V31A-2519

The Lancaster Environment Centre

Estimating rheological properties of lava flows using high-resolution time lapse imaging

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1. Introduction

The rheology of a lava flow is one of the main factors controlling its advance, but is extremely challenging to measure directly. Here we demonstrate the use of integrated, remotely sensed topographic and time-lapse image data to estimate rheological properties using the method of Ellis et al. (2004)[1].

2. Data Collection

During the 2008 – 2009 eruption of Mt. Etna, Sicily, a large lava delta developed on the headwall of the Valle del Bove (Fig. 1). By June 2009, activity was limited to the upper part of the delta, where ephemeral vents fed 'a'ā lava flows that advanced a few hundreds of metres over lifetimes of hours to a few days. At this time, we deployed a Canon EOS 450D camera at Pizzi Deneri (Fig. 1) that captured images at 15-minute intervals until the end of the eruption. In addition, on 06/06/2009 we collected topographic data of the active flows using a terrestrial laser scanner[2] (Fig. 2).

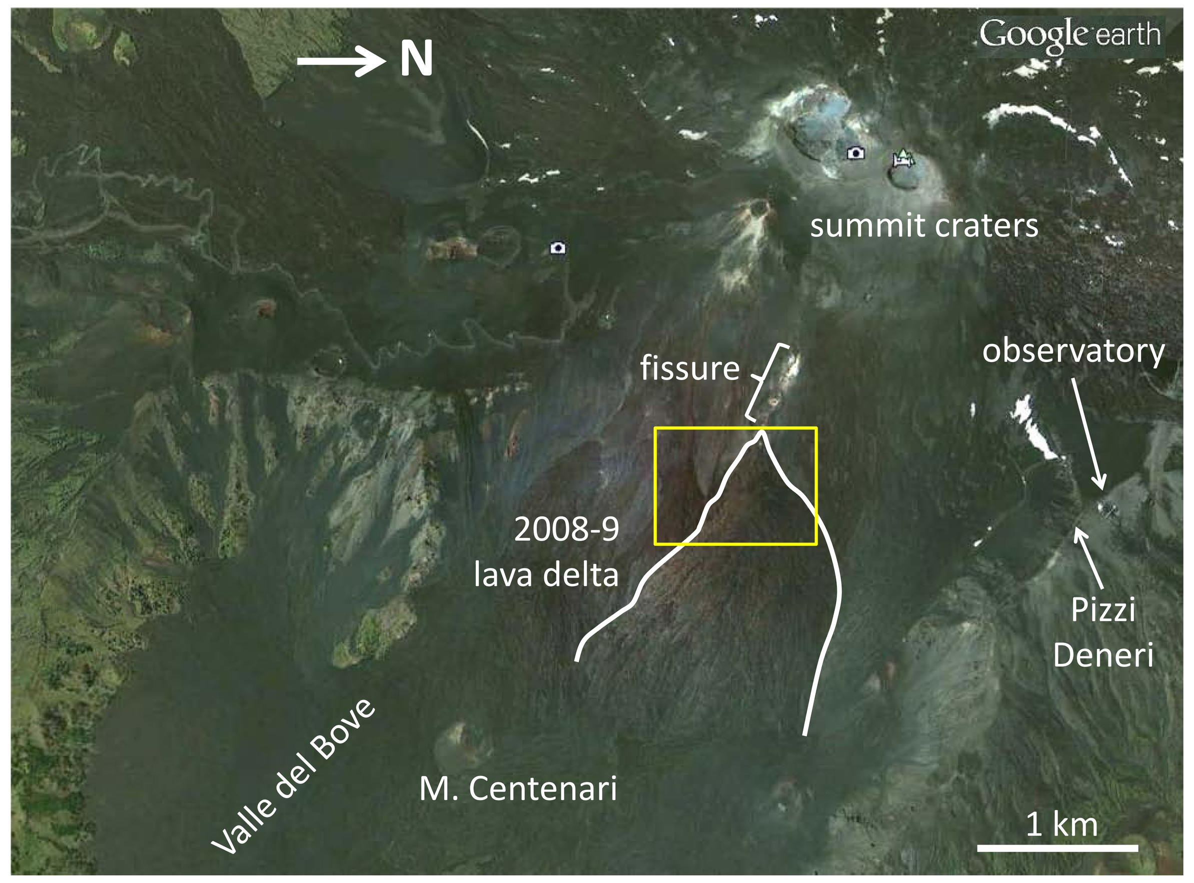

Fig. 1. Overview of the 2008-9 lava delta, on the E side of Mt. Etna, Sicily. In June 2009, active 'a'ā flows were limited to the upper ~1 km of the delta. Image and topographic data were collected from Pizzi Deneri, on the N side of the Valle del Bove. The yellow box shows the region enlarged in Fig. 3a.

