PAIRED NAKHLITES MIL 090030, 090032, 090136, AND 03346: NEW INSIGHTS INTO THE CUMULATE PILE

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Introduction: Nakhlites are rare martian clinopyroxenites consisting of cumulus augite and minor olivine as well as intercumulus phase. Several authors have postulated a cumulate pile to explain their emplacement and petrologic characteristic [1-3]. One nakhlite differs from the others: MIL 03346, which is the most oxidized and least equilibrated, has the highest amount of intercumulus phase [3, 8], and may have been located near the top of the pile. Three newly discovered nakhlites MIL 090030, MIL 090032, and MIL 090136 were collected during the 2009 season in Miller Range, geographically close to the location of MIL 03346, which was found in 2003. This location suggests a possible pairing of the four nakhlites. We confirm the pairing between MIL 090030, 090032, 090136, and 03346 by investigating their textures, mineralogies, and major and trace element compositions as well as modal abundance variations.

Petrology and geochemistry: One thin section for each nakhlite was analyzed, with surface areas of 58 cm^2 for MIL 090030, 101 cm^2 for MIL 090032 and 29 cm^2 for MIL 090136.

Petrographic description. Nakhlites MIL 090030, MIL 090032, and MIL 090136 display euhedral to subhedral augite with minor amount of large euhedral to subhedral olivine set in a vitrophyric intercumulus phase (figure 1). Modal abundances for the three nakhlites, respectively, are as follows: 66.3%, 74.3%, and 64.1% pyroxene, 9.8%, 3.85%, and 9.5% olivine, and 23.9%, 21.9%, and 26.4% intercumulus matrix. Pyroxenes are euhedral to subeuhedral and display Fe-rich rims of 10 µm in thickness. They exhibit single twin planes, probably formed by impact shocks. Two types of olivine are present in the three nakhlites: rare and large euhedral to subeuhedral phenocrysts and skeletal fayalites that occur in the intercumulus phase. The large olivines display Fe-rich rims that can reach 100 µm in thickness. They enclose pyroxene, demonstrating that olivine crystallized after them. The intercumulus phase consists of incompletely crystallized feldspathic glass and fine-grained fayalite laths, pyrrhotite, pyroxene, tiny acicular P-rich phases, skeletal titanomagnetite, and "filaments" composed of aligned sulfide, fayalite and Fe-Ti oxides [3]. No plagioclase or K-feldspar have been found in the intercumulus phase. The main alteration phase is iddingiste, found in veins and cracks of the large olivines.

CSD analyses. Crystal size distribution (CSD) is a useful tool that allows quantification of crystal sizes and an assessment of the growth histories of crystal populations. CSD analyses were applied to pyroxene grains in MIL 090030, MIL 090032, and MIL 090136, using the CSD*slice* software [4]. The calculated pyroxene grain shape ratios are 1.0:1.25:1.30; 1.0:1.25:1.40; and 1.0:1.2:1.5, respectively. The three nakhlites display a similar pattern. We calculated residence times of 54.5 ± 19.5 Earth years using the slope of the CSD patterns ($m= -1/(G\tau)$). The same growth rate used by [3] was applied to our study.

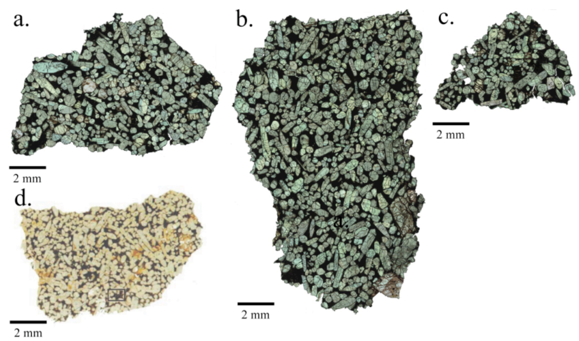

Figure 1: Plain polarized light images of a) MIL 090030, b) MIL 090032, c) MIL 090136 and d) MIL 03346 [3]. The overall texture appears similar for the four meteorites.

Mineral major element composition. Cumulus pyroxenes display homogeneous magnesian cores ($Wo_{39-41}En_{35-38}Fs_{22-25}$), with composition similar to other nakhlites (figure 2) [5]. Their Fe-rich rims have a composition of $Wo_{34-42}En_{6-24}Fs_{37-49}$. The large olivines display compositions varying from Fo_{43} in cores to Fo_{13} in rims. The intercumulus olivines have fayalitic compositions of Fo_{2-15}. The intercumulus phase mainly consists of feldpathic glass, which varies in composition from trachy-basalt to trachyte.

Pyroxene trace element composition. Pyroxene cores and rims display the same REE patterns, although the rims are enriched in REEs. MIL 090030, MIL 090032, MIL 090136, and MIL 03346 pyroxene rims and cores exhibit the same REE and trace element composition, such as Cr, Ti, and Y.

Discussion:

Evidence of pairing. MIL 090030, MIL 090032, MIL 090136, and MIL 03346 were collected geographically close to each other, suggesting a pairing. In addition, several petrographic evidences show a pairing between the four meteorites. The four meteorites display similar overall textures as shown in figure 1 [3,7]. Moreover, CSD patterns and residence times from nakhlites of this study and MIL 03346 [3] are similar.

