

RELATIVE BURIAL DEPTHS OF NAKHLITES: AN UPDATE. T. Mikouchi¹, M. Miyamoto¹, E. Koizumi¹, J. Makishima¹ and G. McKay², ¹Dept. of Earth and Planetary Science, University of Tokyo, Hongo, Tokyo 113-0033, Japan (mikouchi@eps.s.u-tokyo.ac.jp), ²KR, NASA Johnson Space Center, Houston, TX 77058, USA.

Introduction: Nakhrites are augite-rich cumulate rocks with variable amounts of olivine and groundmass plus minor Fe, Ti oxides [e.g., 1]. Our previous studies revealed that nakhrites showed correlated petrography and mineralogy that could be explained by different locations (burial depths) in a common cooling cumulate pile [e.g., 2]. We so far analyzed six of the seven currently known nakhrites, Nakhla (Nak), Governador Valadares (GV), Lafayette (Laf), NWA817, Y000593 (Y) and MIL03346 (MIL) [e.g., 2,3] and calculated cooling rates of four nakhrites (Nak, GV, Laf, and NWA817) by using chemical zoning of olivine [e.g., 4]. In this abstract, we complete our examination of petrographic and mineralogical variation of all currently known nakhrites by adding petrology and mineralogy of NWA998. We also report results of cooling calculations for Y, MIL and NWA998. Then, we update our model of the nakhrite igneous body in terms of relative burial depth of each sample.

Groundmass variation: Although all the nakhrites show a similar unbrecciated cumulate texture, modal abundances of augite, olivine and interstitial groundmass (or mesostasis) show some variations from one sample to another. The groundmass abundance is the most variable. In Nak, GV and Laf, the groundmass abundance is about 7-8%. Y and NWA998 have a slightly higher abundance of 10%. NWA817 and MIL have much higher abundance of 20-24%. The groundmass texture is generally related to its abundance. The groundmass of Nak, GV and Laf is mainly composed of lathy feldspar grains (~50 μm wide). The Y groundmass is similar to that of Nak, GV and Laf, but plagioclase laths are slightly thinner (~20 μm wide). In NWA998, feldspar is a large blocky crystal (some reaching 500 μm) with clear twinning and one single grain usually constitutes each interstitial groundmass area. In contrast, NWA817 and MIL have glassy mesostasis with few or no feldspar crystals and skeletal titanomagnetite is the most abundant crystalline phase in the mesostasis.

Mineral compositional variation: Augite grains in all samples have a nearly identical core composition of $\text{En}_{39}\text{Fs}_{22}\text{Wo}_{39}$, but MIL augite is slightly higher in Ca content ($\text{En}_{38}\text{Fs}_{21}\text{Wo}_{41}$) (Fig. 1). The cores are large and constitute most areas of the grains. In all samples, there are thin Fe-rich rims where augite grains abut groundmass or mesostasis.

The degree of chemical zoning towards the Fe-rich rims varies from one sample to another (Fig. 1). The interior portions of the Fe-rich rims have a fairly uniform Wo content, but the Wo contents drop at the outer edge of the grain except for MIL pyroxene (Fig. 1). NWA998 has the most Mg-rich edge composition. The edge composition becomes more Fe-rich in the order of Laf, Nak/GV, Y and NWA817. MIL shows a qualitatively different zoning pattern from the others as the Fe-rich edge is zoned to the hedenbergite composition (Fig. 1). We found fine exsolution lamellae (~1 μm) of augite at Fe-rich pigeonite edges except for NWA817 and MIL. In NWA998, some of the lamellae reach ~3 μm wide. Nakhrite pyroxenes also show correlated variations in minor elements, and it will be discussed in a separate abstract [5].

Olivine grains in all samples except Laf and NWA998 show extensive chemical zoning whose degree is clearly related to the zoning patterns in pyroxenes (Fig. 1). MIL and NWA817 have the widest compositional ranges (Fa_{54-93}). Y shows a similar but slightly narrower compositional range of Fa_{58-85} . Nak and GV have even narrower ranges of Fa_{58-72} . In contrast to these samples, Olivines in Laf and NWA998 are quite homogeneous (Fa_{66-67} and Fa_{61-62} , respectively). Olivines in Nak, GV and Y are also different from other samples in the presence of symplectic exsolution.

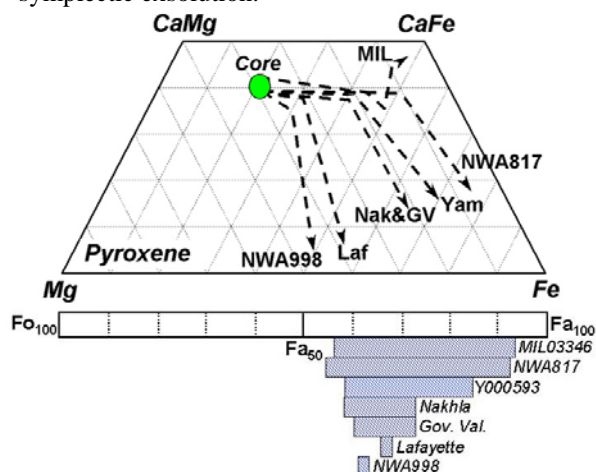


Fig. 1. Major element compositional variation of pyroxenes and olivines in nakhrites. MIL pyroxene shows different zoning trends from others and its core composition is higher in Ca. Olivines in MIL and NWA817 show wider compositional ranges than others, and the most Fe-rich olivine reaches $\text{Fa}_{>90}$. Laf and NWA998 olivines are homogeneous, but NWA998 is more magnesian.

