SEG 2024 Conference: Sustainable Mineral Exploration and Development

A Process-Based Approach to Constraining Metal Enrichment in Alkaline-Silicate Magmatic Systems Using New Thermodynamic Models

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Alkaline-silicate magmatic systems are an important host for a variety of specialty metals, including rare earth elements (REEs). However, what controls whether a given system will become sufficiently enriched to form an ore deposit remains poorly understood. Phase diagram analysis provides a tool to investigate such controls, but currently it is not possible to apply this method to alkaline compositions due to of an absence of thermodynamic models for the constituent phases. Here we present new thermodynamic models that fill this knowledge gap and allow for the generation of phase diagrams for alkaline igneous compositions. The phase diagrams provide a novel tool to explore the role of variables such as pressure, fractionation, and crustal assimilation in the petrogenesis of these systems. Furthermore, by integrating trace-element partitioning, we can investigate the controls on residual enrichment of specialty metals such as REEs as precursors to magmatic ore deposits.

The thermodynamic models are calibrated using experimental phase relation data, and the model performance is benchmarked with independent experimental data sets, encompassing a range of pressure (0–22 kbar), temperature (680°–1350°C), and global compositional ranges observed in alkaline-silicate systems. The calculated phase diagrams successfully reproduce experimental crystallisation sequences and phase compositions, indicating that the models are well calibrated across this spectrum of conditions. Applying our models to alkaline-silicate bulk compositions (e.g. nepheline syenite) yields solid assemblages consistent with those reported for natural systems. Analysis of the liquid line of descent reveals that the final melt fraction and associated equilibrium mineralogy (e.g. pyroxene, feldspar) evolves to extremely alkali-rich compositions, consistent with alkali-rich ‘fenitised’ zones observed in and around some alkaline-silicate intrusions. Finally, examples will be presented that showcase which crystallisation conditions are conducive to the formation of REE-rich alkaline-igneous rocks. Importantly, this new methodology can be applied to any specialty metal of interest in magmatic systems.