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1 **VolcFlow capabilities and potential development for the simulation of lava**
2 **flows**

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9

10 **Abstract:** VolcFlow is a finite difference Eulerian code based on the depth-averaged
11 approach and developed for the simulation of isothermal geophysical flows. Its capability for
12 reproducing lava flows is tested here for the first time. The field example chosen is the 2010
13 lava flow of Tungurahua volcano (Ecuador), whose emplacement is tracked by projecting
14 thermal images onto a georeferenced digital topography. Results show that, at least for this
15 case study, the isothermal approach of VolcFlow is able to simulate the velocity of the lava
16 through time, and the extent of the solidified lava. However, the good fit between the
17 modelled and the natural flow may be explained by the short emplacement time (~20 hours)
18 of a thick lava (~5 m), which could limit the influence of cooling on the flow dynamics, thus
19 favouring the use of an isothermal rheology.

20

21

22

23 Lava flows exhibit complex rheologies, which vary in time and space and control their
24 emplacement. Numerical models simplify their physics, to a greater or lesser extent, in an
25 attempt to predict their evolution and the areas impacted. Some approaches are simply based
26 on trajectory estimation from topographic analysis, adding probabilistic or stochastic
27 variations of the trajectories to calculate a flow width (DOWNFLOW, Favalli et al. 2005;
28 VORIS, Felpeto et al. 2007). The runout of the lava flow cannot be simulated. Other
29 approaches are in 2D, using a thickness below which the lava cannot flow and above which it
30 is distributed to the neighbouring cells. This thickness is dependent on the topographic slope
31 (FLOWFRONT, Wadge et al. 1994) or on the lava temperature (SCIARA, Crisci et al. 2004)
32 but dynamics are not included in the model. Ishihara et al. (1990) and Miyamoto and Sasaki
33 (1998) use fluid dynamics and cooling equations to calculate the lava spreading in 2D (runout
34 and width) on an incline. FLOWGO (Harris and Rowland 2001) estimates the lava trajectory
35 based on similar dynamics and cooling equations on a realistic topography, the lava width
36 being calculated from volume conservation. The equations of mass, momentum and thermal
37 balances have also been solved in 2D (runout and width) using a depth-averaged approach (no
38 variation of the properties vertically or at right angles to the ground) on a realistic topography,
39 the rheology of the lava being related to its cooling (Costa and Macedonio 2005). LavaSIM
40 (Hidaka et al. 2005) uses similar equations to simulate the lava flow but it solves them in 3D.
41 This allows a vertical structure to be calculated with a crust and a fluid core. A more detailed
42 review of existing models can be found in Hidaka et al. (2005). The smoothed particle
43 hydrodynamics is a promising approach that is starting to be applied to lava flow simulation
44 (e.g. Hérault et al. 2011).

45 For hazard assessment, observatories and public authorities need user-friendly tools to predict
46 the emplacement of the lava both sufficiently accurately and relatively rapidly. Some models
47 are not available, others are too simple to be used for hazard assessment, while the more

48 complex models require powerful computing resources and calculation times which are longer
 49 than the emplacement times of real flows (e.g. Hidaka et al. 2005). The numerical code,
 50 VolcFlow, has been created for the simulation of geophysical flows within a few hours using
 51 a desktop computer. It has been applied successfully to the simulation of debris avalanches,
 52 dense pyroclastic flows and tsunamis generated by landslides (Kelfoun and Druitt 2005;
 53 Kelfoun et al. 2008; Kelfoun et al. 2009; Kelfoun et al. 2010; Giachetti et al. 2011;
 54 Charbonnier et al. 2013). The aim of this chapter is to present the VolcFlow code, which is
 55 used in two other chapters of this book, and to discuss its limitations and possible evolution
 56 for the simulation of lava flows. We show that the simple isothermal approach of VolcFlow
 57 can accurately reproduce – at least for the case studied - the lava flow emplacement.

58

59 **Model**

60 VolcFlow uses a topography-linked coordinate system, with x and y parallel to the local
 61 ground surface. The flow is simulated by a depth-averaged approach that solves mass (eq. 1)
 62 and momentum (eqs. 2, 3) balance equations:

$$63 \quad \frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = \frac{\partial h_s}{\partial t} \quad (1)$$

$$64 \quad \frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu^2) + \frac{\partial}{\partial y}(huv) = gh \sin \alpha_x - \frac{1}{2} \frac{\partial}{\partial x}(gh^2 \cos \alpha) + \frac{\tau_x}{\rho} \quad (2)$$

$$65 \quad \frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(hvu) + \frac{\partial}{\partial y}(hv^2) = gh \sin \alpha_y - \frac{1}{2} \frac{\partial}{\partial y}(gh^2 \cos \alpha) + \frac{\tau_y}{\rho} \quad (3)$$

66 The variable h is the flow thickness, perpendicular to the topography, $\mathbf{u} = (u, v)$ is the flow
 67 velocity, α is the ground slope, $\boldsymbol{\tau} = (\tau_x, \tau_y)$ is the retarding stress, ρ is the bulk density of the
 68 lava flow and the subscripts denote components in the x and y directions. The approach is

69 similar to the model of Costa and Macedonio (2005), except that VolcFlow does not
70 incorporate an equation of thermal balance, nor is cooling calculated.

