Constraining Magma Ascent Rate Using Water Diffusion in Olivine and Clinopyroxene — Mt. Pavlof, Alaska

UNIVERSITY OF MARYLAND 1856 DEPARTMENT OF GEOLOGY

Nicholas Culbreth (GEOL 394)

Advisor: Dr. Megan Newcombe

UNIVERSITY OF MARYLAND 1856 DEPARTMENT OF GEOLOGY

Introduction

Located in the Aleutian Range, Mount Pavlof is a highly active stratovolcano with a diverse history of eruptive styles. On March 27th, 2016, the volcano erupted without any detectable seismic precursors; this marked the 16th eruption in 50 years. The eruption continued for 29 hours and emitted an abnormally large ash plume. Reaching 9 km in height and extending over 600 km to the northeast, the ash plume resulted in the cancellation of over 100 flights. This eruption was ultimately classified as a 2 on the volcanic explosivity index: a logarithmic scale of relative eruption explosiveness, akin to Richter Magnitude.

Fig. 1: Location of Mt. Pavlof, Alaska, from Google Earth Pro.

Hypotheses

Hypothesis: Magma ascent rates during Mount Pavlof's 2016 eruption exceed those of comparable VEI 2 and 3 eruptions, as evidenced by the exceptional plume height and lack of seismic precursors.

Null Hypothesis: The magma ascent rate of Mount Pavlof overlaps with the uncertainty bounds of comparable VEI 2 and 3 eruptions.

Methods

The syneruptive magma ascent rate during Mount Pavlof's 2016 eruption was constrained by applying water diffusion chronometry to a sample of erupted tephra. Three grains of olivine were doubly polished to expose parallel faces of glassy melt inclusions (MIs). These MIs are solidified pockets of preserved magma within crystals that reflect melt characteristics at the time of entrapment. Water concentration, a function of pressure, was measured for each MI using Fourier-transform infrared spectroscopy (FTIR). A magma degassing path based on the MI water concentrations was reconstructed using VolatileCalc 2.0, an excel based program for calculating volatile-melt equilibria.

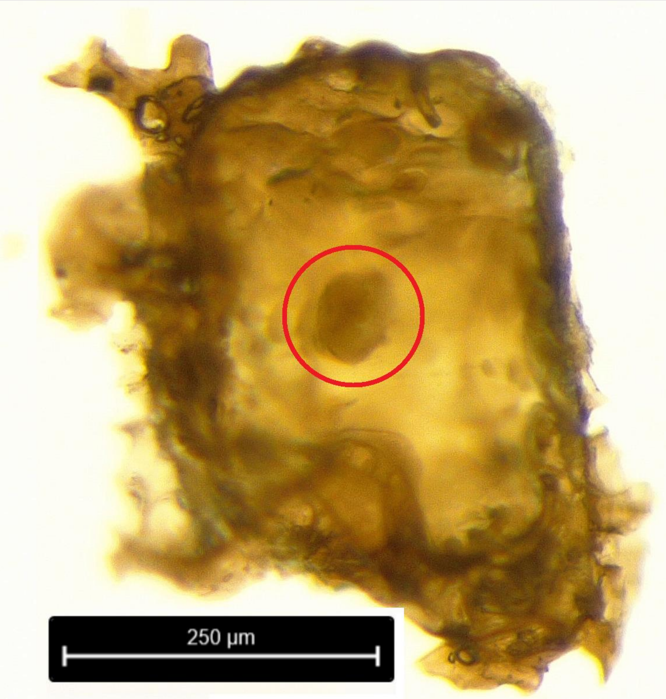

Fig. 2: Transmitted light photomicrograph of sample Ol-20, 40x magnification, MI circled in red.

A clinopyroxene (CPX) grain without melt inclusions was doubly polished to expose parallel faces at an arbitrary thickness of 150 microns. A water concentration gradient was measured by FTIR along a transect from the center of the CPX to the rim. Compositional constraints on the CPX phase were established using rhyolite-MELTs, a thermodynamics-driven phase equilibrium software package. The CPX's calculated composition was used to constrain the diffusion rate (D_H) and crystal-melt partition coefficient (k_d) of water within the grain.

1-D diffusive water loss in the CPX was modeled in MATLAB as a function of the highest MI water concentration (C_{MI}), D_H, and k_d. A 2000-iteration Monte Carlo analysis was performed. Water concentration measurements along the CPX transect, C_{MI}, D_H, and k_d were varied within their uncertainties. An ascent rate for each iteration's parameters was fit using the least squares method.

