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Northwest Africa 5790: Revisiting nakhlite petrogenesis

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Abstract

Northwest Africa 5790, the latest nakhlite find, is composed of 58 vol.% augite, 6% olivine and 36% vitrophyric intercumulus material. Its petrology is comparable to previously discovered nakhlites but with key differences: (1) Augite cores display an unusual zoning between Mg# 54 and 60; (2) Olivine macrocrysts have a primary Fe-rich core composition (Mg# = 35); (3) The modal proportion of mesostasis is the highest ever described in a nakhlite; (4) It is the most magnetite-rich nakhlite, together with MIL 03346, and exhibits the least anisotropic fabric. Complex primary zoning in cumulus augite indicates resorption due to complex processes such as remobilization of former cumulates in a new magma batch. Textural relationships indicate unambiguously that olivine was growing around resorbed augite, and that olivine growth was continuous while pyroxene growth resumed at a final stage. Olivine core compositions (Mg# = 35) are out of equilibrium with the augite core compositions (Mg# 60–63) and with the previously inferred nakhlite parental magma (Mg# = 29). The presence of oscillatory zoning in olivine and augite precludes subsolidus diffusion that could have modified olivine compositions. NWA 5790 evidences at least two magma batches before eruption, with the implication that melt in equilibrium with augite cores was never in contact with olivine. Iddingsite is absent.

Accordingly, the previous scenarios for nakhlite petrogenesis must be revised. The first primary parent magmas of nakhlites generated varied augite cumulates at depth (Mg# 66–60) as they differentiated to different extents. A subsequent more evolved magma batch entrained accumulated augite crystals to the surface where they were partly resorbed while olivine crystallized. Trace element variations indicate unambiguously that they represent consanguineous but different magma batches. The compositional differences among the various nakhlites suggest a number of successive lava flows. To account for all observations we propose a petrogenetic model for nakhlites based on several (at least three) thick flows. Although NWA 5790 belongs to the very top of one flow, it should come from the lowest flow sampled, based on the lack of iddingsite.

Key words: NWA 5790; Nakhlite; Mars; Oscillatory zoning

1. INTRODUCTION

As of January 2016 there are 162 recorded Martian meteorites, the so-called SNC (S for Shergottites, N for Nakhlites and C for Chassignites), plus a few non-SNC

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(see Meteoritical Bulletin database). Among those, the nakhlites represent only 7 meteorites (MIL 03346, NWA 817, Y-000593, Nakhla, Governador Valadares, Lafayette and NWA 998); Northwest Africa (NWA) 5790 and pairs thereof. NWA 5790 was found in the Sahara by nomads and purchased in Erfoud (Morocco) in 2010.

The seven previously described nakhlites share a number of common features, such as their crystallization and cosmic ray exposure ages (1.3–1.4 Ga and 11 ± 1.5 Ma respectively, Nyquist et al., 2001). They are all olivine-bearing clinopyroxenites with a cumulate texture defined by coarse augite and olivine crystals set in a fine-grained mesostasis. The coarse subhedral crystals suggest a rather slow growth over a relatively long period of time (>100 y) (Friedman-Lentz et al., 1999; Day et al., 2006) within a sub-surface magma chamber while microcrystals in the mesostasis correspond to a faster cooling stage as crystal mushes were extruded to the surface. It is noteworthy that for a lava flow to spread out, the crystal to melt ratio may not exceed 50%; this implies that nakhlites accumulated phenocrysts after emplacement. The previously studied nakhlites show subtle differences (mesostasis proportions, cumulus crystal compositions and overgrowths, cristallinities of the mesostasis), which allows them to be positioned within a lava pile with some stratigraphic order from MIL 03346, the uppermost part of the pile, down to NWA 998 at the base of the flow (Mikouchi et al., 2003; Treiman, 2005 and references therein). Crystal settling and increasing compaction throughout the nakhlite pile likely occurred after extrusion (Day et al., 2006). Estimates of the final cooling rate increase from NWA 998 to MIL 03346 and range 1–6 °C/h (Sautter et al., 2002; Hammer and Rutherford 2005). Thus nakhlites would have cooled at the Martian surface over short periods of time from 8 to 48 days (Day et al., 2006). The discovery of NWA 5790 offers additional information to better constrain the formation of nakhlite in the magma chamber and extrusion conditions onto the surface. In this paper, we present the petrology, mineralogy and geochemistry of NWA 5790, and compare this new find with the other nakhlites to discuss: (1) the crystallization conditions of cumulus augite in the nakhlite magma chamber, (2) the status of olivine in the Nakhlite Parental Magma, and (3) the final position of NWA 5790 within the pile at the Martian surface.

