Towards improved hazard assessments for large effusive eruptions: Lava flow advance during the 2018 Kīlauea Lower East Rift Zone eruption

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Abstract

The 2018 eruption of Kīlauea volcano produced the largest and most destructive lava flows in the lower East Rift Zone (LERZ) in the past 200 years. Average effusion rates exceeded 100 m3 s-1 (DRE) for more than two months as lava covered > 30 km2 of land area. The largest and longest-lived lava flow was produced by fissure 8 and had flow advance rates exceeding 100 m hr-1 and a run-out length of 13 km. While residents were able to safely evacuate from this rapidly advancing flow, hundreds of structures were destroyed. We integrate observed eruption parameters from the fissure 8 flow with numerical models for lava flows to investigate how eruption rate, topography, and rheology affect the initial path, advance rate, and extent of a lava flow. Many numerical models have been created to represent the advance and/or extent of lava flows. We apply both 1D and 2D, rules-based and physics-based models to explore the advantages and limitations of these model types. First, we validate the models for fissure 8 flow parameters using existing datasets from field observations and sample analysis. Second, we vary the eruption rate and lava rheology to test the influence of these parameters on the advance rate and flow extent. This analysis demonstrates the level of confidence that can be associated with modeling results when estimating difficult-to-constrain parameters during an eruption. Third, using input digital elevation models (DEM) of different resolutions, we examine the sensitivity of model accuracy to DEM resolution, with a specific focus on the influence on flow advance of smaller-scale topographic features that may not be resolved in coarse-resolution DEMs. Through better understanding of how different parameters control flow emplacement, and how to best apply the models describing that emplacement, we aim to improve the ability to estimate advance rate and flow path during (and prior to) the initial stages of flow emplacement and provide more detailed hazard assessments for future eruptions.

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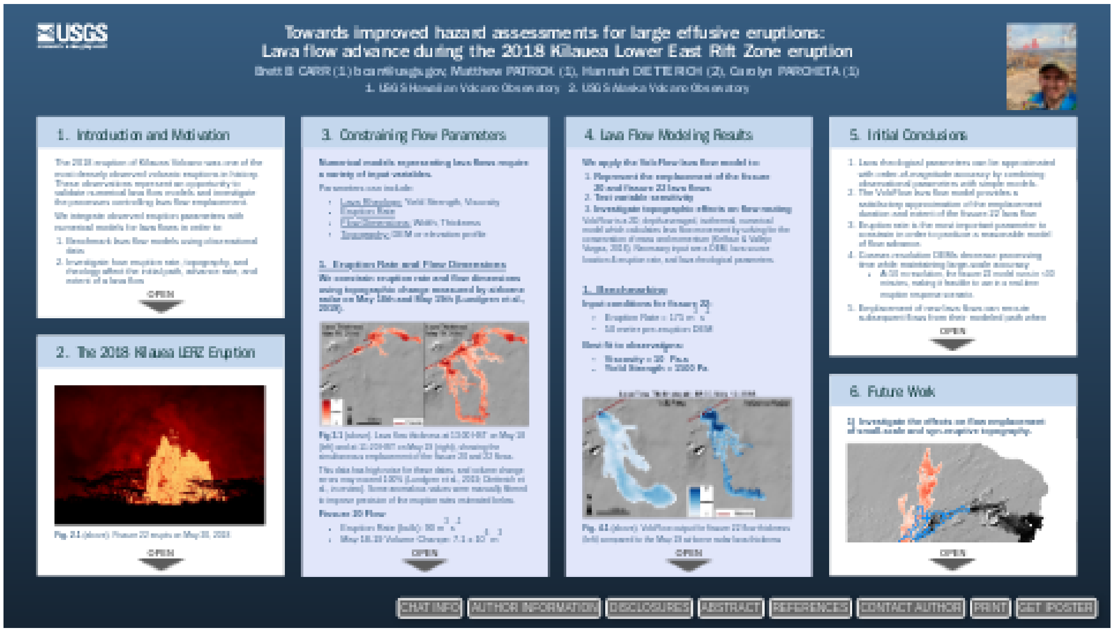

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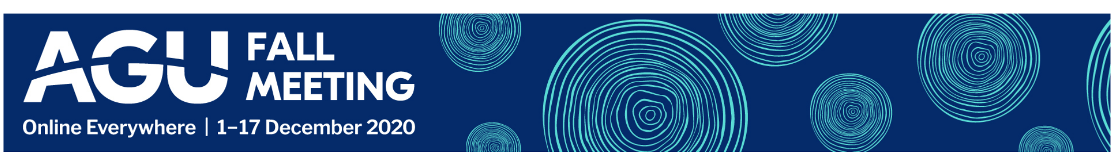


1. INTRODUCTION AND MOTIVATION

The 2018 eruption of Kīlauea Volcano was one of the most densely observed volcanic eruptions in history. These observations represent an opportunity to validate numerical lava flow models and investigate the processes controlling lava flow emplacement.

