

# What controls the geochemical variability of massive sulfide deposits on mid-ocean ridges? Indications from multivariate statistical analysis

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Massive sulfide (MS) deposits on mid-ocean ridges may have remarkable base (Cu, Zn), precious (Au, Ag) and critical (Co) metal grades and have gained attention as potential mining targets. These deposits show significant geochemical variability along the same ridge and even at the hand-specimen scale, suggesting a complex interplay of regional and local controlling factors. We investigated these factors by means of robust principal component analysis and robust factor analysis of chemical data for on-seafloor MS from worldwide mid-ocean ridges and thermodynamic modeling of basalt- and peridotite-seawater hydrothermal systems. We found that most of the MS geochemical variability (73%) can be explained by three independent factors, which are interpreted to represent (in order of importance): (1) the temperature of sulfide deposition, (2) the rock-to-water (r/w) ratios in the reaction zone, and (3) zone refining. The first and the third factors are mostly related to processes operating near the seafloor and effectively control the relative proportions of the main sulfide minerals and of two main groups of anti-correlated elements, i.e., Cu, Se, Co vs. Zn, Ag, Sb, Pb. Therefore, the relative enrichment in these elements mostly reflects the final depositional conditions and the evolution of mound and vent structures rather than the original geochemistry of the hydrothermal fluid. As regards the second factor, higher r/w ratios at slow-spreading ridges enhance the release of Au and Ag to the fluid, but may limit that of Ni due to the stabilization of Ni-bearing minerals at depth. This may explain why MS on slow-spreading, ultramafic-rich ridges are systematically enriched in Au relative to Ni, compared with those on fast-spreading, mafic-dominated ridges. Despite the obvious role of substrate rocks as metal sources, their nature does not emerge as a statistically significant independent factor, casting doubts on the classification of MS deposits as mafic- vs ultramafic-hosted based on geochemical data. The substrate composition, however, may become relevant in subseafloor mineralization, where sulfides precipitate by reaction of hydrothermal fluids with Ni-poor mafic or Ni-rich ultramafic host-rocks. The statistical factors may provide a broad geochemical discrimination of ophiolite-hosted MS in terms of deposition temperature and oceanic spreading rate.