THERMAL HISTORY AND GEOLOGIC SETTING OF NAKHLITES REVISITED. F.M. Richter[1,2], M. Chaussidon[3], and R.A. Mendybaev[1,2] [1]University of Chicago, [2]Chicago Center for Cosmochemistry, [3]Institute Physique du Globe de Paris. (richter@geosci.uchicago.edu).

Introduction: Nakhlites are Martian pyroxenite cumulates that have the same crystallization age of about 1.35 Ga and ejection age of about 11 Ma, which suggests that they were derived from a common lava flow or shallow sill [1]. They are very augite-rich (70-80%) with variable amounts of olivine (~3-15%), and 10-20% mesostasis. Figure 1 shows a backscattered electron image of mineral grains from nakhlite NWA 817.

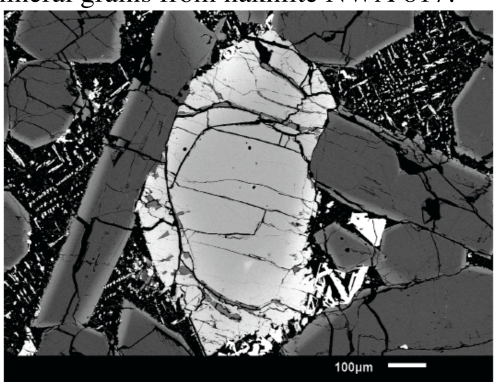

Figure 1. Backscattered electron image of a portion of NWA 817. The large light-colored grain is olivine, the lighter the color the greater iron content. The darker gray grains are augite showing a homogenous core and a thin (10-20μm) Fe-rich layer where the augite is in contact with the mesostasis, which appears black with a large number of small white crystals. The length scale of the Fe-Mg zoning at the edges the olivine grain is larger (~100 μm) than in the augite.

The augite in all the nakhlites have very similar core compositions with Mg#~65, while the olivines have variable composition (Mg#~35-43) and are too Fe-rich to be in equilibrium with the augite cores (see Sautter et al., 2012). Cooling rates of the nakhlites have been estimated based on Fe-Mg zoning of the olivine grains [2,3], Li zoning [4] and the texture of the mesostasis [5]. Table 1 lists these estimates for the two nakhlites we focus on here. The cooling rates have been used by several of the authors to infer the relative position of the nakhlites in terms of their depth below the surface of an assumed was a lava flow.

Method	MIL 03346	NWA 817	
Fe-Mg in Ol.	0.8˚C/hr (1 m)	2.2˚C/hr (0.5m)	[2]
Ca in Ol.	0.04˚C/hr (4 m)	0.5˚C/hr (1-2m)	[2]
Fe-Mg in Ol.		0.11˚C/hr 0.012˚C/hr	[3]
Li in Px	50˚C/hr	65˚C/hr	[4]
mesostasis texture	20˚C/hr (0.4m)		[5]

Table 1. Recent estimates of the cooling rate, and depth below the surface of an assumed cooling lava layer, of nakhlites MIL 03346 and NWA 817 based on the Fe-Mg, Ca, and Li zoning, and the texture of the mesostasis.