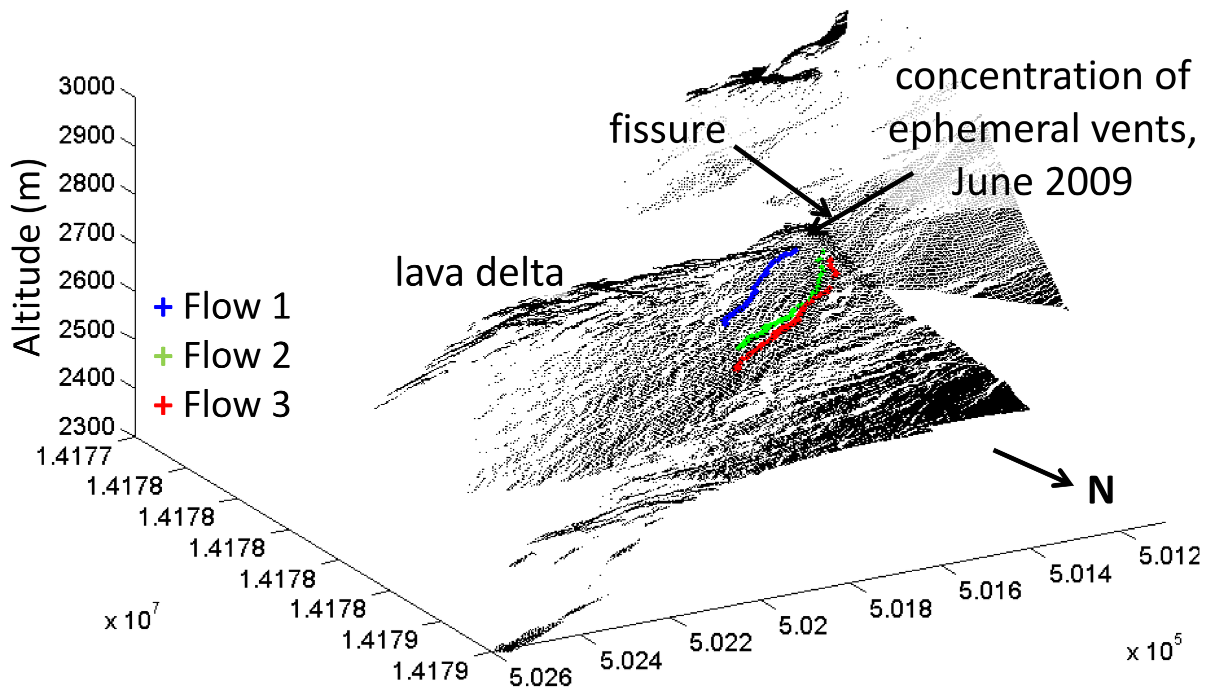

Fig. 2. Topographic data collected on 06/06/2009 from Pizzi Deneri (black points), showing the 3-D structure of the lava delta. The superimposed coloured points represent the advance of three flow units that were tracked through the time lapse image sequence, as discussed in the text.

3. Flow measurements and behaviour

The fronts of 3 flows were tracked through the time-lapse image sequence (Fig. 3b). Using knowledge of the camera imaging geometry, the pixel tracks were reprojected onto the topography (Fig. 2) to determine flow advance in 3-D geographic coordinates, allowing flow lengths (**L**), mean velocities (**u**) and slopes (**S**) to be measured. Fig. 4 shows a decrease in advance rate for all flows at ~200 m that is not correlated with any change either in slope or lava supply, so is inferred to be due to internal factors such as cooling. F1 and F2 are considered to be cooling-limited[3], though F3 shows more complex behaviour.