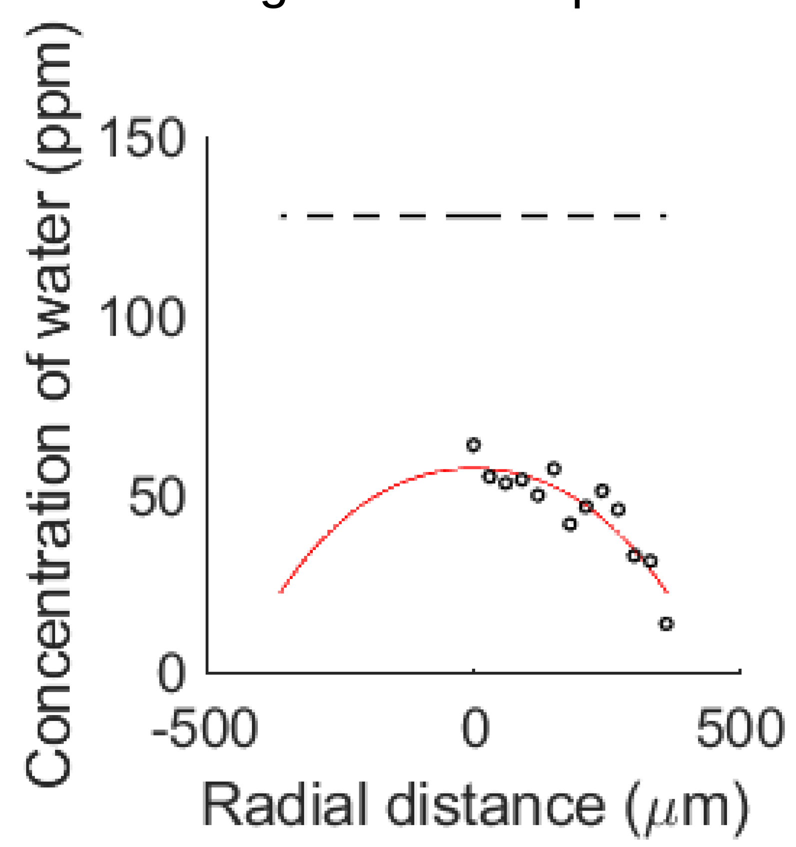

Fig. 3: Single iteration example of CPX water diffusion model.

An example of a single model run, with water concentration (ppm) plotted against radial distance (µm). Dashed black line represents initial water concentration, the product of C_{MI} and k_d. Open circles are water concentrations measured along the transect. The solid red line is the least squares fitted ascent rate (MPa/s) solution.

