THE NAKHLA PARENT MAGMA: OLD PROBLEMS, NEW APPROACHES. C.A. Goodrich[1], A.H. Treiman[2], J. Filiberto[2,3] and M.J. Jercinovic[4]. [1]Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, AZ 85719 USA (cgoodrich@psi.edu). [2]Lunar and Planetary Institute, Houston, TX 77058 USA. [3]Dept. of Earth Sciences, Rice University, Houston, TX 77005, USA. [4]Dept. of Geosciences, Univ.of Massachusetts, Amherst, MA 01003 USA.

Introduction: Nakhlites are olivine-augite cumulates that formed in flows or shallow intrusions of basaltic magma on Mars [1]. There have been at least 6 independent attempts to determine the composition of the Nakhla parent magma, and at least 14 variants have been published [2-12]. Four distinct methods have been used: 1) mass balance; (2) augite/melt element partitioning; 3) melt inclusions in olivine; 4) melt inclusions in augite. Table 1 shows the compositions that we consider the most robust products of each of these methods. One striking difference among them is that the one derived by [4] from melt inclusions in olivine, NK93 (and variants NK93' and NK93"), has much higher K_2O and K_2O/Na_2O than all others. High K_2O in the nakhlite parent magma would have significant implications for the depth and composition of the mantle source [3,13,14]. Thus, we are using new approaches to determine whether high K_2O is a real property of the melt trapped in olivine, and if so, whether it is also a property of the parent magma.

Analytical: Sections NK19 and NK12 were examined with the Zeiss EVO50 XVP scanning electron microscope and Cameca SX-Ultrachron electron microprobe at the University of Massachusetts. Compositional maps were collected with the Ultrachron using an optimized CeB6 cathode at 15kV and 600nA (regulated), with 100ms pixel dwell time and 2 μm step size (600x600 pixels). Elements, acquired lines, and monochromators were: Al Kα (TAP), Ca Kα (LPET), P Kα (VLPET), S Kα (VLPET), Cr Kα (LLIF).

Unrepresentative Sampling? NK93 could be inaccurate due to unrepresentative sampling of 3-D objects in 2-D sections. However, Treiman [4] analyzed 13 large (>70 μm diameter) melt inclusions and all of them showed bulk compositions with high K_2O. In averaging these compositions, [4] weighted them by inclusion area, which coincidentally gave the greatest weight to the inclusion with the highest K_2O. Nevertheless, a recalculated NK93 without weighting (NK93") still has very high K_2O (Table 1). In fact, even if K_2O of the average bulk inclusion were reduced to the lowest measured value, NK93 would still have >2× as much K_2O as any other proposed parent magma composition. So, we tentatively conclude that the K_2O content of NK93 is not erroneously high due to unrepresentative sampling.

Table 1. Some proposed Nakhla parent magma compositions.

	B''	N'	NK93'	NK93''	NA03
SiO_2	46.9	50.5	47.2	48.0	47.2
TiO_2	0.67	1.4	0.8	0.85	0.88
Al_2O_3	3.4	6.8	7.2	7.5	5.9
Cr_2O_3	0.22	0.10	0.04	0.07	0.05
FeO	27.4	21.9	25.4	23.8	26.9
MgO	5.9	4.3	5.3	5.0	4.6
MnO	0.50	0.40	0.27	0.23	0.71
CaO	13.3	13.0	9.9	10.6	10.1
K_2O	0.36	0.30	2.3	1.7	0.39
Na_2O	1.05	1.2	1.0	1.5	2.3
P_2O_5	0.33		0.58	0.77	0.09
Total	100.0	99.9	100.0	100.0	99.1
Ref.	[2,4]*	[3]*	[4]*	[4]*	[12]

* Variants on original compositions.

Errors in Spread-Beam Analysis: The bulk inclusion analyses of [4] were obtained by averaging many rastered beam analyses (RBA), a form of spread-beam EMPA. Spread-beam analysis can be inaccurate because it violates the assumption of target homogeneity in EMP matrix correction [15,16]. In

