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Nanostructural domains in martian apatites that record primary subsolidus exsolution of halogens: Insights into nakhlite petrogenesis

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Abstract

The microstructures of selected F-, Cl-, and OH-bearing martian apatite grains, two in Northwest Africa (NWA) 998 (cumulus apatites, embedded in pyroxene) and a set of four in Nakhla (intercumulus apatites), were studied by focused ion beam–transmission electron microscopy (FIB-TEM) techniques. Our results show that the nanostructure of martian apatite is characterized by a domain structure at the 5–10 nm scale defined by undulous lattice fringes and slight differences in contrast, indicative of localized elastic strain within the lattices and misorientations in the crystal. The domain structure records a primary post-magmatic signature formed during initial subsolidus cooling (T <800 °C), in which halogens clustered by phase separation (exsolution), but overall preserved continuity in the crystalline structure. Northwest Africa 998 apatites, with average Cl/F ratios of 1.26 and 2.11, show higher undulosity of the lattice fringes and more differences in contrast than Nakhla apatites (average Cl/F = 4.23), suggesting that when Cl/F is close to 1, there is more strain in the structure. Vacancies likely played a key role stabilizing these ternary apatites that otherwise would be immiscible. Apatites in Nakhla show larger variations in halogen and rare-earth element (REE) contents within and between grains that are only a few micrometers apart, consistent with growth under disequilibrium conditions and crystallization in open systems. Nakhla apatite preserves chemical zonation, where F, REEs, Si, and Fe are higher in the core and Cl increases toward the outer layers of the crystal. There is no evidence of subsolidus ionic diffusion or post-magmatic fluid interactions that affected bulk apatite compositions in NWA 998 or Nakhla. The observed zonation is consistent with crystallization from a late-stage melt that became Cl-enriched, and assimilation of volatile-rich crustal sediments is the most plausible mechanism for the observed zonation. This work has broader implications for interpreting the chemistry of apatite in other planetary systems.

Keywords: Apatite, halogens, nanostructures, FIB-TEM, nakhlites, Mars