We integrate observed eruption parameters with numerical models for lava flows in order to:

1. Benchmark lava flow models using observational data
2. Investigate how eruption rate, topography, and rheology affect the initial path, advance rate, and extent of a lava flow
3. Analyze the advantages & limitations of different lava flow models to develop a workflow for their best use in assessing hazards and real-time response to future eruptions

2. THE 2018 KĪLAUEA LERZ ERUPTION

Fig. 2.1 (above). Fissure 22 erupts on May 20, 2018

Summary (Neal et al., 2019)

- Began May 3, ended September 5

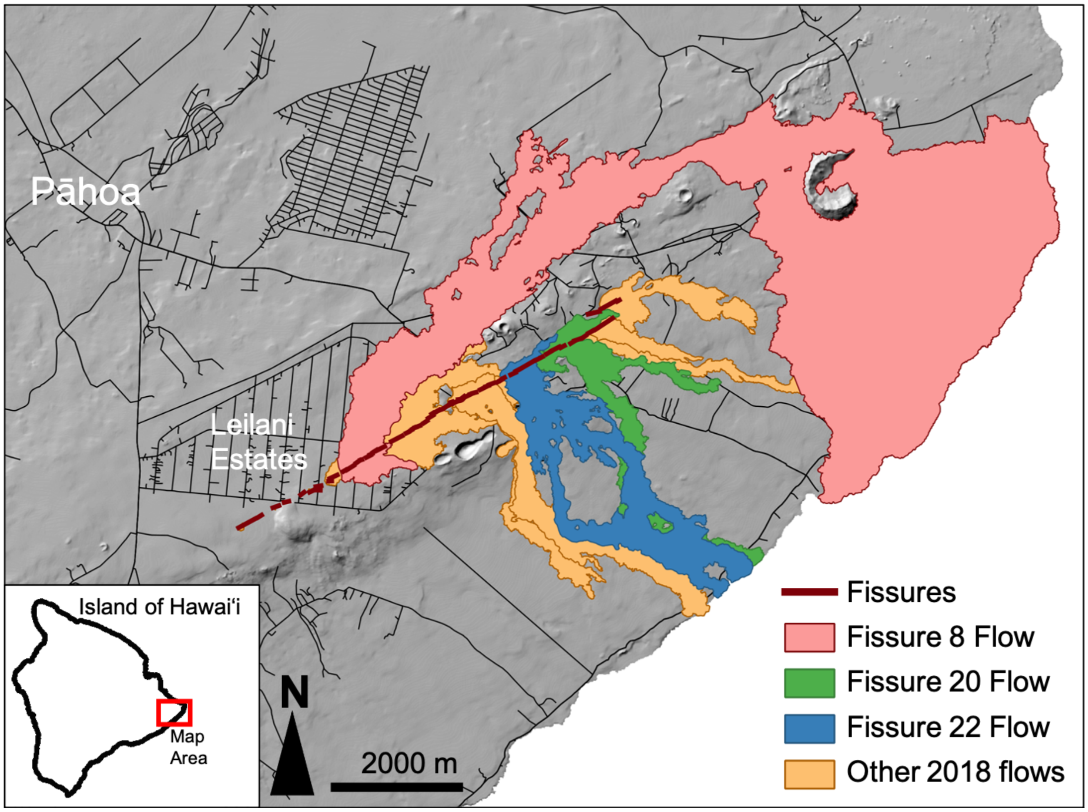
- Effusive eruption in the Lower East Rift Zone (LERZ) and collapse of the summit caldera

- Lava flows from 24 fissures covered >30 km^2

- Total erupted volume of ~1 km^3

- Largest flow formed by re-activation of fissure 8 (active May 28 to Aug 4)

Fig 2.2 (below). Location of the lava flows and fissures formed during the 2018 LERZ of Kīlauea



In this presentation, we focus on the emplacement of lava flows from fissure 20 and fissure 22.

Lava flows fed by fissures 20 and 22 began forming in the afternoon of May 18th (fissure 20) and overnight between the 18th and 19th (fissure 22). The flows entered the ocean just prior to midnight on May 19th (Neal et. al., 2019; Parcheta et al. *in prep*; deGraffenried et al., *in prep*).

Fig. 2.3 (above). The active fissure 22 flow on May 22. The inactive fissure 20 channel is seen on the right.

For more information on lava flows during the 2018 eruption of Kīlauea, please see these other AGU presentations:

- **Patrick et al.** New insights into lava flow dynamics during the 2018 eruption of Kīlauea. V002-0009. Poster Monday, December 7.

- **Dietterich et al.** Lava flow forecasting aided by remote sensing during the 2018 Kīlauea lower East Rift Zone eruption. V029-02. Talk Friday, December 11.
- **Halverson et al.** Vesicularity, crystallinity, and implications for rheology of the Kīlauea 2018 Lava Flows. V002-0016. Poster Monday, December 7.

3. CONSTRAINING FLOW PARAMETERS

Numerical models representing lava flows require a variety of input variables.

Parameters can include:

- Lava Rheology: Yield Strength, Viscosity
- Eruption Rate
- Flow Dimensions: Width, Thickness
- Topography: DEM or elevation profile

1. Eruption Rate and Flow Dimensions

We constrain eruption rate and flow dimensions using topographic change measured by airborne radar on May 18th and May 19th (Lundgren et al., 2019).

