
Introduction: The nakhlites are Martian igneous cumulate rocks [1]. Two nakhlites have been investigated in this study: Nakhla and MIL 03346. Texturally, these meteorites are dominated by elongate subhedral to euhedral augite with minor olivine and intercumulus mesostasis. A simple model for nakhlite petrogenesis involves a protracted, subsurface cooling history at oxidizing conditions followed by eruption of the crystal-rich magma. The latter event is associated with crystal settling, overgrowth and partial equilibration within the lava flow [1]. It is this portion of the meteorite’s crystallization history that is addressed in this study – the cooling conditions at the Martian surface.

Crystals observed in the mesostasis have shapes indicative of rapid diffusion-controlled growth under far from equilibrium conditions (swallowtail, dendritic etc.). These crystals exhibit fractal properties and may be quantified using numerical modeling techniques. Comparison of the fractal dimension, $d_f$, of mesostasis crystals between meteorites, in conjunction with previous fractal studies applied to dynamic crystallization experiments, can constrain relative cooling rates.

Analytical Methods: Polished thin sections of Nakhla and MIL 03346 were initially investigated using optical microscopy (reflected and transmitted light). Detailed observation of mesostasis texture utilized a JEOL 6301 field emission scanning electron microscope (FE-SEM) at beam operating conditions of 20 kV and a working distance of 7 mm. Crystal shapes have been quantified by their fractal dimension using the correlation function technique, as outlined in [2, 3]. X-ray elemental maps and quantitative analyses were obtained using a JEOL 8900 microprobe equipped with 5 wavelength dispersive spectrometers.

Petrography: Texturally, the mesostasis is distinct between Nakhla and MIL 03346 in terms of modal phase abundance, mineral assemblage and crystal shape. MIL 03346 contains the highest modal proportion (% abundance) of mesostasis (21.4 ± 5.7), while Nakhla contains significantly less (8.4 ± 2.1) [1].

For Nakhla, the mesostasis is marked by equant crystals of titanomagnetite interspersed among plagioclase laths (Fig. 1). These crystals are embedded in devitrified silicate glass. Skeletal augite and pigeonite crystals extend from large augite phenocrysts into the mesostasis. Augite also occurs as subhedral to anhedral grains between plagioclase laths (Fig. 1).

In contrast, MIL 003346 mesostasis does not contain plagioclase and is characterized by dendritic olivine and titanomagnetite crystals, and anhedral silica grains embedded in devitrified silicate glass (Fig. 2). Oxides form a vermicular texture, observed at high magnification.

![Fig. 1. BSE image illustrating textural characteristics of Nakhla. Higher magnification images, located on the right side, show crystal shapes observed in Nakhla mesostasis. The scale bar applies to the overview image. Plagioclase f.o.v. = 300 μm, Ti-mag (titanomagnetite) f.o.v. = 160 μm, augite f.o.v. = 180 μm.](image1.png)

![Fig. 2. BSE image illustrating textural characteristics of MIL 03346. Higher magnification images (right) show mesostasis crystal shapes. The scale bar applies to the overview image. Ti-mag f.o.v. = 250 μm, olivine f.o.v. = 160 μm, oxide f.o.v. = 18 μm.](image2.png)
**Fractal Analysis:** BSE images of mesostasis crystals were converted to binary maps (crystal pixels = black, non-crystal pixels = white). A custom-designed texture correlation program was used to calculate the probability that a pixel, within a series of concentric shells of radius \( r \), belongs to the crystal. This function, the texture correlation function, \( n_C(r) \), has been shown to scale in the same way as the density of pixels in a 2D fractal object [2], i.e., the number of crystal pixels is not proportional to the square of \( r \), but to the power \( df \), where \( n_C(r) = r^{df/2} \).

This process of selecting a crystal pixel as the origin of a series of subshells is repeated for all black pixels. After the data is processed \( df \) is determined from a log-log plot of radius, \( r \), versus the normalized texture correlation, \( n_C(r) \), where \( 2 + \text{slope} = \text{fractal dimension} \) (Fig. 3). For MIL 03346 all analyzed crystal shapes are fractal: olivine \( df = 1.7905 \) and titanomagnetite \( df = 1.7420 \). For Nakhl, the analyzed crystal shapes have a more compact density distribution and log-log plots of \( r \) versus \( n_C(r) \), do not fall along a straight line. Augite and titanomagnetite are equant and plagioclase exhibits lath shapes with smooth edges, i.e., no branching or tip-splitting.

**Discussion:** By performing fractal analysis on crystal shapes formed under controlled laboratory conditions, [4] established a relationship between cooling rate and fractal dimension. Crystals grown far from equilibrium (faster cooling rates) have higher fractal dimensions compared to crystals cooled at slower rates. This is observed empirically as a transition from swallowtail and dendritic shapes to crystals having a more compact density distribution. This same relationship has been established for MIL 03346 and Nakhl in this study: MIL 03346 mesostasis contains crystals with a high fractal dimension (\( df > 1.7 \)), indicative of fast cooling compared to Nakhl, whose mesostasis contains crystals with a compact density distribution indicative of slower cooling rates. These results are consistent with previously estimated cooling rates for the nakhlites [1], based on observed post-accumulation effects.

**Conclusion:** Fractal analysis provides a useful tool for quantitatively comparing crystal shapes between meteorite samples. Through application of the texture correlation technique to mesostasis crystal shapes, we are able to show that, upon eruption of a crystal-rich magma at the Martian surface, MIL 03346 cooled at a faster rate compared to Nakhl.