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Numerical model of magmatically driven hydrothermal system THM(C) in volcanic settings

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Context

Volcanic flank collapse is a recurrent natural disaster documented at volcanoes worldwide, including Mount St. Helens (1980), Bezymianny (1956), Bandai (1888), and Unzen (1792) ([1], [2]). These large-scale instabilities are often linked to hydrothermal alteration, in which circulating fluids and heat interact with volcanic rocks, altering their mineral composition and weakening their mechanical properties [7].

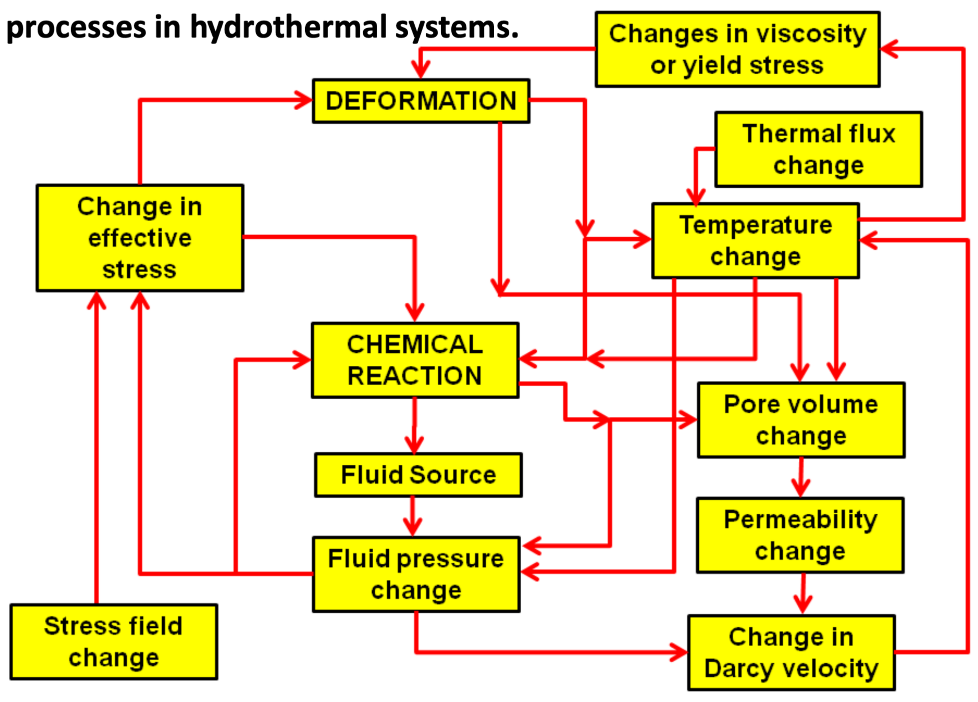


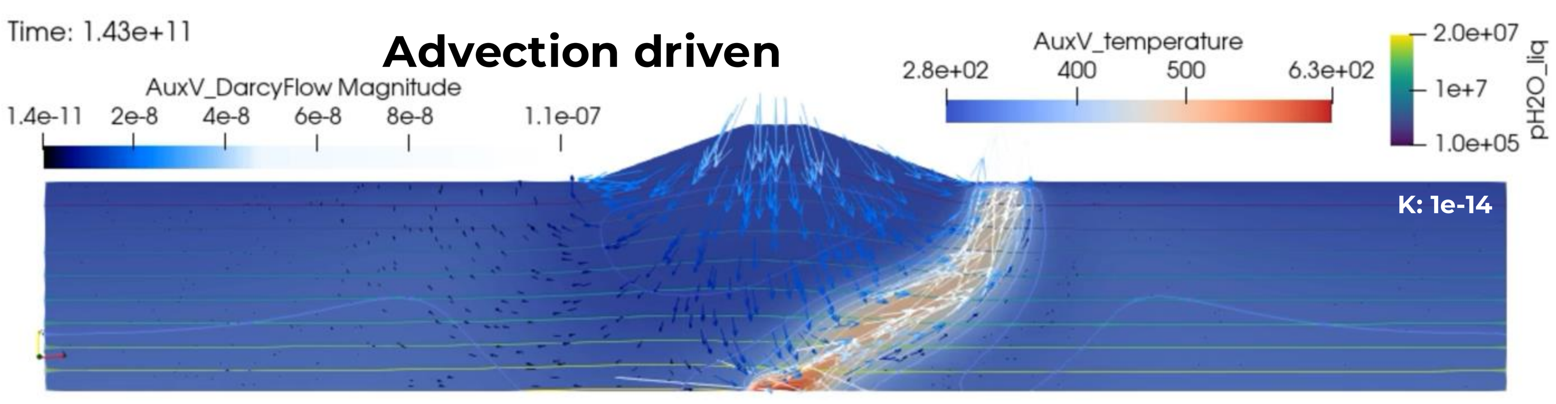
FIGURE 1 – Diagram representing the multi-physics processes acting in a hydrothermal system. Source: Bruce HOBBS

