Syn- and Late-Orogenic Hydrothermal Si-Al-Ca Alteration of Ultramafic Rocks: Evidence for Ni-Co Downgrading in Outokumpu, Eastern Finland

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The Outokumpu Cu-Zn-Co-Ni deposit is a Paleoproterozoic ultramafic-hosted VMS deposit in Eastern Finland. It is polygenetic and characterized by metal remobilization through deformation and regional amphibolite-facies metamorphism. Samples were retrieved from the Outokumpu Deep Drill Hole, which crosscuts Archean pegmatitic granitoids, the Outokumpu ophiolite, and overlying turbiditic schist and gneiss. The samples investigated belong to rocks of the Outokumpu assemblage, i.e., ultramafic rock (serpentinite, metaperidotite), diopside and/or tremolite calc-silicate rock (skarn) and black schist. This study utilizes petrography, pyrrhotite EPMA and LA-ICP-MS data. The focus is to distinguish different remobilization steps of Fe-sulfides during retrogression. During prograde metamorphism (M_1-M_2), pyrrhotite in skarn and black schist breaks down. This manifests Ni-Co-depletion in residual pyrrhotite, which lacks significant pentlandite exsolutions. Granoblastic and coarse (0.5-5.0 mm), Ni-Co-rich pyrrhotite in serpentinite defines peak (M_3, >550-670°C, 2-4 kbar) to early post-peak (static-M_3) metamorphic stages with antigorite-olivine-anthophyllite assemblages. Contemporaneously and following the peak conditions, tremolite and, subsequently, talc and chlorite (M_4-$_5$) indicate a Si-Al-Ca-metasomatism in both ultramafic rocks during retrograde evolution. Granular pentlandite exsolutions in pyrrhotite formed below 550°C. A second generation of Ni-Co-poor µm-scale pyrrhotite is hosted in the tremolite-chlorite-talc-carbonate-graphite alteration zone and formed in reaction zones between the peak-metamorphic serpentine and the hydrothermal alteration assemblage by retrograde mineral reactions. Below 480-500°C, the increased SiO_2-activity (ca. 0.001-0.01 m) suppresses magnetite growth from pyrrhotite. Fluid-saturated greenschist-facies conditions, testified from thermodynamic calculations, and high sulfur fugacity (fS_2~1E-8.8 Pa) drive the replacement of pyrrhotite to serpentine and tochilinite, a rare hydrous Mg-Fe-sulfide. Petrographic and geochemical evidence indicate Ni-Co-ore mineral pyrrhotite has undergone downgrading during the retrograde metasomatic evolution. This sets a precedent for ore deposits in similar geotectonic environments.