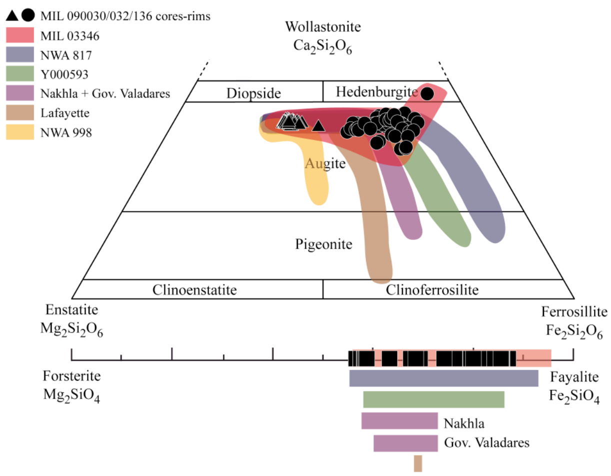

Figure 2: Fig. 12. Pyroxene cores (triangles) and rims (circles) composition in MIL 090030/32/136. Envelopes of MIL 03346 [2-3,5-6], NWA 817 [7], Y000593, Nakhla + Governador Valadares, Lafayette and NWA 998 [1,6]. Olivine envelopes from [3,7] for MIL 03346 and from [1] for NWA 817, Nakhla, Gov. Valadares and Lafayette.

Furthermore, pyroxene and olivine major element compositions (figure 2) as well as pyroxene trace element composition of MIL 090030/32/136 plot within the field of MIL 03346. Thus, textures, CSD analysis and major and trace element compositions of cumulus phases support pairing of the four nakhlites.

Modal abundances. Modal abundance of intercumulus phase is one of the characteristics used to reposition a nakhlite sample in the cumulate pile. Other criteria are the degree of crystallinity of the intercumulus phases, the cooling rate, the degree of equilibration of cumulus phases with the intercumulus phase, and the cumulus pyroxene composition. Due to fast quenching and degree of packing [1,7], the intercumulus phase should be more abundant at the top rather than the base of the cumulus pile. As shown by the figure 3, modal abundances of MIL 090030/32/136 and MIL 03346 are different showing that MIL 03346 is not modally representative of the parent sample. Moreover, the modal abundances between the different minerals and the ratio intercumulus/cumulus phase show variations, which are not consistent with the idea that intercumulus phase modal abundances is a characteristic that allows positioning of nakhlites within the cumulate pile. We assume all the modes are representative since the areas of the studied thin sections are comparable to those of the other nakhlites samples [3,5,7,11]. Calculated weighted modal abundances, including areas and modal abundances of the samples of this study, and MIL 03346 data [3,5] were estimated to be 72.3% pyroxene, 3.9% olivine, and 23.7% intercumulus phase, still locating MIL 03346 at the top of the pile.

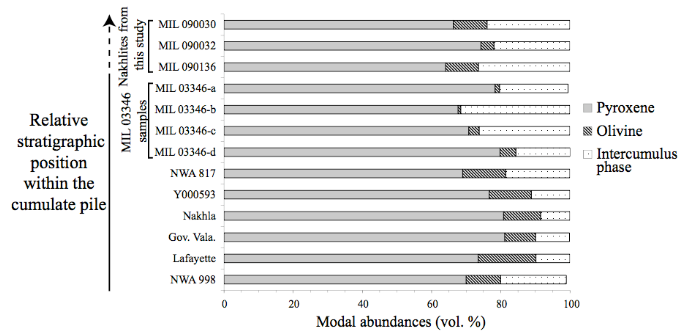

Figure 3: Histograms showing modal abundances of pyroxene, olivine, and intercumulus phase from the different nakhlites. The modal abundances of MIL 03446 come from a) [3], b) [5], c) [8], and d) [9]; NWA 817: [7]; Y000593: [10]; Nakhla, Governador Valadares and Lafayette: [11]; NWA 998: [2]. The different nakhlites MIL 03346 do not have a relative stratigraphic position between each other.

Conclusions: MIL 090030, MIL 090032, MIL 090136, and MIL 03346 have:
- similar mineralogy for the cumulus and intercumulus phases.
- similar major element composition for the cumulus phase as well as similar pyroxene REE composition.
- similar textures, CSD patterns, and estimated residence times showing a similar grain size distribution.

However, modal abundances of MIL 090030/32/136 and MIL 03346 show variations indicating that MIL 03346 is not modally representative of the parent sample. Modal abundances of nakhlites show variations that are not consistent throughout the cumulate pile. This indicates that single samples should be placed within the pile cautiously based on intercumulus phase modal abundance.

References: [1] Mikouchi et al. (2003) *LPS XXXIV*, Abstract #1883. [2] Treiman (2005) *Chemie der Erde*, 65, 203-270. [3] Day et al. (2006) *Meteoritics & Planet. Sci.*, 41, 581-606. [4] Morgan and Jerram (2006) *Journal of Volc. and Geoth. Res.*, 154, 1-7. [5] Imae and Ikeka (2007) *Meteoritics & Planet. Sci.*, 42, 171-184. [6] Treiman and Irving (2008) *Meteoritics & Planet. Sci., 43, 829-854* [7] Sautter et al. (2002) *EPSL*, 195, 223-238. [8] Dyar et al. (2005) *JGR,* 110, E09005. [9] McKay and Schwandt (2005) *LPS XXXVI*, Abstract #2351. [10] Imae et al. (2002) *Antarct. Meteorite Res.*, 16, 13-33. [11] Lentz et al. (1999) *Meteoritics & Planet. Sci.*, 34, 919-932.