MOOSE

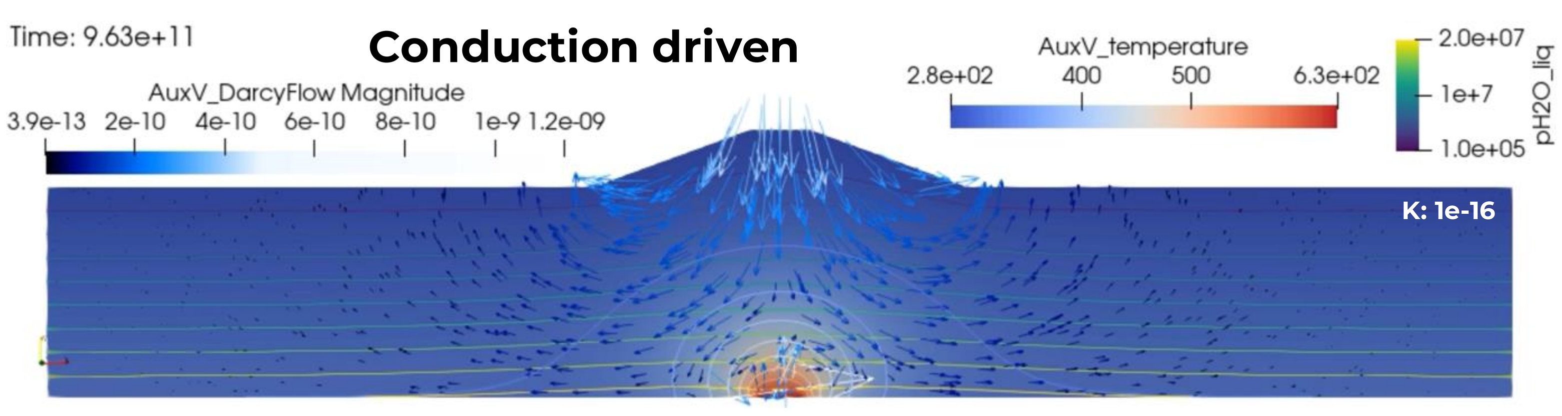
FIGURE 2 – Moose Framework, and its module PorousFlow, is the chosen FEM architecture to develop the THM(C) model for magmatically driven hydrothermal systems.

However, numerical investigation of mineral alteration and deposit formation in volcanic hydrothermal systems remains largely undeveloped. Current models of magmatically driven hydrothermal systems primarily address fluid and heat transport, often neglecting the mechanical response of host rocks. This limits their usefulness in assessing volcanic stability. In this context, modeling the coupled thermal, hydraulic, mechanical, and chemical processes offers a new way to identify zones prone to alteration and potential flank instability.

Permeability, a driving parameter



Permeability is the main factor determining the driving heat transfer mechanism between advection (up) and conduction (down) ([3], [4])



In volcanic edifices, cold meteoric water flows from the head at the center to the toes on the sides ([3], [4]). This flow shields the volcanic edifice from the hot mineralized (magmatic) water from deep below. This process also facilitates the accumulation of high-temperature areas near the bottom of the volcanic slopes and mineral transport.