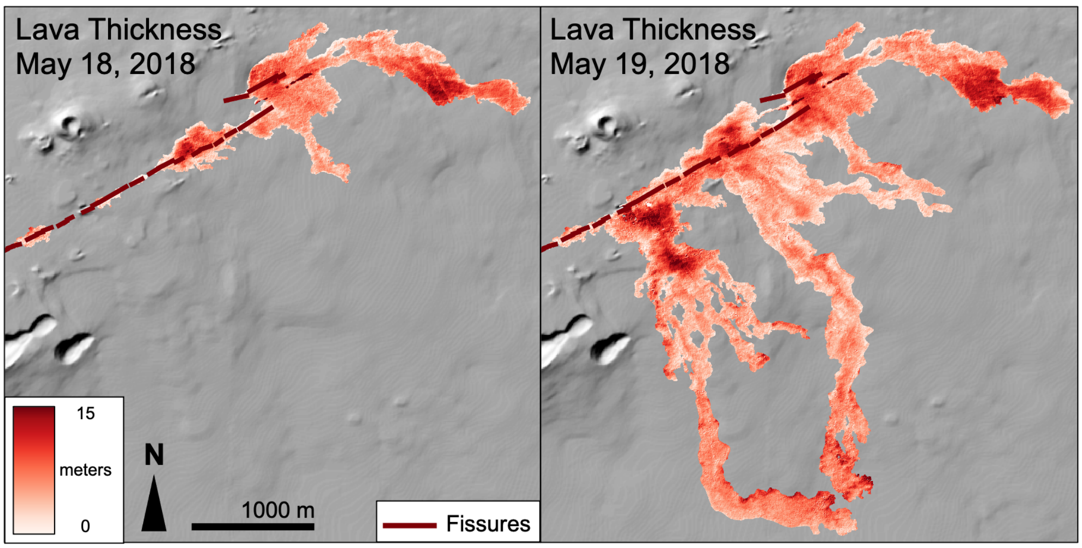


Fig 3.1 (above). Lava flow thickness at 13:00 HST on May 18 (left) and at 11:20 HST on May 19 (right), showing the simultaneous emplacement of the fissure 20 and 22 flows.

This data has high noise for these dates, and volume change errors may exceed 100% (Lundgren et al., 2019; Dietterich et al., *in review*). Some anomalous values were manually filtered to improve precision of the eruption rates estimated below.

Fissure 20 Flow

- Eruption Rate (bulk): 90 $m^3 s^{-1}$
- May 18-19 Volume Change: 7.1 x 10^6 m^3
- Avg. Thickness: 4.7 m
- Avg. Width: 420 m

Fissure 22 Flow

- Eruption Rate (bulk): 175 $m^3 s^{-1}$
- May 18-19 Volume Change: 8.3 x 10^6 m^3
- Avg. Thickness: 6.1 m
- Avg. Width: 350 m

2. Rheological Parameters

We use the Jeffreys' equation to estimate viscosity

(Jeffreys, 1925; Nichols, 1939; Chevrel et al., 2013)

$$\mu = \frac{\rho g H^3 W sin(\alpha)}{nQ} \approx 8x10^4$$

μ - viscosity (Pa-s) ρ - density (kg m^{-3})

H - flow thickness (m) W - flow width (m)

α - slope (radians) Q - eruption rate (m^3 s^{-1})

n - constant (= 4 for narrow flows, Chevrel et al., 2013)

We use the Hulme equation to estimate yield strength

(Hulme, 1974; Chevrel et al., 2013)

$$\tau_o = \rho g H sin(\alpha) \approx 4000$$

τ_o - yield strength (Pa)

As these equations were developed for a stagnating, cooling-limited flow and not for actively advancing flows (as was the case for the fissure 20 and 22 flows on May 19), these values represent maximum value approximations.

Application of the Castruccio et al. (2013) Model

Lava flow advance driven by gravity and resisted by:

- Newtonian viscosity of the lava,
- Yield strength of a growing flow crust, or
- Yield strength of the flow core

The viscosity and yield strengths can be estimated by fitting the modeled flow length to observations when knowing the eruption rate, flow width, and ground slope.

