cooling rates of up to ~5°C/hr in NWA 5790 and up to ~12°C/hr in the Miller Range '09 nakhlites [10]. Given that the cooling rates inferred from the morphology of NWA 5790 conform to experimental cooling rates that sample one small (slow) part of a 2-3 orders-of-magnitude range of experimental cooling rates [11], and overlap with one small (fast) part of the 2-3 orders-of-magnitude range of cooling rates inferred from Fe-Mg and Ca diffusion profiles among the known nakhlites [10], the conformity and overlap of the two ranges for NWA 5790 around ~0.3-40°C/hr (~20±20°C/hr) seems reasonable. Further refinements are possible from improved understanding of the influence of melt parameters on olivine-growth morphology – cooling rate relationships.

Augite composition and magma oxidation state: Augite-hosted Fe in some nakhlites occurs in abundances suggestive of some oxidation of Fe(II) to Fe(III) in the magmatic environment of augite crystallization. [12] reported several lines of evidence that MIL 03346 was the most oxidized nakhlite known at that time. One line of evidence was a deficiency of positive charge in EPMA analyses of augites if Fe was assumed to be entirely Fe(II). Octahedral and tetrahedral site occupancies calculated from EPMA analyses of NWA 5790 augite and olivine [7] are within 1% of stoichiometric, and olivine analyses yield charge-balance if Fe is assumed to be entirely Fe(II). However, augite in NWA 5790 requires that 8-17% of its total Fe be Fe(III) for charge balance. [12] found that MIL 03346, NWA 817 and Lafayette required ~10% of total iron to be in the Fe^{3+} form for charge balance, while Nakhla and Y000593 required nearly none. NWA 5790 is thus another member of the more oxidized group of nakhlites.

Absence of preterrestrial aqueous alteration and implications for water: The fact that NWA 5790 appears to have entirely escaped iddingsitization [13] militates against [3]'s suggestion that Cl-rich fluids drove eruption of the fastest-cooled ("uppermost") nakhlites, at least to the extent that it indicates such fluids did not interact with all of the fastest-cooled nakhlites.

References: [1] Friedman Lentz et al. (1999) *MAPS, 34,* 919 [2] Mikouchi et al. (1996) *27th LPSC,* #2363 [3] McCubbin et al. (2013) *GCA, 73,* 4907 [4] Jambon et al. (2010) *41st LPSC*, #5696 [5] Corrigan et al. (2011) *42nd LPSC,* #2657 [6] McKay G. et al. (2006) *37th LPSC* #2435 [7] Corrigan et al., 2014, *45th LPSC* #2128 [8] Marsh (1996) *Min. Mag. 60*, 5. [9] Lentz et al. (2011) *GSA SP* 483, 263 [10] Mikouchi et al. (2012) 43rd *LPSC* #2363 [11] Donaldson (1976) *Cont. Min. Pet.* 57, 187 [12] Dyar et al. (2005) *JGR* 110 E09005 [13] Hicks et al. (2014) *GCA* 136, 194.

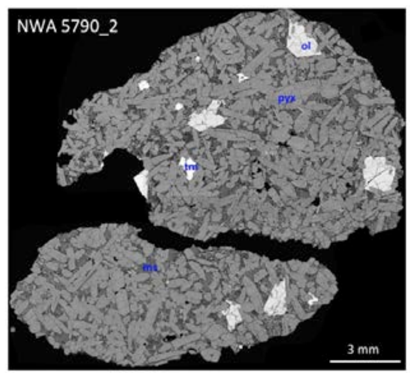

Figure 1: Backscattered electron image of NWA 5790_2 showing (from brightest to darkest) titanomagnetite, olivine, clinopyroxene and mesostasis.

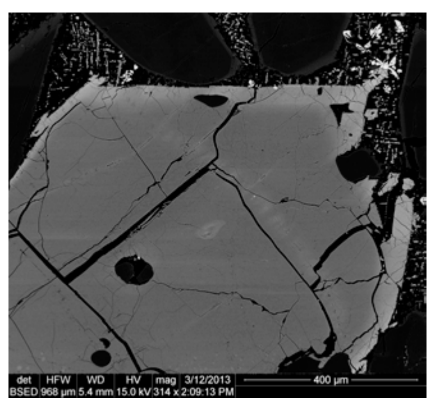

Figure 2: Backscattered electron image of NWA 5790 showing skeletal growth of olivine from edges and corners.