https://doi.org/10.1130/G52679.1

Manuscript received 13 August 2024

Revised manuscript received 1 October 2024

Manuscript accepted X Month 2024

Brenna Halverson[ID]https://orcid.org/0009-0009-7766-7384

*halversonbrenna@gmail.com

CITATION: Halverson, B.A., and Whittington, A., 2024, From flow to furnace: Low viscosity of three-phase lavas measured at Kīlauea 2018 eruption conditions: Geology, v. XX, p. XXX–XXX, https://doi.org/10.1130/G52679.1

Printed in the USA

[1]Supplemental Material. **[[Please provide a brief description here.]]** Please visit https://doi.org/10.1130/GEOL.S.XXXX to access the supplemental material; contact editing@geosociety.org with any questions.

From flow to furnace: Low viscosity of three-phase lavas measured at Kīlauea 2018 eruption conditions

Brenna A. Halverson[1,*] and Alan Whittington[1]

[1]*Department of Earth and Planetary Sciences, The University of Texas at San Antonio, One UTSA Circle, San Antonio, Texas 78255, USA*

ABSTRACT

DOI:10.1130/G52679.1

Melt composition, temperature, and crystallinity are often seen as the three most important characteristics driving lava rheology, which controls eruptive behavior. Traditional methods of measuring the viscosity of crystallizing basalts often yield different mineral characteristics to natural samples and are typically bubble-free. To quantify the viscosity of basalts inclusive of bubble and crystal cargo, we developed a new technique to measure high-temperature three-phase isothermal lava viscosity and applied it to samples from the 2018 eruption of Kīlauea. This new experimental technique begins at subliquidus temperatures, preserving original phenocrysts. A short experimental duration allows for the retention of most of the original bubble population (19%–31% vs. 36% in the original lava) and accurate replication of crystal textures from field samples, as documented in quenched postexperiment samples. The observed rheological behavior in these experiments, conducted at syneruptive temperatures (1150–1105 °C) and strain rates (0.4–18 s^{-1}), should therefore be representative of the lava flows. We measured average viscosities of 116 Pa·s at 1150 °C to 167 Pa·s at 1115 °C, i.e., only 10%–25% higher than calculated liquid viscosities at those temperatures, and a maximum of 1800 Pa·s at 1105 °C. These results are much lower than viscosity measured in traditional bubble-free experiments, which plateaued at ~14,000 Pa·s at 1115 °C. Our results suggest the effect of bubbles in three-phase magmas may be greater than predicted by models based on two-phase bubbly liquids, and this effect must be included in realistic lava flow rheology models. The method proposed here supplies a framework for providing the necessary experimental constraints.

INTRODUCTION

Characterization of lava viscosity is crucial for modeling lava flow emplacement and hazards (e.g., Cappello et al., 2016; Chevrel et al., 2018**[[Not in the reference list.]]**). Lavas consist of crystals and/or bubbles in a silicate melt, where changes in temperature, melt chemistry, and size, shape, and abundance of bubbles and crystals can result in large variations in rheological behavior (e.g., Mader et al., 2013; Kolzenburg et al., 2022). Experiments on two- and three-phase analog materials (e.g., Truby et al., 2015; Pistone et al., 2016; Birnbaum et al., 2021) are used to measure the impact of bubbles and crystals on suspension rheology but are limited in their ability to emulate the complexity of magmatic systems.

Laboratory experiments measuring the viscosity of basaltic lavas near eruption temperatures (~1200–1100 °C) account for changes in temperature and melt composition (e.g., Sehlke et al., 2014; Soldati et al., 2016; Kolzenburg et al., 2022). Traditional isothermal subliquidus experiments first heat samples above the liquidus and then cool to and hold samples at the target temperature until viscosity plateaus, which often takes ≥10 h (e.g., Ryerson et al., 1988; Ishibashi and Sato, 2007; Chevrel et al., 2015**[[Not in the reference list.]]**; Sehlke and Whittington, 2015). The initial high temperatures and long experimental duration result in a loss of bubbles, phenocrysts, and phases such as olivine, which are difficult to grow in atmospheric conditions (e.g., Mourey and Shea, 2019), creating a measured lava with very different textural characteristics than the parent lava.

