Quantifying the Water Budget of a Caldera-Hosted Magmatic System

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Formation of shallow upper-crustal magma reservoirs is commonly accompanied by exsolution of aqueous fluids, potentially generating exploitable geothermal systems. Despite the importance of this process, quantitative estimates of fluid release during extraction of eruptible magma from a mush zone remain limited. Here we quantify the amount of aqueous fluid released during the formation of a shallow magma chamber associated with a large caldera-forming eruption and present a methodological framework for estimating fluid fluxes that can be applied to other magmatic systems with geothermal potential.
Our case study is the well-described ~60 km^3 DRE caldera eruption of Mendeleev Volcano (Kunashir Island, Kuril Islands; Kotov et al., 2023). Previous studies demonstrated that rhyodacitic melts feeding the eruption were extracted from an amphibole-bearing mush zone at depths of up to ~12 km (~3 kbar). Primary rhyodacitic melt inclusions hosted in high-Ca plagioclase and high-Mg pyroxene crystal clots contain up to 7.7 wt% H_2O and are interpreted to represent melts trapped in the deep storage region prior to extraction. After extraction and before eruption, magmas were emplaced in a shallow reservoir at ~3 km depth under pre-eruptive conditions of 820-830°C and 0.77-1.16 kbar. Primary melt inclusions hosted in the late-crystallizing mineral quartz are rhyolitic, contain ~4 wt% H_2O, and record shallow storage conditions.
Using Rhyolite-MELTS modelling, we reconstructed the crystallization path during melt extraction from the deep mush zone, taking the compositions of primary rhyodacitic melt inclusions in high-Ca plagioclase cores as the starting melt composition (Miyagi, 2025). The modelling results reproduce the compositions and H_2O contents of quartz-hosted melt inclusions after ~21-28% crystallization, consistent with the observed crystallinity and mineral assemblage of the erupted products. These results demonstrate that crystallization of melts corresponding to the earliest trapped inclusions, accompanied by fluid exsolution, can generate the final melt compositions recorded by late quartz-hosted inclusions.
Using the known erupted volume, melt H_2O contents before and after extraction, and the estimated degree of crystallization, we performed mass-balance calculations to quantify excess water released during melt extraction and shallow reservoir formation. The estimated excess water release is 5.3-6.5 Gt, equivalent to 55-70% of the initially dissolved H_2O.
Integrating geological constraints on the duration of shallow batholith formation in the Southern Kuril region during the Pleistocene with published magma extraction rates for silicic plutons (de Saint Blanquat et al., 2011 and references therein), we estimate the resulting fluid flux to be 1.5-15.5 t/yr/m of subduction zone length, or 277-2812 t/yr/km^2. These values overlap with independent estimates of slab-derived water input into the NE Honshu crust (~13 t/yr/m for a ~500 km segment; Kimura and Nakajima, 2014).
Because shallow crustal magma bodies are localized beneath volcanic centers rather than distributed continuously along the subduction zone, our results suggest that volcanic systems act as focused zones of fluid release, discharging amounts of water comparable to slab-derived fluxes entering the crust.

Keywords: Water budget, Fluid flux, Caldera eruption, Rhyolite-Melts, Melt inclusions

