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Probing the origins of sub-arc copper-rich cumulates through direct analysis of osmium and oxygen isotopes

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The genesis of deep-seated copper-rich magmatic cumulates beneath arc crusts has been proposed as a critical process influencing the geochemical evolution of the continental crust and the formation of large ore deposits of copper. However, the extent to which the lower crustal evolution of magmatic systems and the formation of copper-rich reservoirs is impacted by open-system interactions and the assimilation of pre-existing crustal materials remains unclear. To address this question, we present direct isotopic evidence on the evolution of deep magmatic systems within arcs by analyzing the osmium and oxygen isotope compositions of hydrous copper-rich ultramafic cumulates found at the base of the Acadian orogen (~40 km deep) in the New England Appalachians. The variably radiogenic $^{187}Os/^{188}Os$ initial ratios (ranging from 0.31 to 0.67) and elevated $\delta^{18}O$ values (8.97 ± 0.42 ‰ for orthopyroxene; 9.25 ± 0.26 ‰ for phlogopite) suggest that open-system magmatic processes, including crustal assimilation, was key in the formation of these cumulates. Isotopic modeling based on the $^{187}Os/^{188}Os$ and $\delta^{18}O$ composition of the cumulates indicates that the observed signatures arise from the initial evolution of parental magmas under sulfide-undersaturated conditions, followed by saturation after approximately 15% to 20% assimilation and fractional crystallization progress. These findings support the hypothesis that assimilation of reducing (graphite-bearing) material resulted in a decrease in the magmatic system's fO_2 (~ΔFMQ < –1), triggering sulfide segregation and the formation of copper-rich cumulates. Our investigation also demonstrates that crystallization-driven differentiation predominantly influences the major element geochemistry of the cumulate line of descent within arc magmatic systems, with processes related to open-system dynamics, such as crustal assimilation, playing a secondary role.