While field measurements of basaltic lava viscosity have been conducted in situ (e.g., Chevrel et al., 2018**[[Not in the reference list.]]**; Harris et al., 2024), these are limited to lava flow margins, where thermal gradients and flow advance result in brief measurements of cooling lava. The lack of high-temperature three-phase lava measurements thus leaves a gap in our ability to accurately model lavas at flow conditions.

Here, we present a new technique for the measurement of high-temperature three-phase isothermal (HTTPI) lava viscosity at syneruptive temperatures (~1145 °C; Gansecki et al., 2019) and strain rates (2–3 s^{-1}; Dietterich et al., 2021), in which the original textures of the basaltic lavas are well replicated, and our results demonstrate that viscosities of lavas at emplacement conditions are likely lower than estimates from traditional experimental methods.

METHODS

Samples along the fissure 8 flow field of the 2018 eruption of Kīlauea (Neal et al., 2019) were collected in January 2020, with emplacement dates determined from unoccupied aircraft system (UAS) video and thermal imaging during the eruption (Desmither et al., 2021; Patrick, 2024). A single sample (F8.13) collected ~2 m below the flow surface was used as the starting material for all viscosity experiments. This sample is chemically indistinct from the rest of the flow (see X-ray fluorescence [XRF] data in Supplemental Material[1]) and provides a homogeneous, highly crystalline, and moderately vesicular (~34%) starting material.

Viscometry experiments were conducted using an Orton 1700 RSV viscometer, with a Brookfield HB head. A wide-gap concentric cylinder geometry was used, with iron-saturated Pt90:Rh10 alloy crucibles of ~70 mm height by 31 mm internal diameter, and alumina spindles sheathed in 7.4-mm-external-diameter iron-saturated Pt90:Rh10. At the start of each measurement, the spindle was immersed to 20 mm depth. Rotation rate was determined by the user, and the viscometer recorded the torque. This resulted in pairs of stress and strain rate data, the ratio of which is referred to as “apparent viscosity,” as the material is often non-Newtonian.

We first conducted a “traditional” isothermal experiment. For this, an ~60 g aliquot of roughly crushed (5 mm to 2 cm diameter) F8.13 was heated to 1500 °C at 10 °C/min, held for 30 min, cooled to 1115 °C at 10 °C/min, and then held for 9 h until viscosity stabilized.

In contrast, the HTTPI experiments began by placing the crucible directly into a preheated furnace at 1175 °C (below the experimentally determined liquidus of 1200–1190 °C) for ~20 min, until a visual inspection indicated no solid rock remaining. The spindle was immersed in the sample, and the furnace temperature was lowered at 10 °C/min to the target temperature (1150 °C, 1115 °C, or 1105 °C) immediately thereafter. Thermal equilibration of the sample was determined by a plateau in the apparent viscosity, ~5 min after the furnace reached the target temperature in each experiment. This is consistent with the experimental dimensions and low thermal diffusivity of basaltic lava, i.e., ~0.3–0.5 $mm^2 s^{-1}$ (Hofmeister et al., 2016).

Once viscosity stabilized, the strain rate was varied every 2–3 min between 0.44 and 18 s^{-1}, depending on the experiment, to quantify non-Newtonian behavior (see Supplemental Data). The spindle was subsequently removed, and the sample quenched within 3 min of the end of experiment by partial immersion of the crucible in water for ~30 s. Total duration above room temperature was constrained to <1 h to ensure minimum bubble loss and oxidation.