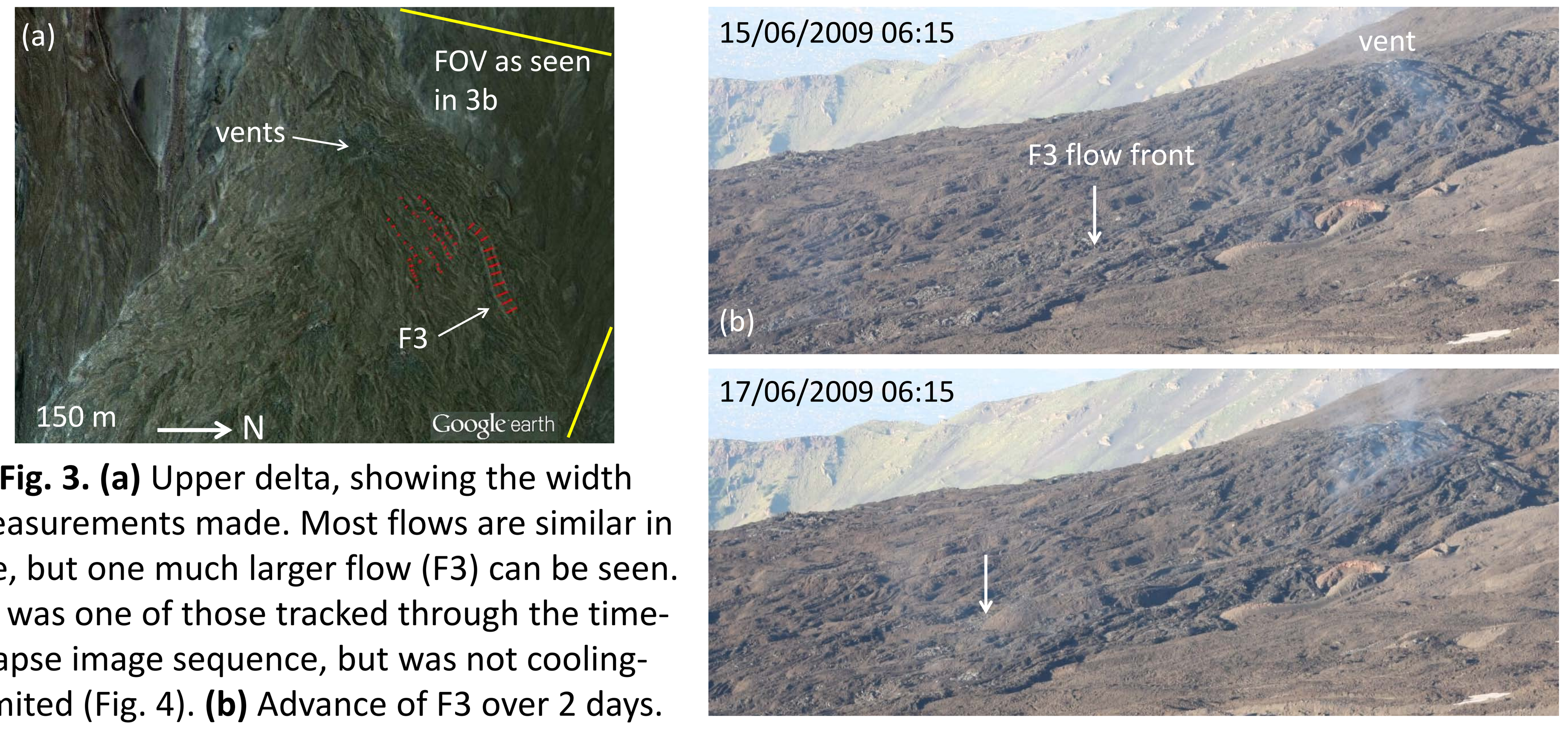

Fig. 3. (a) Upper delta, showing the width measurements made. Most flows are similar in size, but one much larger flow (F3) can be seen. F3 was one of those tracked through the time-lapse image sequence, but was not cooling-limited (Fig. 4). **(b)** Advance of F3 over 2 days.

