

# Unraveling the Behavior of Rare Earth Elements in Iron Oxide-Apatite Systems: Insights from Apatite Hyperspectral Cathodoluminescence

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Iron oxide-apatite (IOA) deposits are potentially significant sources of iron and rare earth elements (REEs), critical metals required for many green and everyday technologies. Deciphering the enrichment mechanisms of REEs in IOAs as an evolving magmatic-hydrothermal system is vital for exploration and extraction strategies. This study used hyperspectral cathodoluminescence (HyCL) imaging and spectroscopy to investigate the behavior of REEs in apatite from three IOA deposits in the Tarom District of northwest Iran: Zaker, Eskand, and Golestan. Apatite is the primary REE-bearing phase, intergrown with massive magnetite. It appears as coarse-grained euhedral to subhedral crystals, occasionally reaching up to four centimeters long. At least four generations of apatite have been identified through detailed petrography. The first generation of apatite (Ap1) consists of large crystals (typically up to 1.5 mm) with abundant mineral and fluid inclusions. Ap2 crystals are medium to fine-grained (<1 mm) with fewer fluid inclusions but considerable mineral inclusions and fractures. Ap3 apatite is less fractured and found in iron-rich veinlets, while Ap4 comprises mineral inclusions nucleated in earlier apatite generations.

The application of HyCL in this study uncovered a variety of previously unidentified textures in the apatite, including oscillatory zoning, dissolution-precipitation, and mineral inclusions that are invisible with other methods. Each feature corresponds with distinctive HyCL intensity patterns and spectral attributes indicative of a complex series of fluid-rock interactions. Most of the spectrum patterns illustrate sharp peaks that correspond to the characteristic emission ranges of REEs commonly found in apatite, such as Ce, Pr, Nd, and Sm. These observations reflect variations in the hydrothermal fluid composition, physicochemical conditions, and mechanisms of element transport within the system. Notably, the heterogeneous distribution of REEs within individual apatite crystals illustrates a multifaceted history of element mobility. By integrating spectral and textural information as well as quantitative geochemical analysis, this research constructs a detailed framework for interpreting the processes of REE mobilization and redistribution throughout an apatite-bearing hydrothermal system. The identification of subtle chemical patterns linked to textural features and REE distribution carries profound implications for deciphering the mechanisms that control the enrichment of critical metals within these IOA deposits.