After quenching, samples were removed from crucibles using a diamond-coated core drill, mounted on glass slides, and polished. These were imaged in reflected light with a Meiji Techno MT9000 polarizing microscope, at a resolution of 0.36 µm/pixel. Images were mosaiced using Fiji® Image Stitching (Preibisch et al., 2009) and Adobe Photoshop®. Characterization of the abundance, size, and shape of crystals and bubbles was done using Dragonfly® software. Deep learning methodology (Halverson, 2024) was used for fast, large-scale segmentation across the samples. This image segmentation, with 30 min of manual refinement, resulted in uncertainties of <<1% area crystallinity. Subsequent crystal size distribution (CSD) calculations to examine crystal size and shape similarity between experimental and natural samples used HabitEST (Liu et al., 2018**[[Not in the reference list.]]**) to approximate crystal habit, and CSDCorrections (Higgins, 2000) to calculate CSD graphs. Uncertainties were approximated by $2\sigma = 2\sqrt{N}$, where N is the number of crystals in each size range (Higgins, 2000; Gualda, 2006).

RESULTS

Textural Analysis

Crystallinity of the recovered HTTPI samples decreased from ~14% at 1175 °C to ~6% at 1150 °C, indicating continued melting during cooling to target temperature (Table 1). However, crystallinity increased to ~13% at 1115 °C and surpassed the zero-time sample to reach ~31% at 1105 °C. Material recovered from the 1115 °C traditional method was different to both the zero-time and HTTPI experimental products, with little to no vesicularity, plagioclase, or olivine, and higher oxide and pyroxene contents relative to HTTPI samples. This matches the assemblage from traditional experiments in controlled fO_2 conditions obtained by Soldati et al. (2021b).

Vesicularity decreased from 36% at 1175 °C to ~19% at 1150 °C and 1115 °C. The 1105 °C experiment retained 31% bubbles, likely related to its higher crystal fraction. Recovered vesicles in the 1150 °C and 1115 °C HTTPI experiments were spherical, due to a calculated relaxation time of <1 s, while at 1105 °C, the bubbles were more deformed (Fig. 1). The latter experiment had a maximum relaxation time of <3 s, indicating that crystal impingement may have contributed more than bulk viscosity to their morphology (Supplemental Data).

Comparison of natural and experimental textures indicates that we can re-create natural crystalline modal abundances and morphologies and achieve similar vesicularities to those seen in distal portions of the flow (Table 1). The crystal assemblage of the 1105 °C experiment resembles the quenched margin of sample F8.11, collected 14 km downflow. This surface-quenched ooze-out structure provides the best estimate for textures present within the flow without overprinting from postemplacement crystallization, which was seen in F8.13. While crystallinity is lower in the HTTPI experiment than in F8.11 (31 vs. 42 area %), we achieved very similar phase assemblages to those seen in the natural sample (Fig. 2; Table 1). CSDs calculated for both assemblages show that plagioclase distributions are statistically indistinguishable (Fig. 2). The narrow (<2 mm) quenched margin in the natural sample precludes the presence of large pyroxene crystals.

The vesicularities of the samples, especially at 1105 °C, were similar to F8.25b, an ‘a’ā sample collected ~13 km from the vent on the lava delta of the fissure 8 flow. This sample has ~26% vesicularity, falling within those recorded from the experimental samples. It also exhibits partially spherical and merging bubbles, similar to those in HTTPI lava at 1105 °C (Fig. 1).

Viscosity Measurements

The viscosity measured during the traditional experiment started at 262 Pa·s, which is slightly higher than the HTTPI experiment at the same temperature. It slowly increased after this, with some brief plateaus at ~970, ~1365, and ~7780 Pa·s, until reaching ~14,000 Pa·s 9 h later. This experiment is consistent with previous subliquidus studies on Kīlauea 2018 lavas, as we measured ~82 Pa·s at 1130 °C during cooling, compared to 77–132 Pa·s measured while holding at 1130 °C by Soldati et al. (2021b).