Thermal history: New measurements of lithium zoning and isotopic fractionation in a number of augite grains from MIL 03346 and NWA 817, and Fe-Mg and Mg isotopic zoning in an olivine grain from NWA 817, were done using the CAMECA ims 1280 at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) in Nancy France. The isotopic measurements are key for determining whether or not the zoning is in fact due to diffusion and thus can give a measure of the cooling rate. The new measurements confirm very rapid cooling rates of the order of degrees per hour (~10-100 ˚C/hr for MIL 03346 and ~1-10˚C/hr for NWA 817) in reasonable agreement with the faster cooling rates listed in Table 1. However, there are a number of other lines of evidence that indicate that there must have been an earlier stage of very much slower cooling. For example, depending on what estimate of the growth rate of minerals in basaltic systems is used, it would take between slightly less than a year to many years to grow augites and olivines of the size found in the nakhlites [6]. Given that the temperature range over which significant amounts of augite crystalize from a plausible nakhlite parental melt is about 100˚C [7] the implied cooling rate is of the order of degrees per month to degrees per year - certainly not degrees per hour. An independent estimate of this stage of slow cooling can be made based on the disequilibrium between the augite core compositions and that of the olivine cores of MIL 03346 and NWA 817. The key assumption for this is that both the augite and the olivine crystallized from the same parental melt and thus were initially in equilibrium. As the system cooled and crystallized, the melt became increasingly Fe-rich which imposed a Fe-rich boundary condition on the already crystallized mineral grains. Because the coefficient for Fe-Mg exchange in augite is about five orders of magnitude smaller than that in olivine, only a very small outer edge (~2 μm) of the augite would have been affected on a time scale over which a 500 μm olivine grain would have maintained equilibrium with the evolving melt composition. This scenario, which as far as we know was originally suggested by [8], accounts for the present disequilibrium of augite and olivine even though they initially crystallized from the same melt and obviates the need for different melt sources for augite versus olivine that some have claimed. It also allows us to place a bound on the cooling rate (<50˚C/yr.) given that the time scale for homogenizing the Fe-Mg composition of a 500 μm fa_{55} olivine grain above the solidus is of the order of a few years. Figure 2 illustrates the two stages of evolution of the nakhlites we have in mind. Both the augite and olivine cores were initially in equilibrium with a parental melt such as NPM05. As the melt continued to crystalize and evolved to lower Mg#, the olivine was able to maintain equilibrium with the melt while only the outer few μm of the augite was affected. The range of core Mg# of MIL 03346, NWA 817 and Nakhla are indicated in the figure. The black double-ended arrow shows the range of Mg# of the mesostasis. Also shown are our estimates of the slow cooling rate responsible for the homogenization of Fe-Mg in olivine and the fast cooling rate responsible for the lithium zoning in augite, the Fe-Mg in olivine, and the final Fe-Mg zoning of the augite over about 10-20 μm.

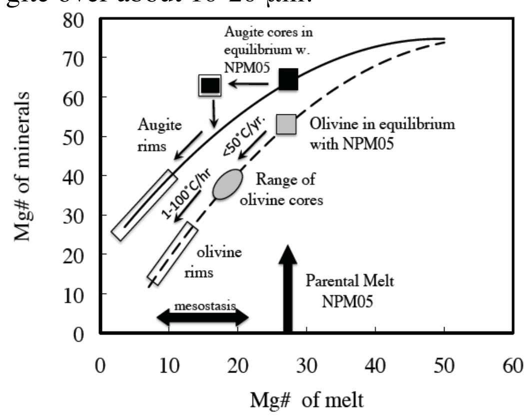

Figure 2. The Mg# of augite (solid curve) and olivine (dashed curve) that would be in equilibrium with a plausible nakhlite parental melt NPM05 (Mg# 27) is from [5]. Also shown is the Mg# of the augite cores, and the range of Mg# of the rims.

Geologic setting: The geologic setting of the slow cooling stage of the nakhlites is almost certainly a shallow crustal magma chamber or sill. The geologic setting for the fast cooling stage must be close to the Martian surface, but given that the nakhlites are cumulates, we believe cooling at the base of a lava flow erupted onto the surface of Mars is more likely than at the top as some have suggested. The initial cooling at the bottom of a flow is not much different than at the surface and thus can account for the fast cooling. The difficult part is finding a plausible way to get the partially molten material with only 20% melt to the Martian surface. Because of this we will discuss other processes that could have resulted in the final very fast cooling of the nakhlites.

References: [1] Treiman A. H. (2005) *Chemie de Erde*, **65**, 203-296. [2] Mikouchi T. et al. (2012) *LPSC XLIII*, #2363. [3] Sautter et al, (2002) *Earth Planet. Sci. Lett.* **195**, 223–238. [4] Beck et al. (2006) *GCA* **70**, 4813-4825. [5] Hammer J. E. (2009) *Meteoritics & Planet. Sci.*, **44**, 141-154. [6] Day et al. (2006) *Meteoritics & Planet. Sci.* **41**, 581-606. [7] Sautter et al. (2012) *Meteoritics & Planet. Sci.*, **47**, 330-344. [8] Longhi & Pan (1989) Proc. 19th LPSC, 451-464.