Microstructures and Mineralogy of a World-Class Graphite Deposit

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The Nunasvaara graphite deposit, Sweden, is the highest grade technical resource in the world and currently contains 1.85 Mt of microcrystalline flake graphite. The deposit is located in the Kiruna IOCG district of northern Sweden, hosted in a sequence of metamorphosed Proterozoic supracrustal rocks (Vittangi Greenstone Group) dated 2.3 to 1.96 Ga. Graphite is present both disseminated throughout the rock matrix and as veins with varying mineralogy. We present a study of the mineralogical development of the Nunasvaara deposit, characterizing the chemical and microstructural variability of the graphitic rocks to understand the sequence of events that formed this giant deposit. At the core scale, X-ray fluorescence (XRF) mapping shows elemental variations related to the original sedimentary bedding as well as retrogressed metamorphic porphyroblasts and multiple, crosscutting vein generations. Different vein orientations contain differing mineralogy, indicating temporal variations in fluid composition. The vein geometries, and their relationships to disseminated sulfides and relict metamorphic porphyroblasts is mapped in 3D using high-resolution X-ray computed tomography (HRXRCT). Most of the sulfide present occurs within the veins rather than disseminated through the rock.

The earliest set of veins contains fine-grained chalcopyrite and pyrrhotite, an intermediate set contains albite, and the latest set is associated with localized chlorite-scapolite mineralization. All three vein sets contain large amounts of graphite. The earliest two vein sets do not have alteration selvedges whereas the scapolite veins show addition of K and Cl, loss of Si and redistribution of Fe and S by coarsening of pyrrhotite within the vein. At the margins of some of the earlier albite veins, later K-metasomatism has led to K-feldspar replacement of albite. In addition, pyrrhotite is breaking down to pyrite with calcite and siderite also formed. Large, 100-µm graphite aggregates in the scapolite-bearing veins are intimately associated with chlorite. Raman thermometry on both the matrix and vein graphite gives temperatures of between 400° and 500°C for the peak temperature experienced by the rocks. Graphite crystallinity is not reset during cooling, thus suggesting that most of the veins were emplaced at the peak temperature of 400° ± 50°C. Carbon isotopes of the matrix and vein material are also indistinguishable with $\delta^{13}C$ values of -23.4 ± 0.46‰ (n = 14), consistent with a biogenic source for the graphite.

Much of the graphite present in the Nunasvaara deposit originates from metamorphosed biogenic sedimentary material. During metamorphism to upper greenschist facies, further deposition of graphite, with the same isotopic composition as the matrix, occurred in multiple generations of veins. The fine-grained chalcopyrite suggests that the graphite vein formation may have occurred at a similar time to the large-scale regional Cu mineralization. Graphite precipitation resulted from supersaturation caused by "drying out" of an aqueous carbon-bearing fluid during chlorite growth. The source of the carbon is likely to be devolatilization of organic material in the sedimentary pile. The last vein generation is associated with K- and Cl-metasomatism, oxidation of pyrrhotite and carbonate formation as the fluids become more dominated by high salinity brines.