The apparent viscosity of the HTTPI experiments increased with decreasing temperature, from an average of 116 Pa·s at 1150 °C, to 167 Pa·s at 1115 °C, to 397–1800 Pa·s at 1105 °C, depending on strain rate. Viscosity became strongly shear-thinning at 1105 °C, as indicated by large variations with changing strain rate (Fig. 3A; Supplemental Material).

At 1115 °C, the viscosity of the HTTPI experiment was nearly two orders of magnitude lower than that at the end of the traditional method. This difference is far greater than could be explained by the difference in total crystallinity (17% traditional vs. 13% HTTPI). Even if the long equilibration time of the traditional method is ignored, and viscosity is recorded at the first plateau, there was still a more than factor of 5 difference between the two methods (~955 Pa·s

DOI:10.1130/G52679.1

for traditional method vs. ~167 Pa·s for HTTPI). This difference reflects two key textural differences: the crystal size and shape distribution, and the presence of bubbles.

DISCUSSION

Our measured three-phase lava viscosities were ~116 Pa·s at 1150 °C and ~167 Pa·s at 1115 °C, for <15% crystals and <20% bubbles. Liquid viscosities for fissure 8 calculated using the VFT **[[Please spell out VFT here.]]** fit to the data of Soldati et al. (2021a) were 86 and 162 Pa·s, i.e., only slightly lower, indicating that the effects of crystals and bubbles largely offset each other in these experiments (Supplemental Data). Higher bubble fractions, as seen in the active channel (e.g., 71%; Dietterich et al., 2021), are expected to result in even lower effective **[[apparent?]]** viscosities, which severely increase rapid inundation hazards.

While bubble loss occurred in all HTTPI samples, it only noticeably affected viscosity measurements at 1150 °C, where viscosity decreased by 0.15 log units over 14 min. This is commensurate with the lower bound of a 8 ± 2 mm decrease in the immersion depth of the spindle calculated from the 16% vesicularity decrease from the zero-time material.

The apparent viscosity of the 1115 °C HTTPI experiment was a factor of ~5 to ~70 lower than the apparent viscosity of the 1115 °C traditional experiment, depending on which viscosity plateau was chosen. Contributing factors included a small difference (~4.5%) in crystal fraction, a difference in crystal assemblage, and the addition of ~20 vol% bubbles. Previous experimental studies of bubbly lavas indicated that the maximum effect of bubbles on viscosity is up to one order of magnitude difference (e.g., Lejeune et al., 1999; Stein and Spera, 2002). Using the traditional method with a crystal-bearing fluid as the effective medium (Mader et al., 2013) and applying the equation of Llewellin and Manga (2005) for the effect of bubbles, we would predict a relative viscosity of 0.71–0.87 for the 1115 °C HTTPI experiment (dependent on strain rate and effective medium viscosity; see Supplemental Data). This is at most a 29% decrease in viscosity relative to the traditional method, whereas we measured an 82%–99% lower relative viscosity.

In principle, three-phase lava rheology can also be modeled starting from the liquid viscosity, using the fit to data from Soldati et al. (2021a). We first applied the Maron and Pierce (1956) equation using these values to calculate the crystal liquid suspension viscosity. We used this as the effective medium and applied Llewellin and Manga (2005) as above. The predicted viscosities agree with our measurements at 1150 °C, and 1105 °C, where both model and measurements vary strongly with strain rate (Fig. 3B). At 1115 °C, however, this method still resulted in a 70%–80% overestimation in three-phase viscosity. This indicates that bubbles may have a stronger effect upon viscosity of crystal-bearing suspensions than is suggested by current models, in certain crystallinity/vesicularity regimes. This effect should be greater in samples with larger bubbles and higher total vesicularity, especially at low crystallinity as seen in active flows, indicating that current models may overestimate lava flow viscosity.