Chemical species transport

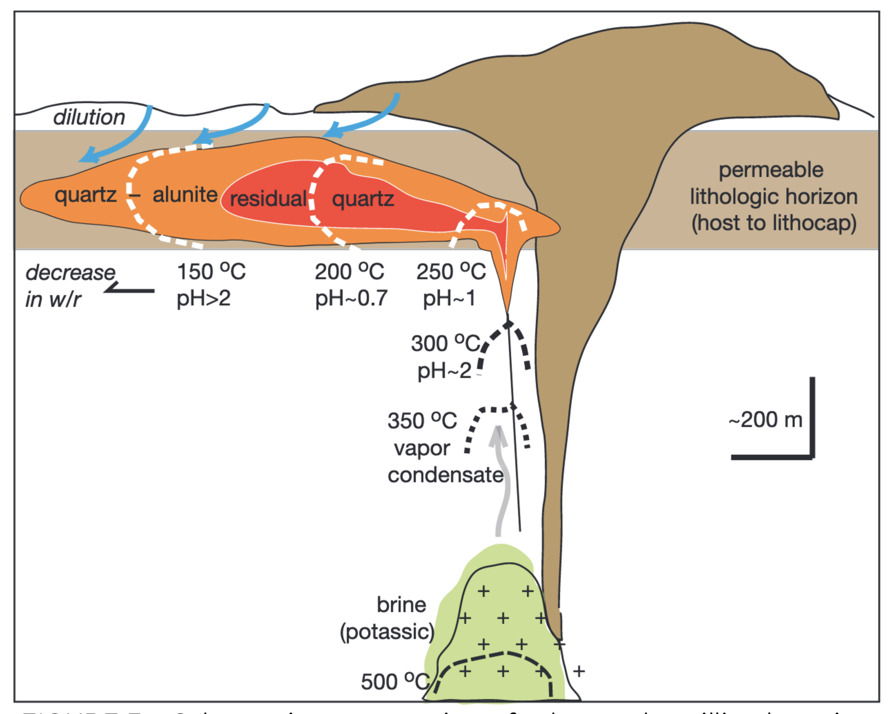
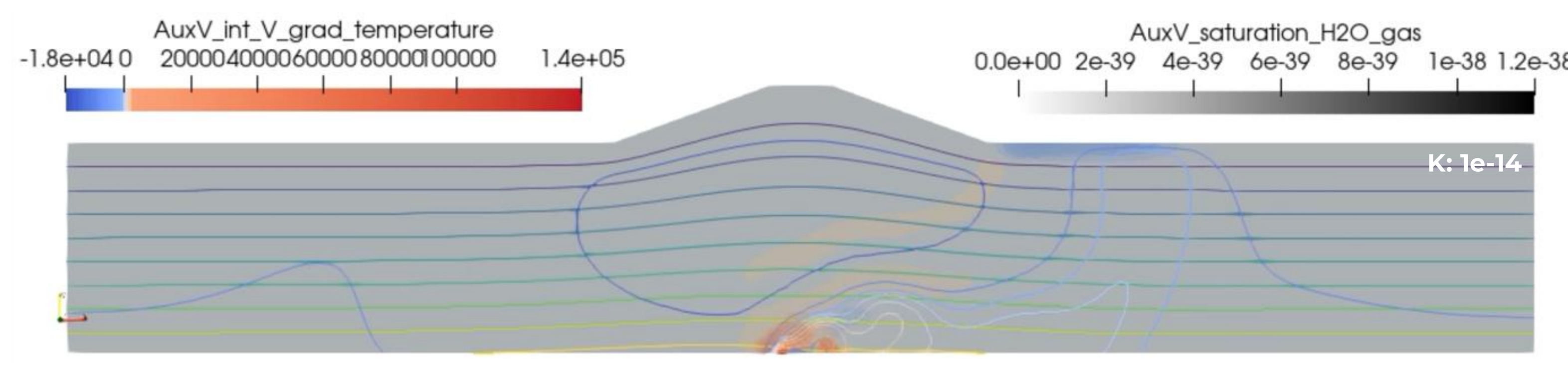
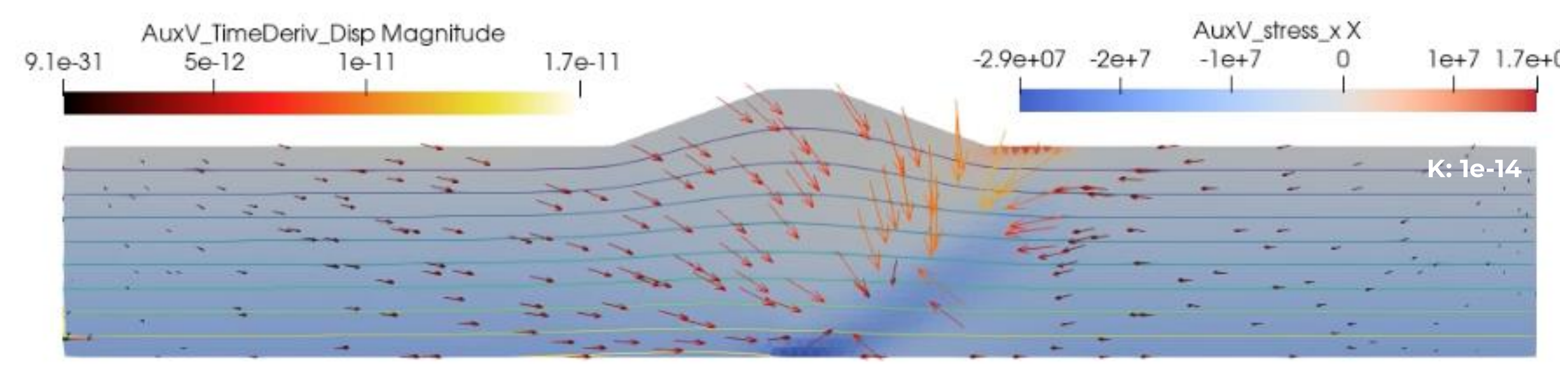