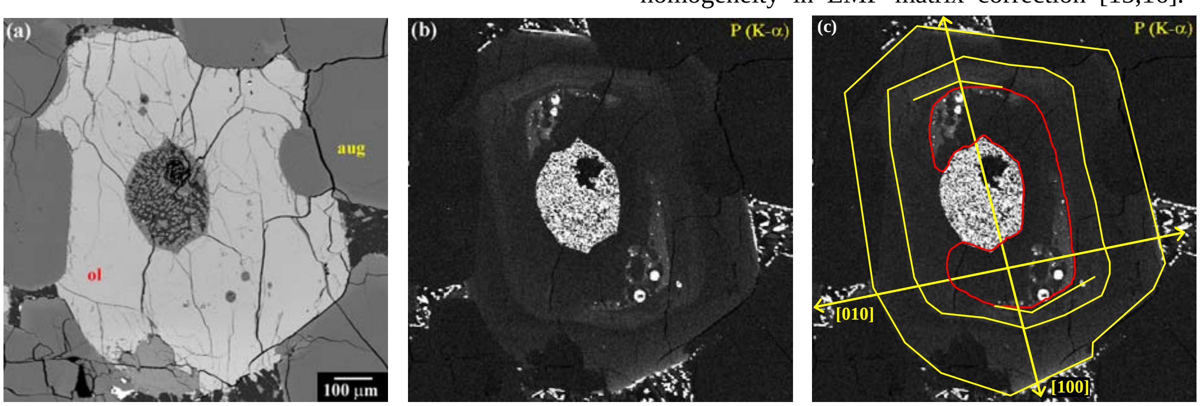

Fig. 1. Olivine crystal in Nakhla (NK19) containing large central and surrounding smaller melt inclusions. (a) BEI; (b) P Kα x-ray map; (c) interpretation of crystallographic orientation and growth zones.

fact, it overestimates abundances of elements concentrated in the less dense phases [16], such as K_2O in alkali feldspar and glass in Nakhla melt inclusions. Berlin et al. [17] found that bulk K abundances from defocused beam analyses of chondrules were 1.5× higher than those obtained by modal recombination. However, even if we apply this factor as a correction in the reconstruction of NK93, we still obtain a composition with 3× more K_2O than any other proposed nakhla parent magma. We tentatively conclude that despite possible overestimation of K_2O through RBA, the melt trapped in olivine in Nakhla has much higher K_2O than parent magma compositions derived by any other method.

Boundary Layer Effects? If the high K_2O content of NK93 truly represents the melt trapped in Nakhla olivines, one may ask whether that melt is representative of the bulk magma, far from the growing olivine crystals. Growing crystals can trap unrepresentative melts because they are always surrounded by a boundary layer, the composition of which is dictated by relative diffusion rates [18,19]. Melt inclusions formed during rapid crystal growth (e.g., skeletal, hopper, dendritic shapes) are likely to trap large volumes of the boundary layer, while those formed during slower crystal growth will not [20].

Phosphorus Zoning Patterns: We have begun a study of P (and other minor element) zoning as an indicator of crystal growth style in Nakhla olivines [21]. Figure 1 shows one such olivine crystal, with a large K-rich melt inclusion (analyzed by [4]) and several smaller inclusions. The P x-ray map of this crystal (Fig. 1b) shows strong zoning; P-rich areas (brighter) represent regimes of rapid growth [21]. The presence of symplectic exsolutions (identified in Cr and Ca maps) that are known to form parallel to the (100) plane [22], allows us to infer probable crystallographic orientation for this crystal (Fig. 1c). Assuming this orientation is correct, the central zone of the olivine (Fig. 1c), is shaped like a rapidly-grown hopper crystal (Fig. 1G and Fig. 8 of [23]), and the large inclusion would represent an embayment which was closed by overgrowth. This type of inclusion can exhibit strong boundary layer effects [20].

Studies of interdiffusion in mixing of silicate melts suggest that alkalis diffuse orders of magnitude faster than non-alkalis such as Al, Ca, Ti [24]. If this is applicable to melt inclusions, then boundary layer effects should result in the Nakhla inclusions being depleted in both K_2O and Na_2O, and enriched in CaO and Al_2O_3 relative to the far-field liquid. Clearly, such effects are not what is needed to explain the differences between NK93 and other proposed nakhla parent magma compositions (Table 1). However, [21] found that boundary layers in melt inclusions in rapidly-grown (hopper, dendritic) olivines were enriched by up to ~30% in K_2O and/or Na_2O. We conclude that available data are ambiguous regarding both the sign and magnitude of expected boundary layer effects on K_2O and Na_2O in systems appropriate to the Nakhla inclusions, thus suggesting an important avenue for future experimental work.

Is the melt trapped in olivine an evolved melt? If the melt trapped in olivine in Nakhla does have high K_2O and is representative of the far-field liquid from which the olivine was crystallizing, then it is possible that it was evolved rather than parental. Most workers [e.g. 2-4] have argued that the difference in *mg* between olivine (~39) and augite (cores ~63) arose by late reequilibration of olivine, and that the parent magma was cosaturated with olivine (mg* ~53) and augite. As a result of this reequilibration, generations of olivine cannot be unambiguously distinguished, which raises the possibility that the large melt inclusions were not trapped in the earliest stages of crystallization. However, intra-crystal stratigraphy revealed by P x-ray maps (e.g. Fig. 1b) does not support this hypothesis. Furthermore, calculated crystallization sequences (from MAGPOX/FOX) for any of the other proposed parent magmas (Table 1) fail to produce a liquid with K_2O/Na_2O anywhere near as high as that of NK93 while olivine is crystallizing. Thus, it is unlikely that the melt trapped in olivine is a highly evolved liquid.

Summary: We conclude that high K_2O is a real property of melt trapped in early olivine in Nakhla, and may be explained by boundary layer effects. We will continue using P zonation to reveal host crystal growth styles and assess this possibility. Experimental work in needed to determine boundary layer effects in systems appropriate to the Nakhla melt inclusions.

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