The larger effect of bubbles on the three-phase viscosities seen in experiments over modeled viscosity may be due to strain partitioning into highly deformable bubbles (e.g., Holtzman et al., 2012). During three-phase rheology experiments on haplogranites, Pistone et al. (2012)**[[Not in the reference list.]]** observed shear-thickening behavior at low strain rates (5.13×10^{-5} to 1.04×10^{-4} s^{-1}), and shear-thinning behavior at high strain rates (4.81×10^{-4} to 9.25×10^{-4} s^{-1}) for “dilute” suspensions of <44% crystals and 10%–12% vesicularity. The transition between shear thickening and thinning was attributed to strain partitioning into deformable bubbles at high strain rates, where the small bubble radii (~5–50 µm) and low strain rates of those experiments likely drove the shear-thickening behavior. Given the fact that our HTTPI experiments had higher bubble contents, lower crystallinity, and larger average bubble radii

(~200–300 μm), the 4-log-unit higher strain rate of our experiments would result in strain partitioning into the bubble phase, causing strong deformation and viscosity decreases.

The HTTPI experiments presented here resulted in very similar crystal populations to those seen in distal samples from the fissure 8 flow field and retained significant bubble volume fractions. In order to match lower-crystallinity and/or much higher-vesicularity samples from closer to the vent, it may be necessary to use a starting material that is more similar to those textures. While we found it easier to retain bubble populations at higher crystallinity, highly vesicular samples from basaltic lava flows are often very crystal poor. The effect of bubbles may be particularly large in the channelized portion of the flow, where lavas exhibit 60%–80% vesicularity and 3%–20% crystals in the first 8 km. Future work should determine the crystal and bubble textures that can be consistently retained in the laboratory, providing three-phase data to improve models of conduit processes, lava flow emplacement, and hazards.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation grant EAR-1928923 to Whittington and the National Aeronautics and Space Administration (NASA) Minority University Research and Education Project (MUREP) Institutional Research Opportunity (IRO) (MIRO) Center for Advanced Measurements in Extreme Environments, grant 80NSSC19M019. We thank three anonymous reviewers for their feedback.

REFERENCES CITED

Birnbaum, J., Lev, E., and Llewellin, E.W., 2021, Rheology of three-phase suspensions determined via dam-break experiments: Proceedings: Biological Sciences, v. 477, no. 2254, https://doi.org/10.1098/rspa.2021.0394.

Cappello, A., Ganci, G., Calvari, S., Pérez, N.M., Hernández, P.A., Silva, S.V., Cabral, J., and Del Negro, C., 2016, Lava flow hazard modeling during the 2014–2015 Fogo eruption, Cape Verde: Journal of Geophysical Research: Solid Earth, v. 121, no. 4, p. 2290–2303, https://doi.org/10.1002/2015JB012666.

[[Not cited in the text]]Castro, J.M., and Feisel, Y., 2022, Eruption of ultralow-viscosity basanite magma at Cumbre Vieja, La Palma, Canary Islands: Nature Communications, v. 13, https://doi.org/10.1038/s41467-022-30905-4.

[[Not cited in the text.]]Chevrel, M.O., Pinkerton, H., and Harris, A.J.L., 2019, Measuring the viscosity of lava in the field: A review: Earth-Science Reviews, v. 196, 102852, https://doi.org/10.1016/j.earscirev.2019.04.024.

Desmither, L., Diefenbach, A.K., and Dietterich, H.R., 2021, Unoccupied Aircraft Systems (UAS) Video of the 2018 Lower East Rift Zone Eruption of Kīlauea Volcano, Hawaii: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9BVENTG.

Dietterich, H.R., Diefenbach, A., Soule, S.A., Zoeller, M., Patrick, M., Major, J., and Lundgren, P., 2021, Lava effusion rate evolution and erupted volume during the 2018 Kīlauea lower East Rift Zone eruption: Bulletin of Volcanology, v. 83, 25, https://doi.org/10.1007/s00445-021-01443-6.

