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The High-grade Gold Ore Paradox of the Brucejack Deposit: Insights from Nanoscale Imaging of Electrum and High-resolution Trace Element and Sulphur Isotope Analyses of Pyrite

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It has been long accepted that epithermal gold deposits form as a result of gold precipitation from hydrothermal fluids in which gold is present as dissolved species. A major weakness of this hypothesis is that it fails to explain the formation of ultra-high-grade or bonanza gold veins. Gold concentrations in the fluids responsible for epithermal mineralisation are typically on the order of 10-30 ppb, which are far too low to explain the occurrence of bonanza-grade epithermal deposits like Brucejack, where drilling has returned grades up to 41,582 g/t Au over 0.5-m intervals. Formation of such high-grade veins by direct precipitation of native gold or electrum from the ore fluids would require that fractures remain open for unreasonably long periods of time or that fluid fluxes be extraordinary.

A potential solution to the paradox of ultra-high-grade gold deposition, in geologically realistic time-frames, is offered by colloidal transport. We have studied the high-grade gold mineralisation from the Valley of the Kings (VOK) and Eastern Promises (EP) zones of Brucejack, a large and exceptionally high-grade, intermediate-sulphidation epithermal gold-silver deposit in British Columbia's Golden Triangle, to evaluate this possibility. Images obtained using transmitted electron microscopy show that: (1) gold commonly occurs as <1-10-nm spherical nanocrystals of electrum embedded within a calcite matrix; (2) larger (100-500 nm) particles of electrum, also embedded in calcite, are composed of hundreds of nanoparticles, each displaying distinct crystal lattice plane orientations; and (3) the margins of >1-µm-wide electrum masses surrounding the calcite matrix comprise nanoparticulate electrum partially crystallised to massive monocrystalline electrum. These images provide compelling evidence for the formation of colloidal suspensions of electrum and their flocculation. Analyses using LA-ICP-MS and EMP-WDS of the trace element composition of pyrite from phyllically-altered wallrock in the VOK and EP zones have identified a trend of increasing enrichment of Co, Ni, Se, and Cu with depth, documenting an otherwise cryptic transition to recently discovered propylitic and potassic alteration and associated Cu-Mo mineralisation in deep drill core from the adjacent Flow Dome Zone. Strong positive shifts in $\delta^{34}S_{pyrite}$ values (>20.0‰) from in situ SIMS analysis of VOK hydrothermal pyrite suggest that seawater mixed with hydrothermal fluids during the late stages of ore formation contemporaneous with the deposition of electrum. We present a model in which the high-grade epithermal gold mineralisation is due to the development of a boiling-induced colloidal gold suspension in a carbonate fluid originating from a porphyry source at depth and its flocculation during the incursion of seawater. According to this model, colloidal and flocculated gold particles are mechanically transported into networks of nano-veinlets that they block, producing millimetric to centimetric knots of electrum in centimetric carbonate veins. Our model offers a solution to the longstanding problem of high-grade gold transport and deposition in epithermal vein systems, as well as an explanation for the extraordinary and challenging grade variability, or "nugget effect," often encountered during the mining of these deposits.