

Alteration Trajectories in Compositional Space: A Dynamical Systems Approach to Hydrothermal Geochemical Evolution at the Thalanga VMS Deposit, Queensland, Australia

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Hydrothermal alteration in VMS systems is a directional geochemical process in which rock compositions evolve along predictable pathways from protolith through progressively more intense alteration assemblages toward the ore zone. Existing machine learning applications to lithogeochemistry treat samples as static, independent points in compositional space, which does not capture this fundamental directionality. This study introduces Alteration Trajectory Analysis in Compositional Space (ATACS), a dynamical systems framework applied to the Thalanga VMS deposit, Queensland, Australia. 81,656 assay records from 5,011 drillholes, 64,431 geological logging intervals, 18,855 downhole survey measurements, and 5,277 collar coordinates were compiled and spatially positioned using the minimum curvature method. Samples with co-located assay and geological log data ($n = 5,978$) were processed via centered log-ratio (CLR) transformation and principal component analysis (PCA), with alteration intensity serving as a proxy for reaction progress. Geochemical centroids were computed at each intensity level for four alteration types: chlorite, sericite, silicification, and epidote. Only silicification converges toward the independently defined ore-zone attractor (massive and semi-massive sulfide lithologies, $n = 256$, median ZnEq = 14.17%), reducing its distance to the ore centroid by 25.3% from weak to intense alteration. The silicification trajectory exhibits a 22-fold increase in median ZnEq grade from intensity level 1 (0.069%) to intensity level 4 (1.517%). Chlorite, sericite, and epidote trajectories diverge from the ore attractor by +1.5%, +3.5%, and +10.3% respectively, consistent with their stratigraphic positions in the footwall, proximal alteration zone, and hanging wall. Three-dimensional visualization of alteration trajectories in both PCA compositional space and physical geographic space confirms that the silicification convergence is spatially coherent, clustering in the ore-proximal corridor between the East and West prospects. These results demonstrate that compositional trajectory geometry provides a physically interpretable, spatially-agnostic vector toward mineralization derivable entirely from standard multi-element assay data combined with routine alteration logging.