2. ANALYTICAL METHODS

Freshly broken pieces of NWA 5790 were polished to obtain two thick sections ***A*** and ***B*** of 0.75 cm^2 and 0.63 cm^2 respectively (Fig. 1). Additional broken pieces were preserved for wet chemical analysis.

Microscopic observations and quantitative chemical analyses of the various phases were made on the polished sections of NWA 5790. Backscattered electron (BSE) images were taken with a Zeiss Supra 55 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) at UPMC. Chemical maps were performed using a Bruker QUAD EDS detector and software Quantax at 15 kV and 36 nA (about 300,000 cps). Electron microprobe (EMP) analyses were performed with a Cameca SX100 (WDS) at UPMC (CAMPARIS). Operating conditions were: 15 kV accelerating voltage with a probe current of 10 nA, a counting time of 10 s, and a focused beam for all phases but feldspar and glass (defocused at 4 μm). Natural silicates and synthetic oxides were used as standards for all elements: albite (Na); orthoclase (K); diopside (Mg, Si, Ca); anorthite (Al); $MnTiO_3$ (Mn, Ti); Cr_2O_3 (Cr); Fe_2O_3 (Fe); NiO (Ni); apatite (P); pyrite (S). Analyses of a reference Atlantic MORB glass (CH98-DR12) and Celessou and San Carlos olivines permit to avoid systematic deviations outside the reported uncertainty (Baghdadi et al., 2015). The analytical reproducibility of the EMP data is 0.5% relative for Si (olivine, augite) and 1–3% relative for elements present in excess of 1 wt.%. It is better than 30% relative for elements on the order of 0.1%. The composite color picture (Fig. 1b) is a WDS X-ray map acquired on the CAMECA SX100 electron microprobe at Laboratoire Magmas et Volcans, Blaise Pascal University (France). Analytical conditions were: 20 kV accelerating voltage, 100 nA beam current, 10 μm defocussed beam, and 40 ms dwell time. Raw intensity maps were combined into RGB pictures.

For in-depth analysis of oscillatory zoning in olivine and augite specific procedures were applied as the relative variations from one point to the next were only several times the analytical uncertainty (see Electronic supplement).

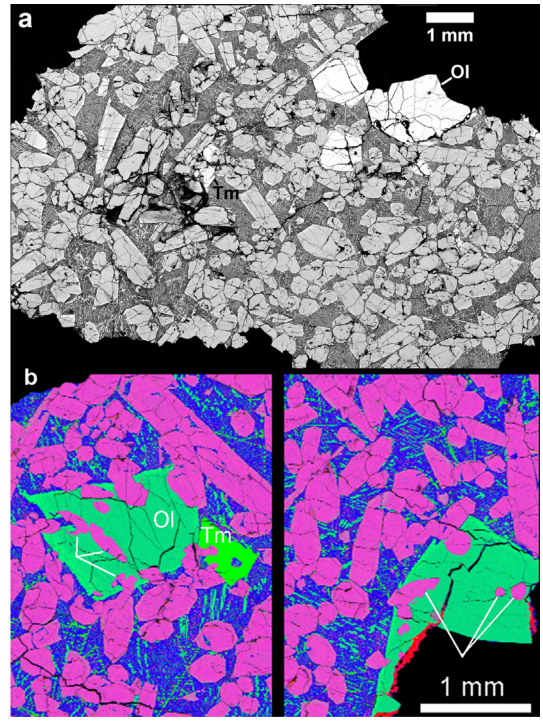

Fig. 1. (a) BSE image of section A. Notice the dominant euhedral augites (light gray), a few subhedral olivines (Ol) and large mesostasis pools with numerous dendritic crystals. Tm = titanomagnetite. (b) False color image of section B (Red = Ca, Green = Fe, Blue = Si. Notice the rounded augites included in olivines (end of white lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)