Gansecki, C., Lee, R.L., Shea, T., Lundblad, S.P., Hon, K., and Parcheta, C., ~~2022~~ 2019, The tangled tale of Kīlauea's 2018 eruption as told by geochemical monitoring: Science, v. 366, https://doi.org/10.1126/science.aaz0147.

Gualda, G.A.R., 2006, Crystal size distributions derived from 3D datasets: Sample size versus uncertainties: Journal of Petrology, v. 47, no. 6, p. 1245–1254, https://doi.org/10.1093/petrology/egl010.

Halverson, B.A., 2024, Textural and Rheological Evolution of Basalts [Ph.D. dissertation]: San Antonio, Texas, University of Texas at San Antonio, 178 p.

Harris, M., Kolzenburg, S., Sonder, I., and Chevrel, M., 2024, A new portable penetrometer for measuring the viscosity of active lava: The Review of Scientific Instruments, v. 95, https://doi.org/10.1063/5.0206776.

Higgins, M.D., 2000, Measurement of crystal size distributions: The American Mineralogist, v. 85, no. 9, p. 1105–1116, https://doi.org/10.2138/am-2000-8-901.

Hofmeister, A.M., Sehlke, A., Avard, G., Bollasina, A.J., Robert, G., and Whittington, A.G., 2016, Transport properties of glassy and molten lavas as a function of temperature and composition: Journal of Volcanology and Geothermal Research, v. 327, p. 330–348, https://doi.org/10.1016/j.jvolgeores.2016.08.015.

Holtzman, B., King, D., and Kohlstedt, D., 2012, Effects of stress-driven melt segregation on the viscosity of rocks: Earth and Planetary Science Letters, v. 359–360, p. 184–193, https://doi.org/10.1016/j.epsl.2012.09.030.

Ishibashi, H., and Sato, H., 2007, Viscosity measurements of subliquidus magmas: Alkali olivine basalt from the Higashi-Matsuura district, southwest Japan: Journal of Volcanology and Geothermal Research, v. 160, no. 3–4, p. 223–238, https://doi.org/10.1016/j.jvolgeores.2006.10.001.

[[Not cited in the text.]]Jeffreys, H., 1925, The flow of water in an inclined channel of rectangular section: The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, v. 49, no. 293, p. 793–807, https://doi.org/10.1080/14786442508634662.

Kolzenburg, S., Chevrel, M.O., and Dingwell, D.B., 2022, Magma/suspension rheology: Reviews in Mineralogy and Geochemistry, v. 87, p. 639–720, https://doi.org/10.2138/rmg.2022.87.14

Lejeune, A.M., Bottinga, Y., Trull, T.W., and Richet, P., 1999, Rheology of bubble-bearing magmas: Earth and Planetary Science Letters, v. 166, p. 71–84, https://doi.org/10.1016/S0012-821X(98)00278-7.

[[Not cited in the text.]]Lev, E., and James, M.R., 2014, The influence of cross-sectional channel geometry on rheology and flux estimates for active lava flows: Bulletin of Volcanology, v. 76, no. 7, https://doi.org/10.1007/s00445-014-0829-3; correction available at https://doi.org/10.1007/s00445-020-1356-z.

[[Not cited in the text.]]Li, J., Yang, Z.F., and Wang, Y., 2022, HabitEst3D: A user-friendly software for estimating mixed crystal habits from two-dimensional sections in igneous rocks: Minerals (Basel), v. 12, no. 8, https://doi.org/10.3390/min12081001.

Llewellin, E., and Manga, M., 2005, Bubble suspension rheology and implications for conduit flow: Journal of Volcanology and Geothermal Research, v. 143, p. 205–217, https://doi.org/10.1016/j.jvolgeores.2004.09.018.

Mader, H.M., Llewellin, E.W., and Mueller, S.P., 2013, The rheology of two-phase magmas: A review and analysis: Journal of Volcanology and Geothermal Research, v. 257, p. 135–158, https://doi.org/10.1016/j.jvolgeores.2013.02.014.

