Factors controlling the pressure-temperature structure of volcanic hydrothermal systems: Insights from numerical modeling

*Nashimoto Subaru[1], Akihiko Terada[1]

1. School of Science Tokyo

1. Background and Purpose

Understanding the structure of volcanic hydrothermal systems is essential for interpreting subsurface physical processes and assessing volcanic unrest. The gas-liquid phase distribution in hydrothermal systems is governed by their pressure-temperature structure, which controls observable parameters such as volcanic gas chemistry (Symonds et al., 2001). It also determines the overall archetype of hydrothermal systems (Fournier, 1999), distinguishing dry systems (e.g., Aso and Asama) from wet systems (e.g., Kusatsu-Shirane).

The controlling factors of pressure-temperature structure remain unclear. Fournier (1999) emphasized magmatic fluid enthalpy as a key parameter; other potential controls such as permeability structure or magmatic mass flux are not sufficiently addressed.

This study aims to identify the primary factors controlling pressure-temperature structures using numerical models. We construct one-dimensional and two-dimensional models assuming uniform permeability in the conduit and surrounding edifice, providing a first-order framework for systematic classification.

2. Method

Fluid flow is modeled as Darcy flow in porous media. Mass and enthalpy conservation equations are solved in terms of pressure and specific enthalpy following Hayba and Ingebritsen (1994).

The one-dimensional model describes flow in a conduit with constant radius. The key parameters are the conduit and edifice permeability, the mass flux and enthalpy of the source fluid, the conduit radius, and the source depth (1500 m). Two representative values of the enthalpy are examined: high-temperature volcanic gas (3600 kJ/kg) and supercritical fluid at 400 degC under lithostatic pressure (1800 kJ/kg).

A two-dimensional axisymmetric model is computed using HYDROTHERM (Hayba and Ingebritsen, 1994) to evaluate the validity of one-dimensional results.

3. Results

The one-dimensional system can be characterized by two composite parameters, beta and Lambda. Beta (dimension 1/length) reflects the permeability contrast and controls the characteristic pressure variation scale. Lambda (dimension pressure/length) represents the magnitude of conduit pressure relative to hydrostatic pressure.

When Lambda > 0, the conduit remains overpressurized, causing the fluid continuously to leak outward along its length. When Lambda < 0, solutions bifurcate into overpressurized and depressurized regimes. At the depths where the conduit pressure falls hydrostatic, groundwater flows into the conduit.

In overpressurized systems with the high source enthalpy, the fluid ascends isenthalpically and remains in the gas phase. For supercritical enthalpy , two-phase conditions develop and the temperature follows the boiling curve above the depth of phase separation.

In depressurized systems, enthalpy distribution is governed by mixing between groundwater inflow and the magmatic flux. Depending on the mixing ratio, the conduit exhibits liquid, two-phase, or gas-phase dominated conditions.

Thus, for a given enthalpy of the source fluid, pressure-temperature structure can be systematically mapped in (Lambda, beta) space.

4. Discussion and Conclusion
Overpressurized systems with high magmatic enthalpy produce gas-phase dominated hydrothermal systems in which fumarolic temperatures reflect the enthalpy of the source fluid at atmospheric pressure. Limited gas-water interaction suppresses gas scrubbing, leading to SO2-rich emissions (Symonds et al., 2001). This behavior is consistent with systems such as Aso and Asama, which experience relatively frequent magmatic eruptions . Aso and Asama may have positive Lambda, possibly due to substantial supply of high enthalpy gas from their magma storage regions.
In contrast, Kusatsu-Shirane exhibits evidence of groundwater circulation and magmatic-meteoric mixing at depth (Ohba et al., 2000, 2008), with fumarolic temperatures near the boiling temperature. These features correspond to the depressurized regime characterized by mixing and phase separation. Kusatsu-Shirane may have negative Lambda, possibly due to smaller magmatic gas input.
The (Lambda, beta) framework therefore provides a physically based classification of volcanic hydrothermal systems in terms of pressure-controlled regimes. Future work should incorporate depth-dependent permeability and topography to refine the model and investigate system responses to variations in magmatic supply.

Keywords: volcanic hydrothermal system , numerical model