

The Source of Sulfur in IOA Deposits: Direct Constraints from Anhydrite-Bearing Melt Inclusions

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Iron oxide–apatite (IOA) deposits host significant Fe and REE resources, yet their genesis remains one of the most enduring controversies in economic geology. Models range from purely magmatic (immiscible iron-rich melts) to hydrothermal replacement, with sulfur sources variably attributed to magmatic, sedimentary, or evaporitic contributions. Resolving this debate requires tracers that can directly record primary ore-forming processes while resisting subsequent hydrothermal overprinting.

Here we present the first in situ SIMS sulfur isotope analyses of anhydrite daughter crystals hosted in sulfate-bearing melt inclusions from four major IOA deposits: El Laco and Laco-Solar (Chile), Kiruna (Sweden), and Iron Springs (USA). These melt inclusions preserve pristine magmatic compositions, shielded from later alteration. The anhydrite daughter crystals yield $\delta^{34}\text{S}$ values that are consistently and significantly enriched relative to typical mantle-derived sulfur, demonstrating variable but substantial crustal assimilation during magma evolution. These elevated values are consistent with involvement of evaporite-derived or sedimentary sulfate sources.

Our results provide three key advances: (1) direct evidence for a magmatic sulfur reservoir in IOA systems, recorded by anhydrite crystallized from trapped sulfate-rich melts; (2) new constraints on crustal contamination processes across major IOA provinces; and (3) validation of melt inclusion daughter minerals as robust recorders of primary sulfur isotopes immune to hydrothermal resetting. The ubiquitous occurrence of anhydrite-bearing melt inclusions further suggests that sulfate-rich melts play a fundamental, and previously underappreciated, role in IOA ore-forming processes.

This study demonstrates that in situ SIMS analysis of melt inclusion daughter minerals offers a powerful new tool for tracing volatile and metal sources in high-temperature magmatic-hydrothermal systems, with direct implications for genetic models and exploration strategies for IOA deposits worldwide.