

EGU21-7903

<https://doi.org/10.5194/egusphere-egu21-7903>

EGU General Assembly 2021

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Modeling the sulfide saturation in continuously assimilating magmatic systems with the Magma Chamber Simulator

Ville Virtanen¹, Jussi Heinonen¹, Nicholas Barber², and Ferenc Molnár³

¹Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland (ville.z.virtanen@helsinki.fi)

²Department of Earth Sciences, University of Cambridge, Cambridge, England

³Geological Survey of Finland, Espoo, Finland

The timing and degree of immiscible sulfide precipitation in a magma effectively controls the formation of magmatic sulfide deposits and the budget of degassing sulfur species in volcanic systems. Besides the absolute sulfur (S) content, sulfide precipitation is strongly affected by the sulfur content at sulfide saturation (SCSS) in the host silicate melt. Assimilation of S-rich wall-rocks, such as black shales, effectively increases the S content in the magma, while simultaneously lowering the SCSS. Accordingly, assimilation has been identified as the most important process in the formation of many economically significant magmatic base metal sulfide deposit, especially in continental tectonic settings. Detailed understanding of the relation between wall-rock assimilation and sulfide saturation requires accurate thermodynamic models for open magmatic systems experiencing assimilation-fractional crystallization (AFC).

The Magma Chamber Simulator (MCS) is currently the only geochemical modeling software that considers the thermodynamic phase equilibria in open magmatic systems involving magma and wall-rock (and recharge) subsystems. We utilized the MCS to explore how assimilation affects the SCSS and S content of the magma. With the current lack of thermodynamic data for sulfides, we tentatively modeled S as a trace element and varied its compatibility to wall-rock in the different models. For a case study, we chose the mafic layered intrusions of Duluth Complex, Minnesota, which host some of the largest Cu-Ni sulfide deposits in the world. Assimilation of the adjacent black shale has been established as the main source for S in the deposits.

Our MCS models show in detail how continuous assimilation of the black shale lowers the SCSS of the melt. Partial melt from the black shale enriches the magma in SiO₂, Al₂O₃, K₂O, and H₂O, while depleting FeO, MgO, CaO, and Na₂O, which causes a first order decrease in the SCSS. The compositional change also replaces troctolitic cumulates (plagioclase, olivine ± clinopyroxene) with norite (plagioclase and orthopyroxene), which leads to more pronounced FeO depletion in the melt, further lowering the SCSS. On the other hand, the assimilated partial melt also increases the melt mass in the magma subsystem, which counteracts the S enrichment. Accordingly, in the model where S is compatible to the wall-rock residual, the degree of sulfide saturation only slightly increases relative to the same magma experiencing FC without assimilation.

More than half of the wall-rock S must partition to the assimilated partial melt in order to meet the

S isotopic criteria of the modeled Cu-Ni-deposits. The main stage of sulfide precipitation is associated with ~30 wt.% crystallization of the assimilating host magma. The proportion of sulfides relative to silicates in these models is smaller than observed in the Duluth Complex deposits, which underlines the role of dynamic processes in concentrating sulfides from the silicate magma.