Results

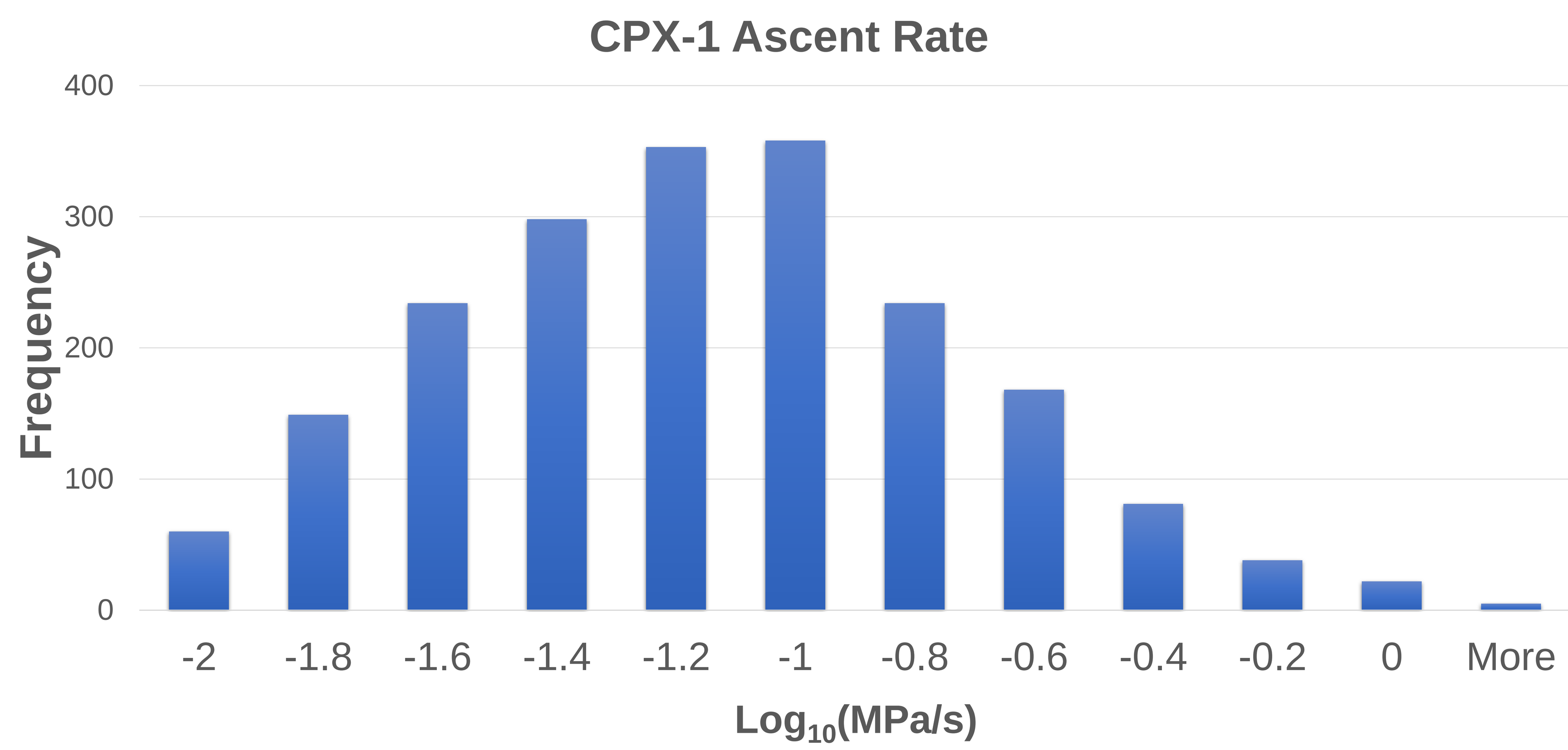

Fig. 4: Histogram showing distribution of CPX-1 magma ascent rate, with a mean value of -1.02 ± 0.872 $\log_{10}$(MPa/s) (2σ uncertainty)—equivalent to 0.097 MPa/s.

Discussion

Water diffusion chronometry of the clinopyroxene largely supports the hypothesis. The syneruptive magma ascent rate during Mt. Pavlof's 2016 eruption exceeds the uncertainty ranges of previous diffusion-based ascent rate studies for VEI 2 and 3 eruptions at Cerro Negro, Nicaragua. Pavlof's 2σ uncertainty overlaps with that of Vulcán de Fuego's 1974 (VEI 4) and Kilauea Iki's 1959 (VEI 2) eruptions. However Kilauea's eruption was of a distinctly different fire fountain style. Observational evidence of explosive eruptions relating plume height to ascent rate yields a peak plume height of 11.2 ± 2.7 km (1σ)—agreeing with Pavlof's observed peak plume height of 9 km and validating the model (Mastin et al., 2009).