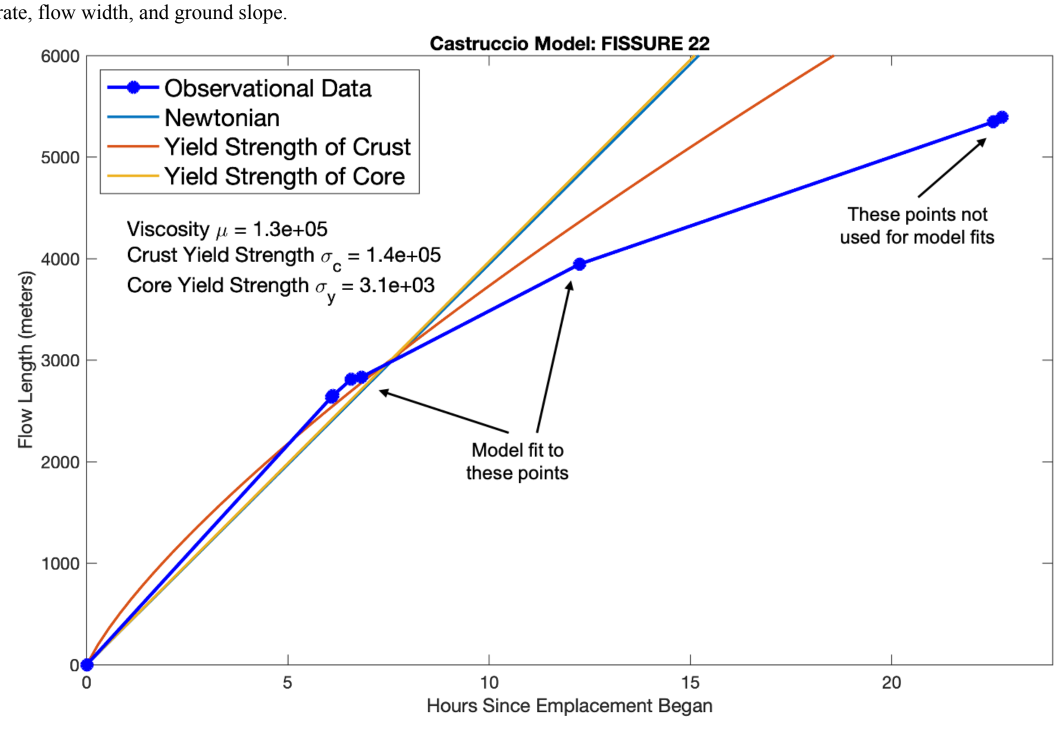


Fig 3.2 (above). Initial fit of each controlling flow mechanism to observational data. Observational data is from deGraffenried et al. *(in prep)*.

Best fit to fissure 22 flow observations

- **Viscosity: 13 x 10^4 Pa-s**
- **Yield Strength: 3100 Pa**

In this initial application of the Castruccio et al. (2013) model, we hold the controlling mechanism constant and fit each curve to only observations through the time of the May 19th radar acquisition. In future work, the fit will be improved by varying the controlling mechanism as the flow advances.

4. LAVA FLOW MODELING RESULTS

We apply the VolcFlow lava flow model to:

1. **Represent the emplacement of the fissure 20 and fissure 22 lava flows**
2. **Test variable sensitivity**
3. **Investigate topographic effects on flow routing**

VolcFlow is a 2D, depth-averaged, isothermal, numerical model which calculates lava flow movement by solving for the conservation of mass and momentum (Kelfoun & Vallejo Vargas, 2016). Necessary input are a DEM, lava source location & eruption rate, and lava rheological parameters.

1. Benchmarking

Input conditions for fissure 22:

- Eruption Rate = 175 $m^3 s^{-1}$
- 50 meter pre-eruption DEM

Best fit to observations:

- **Viscosity = 10^4 Pa-s**
- **Yield Strength = 1500 Pa**

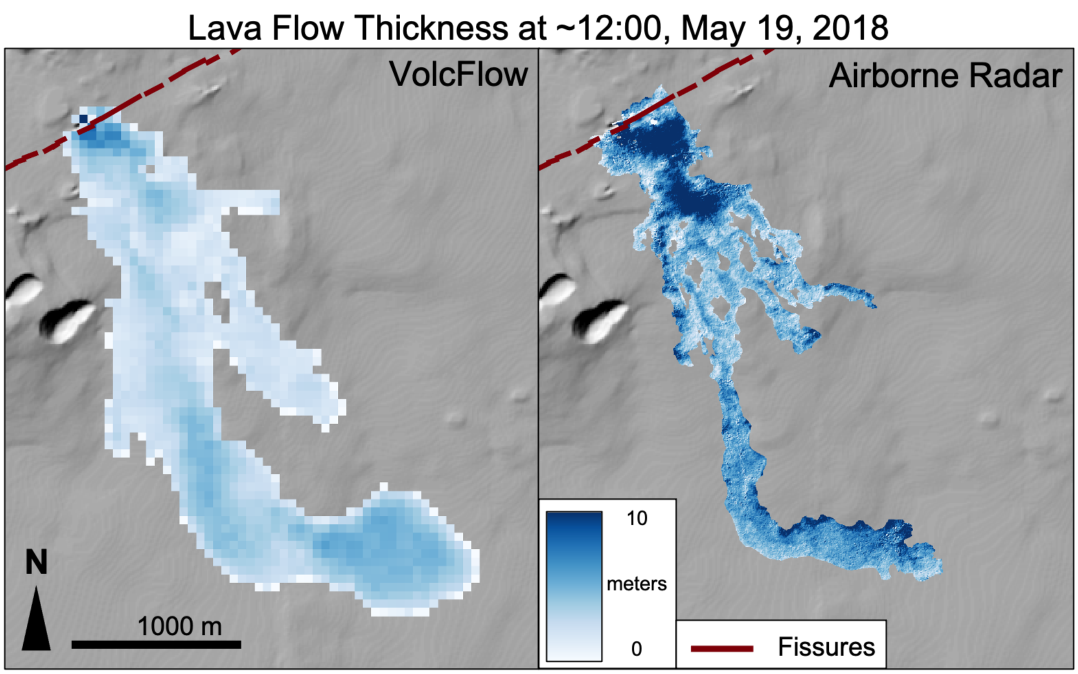
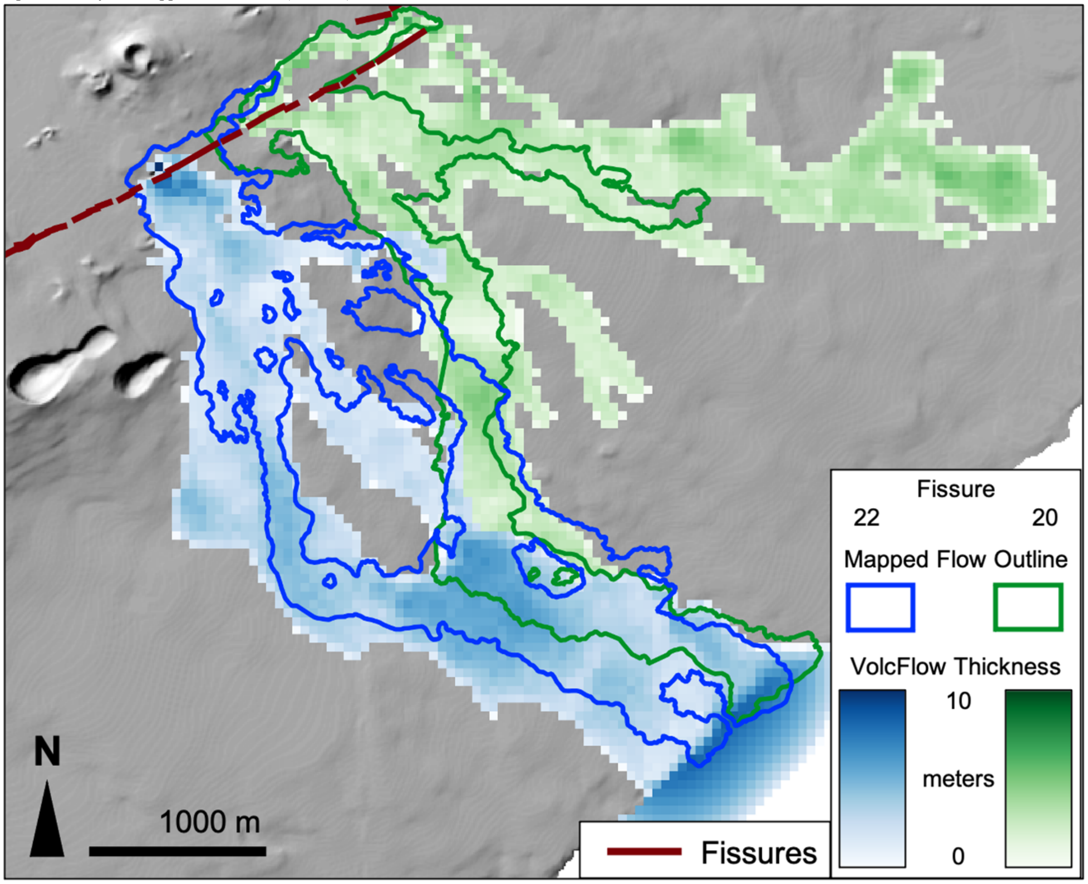


Fig. 4.1 (above). VolcFlow output for fissure 22 flow thickness (left) compared to the May 19 airborne radar lava thickness map (right), representing the same time since flow emplacement began.

Fig. 4.2 (below). The combined fissure 20 (green) and fissure 22 (blue) VolcFlow model output generally shows good agreement with observations, represented by the mapped flow extent (outlines).



VolcFlow identifies the area covered by lava flows well, but tends to overpredict flow extent. For the fissure 20 and 22 flows combined:

80% of the observed flow area matches the modeled flow area

45% of the modeled flow area matches the observed flow area

Best-fit values of viscosity and yield strength are lower than those estimated with the Jeffreys and Hulme equations, but are of the same order of magnitude. The best-fit viscosity is an order of magnitude higher than the value of 1150 Pa-s Gansecki et al. (2019) estimated for the viscosity at the vent.

2. Parameter Sensitivity

We vary one of **eruption rate**, **yield strength**, and **viscosity** by ± 20% while holding the others constant at the 'best fit' values.

We also test the effect of using a 25 m input DEM compared to a 50 m DEM.