Calculated burial depths: Chemical zoning of nakhlite olivines is useful to estimate their cooling rates. In the same manner that we calculated cooling rates and burial depths of Nak, GV, Laf and NWA817 [4], we did the same calculations for Y, MIL and NWA998 olivines by using Fe-Mg and Ca chemical zoning profiles in the temperature range of 1100-700 °C. We assumed that the original composition was homogeneous (Fa₅₄ and 0.54 wt% CaO, respectively) as represented by the core of NWA817 olivine. Ca results always gave x1.5-20 slower cooling rates (thus deeper burial depths) than Fe-Mg results, and thus we employed Ca results as maximum. Namely, the burial depths should be shallower than these obtained depths. Newly obtained burial depths are 4 m for MIL, 7 m for Y and >30 m for NWA998. MIL has a deeper burial depth than that of NWA817 (1-2 m) [4]. The Y burial depth of 7 m is slightly shallower than those for Nak and GV (~10 m) [4]. The burial depth of NWA998 (>30 m) is consistent with the result of Laf (>30 m), but other mineralogical observations suggest that NWA998 was deeper than Laf.

Further correlation between mineralogical characteristics and relative burial depth:

According to the obtained burial depths, nakhlites are located from the top to the bottom in the order of NWA817, MIL, Y, Nak/GV, Laf/NWA998 (Fig. 2). This order is generally related to mineralogical characteristics of each sample. For example, the degree of chemical zoning of pyroxene systematically varies with these relative burial depths (Fig. 1), supporting the idea that chemical zoning in pyroxene was produced by interaction between cumulus grains and evolved intercumulus melts [e.g., 2]. It is not clear why MIL augite shows a different zoning pattern and the calculated burial depth is slightly deeper than NWA817. As is pointed out by

[6], MIL may have derived from another related flow. If we consider that gravitational settling of crystallizing grains played a significant role in the nakhlite igneous body, cumulus phases should have been more densely packed in deeper areas. This could produce loose cumulus framework for shallower samples, forming abundant groundmass or mesostasis areas. NWA817 and MIL have higher mesostasis abundances and thus appear that they are shallow samples. In fact, the obtained burial depths for these two samples are shallowest among nakhlites, and glassy nature of mesostasis is also consistent with fast cooling of the intercumulus melt. In contrast, the other samples contain crystalline feldspar grains consistent with slow cooling at depth. Especially, the presence of large blocky feldspar in NWA998 is distinct from other samples. NWA998 is likely to represent the deepest sample among nakhlites, even deeper than Laf.

Thus, it appears that all nakhlites fit a scenario wherein they are samples of a single cumulus pile whose cumulus crystals are loosely packed near the surface and become more closely packed with increasing depth (Fig. 2). Now NWA998 takes a place of Laf as the deepest sample of the nakhlite igneous body. The inconsistency between mineralogical characteristics and obtained burial depths of NWA817 and MIL should be further explored to check the possibility of multiple flows [6].

References: [1] Treiman A. H. (2005) *Chemie de Erde*, 65, 203-296. [2] Mikouchi T. et al. (2003) *Antarct. Meteorite Res.*, 16, 34-57. [3] Mikouchi T. et al. (2005) *LPS XXXVI*, Abstract #1944. [4] Mikouchi T. and Miyamoto M. (2002) *LPS XXXIII*, Abstract #1343. [5] McKay G. et al. (2006) *LPS XXXVII* (this volume). [6] Lentz R. C. F. et al. (2005) *Meteoritics & Planet. Sci.*, 40, A91.

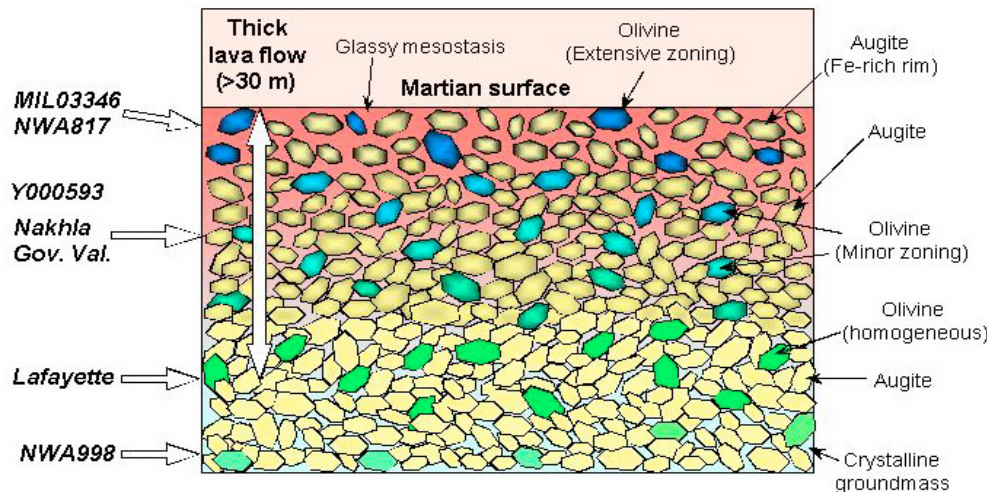


Fig. 2. Schematic illustration of a nakhlite igneous body at the time of final solidification. The crystallization should have occurred at 1.3 Ga [1]. The burial depths are 1-2 m for NWA817, ~4 m for MIL, 7 m for Y, ~10 m for Nak/GV and >30 m for Laf and NWA998. NWA998 is probably the deepest sample among nakhlites.