RELATIVE BURIAL DEPTH OF NAKHLITES REVISITED. T. Mikouchi[1], J. Makishima[1], T. Kurihara[1], V. H. Hoffmann[2,3] and M. Miyamoto[1], [1]Dept. of Earth and Planetary Science, University of Tokyo, Hongo, Tokyo 113-0033, Japan (mikouchi@eps.s.u-tokyo.ac.jp), [2]Dept. of Geosciences, University of Tuebingen, 72076 Tuebingen, Germany, [3]Dept.of Geo.-Env. Sciences, University of Munich, 80333 Munich, Germany.

Introduction: Nakhlites are olivine-bearing augite-rich cumulate rocks with variable amounts of interstitial groundmass (or mesostasis) of feldspar and Fe-Ti oxides [e.g., 1]. Our previous studies revealed that nakhlites showed correlated petrography and mineralogy that could be explained by different locations (burial depths) in a common cooling cumulate pile [2,3]. We calculated their cooling rates using Fe-Mg and Ca zoning of olivine and the obtained cooling rates are generally consistent with variable mineralogy of each sample [3]. Recent studies have further suggested that secondary mineralogy exhibits correlation with their burial depths [e.g., 4]. Since our last report, several new nakhlites have been discovered, and it is of great interest whether these new nakhlites can 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 [3]. Therefore, it is important to know their differences in order to better reconstruct their original igneous body. Here we report an updated estimate of their relative burial depths including new samples.

Samples: We previously studied Nakhla (Nak), Governador Valadares (GV), Lafayette (Laf), NWA 817 (N817), Y000593 (Y), NWA 998 (N998), and MIL 03346 (MIL03) [e.g., 2,3]. We newly analyzed three MIL09 samples (MIL 090030, 090032 and 090136) and NWA 5790 (N5790).

MIL 09s: Three MIL09s are reported to be paired with MIL03 [5,6] and our mineralogical analysis also confirmed it. The mesostasis abundance is nearly identical among them (MIL090030: 22.7%, MIL090032: 23.4%, MIL090136: 21.3%), which is close to MIL03 (22.0%) (Table 1). They show some variations in olivine abundance (4~17%) as found for different MIL03 sections. The MIL09 nakhlites show extensive chemical zoning for both augite and olivine except for large homogeneous cores (augite: $En_{38}Wo_{41}$, olivine: Fa_{56}). The thickness of zoned rims of augite is 20~30 μm, reaching towards the hedenbergite composition (~En_5Wo_{47}), while olivine has a slightly thicker zoned rim (~50 μm) due to its faster cation diffusion compared to pyroxene. The mesostasis is composed of feldspathic glass with skeletal Ti-magnetite (with fine exsolution lamellae of ilmenite), chains of small fayalite ($Fa_{\sim 90}$) and hedenbergite crystals, Ca phosphate and silica. All these observations are identical to MIL03.

NWA 5790: N5790 is a mesostasis-rich nakhlite texturally similar to N817 and MILs [7]. The mesostasis abundance is the highest (33.6%) among nakhlites (Table 1). Another similarity to N817 and MILs is the presence of extensive chemical zoning of augite and olivine with similar compositions and thickness of zoned rims (Table 1), although they have homogeneous cores (augite: $En_{36}Wo_{40}$, olivine: Fa_{66}). We have not yet analyzed many grains, but the augite core compositions are slightly more Fe-rich than those of other nakhlites ($En_{39}Wo_{39}$). The olivine core composition is clearly more Fe-rich than N817 (Fa_{54}) and MILs (Fa_{56}). The zoned rim of augite extends to the hedenbergite composition, which is similar to MILs, but distinct from N817 [3]. The constituent phases of the N5790 mesostasis is similar to those observed in N817 and MILs, although N817 has smaller amounts of Ca phosphates. The absence of hedenbergite in N817 may be related to the Ca-poor content of the mesostasis melt.

Table 1. The mesostasis abundance and related mineralogical characteristics of nakhlites.

Sample	Mesostasis abundance	Plagioclase size	Olivine composition	Pyroxene composition
NWA 5790	34%	<5 μm	Fa_{94}	*fe#* =0.88
MIL 090030, 032, 136	22%	<5 μm	Fa_{92}	*fe#* =0.89
MIL 03346[3]	22%	<5 μm	Fa_{93}	*fe#* =0.90
NWA 817[3]	24%	<5 μm	Fa_{90}	*fe#* =0.78
Y000593[3]	10%	~20 μm	Fa_{85}	*fe#* =0.71
Nakhla[3]	8%	~50 μm	Fa_{72}	*fe#* =0.66
Governador Valadares[3]	7%	~50 μm	Fa_{70}	*fe#* =0.66
Lafayette[3]	7%	~50 μm	Fa_{67}	*fe#* =0.55
NWA 998[3]	10%	~500 μm	Fa_{62}	*fe#* =0.50

Cooling rates of olivine: In the same manner which we have previously done [3], we calculated cooling rates of olivine in N5790 and MIL09s. In our previous study, we assumed that the initial composition of olivine was homogeneous at Fa_{54} and CaO=0.54 wt% in all samples. These compositions were employed from the most Mg-rich core of N817 olivine. We did not seriously consider the difference of olivine compositions in our previous study because N817 and MIL03 had similar compositions (Fa_{54} *vs.* Fa_{56}). However, we found that N5790 olivine has much more Fe-rich core composition (Fa_{66}), and consider that such variable olivine compositions (albeit homogeneous in each sample) found in mesostasis-rich nakhlites may suggest olivine crystallization from evolving intercumulus melt. In fact, olivine in equilibrium with the augite core ($En_{39}Wo_{39}$) is Fa_{47}, which is more Mg-rich than any of nakhlite olivines. Alternatively, olivine may have been derived from external sources during or subsequent to accumulation in the magma chamber.