Maron, S.H., and Pierce, P.E., 1956, Application of Ree-Eyring generalized flow theory to suspensions of spherical particles: Journal of Colloid Science, v. 11, p. 80–95, https://doi.org/10.1016/0095-8522(56)90023-X.

Mourey, A.J., and Shea, T., 2019, Forming olivine phenocrysts in basalt: A 3D characterization of growth rates in laboratory experiments: Frontiers of Earth Science, v. 7, https://doi.org/10.3389/feart.2019.00300.

Neal, C.A., et al., ~~Brantley, S.R., Antolik, L., Babb, J.L., Burgess, M., Calles, K., Cappos, M., Chang, J.C., Conway, S., Desmither, L., Dotray, P., Elias, T., Fukunaga, P., Fuke, S., Johanson, I.A., Kamibayashi, K., Kauahikaua, J., Lee, R.L., Pekalib, S., Miklius, A., Million, W., Moniz, C.J., Nadeau, P., Okubo, P., Parcheta, C., Patrick, M.R., Shiro, B., Swanson, D.A., Tollett, W., Trusdell, F., Younger, E.F., Zoeller, M.H., Montgomery-Brown, E.K., Anderson, K.R., Poland, M.P., Ball, J.L., Bard, J., Coombs, M., Dietterich, H.R., Kern, C., Thelen, W.A., Cervelli, P.F., Orr, T., Houghton, B.F., Gansecki, C., Hazlett, R., Lundgren, P., Diefenbach, A., Lerner, A.H., Waite, G., Kelly, P., Clor, L., Werner, C., Mulliken, K., Fisher, G., and Damby, D.,~~ 2019, The 2018 rift eruption and summit collapse of Kīlauea Volcano: Science, v. 363, p. 367–374, https://doi.org/10.1126/science.aav7046.

Patrick, M.R., 2024, Thermal Maps of the 2018 Lower East Rift Zone Eruption of Kīlauea Volcano, Island of Hawai‘i: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9C8W3NT.

Pistone, M., Cordonnier, B., Ulmer, P., and Caricchi, L., 2016, Rheological flow laws for multiphase magmas: An empirical approach: Journal of Volcanology and Geothermal Research, v. 321, p. 158–170, https://doi.org/10.1016/j.jvolgeores.2016.04.029.

Preibisch, S., Saalfeld, S., and Tomancak, P., 2009, Globally optimal stitching of tiled 3D microscopic image acquisitions: Bioinformatics (Oxford, England), v. 25, no. 11, p. 1463–1465, https://doi.org/10.1093/bioinformatics/btp184.

Ryerson, F.J., Weed, H.C., and Piwinskii, A.J., 1988, Rheology of subliquidus magmas: 1. Picritic compositions: Journal of Geophysical Research, v. 93, no. B4, p. 3421–3436, https://doi.org/10.1029/JB093iB04p03421.

Sehlke, A., and Whittington, A.G., 2015, Rheology of lava flows on Mercury: An analog experimental study: Journal of Geophysical Research: Planets, v. 120, no. 11, p. 1924–1955, https://doi.org/10.1002/2015JE004792.

Sehlke, A., Whittington, A., Robert, B., Harris, A., Gurioli, L., Médard, E., and Sehlke, A., 2014, Pahoehoe to ‘a‘a transition of Hawaiian lavas: An experimental study: Bulletin of Volcanology, v. 76, no. 11, https://doi.org/10.1007/s00445-014-0876-9.

Soldati, A., Sehlke, A., Chigna, G., and Whittington, A., 2016, Field and experimental constraints on the rheology of arc basaltic lavas: The January 2014 eruption of Pacaya (Guatemala): Bulletin of Volcanology, v. 78, no. 6, https://doi.org/10.1007/s00445-016-1031-6.