FIGURE 3 – Schematic cross section of advanced argillic alteration due to vapor condensate ascending along a structure; the alteration widens upward due to an increase in reactivity (lower pH) at lower temperature [6].

Due to the shielding effect of the cold downward flow, the chemical species are not transported to or from the body of the volcanic edifice. Instead, they are transported on the sides at the base of the volcanic edifice's slopes. Since hydrothermal alteration decreases rock mechanical strength, it could explain volcanic flank instabilities, especially since it occurs at the critical slope toe.



Mechanical tension



Thermal stresses around the volcanic edifice can reach 20 MPa of tension when assessed elastically. Volcanic rocks do not have a tension strength of 20 MPa, so such elastic assessment is physically incorrect. Nevertheless, the thermal stresses are sufficient to explain the nucleation of faults and the opening of existing ones.

Faults

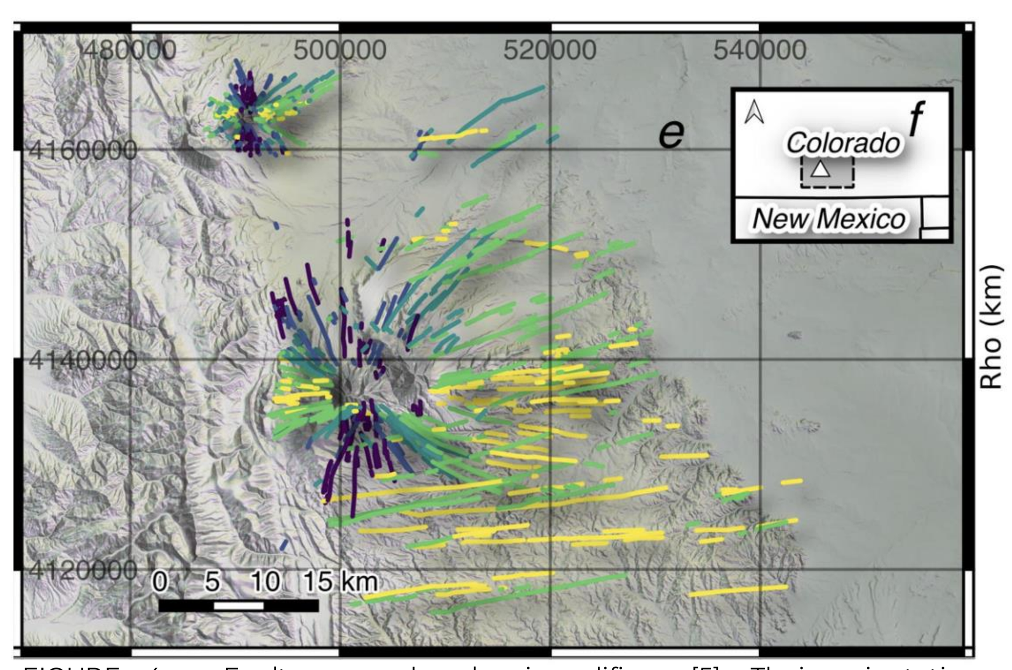


FIGURE 4 – Faults around volcanic edifices [5]. Their orientation demonstrate the volcanic conditions are prone to fault opening and nucleation.

The numerical model, which is already providing meaningful insights into magmatically driven hydrothermal systems, is still being mechanically developed. The goal is to couple the opening of existing faults, the nucleation of faults, and plastic computations with the other physics.

Conclusions

This study presents a two-dimensional numerical model of magmatically driven hydrothermal systems that couples thermal, hydraulic, and mechanical processes. Chemical transport is represented through proxy conditions. The model reproduces thermal and hydraulic patterns consistent with those reported in the scientific literature ([3], [4]), which reinforces the reliability of its results. The model also extends beyond the state of the art by explicitly incorporating the mechanical response of the host rock. The model highlights the key role of permeability in controlling advective versus conductive flow regimes, which govern