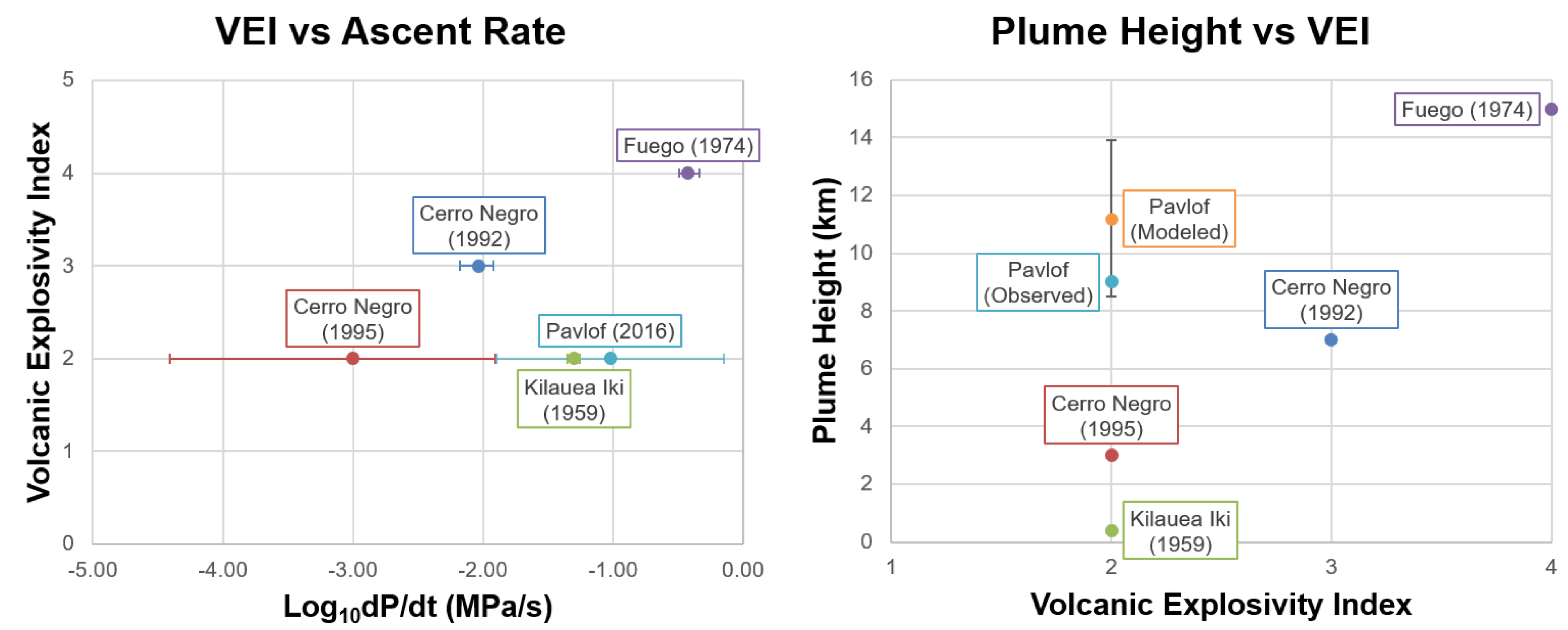

Fig. 5: Plots of VEI vs Ascent Rate (left) and VEI vs Plume Height (right) for Pavlof and previous water diffusion chronometry studies.

Cerro Negro (Barth et al., 2019); Vulcán de Fuego (Lloyd et al., 2014); and Kilauea Iki (Ferguson et al., 2016)

Pavlof's remarkable magma ascent rate highlights known limitations of VEI, which favors total volume erupted over other eruption parameters. Large uncertainties in the data limit further interpretations. This could be remedied in the future by an increase in sample size, grain-specific rather than phase-specific compositional constraints, and direct measurement of water diffusion coefficients through sub-solidus heating of analyzed grains. Additionally, the data may be biased towards a single phase of the eruption due to the localized nature of the sample. This emphasizes the need for timestamped sample collection throughout entire eruptions for future diffusion chronometry studies.

References

Barth, A., Newcombe, M., Plank, T., Gonnermann, H., Hajimirza, S., Soto, G. J., Hauri, E. (2019). Magma decompression rate correlates with explosivity at basaltic volcanoes — Constraints from water diffusion in olivine. Journal of Volcanology and Geothermal Research, 387.

Ferguson, D. J., Gonnermann, H. M., Ruprecht, P., Plank, T., Hauri, E. H., Houghton, B. F., & Swanson, D. A. (2016). Magma decompression rates during explosive eruptions of Kīlauea volcano, Hawaii, recorded by melt embayments. Bulletin of Volcanology, 78(10).

Ghiorso M.S., Gualda, G.A.R., (2015) An H2O-CO2 mixed fluid saturation model compatible with rhyolite-MELTS. Contributions to Mineralogy and Petrology, 1 69(53).

Lloyd, A. S., Ruprecht, P., Hauri, E. H., Rose, W., Gonnermann, H. M., & Plank, T. (2014). NanoSIMS results from olivine-hosted melt embayments: Magma ascent rate during explosive basaltic eruptions. Journal of Volcanology and Geothermal Research, 283, 1–18.

Mastin, L., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., … Waythomas, C. (2009). A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. Journal of Volcanology and Geothermal Research, 186(1-2), 10–21.

Newman, S., & Lowenstern, J.B. (2002). VolatileCalc: a silicate melt-H2O-CO2 solution model written in Visual Basic for Excel. Computers and Geosciences, 28(5), 597-604.