Soldati, A., Houghton, B.F., and Dingwell, D.B., 2021a, A lower bound on the rheological evolution of magmatic liquids during the 2018 Kilauea eruption: Chemical Geology, v. 576, https://doi.org/10.1016/j.chemgeo.2021.120272.

Soldati, A., Houghton, B.F., and Dingwell, D.B., 2021b, Subliquidus rheology of basalt from the 2018 Lower East Rift Zone Kilauea eruption: Isothermal vs. dynamic expression: Chemical Geology, v. 581, https://doi.org/10.1016/j.chemgeo.2021.120363.

Stein, D.J., and Spera, F.J., 2002, Shear viscosity of rhyolite-vapor emulsions at magmatic temperatures by concentric cylinder rheometry: Journal of Volcanology and Geothermal Research, v. 113, p. 243–258, https://doi.org/10.1016/S0377-0273(01)00260-8.

Truby, J.M., Mueller, S.P., Llewellin, E.W., and Mader, H.M., 2015, The rheology of three-phase suspensions at low bubble capillary number: Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 471, https://doi.org/10.1098/rspa.2014.0557.

Figure 1. Reflected light images of postexperimental samples, oriented with surface of experiment toward top of page. Sample F8.25b (collected from fissure 8 flow field of 2018 Kīlauea eruption) is shown for vesicle comparison; its orientation is unknown. All scale bars are 2 mm. Experimental samples are from top 1–2 cm of crucible, recording only that material measured by spindle. HTTPI—high-temperature three-phase isothermal.

Figure 2. (A–B) Reflected light images of high-temperature three-phase isothermal (HTTPI) sample at 1105 °C (A) and sample F8.11, collected from fissure 8 flow field of 2018 Kīlauea eruption (B). (C–D) Crystal size distribution graphs for both samples for plagioclase (C) and pyroxene (D).

Figure 3. (A) Viscosity data for all high-temperature three-phase isothermal (HTTPI) experiments. Arrows indicate changes in strain rate. (B) Three-phase viscosity calculations compared to HTTPI experiments. MP—Maron and Pierce (1956) equation; Mader—Mader et al. (2013) **[[method, medium, equation?]]**; VFT—**[[Define here.]]**. **[[Figure edits: Fix spelling of 1150 Experiment in legend in B. Define VFT in caption and verify definitions for MP and Mader.]]**

TABLE 1. CRYSTALLINITY AND VESICULARITY VALUES FOR EACH HIGH-TEMPERATURE THREE-PHASE ISOTHERMAL (HTTPI) AND ZERO-TIME (QUENCHED AFTER THE 20 MIN HOLD AT 1175 °C) EXPERIMENT, A TRADITIONAL ISOTHERMAL METHOD EXPERIMENT AT 1115 °C, AND TWO OTHER SAMPLES FROM THE FISSURE 8 FLOW OF THE 2018 KĪLAUEA ERUPTION (F8.11 AND F8.25)

Sample	Vesicle-normalized %					
	Vesicularity	Plagioclase	Pyroxene	Olivine	Oxides	Total crystallinity
1105 °C	31.1%	12.8%	13.8%	3.2%	1.0%	30.8%
1115 °C	18.8%	7.6%	1.9%	2.7%	0.3%	12.6%
1150 °C	19.2%	2.4%	0.2%	2.6%	0.4%	5.6%
1175 °C zero-time sample	36.1%	6.5%	1.9%	5.6%	3.5%	14.3%
1115 °C traditional method	2.0%	0.0%	14.9%	0.0%	2.5%	17.4%
F8.11	13.5%*	21.4%	14.4%	0.0%	0.0%	41.5%[†]
F8.25b		25.7%*	N/A			N/A

*Vesicularity and olivine values from the entire thin section.

[†]Total crystallinity value only for the olivine-free quenched margin; includes pyroxene and plagioclase and incipient crystallization, where nanoscale crystallization fronts form around the larger laths.