

Geochemical Variation Across Magmatic Stratigraphy of the Duluth Complex, Midcontinent Rift, Minnesota: Chalcophile Enrichment and Mg-Number Controls on Sulfide Saturation

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The Duluth Complex of the Mesoproterozoic Midcontinent Rift (MCR) hosts one of the world's largest undeveloped Cu-Ni-platinum-group element (PGE) resources, yet the geochemical controls on chalcophile element distribution within its intrusive stratigraphy remain incompletely quantified at the multi-deposit scale. A systematic geochemical analysis of 347 drill-core and surface samples across five stratigraphic zones is presented: the Basal Mineralized Zone (BMZ), Unit I of the Northmet deposit, the Augite Troctolite Unit, the Crocodile Lake Gabbro, and an Archean basement reference suite, using the USGS Midcontinent Rift geochemistry dataset (Verplanck et al., 2024). Compositional data were treated with centered log-ratio (CLR) transformation prior to multivariate statistical analysis. Kruskal-Wallis tests confirm that all seven chalcophile elements (Cu, Ni, Co, S, Pd, Pt, Au) and two petrogenetic indices (Mg-number, Differentiation Index) are statistically significantly stratified across zones ($H > 110$, $p < 0.001$ in all cases). The BMZ and Unit I carry median Pd concentrations of 283 and 247 ppb, respectively, two to three orders of magnitude above the barren Augite Troctolite Unit (median 1 ppb). Chondrite-normalized REE patterns reveal positive Eu anomalies in the BMZ ($\text{Eu}/\text{Eu}^* = 1.56$) and Unit I ($\text{Eu}/\text{Eu}^* = 1.97$), interpreted as evidence for plagioclase cumulate entrainment during sulfide segregation. Logistic regression identifies an Mg-number threshold of 58.8 (AUC = 0.654) for distinguishing mineralized from trace zones, with a complementary accuracy-maximizing cutoff at Mg# 63.0 (75.6% accuracy) derived from grid search. Elevated BMZ Cu/Pd ratios (median 21,393) relative to world-class systems such as Norilsk (approximately 500 to 2,000) confirm substantial PGE dilution driven by large silicate magma volumes. These findings constrain the conditions under which sulfide saturation was achieved during MCR rifting and provide a quantitative geochemical framework for exploration targeting in analogous Proterozoic rift systems globally.