the distribution of heat and potential zones of mineral alteration. Although thermal stresses are elastically overestimated, they appear sufficient to promote fault nucleation and aperture widening, providing a primary explanation for enhanced permeability pathways. Overall, the model shows that hydrothermal circulation can localize alteration in areas that are structurally sensitive, such as volcanic slopes. This has direct implications for the stability of volcanic flanks. Future work will focus on extending the mechanical formulation beyond elasticity to realistically capture plastic deformation and fault evolution.

References:

[1] L. Siebert, "Large volcanic debris avalanches: Characteristics of source areas, deposits, and associated eruptions," *Journal of Volcanology and Geothermal Research*, vol. 22, no. 3–4, pp. 163–197, Oct. 1984, doi: 10.1016/0377-0273(84)90002-7.
[2] L. Siebert, H. Glicken, and T. Ui, "Volcanic hazards from Bezymianny- and Bandai-type eruptions," *Bull Volcanol*, vol. 49, no. 1, pp. 435–459, Feb. 1987, doi: 10.1007/BF01046635.
[3] S. Scott, T. Driesner, and P. Weis, "Geologic controls on supercritical geothermal resources above magmatic intrusions," *Nat Commun*, vol. 6, no. 1, p. 7837, July 2015, doi: 10.1038/ncomms8837.
[4] S. Scott, T. Driesner, and P. Weis, "Boiling and condensation of saline geothermal fluids above magmatic intrusions," *Geophysical Research Letters*, vol. 44, no. 4, pp. 1696–1705, Feb. 2017, doi: 10.1002/2016GL071891.
[5] A. Kubo, "Multiscale Modeling of High and Low Reynolds Number in Small and Large Volume Volcanic Events."
[6] J. W. Hedenquist and Y. A. Taran, "Modeling the Formation of Advanced Argillic Lithocaps: Volcanic Vapor Condensation Above Porphyry Intrusions," *Economic Geology*, vol. 108, no. 7, pp. 1523–1540, Nov. 2013, doi: 10.2113/econgeo.108.7.1523.
[7] M. Detienne, "Unravelling the role of hydrothermal alteration in volcanic flank and sector collapses using combined mineralogical, experimental, and numerical modelling studies," Université catholique de Louvain, Louvain-la-Neuve, 2016.