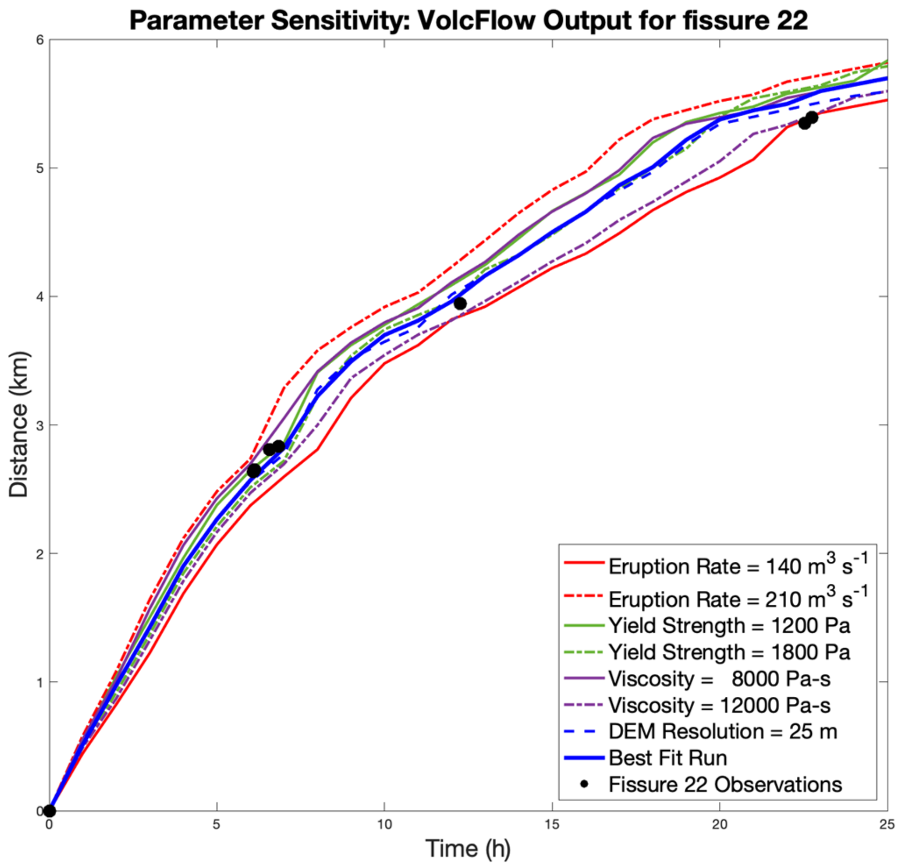
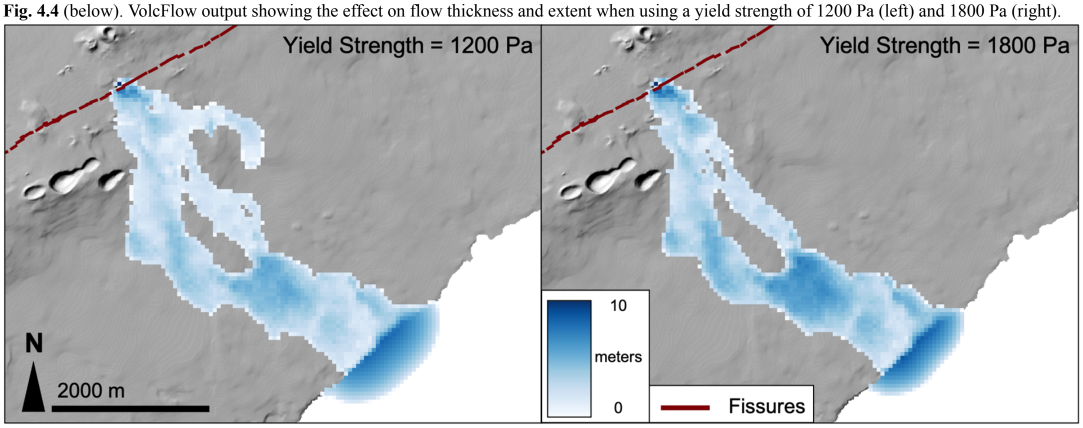


Fig. 4.3 (above). VolcFlow output showing changes in flow advance rate when varying one input parameter.

In general, flow advance rate varies by ≤ 20% when individual input parameters are varied by 20%. Eruption rate has the greatest effect on flow advance rate.

Fig. 4.4 (below). VolcFlow output showing the effect on flow thickness and extent when using a yield strength of 1200 Pa (left) and 1800 Pa (right).



Yield strength has comparatively little effect on flow advance rate, but greater control on flow thickness and flow extent.

The resolution of the input DEM has a minimal effect on advance rate (Fig. 4.3), though our initial analysis does suggest that higher resolution DEMs will generally produce more accurate results. However, we also find that a 50 m DEM can produce satisfactory results with less processing time (the 25 m DEM increased processing time compared to the 50 m DEM by a factor of 3).

3. Effect of Syn-Eruptive Topography

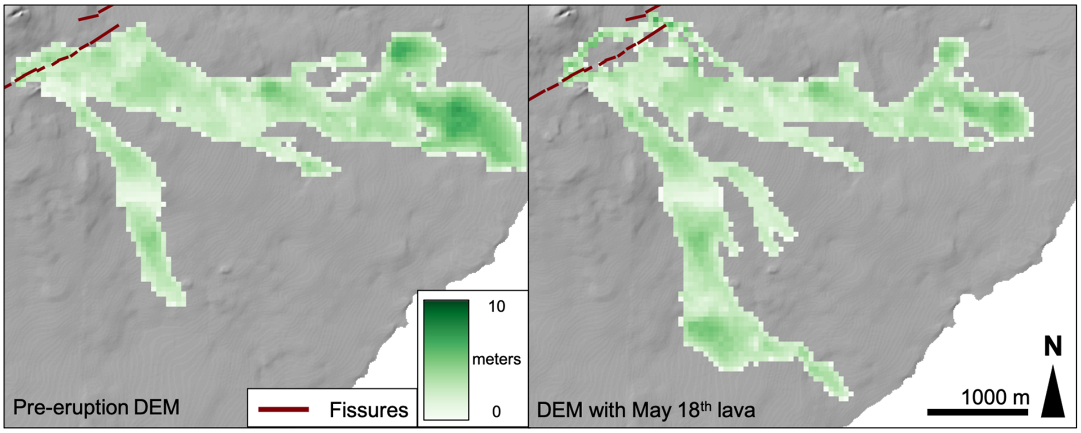


Fig. 4.5 (above). Comparison of VolcFlow output for the fissure 20 flow when using a 50 m pre-eruption DEM (left) and when adding lava already erupted prior to the emplacement the fissure 20 flow (right).

