Mineral Systems Modeling: New Technologies for Exploration Vectoring

Daniel Palmowski[1], Thomas Hantschel[1], Adrian Kleine[1]
[1]Terranta GmbH, Aachen, Germany

The rapid and large-scale increase in critical metal production required for the global energy transition demands innovative exploration technologies and predictive models to support informed investment decisions and reduce geological risk. Geological process modeling provides a framework for simulating the dynamic evolution of mineral systems, enabling a better understanding of ore-forming processes and guiding the definition of exploration vectors. Unlike petroleum systems, mineral systems are characterized by greater structural, hydrological, and geochemical complexity, necessitating more sophisticated and versatile simulation approaches. This study presents a generic geological process modeling workflow, demonstrated with a detailed case study of the Kupferschiefer sedimentary copper system.

We extended the classical Darcy flow formulation with advective and diffusive transport to enable accurate modeling of convection cells in complex and heterogeneous flow regimes. High-dimensional finite elements, unstructured grids, and adaptive local grid refinement techniques are used to resolve fluid transport at multiple scales, including advective, diffusive, and reactive transport. Chemical processes involving mineral, aqueous, and gas phases are modeled using Gibbs energy minimization solvers. To maintain computational efficiency, macro-models reduce solver runtimes from milliseconds to microseconds per call, making full-basin, multi-million-cell 3D simulations feasible.

The Kupferschiefer system, a world-class stratiform copper deposit in Central Europe, is modeled to understand basin-scale fluid-rock interaction, metal transport, and precipitation. Results highlight two critical ore-forming mechanisms: (1) focused fluid flow that channels oxidized, metal-bearing fluids into structurally and chemically favorable horizons, and (2) an advancing redox front that triggers copper precipitation, producing characteristic mineral zonation. The model reproduces observed vertical and lateral zoning patterns, including enrichment in chalcocite and bornite in relation to the advancing reduction front. These patterns serve as calibration targets and provide predictive criteria for exploration. The case study demonstrates how 3D geological process modeling enhances understanding of complex mineral systems and supports strategic exploration in sedimentary basins.