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Magmatic Sulfur in Iron Oxide–Apatite Deposits: In Situ SIMS Constraints from Anhydrite in Melt Inclusions

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Iron oxide–apatite (IOA) deposits have long been the subject of genetic debate, with models ranging from purely magmatic origins to hydrothermal replacement and sedimentary or evaporitic sulfur contributions. Resolving this controversy requires robust geochemical tracers capable of directly recording primary ore-forming processes. Here, we report the first in situ SIMS sulfur isotope analyses of anhydrite daughter crystals hosted in sulfate-bearing melt inclusions, providing a novel and direct approach to evaluate the magmatic heritage of IOA systems.

Melt inclusions were analyzed from samples collected at El Laco and Laco-Solar (Chile), Kiruna (Sweden), and Iron Springs (USA). The $\delta^{34}S$ values of anhydrite daughter crystals show significant variation and range to values considerably higher than typical mantle-derived sulfur, pointing to variable crustal contributions during magma evolution. The occurrence of anhydrite as a daughter phase crystallized from trapped sulfate-rich melts provides direct evidence for a magmatic sulfur reservoir. Importantly, the sulfur isotope signatures are preserved within the closed system of the melt inclusion, effectively shielding them from later hydrothermal overprinting.

These results demonstrate that variable incorporation of crustal sulfur plays a key role in IOA mineralization and highlight the utility of in situ SIMS analysis of melt inclusion daughter minerals as a powerful tool for tracing sulfur sources in high-temperature magmatic–hydrothermal systems.