Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.37722

In-situ trace element signatures reveal multi-stage magnetite crystallization in Neoarchean iron formations from Carajás (Brazil)

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Iron formations (IFs) constitute key archives of Precambrian ocean chemistry, yet the crystallization pathways of iron oxides and their capacity to preserve primary environmental signatures remain debated. In particular, distinguishing primary depositional magnetite from diagenetic or fluid-mediated overprints is critical for assessing the reliability of trace element proxies. Here, we integrate petrography, rock magnetism, and in-situ LA-ICP-MS trace element analyses to investigate magnetite formation in a 230-meter drill core intercepting pristine ~2.74 Ga IFs from the Carajás Formation (Brazil). Petrographic and magnetic data reveal that magnetite formed after nano-scale hematite dispersed within a silica-rich matrix, preserving relict Si-spherules within magnetite cores. Low-temperature magnetic measurements indicate multiple magnetite populations with distinct stoichiometries. In-situ trace element analyses (Ti, V, Co, Ni, Zn, Mg, Pb, among others) define two main magnetite populations: (1) compositionally homogeneous grains with narrow trace element distributions, interpreted as early-diagenetic magnetite formed in a closed system; and (2) grains exhibiting broader compositional variability, consistent with localized hydrothermal influence and late diagenetic alteration. Bulk-rock compositions average out this mineral-scale heterogeneity, masking the variability revealed by spatially resolved analyses. Compared to Archean and Proterozoic IFs worldwide, Carajás magnetite is among the most trace-element-depleted, particularly in Ti and V, supporting relatively low-temperature and possibly more reducing formation conditions. Our results demonstrate that magnetite in Carajás IFs records multi-stage crystallization processes and that trace element systematics effectively discriminate between early and late diagenetic magnetite generations. These findings underscore the intrinsic microtextural and geochemical complexity of IFs and emphasize the necessity of petrographic and statistical screening when interpreting trace metal signatures.