NAKHLITES AND THEO'S FLOW: FORMATION OF EXTRUSIVE PYROXENITES
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Previously, we examined the suitability of Theo's flow as a formation analog for the nakhlites, using a preliminary quantification of textures [1]. Here, we extend the comparison between the martian pyroxenites and this thick, layered Canadian flow to include specific petrologic features, mineral and bulk chemistry, and further quantification of the size and spatial distributions of cumulus grains. The similarities between the two rock suites in all these aspects suggest to us that the two pyroxenites formed by similar processes. This involved steady-state nucleation and growth of clusters of pyroxene grains, circulating in a strongly convecting melt pool, followed by settling and continued growth in a thickening cumulate pile. Melt pockets evolved, growing Fe-enriched rims on pyroxene and olivine grains, until supersaturation finally caused rapid growth of sprays of plagioclase.

The nakhlites and Theo's flow: A terrestrial analog for the formation of the martian nakhlites presents itself in the 120-m thick Theo's flow, Ontario, Canada [1,2]. This unusual flow differentiated in place, forming a 9-m basal peridotite and thick pyroxenite (57 m) and gabbro (42 m) layers, all insulated by a capping hyaloclastic top generated during submarine extrusion [3]. Theo's pyroxenite and the nakhlites share a strikingly similar petrography, with concentrated euhedral to subhedral augite grains set in a plagioclase-rich matrix. There are many other similarities, implying the same processes probably contributed to the formation of both rock suites.

Petrographic: Most of Theo's pyroxenite is olivine free, but one layer did have coexisting cumulus phases. In this layer, pseudomorphous olivine shapes resemble nakhlite olivines, with euhedral faces bordering mesostasis areas and more anhedral morphologies when abutting other grains. As in the nakhlites, olivines in Theo's flow show a tendency towards clumping, and some even bear traces of once primary magmatic inclusions, an abundant feature in nakhlite olivines. The mesostasis of Theo's pyroxenite also mimics nakhlite mesostasis, with plagioclase arranged in sprays of long lathes, differing from nakhlite plagioclase only in size. The fact that Theo's mesostasis is nearly twice as coarse as the nakhlites’ is likely associated with the abundance of interstitial melt when plagioclase grew (30-40 vol% in Theo's vs. 8-10 vol% in nakhlites).

Mineralogic: Ignoring the expected martian Fe-enrichment, pyroxene compositions show some interesting similarities. An important genetic feature found in the nakhlite pyroxenes is a compositional zoning from cores to Fe-enriched rims. Zoning is also found in Theo's pyroxenes, with a similar increase in Fs from core to rim (Fig. 1). Curiously, both martian and terrestrial pyroxenites display surprisingly large variations in pyroxene core Fe#'s within a single thin section, as much variation as between some sections.

Whole Rock: Comparison of bulk rock compositions reveal that both Nakhla and Theo's pyroxenite have low Al₂O₃/CaO values (0.11 and 0.41, respectively), suggesting their parental magmas were also Al-depleted [4]. This depletion, combined with high FeO+MgO, promoted an extended period of post-settling pyroxene growth, before plagioclase saturation. Nakhla, which is more mafic than Theo's pyroxenite, may have had an even longer pyroxene growth period, accounting for a higher pyroxene content (70-80 vol%) than expected from simple accumulation.

Parent magma: We can use the knowledge of compositions of Theo's pyroxenite and bulk flow to evaluate previously calculated Nakhla parent magmas. The location of Theo's parent magma in relation to its pyroxenite, in Figure 2, reflects a balance of the other lithologies that formed from it: a small, more mafic peridotite and a thick, more aluminous gabbro. Similarly, the locations of calculated Nakhla parent magmas, in relation to Nakhla (Fig. 2), suggest missing components or lithologies which should also have formed. D [5] as a parent magma would require an additional large, very mafic component, like a peridotite, which is not unreasonable. N [6] also seems reasonable, requiring only a extra, small gabbroic component. NIM [7] and NK93 [8], however, are too aluminous and seem unlikely as parent magmas. They are more similar to Theo's parent which should produce a pyroxenite not nearly as mafic as Nakhla.

Qualitative petrography: Cluster analysis [9] of Theo's pyroxenite and the nakhlites demonstrate that cumulus grains in both cases were definitely clustered, implying their emplacement was governed by settling of clumps or chains of grains. Results of this technique also support that the extra concentration of pyroxene in the nakhlites was due more to additional overgrowth than any mechanical compaction.
Crystal size distribution (CSD) analysis [10] reveals that while the nakhlites have slightly larger average grain sizes than Theo’s pyroxenite samples, the range of average sizes between samples is very similar: 180, 200, and 230 µm for Lafayette, Governador Valadares, and Nakhla, respectively, vs. 170, 160, 200, 150, and 180 µm for Theo’s samples at 12, 23, 42, 51, and 61 m. In addition, there is no systematic variation of size with depth, preventing the use of grain size as a depth indicator. This also suggests that variations in nucleation and growth conditions overwhelm any simple cooling factors in governing final grain size. CSD plots of nakhlites and Theo’s pyroxenite are remarkably similar, with the only differences reflecting the greater grain densities of the nakhlites. Similar grain sizes and log-linear slopes mean that calculated grain growth times are the same order of magnitude: 8-11 days for Theo’s, 10-14 days for the nakhlites [11].

Formation model: There are so many unusual features shared by Theo’s flow and the nakhlites that while the details of their formations may not be identical, Theo’s flow appears to be a remarkably good analog for investigating the processes that formed the nakhlites. We developed a model for Theo’s formation based on a detailed study of the flow [11] and here present a slightly altered version to account for nakhlite differences.

A magma of highly mafic composition with low viscosity erupted and pooled into a thick pile. Strong convection began almost immediately, but cooling through the overlying crust created an undercooled nucleation zone near the top of the melt pool. Clusters of nuclei formed, began to grow, and then sank into the convection cell below, where growth of pyroxene and olivine continued. As the top of each cycle brought the clusters back through the undercooled zone, new grains nucleated, and all grains continued growing during the rest of the cycle. Once the clusters became too heavy to be wafted about by the hot thin lava, they settled to the bottom of the melt pool, adding to the growing pile below. The cumulative pile would have been too small to allow compaction by crystal deformation to take place. (For typical viscosities, the compaction length is >100 m [e.g., 12], as large or larger than the entire flow.) Instead, we envision that the interstitial melt maintained contact with the overlying melt pool, allowing pyroxene cores to grow larger. Once underlying layers were cut off from the main melt pool, growth continued at the expense of trapped melt pockets, producing the more Fe-rich olivine and pyroxene rims, until the melt was supersaturated in plagioclase. At that point, inhibited nucleation was overcome and rapid crystallization formed the distinctive sprays of the nakhlite mesostasis. This model accounts for so many of the similar features in the nakhlites and Theo’s flow that it strengthens the possibility that the nakhlites formed in a surface lava flow.


Figure 1: Comparison of pyroxene Fe zoning patterns in the nakhlites and in TS8 from Theo’s flow.

Figure 2: Comparison of pyroxenite vs. parent magma compositions for Theo’s flow and Nakhla.