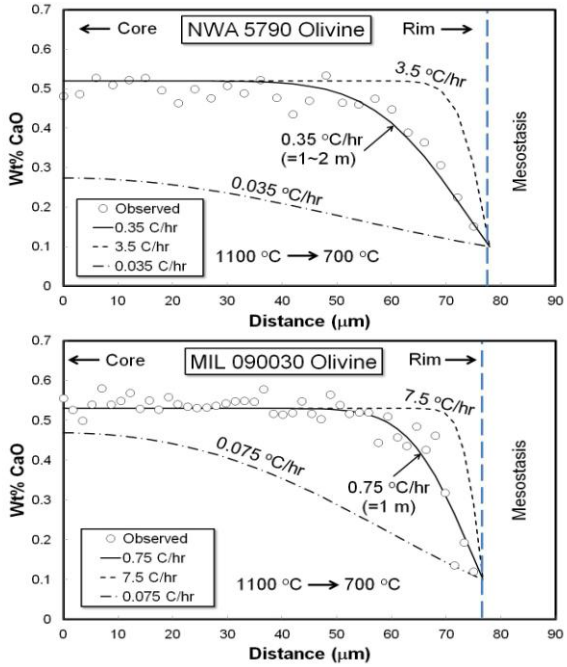

Fig. 1. Calculated cooling rates of olivine in NWA 5790 and MIL 090030 using Ca zoning profiles.

In our calculation, we assumed that the initial composition of N5790 olivine was Fa_{66} and 0.53 wt% CaO, and calculated the best fit cooling rate matching the observed profiles (cooling: 1100-700 ^{o}C). The observed Fe-Mg profiles are somewhat flattened near the rims, but the obtained best fit cooling rate is 4.5 ^{o}C/hr (burial depth: 0.4 m). The Ca profile gives a slower cooling rate of 0.35 ^{o}C/hr (1~2 m) (Fig. 1a). Similarly, we assumed that the initial composition of MILs olivine was Fa_{56}. We have done this calculation before [3], but this time we carefully selected olivine grains showing good diffusion patterns (we've got three MIL09s) and recalculated cooling rates. The obtained cooling rates for Fe-Mg and Ca are 11 ^{o}C/hr (0.3 m) and 0.75 ^{o}C/hr (1 m), respectively (Fig. 1b), that are faster than our previous estimates [3] (Table 2). The revised MIL cooling rate is closer to [8], which employed pyroxene morphology in the MIL03 groundmass (20 °C/hr).

Relative burial depth, reappraisal: In our model [3], we proposed that nakhlites are located from the top to the bottom in the order of N817, MIL03, Y, Nak/GV, Laf, and N998. We suggested that N817 cooled faster than MIL03. However, the recalculated cooling rate for MIL olivine is now indistinguishable from that of N817 (Table 2). The size of ilmenite exsolution in MIL Ti-magnetite is rather thinner than that of N817, suggesting even faster cooling for MILs.

Table 2. Summary of the cooling calculation results.

Sample	Best fit cooling rate (°C/hr)		Corresponding burial depth (m)*	
	Fe-Mg	Ca	Fe-Mg	Ca
NWA 5790	4.5	0.35	0.4	1~2
MIL090030, 032, 136	11.0	0.75	0.3	1
MIL03346[3]	0.8	0.04	1	4
NWA 817[3]	2.2	0.5	0.5	1~2
Y000593[3]	0.03	0.015	4~5	7
Nakhla[3]	0.04	0.01	4~5	10
Governador Valadares[3]	0.085	0.01	3	10
Lafayette[3]	<0.015	<0.001	>5~6	>30
NWA 998[3]	<0.015	<0.0009	>5~6	>30

*Covered with rock-like material.

Then, where was N5790 located? First of all, it is important to consider if N5790 originated from the same cumulate pile. The petrographic and mineralogical features of N5790 are generally similar to other nakhlites, particularly N817 and MILs. However, the pyroxene and olivine compositions (olivine in particular) of N5790 are more Fe-rich than others. It is also reported that augite cores have relatively higher REE abundances related to more evolved parent melt [9]. Thus, it is likely that cumulate minerals in N5790 are products from more evolved parent melt. However, it is not clear whether this means that N5790 originated from a separate flow as suggested for MIL03 [10] or more evolved portions of the same flow. Minor elements in cumulus augite of some nakhlites show sector-like zoning, and are generally correlated with cooling rates [11]. The Al, Ti, and Cr in N5790 augite exhibits sector-like zoning similar to that of Nak and Y rather than those of N817 and MILs. Because cumulus augite should record crystallization at depth, different minor element zoning may suggest a different origin.

Conclusions: It is obvious that N817, MILs, and N5790 are mesostasis-rich nakhlites suggestive of faster cooling than other samples. Their olivine zoning gave comparable cooling rates, corresponding to the burial depth shallower than 2 m. The highest mesostasis abundance of N5790 indicates the topmost section of a common lava pile [7], but N5790 is slightly different from other mesostasis-rich samples in mineral chemistry, which may suggest a separate flow.

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