Using a pre-eruption DEM, the modeled fissure 20 flow travels mostly to the east (Fig. 4.5, left)

Using a DEM including lava erupted prior to the May 18-19 emplacement of fissure 20, the modeled fissure 20 flow travels more in the observed (south) direction (Fig. 4.5. right)

5. INITIAL CONCLUSIONS

1. Lava rheological parameters can be approximated with order-of-magnitude accuracy by combining observational parameters with simple models.
2. The VolcFlow lava flow model provides a satisfactory approximation of the emplacement duration and extent of the fissure 22 lava flow
3. Eruption rate is the most important parameter to constrain in order to produce a reasonable model of flow advance.
4. Coarser-resolution DEMs decrease processing time while maintaining large-scale accuracy
   - At 50 m resolution, the fissure 22 model runs in <30 minutes, making it feasible to use in a real-time eruption response scenario.
5. Emplacement of new lava flows can reroute subsequent flows from their modeled path when using a pre-eruption DEM
   - The modeled ocean entry location for fissure 20 changed by 3 km when a syn-eruptive DEM was used rather than a pre-eruption DEM.
   - For eruptions with multiple vents and/or flows, updated topography is crucial for hazard analysis

6. FUTURE WORK

1) Investigate the effects on flow emplacement of small-scale and syn-eruptive topography.

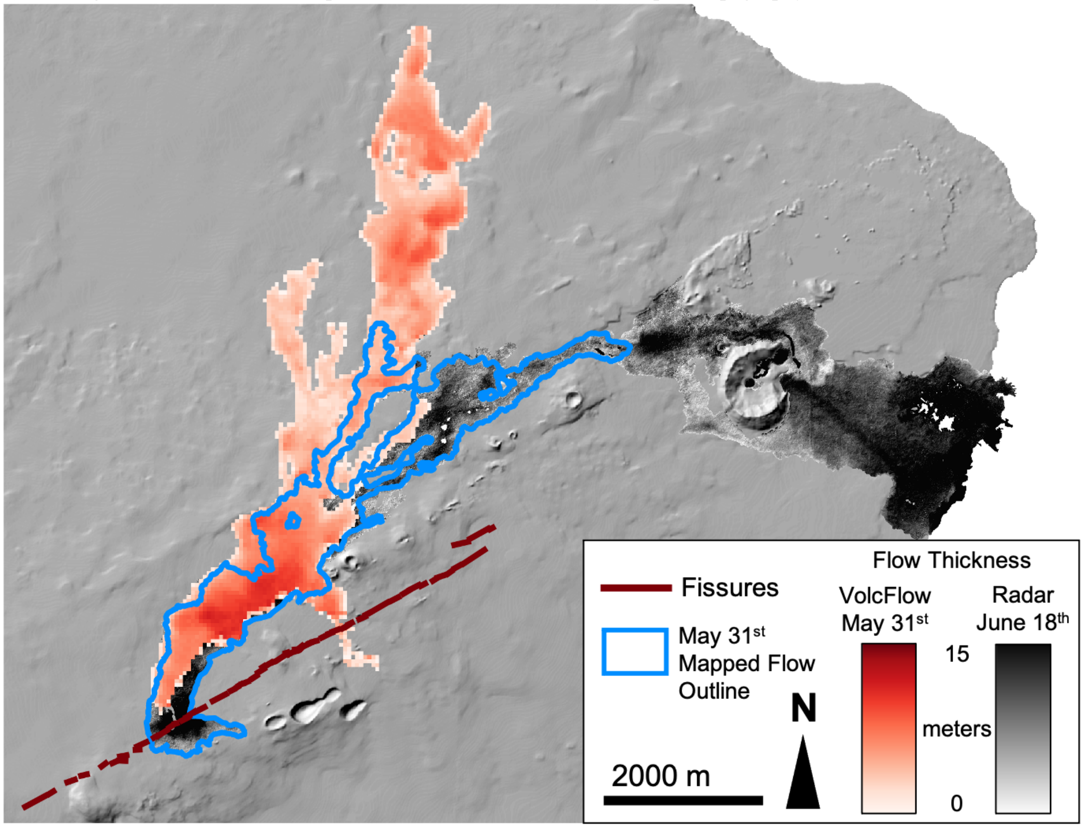


Fig. 6.1 (above). Initial results using VolcFlow to model fissure 8 indicate a strong effect of small-scale topographic features on determining the flow direction. For a 50 m input DEM, the flow travels north as opposed to the observed eastern direction.