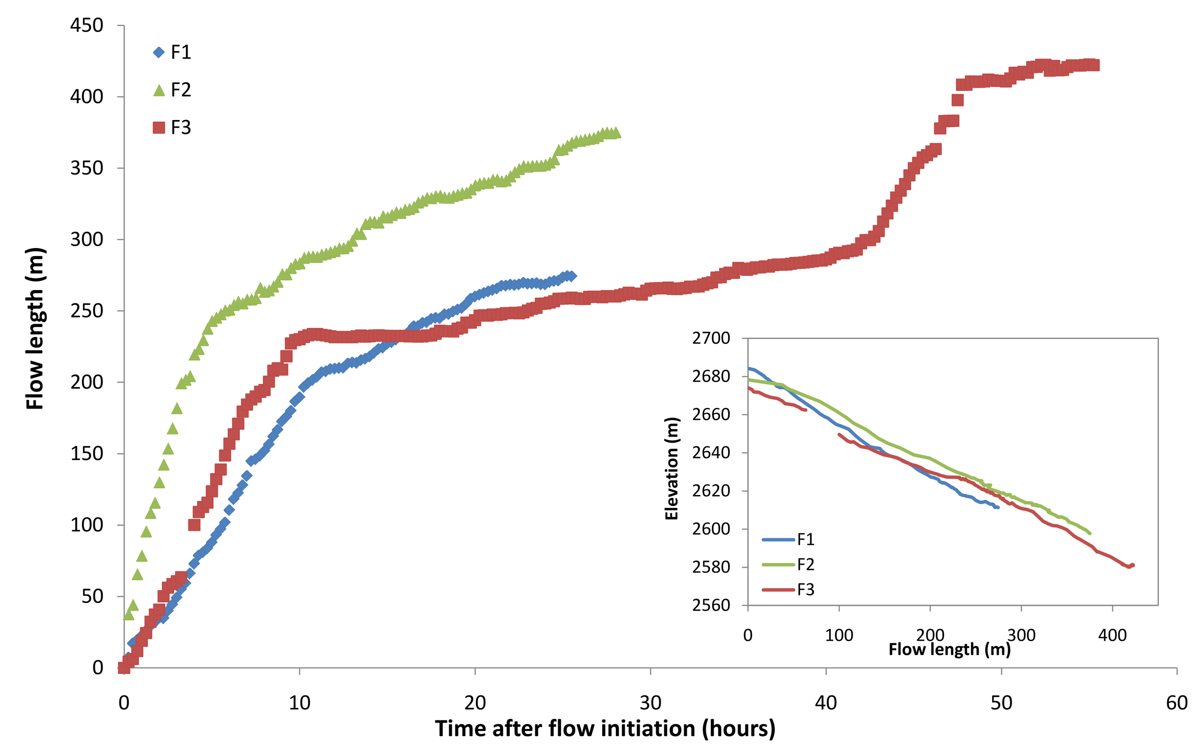

Fig. 4. Flow advance with time for 3 units tracked through the image sequence (Figs. 2 & 3b). All flows slowed beyond ~200 m length. F1 and F2 were cooling-limited. F3 had a more complex advance pattern, with a period of reactivation after ~40 hours. Because of this behaviour, **Gz** cannot be calculated for F3. Inset shows the underlying slope, which is almost constant and similar for each flow.

References: 1. Ellis B, Wilson L, Pinkerton H (2004) Lunar& Planetary Science XXXV Abst. 1550. **2. James MR**, Pinkerton H, Applegarth LJ (2009) Geophys. Res. Lett. 36 L22305. **3. Guest J**, Kilburn CRJ, Pinkerton H, Duncan AM (1987) Bull. Volc. 49:527-540. **4. Knudsen JG**, Katz DL (1958) Fluid Dynamics, McGraw-Hill: 81-82. **5. Pinkerton H**, Sparks RSJ (1976) J. Volc. Geotherm. Res. 1:167-182. **6. Pinkerton H**, Wilson L (1994) Bull. Volc. 56:108-120. **7. Tallarico A**, Dragoni M (1999) Bull. Volc. 61:40-47. **8. Robson GR** (1967) Nature 216:251-252.

Flow widths (**w**) were estimated from aerial images (Fig. 3a). Depths (**d**) of cooling-limited flows can be constrained using the Gratz number[4], which characterises conductive heat loss: $\mathbf{Gz} = \mathbf{u}\,\mathbf{d_e}^2 / (\kappa\,\mathbf{L})$, where $\mathbf{d_e} = 2\,\mathbf{w}/(\mathbf{w}+\mathbf{d})$, and κ = thermal diffusivity. Cooling-limited flows cease advancing when $\mathbf{Gz} \approx 300$[5,6], so **d** was estimated assuming **Gz** = 300 at cessation (Table 1).

Flow	u (m hr^{-1})	L (m)	w (m)	d (m)	d_e (m)	S ( )	κ[6] (m^2 s^{-1})	ρ[7] (kg m^{-3})	g (m^2 s^{-1})
F1	18.4	207	5.7	3.8	4.6	16.1	7.1×10^{-7}	2650	9.81
	10.8	267				15.5			
F2	64.1	144	5.7	3.8	4.6	14.5	7.1×10^{-7}	2650	9.81
	13.4	375				13.2			

Table 1. Parameters used to calculate rheological properties. **u**, **L** and **S** were derived from the topographic and image data, and **d** from setting **Gz** = 300 at flow cessation. **u**, **L** and **S** were estimated for an intermediate stage as well as the whole flow, so values are shown for both stages. F1 and F2 could not be individually identified in Fig. 3(a), but because the majority of flows had similar **w** values (15%, Fig. 3a), average widths were calculated from several flow units. Density (**ρ**) and thermal diffusivity (**κ**) values are from the literature.

4. Calculating rheological properties

Assuming that lavas behave as Bingham (plastic) materials, Ellis et al. (2004)[1] suggested that flow rheology could be described by an apparent viscosity with the form of a Newtonian viscosity, $\eta = (\rho\, g\, d^2 \sin S) / 3\,u$, and an effective yield strength, $Y = \rho\, g\, d \sin S$. **η** and **Y** were calculated for F1 and F2 for the intermediate and final conditions (Table 1), and are shown in Fig. 5.

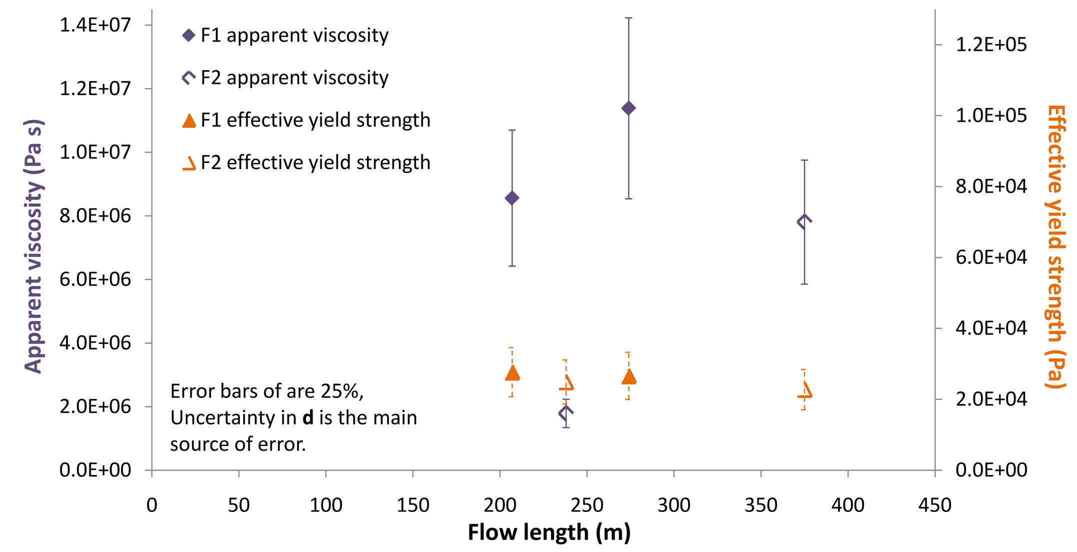

Fig. 5. **η** and **Y** for 2 stages of F1 and F2 advance. **η** increases by nearly an order of magnitude, with flow cessation at $\eta \sim 10^7$ Pa s. The lack of change in **Y** reflects the single value used for **d**. Robson (1967)[8] suggested that Etna flows stop when $Y \sim 10^5$ Pa s. As we cannot measure changes in **d**, we cannot test this theory.

5. Summary

The Etna flows appear to stop when $\eta \sim 10^7$. Ellis et al. (2004) found a similar result for Hawaiian flows. However the estimation of **d** needs to be improved so that the influence of **Y** can be investigated further. This approach has the potential to allow rheological properties to be estimated from remotely sensed data during eruptions, when field measurements are not available.