2) Apply additional models to 2018 LERZ lava flows

Models to be tested include:

- FLOWGO (Harris & Rowland, 2001)
  - 1D, physics-based, thermal-rheological
- MOLASSES (Connor et al., 2012)
  - 2D, rules-based, deterministic
- DOWNFLOW (Favalli et al., 2005)
  - 2D, rules-based, probabilistic

While VolcFlow can model flow advance rate and direction, it does not account for changing rheology due to cooling. FLOWGO does this, but as a 1D model it cannot determine flow path. MOLASSES and DOWNFLOW, as 2D, rules-based models, can represent flow path and have lower computational time than physics-based models, but cannot model temporal changes in flow length and extent.

DISCLOSURES

- Support for author BC is through the USGS Mendenhall Postdoctoral Fellowship Program, Position 17-16.
- Flow advance data for the fissure 22 lava flow is generously shared by Rebecca deGraffenried (University of Hawaii at Mānoa)

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ABSTRACT

The 2018 eruption of Kīlauea volcano produced the largest and most destructive lava flows in the lower East Rift Zone (LERZ) in the past 200 years. Average effusion rates exceeded 100 $m^3 s^{-1}$ (DRE) for more than two months as lava covered > 30 km^2 of land area. The largest and longest-lived lava flow was produced by fissure 8 and had flow advance rates exceeding 100 m hr^{-1} and a run-out length of 13 km. While residents were able to safely evacuate from this rapidly advancing flow, hundreds of structures were destroyed. We integrate observed eruption parameters from the fissure 8 flow with numerical models for lava flows to investigate how eruption rate, topography, and rheology affect the initial path, advance rate, and extent of a lava flow. Many numerical models have been created to represent the advance and/or extent of lava flows. We apply both 1D and 2D, rules-based and physics-based models to explore the advantages and limitations of these model types. First, we validate the models for fissure 8 flow parameters using existing datasets from field observations and sample analysis. Second, we vary the eruption rate and lava rheology to test the influence of these parameters on the advance rate and flow extent. This analysis demonstrates the level of confidence that can be associated with modeling results when estimating difficult-to-constrain parameters during an eruption. Third, using input digital elevation models (DEM) of different resolutions, we examine the sensitivity of model accuracy to DEM resolution, with a specific focus on the influence on flow advance of smaller-scale topographic features that may not be resolved in coarse-resolution DEMs. Through better understanding of how different parameters control flow emplacement, and how to best apply the models describing that emplacement, we aim to improve the ability to estimate advance rate and flow path during (and prior to) the initial stages of flow emplacement and provide more detailed hazard assessments for future eruptions.

REFERENCES

Castruccio et al., 2013, Evolution of crust- and core-dominated lava flows using scaling analysis, *Bulletin of Volcanology,* 75:681, http://dx.doi.org/10.1007/s00445-012-0681-2

Chevrel et al., 2013, Lava flow rheology: A comparison of morphological and petrological methods, *Earth and Planetary Science Letters*, 384, 109-120, http://dx.doi.org/10.1016/j.epsl.2013.09.022

Connor, L. J., Connor, C. B., Meliksetian, K., & Savov, I., 2012, Probabilistic approach to modeling lava flow inundation: a lava flow hazard assessment for a nuclear facility in Armenia. Journal of Applied Volcanology (1):3. http://dx.doi.org/10.1186/2191-5040-1-3

deGraffenried et al., (*in prep*), Ground-truthing lava flow propagation models with examples from the 2018 eruption of Kīlauea Volcano, HI

Dietterich, H.R., et al., (*In Review*), Lava effusion rate evolution and erupted volume during the 2018 Kīlauea lower East Rift Zone eruption. *Bulletin of Volcanology.*

Favalli et al., 2005, Forecasting lava flow paths by a stochastic approach, *Geophysical Research Letters,* 32, L03305, http://dx.doi.org/10.1029/2004GL021718

Gansecki et al., 2019, The tangled tale of Kilauea's 2018 eruption as told by geochemical monitoring, *Science,* 366, eaaz0147, http://dx.doi.org/10.1126/science.aaz0147

Harris, A.J.L., & Rowland, S.K., 2001, FLOWGO: a kinematic thermo-rheological model for lava flowing in a channel, *Bulletin of Volcanology*, 63:20-44, http://dx.doi.org/10.1007/s004450000120

Hulme, G., 1974. The interpretation of lava flow morphology. *Geophys. J. R. Astron. Soc.* 39, 361–383. http://dx.doi.org/10.1111/j.1365-246x.1974.tb05460.x

Jeffreys, H., 1925. The flow of water in an inclined channel of rectangular section. *Philos. Mag. Ser.* 6 49 (293), 793–807.

Kelfoun & Vallejo Vargas, 2016, VolcFlow capabilities and potential development for the simulation of lava flows, *Geological Society, London, Special Publications*, 426(1):337 http://dx.doi.org/10.1144/SP426.8

Lundgren et al., 2019, Topographic changes during the 2018 Kīlauea eruption from single–pass airborne InSAR. *Geophysical Research Letters*, 46, 9554–9562, https://doi.org/10.1029/ 2019GL083501

Neal et. al., 2019, *Science*, The 2018 rift eruption and summit collapse of Kilauea Volcano, 363, 367-374 http://dx.doi.org/10.1126/science.aav7046

Parcheta et al. (*in prep*)