71 Equation (1) means that the thickness, h , of the lava at a given area varies with time
72 depending on the lava flux that enters or leaves the area (2nd and 3rd terms) or on the lava flux
73 at the vent, $\frac{\partial h_s}{\partial t}$ (this term equals 0 elsewhere). Equations (2) and (3) calculate the momentum
74 variations, and thus the velocity of the lava, related to lava flux (2nd and 3rd terms) and the
75 stresses exerted (4th to 6th term). No “vent” term is included in the momentum equations
76 because we have assumed in the following that the lava is emitted with no velocity along x
77 and y . VolcFlow allows the user to define constant or time-dependent effusions rates, several
78 eruptive sources, as well as the locations and the geometries of the sources.

79 The retarding stress, τ , varies depending on the rheology chosen. The advantage of VolcFlow
80 is that it can solve several types of rheological equations: frictional, viscous, plastic, etc. It can
81 also solve other more complex user-defined rheological laws (e.g. Davies et al. 2010). A fully
82 molten lava exhibits a Newtonian rheology (Gonnermann and Manga 2007). However
83 crystallization of lava by cooling and degassing changes this behaviour (e.g., Pinkerton and
84 Sparks 1978; Cimarelli et al. 2011; Lev et al. 2012). The lava then requires a minimal shear
85 stress in order to flow. The Bingham law is the simplest approximation of the behaviour of
86 threshold fluids: a Bingham body remains at rest while the applied shear stresses (caused by
87 lava weight, for instance) are less than the yield strength τ_0 . Once the yield strength is
88 overcome, the body flows with a flow velocity that depends on its viscosity, thickness and
89 yield strength. The latter allows the effect of the resistant crust that stops the flow when it
90 becomes too thin to be simulated. The resisting stress exerted by a Bingham flow is given by:

91
$$\tau = \tau_0 + \eta \frac{du}{dh} \tag{4}$$

92 where η is the dynamic viscosity (in Pa s). Rewritten in a depth-averaged form compatible
93 with equations (2) and (3), equation (4) becomes:

$$94 \quad \tau_x = \tau_0 \frac{u_x}{\|\mathbf{u}\|} + 3\eta \frac{u_x}{h} \quad \text{and} \quad \tau_y = \tau_0 \frac{u_y}{\|\mathbf{u}\|} + 3\eta \frac{u_y}{h} \quad (5)$$

95

96 The equations are solved using a shock-capturing numerical method based on a double
97 upwind Eulerian scheme. The method, and some tests done to ensure the quality of VolcFlow
98 using various rheologies, are presented in Kelfoun and Druitt (2005). Another test of the
99 capability of VolcFlow to reproduce analytical solutions for viscous rheology is presented in
100 this book by Cordonnier et al. (2015). VolcFlow runs in the Matlab® environment and
101 benefits from its powerful programming capacities for complex scenario definition
102 (topography, source geometry, rates, etc.), the post treatment of the results, and the graphical
103 output. The code and some examples of simulation can be found on the VolcFlow webpage.

104

105 **Application to a lava flow of Tungurahua volcano**

106 *The eruption of December 4-5, 2010*

107 Tungurahua stratovolcano (5023 m a.s.l.) is located in the Eastern Cordillera of Ecuador, and
108 is one of the most active volcanoes in the country (Hall et al. 1999; Le Pennec et al. 2008). It
109 is andesitic in composition (58-59 wt% SiO₂, Samaniego et al. 2011). The present activity,
110 which began in 1999, is characterized by vulcanian, strombolian and subplinian explosions
111 (Steffke et al. 2010; Samaniego et al. 2011), generating a variety of volcanic products from
112 the single vent located in the summit crater. In this study we focus on the paroxysm of the
113 November – December phase of 2010, which took place on December 4. The eruption started
114 at 13h50 UTC (= local time +5). It initiated a strong explosive phase, which continued for ~5

115 hours, with a high eruptive ash column that rose about 4 km a.s.l., accompanied by the
116 generation of ~34 pyroclastic density currents that flowed down gullies to the northeast,
117 northwest, west and southwest of the volcano. At about 22h40 UTC on December 4 a new
118 pulse of activity began, related to a harmonic tremor signal which was recorded for ~2.5 hours
119 by all the volcano's seismic stations. Thanks to the favourable weather conditions, scientists
120 at the Tungurahua Volcano Observatory (OVT, 13 km NW of the summit) were able to
121 observe the emission of a lava flow, flowing out of the summit crater and descending the
122 upper part of the NW flank of the volcano (*Weekly reports, OVT-IG, www.ig.epn.edu.ec,*
123 *Vallejo et al. 2012*). The lava flow emplacement was recorded by a thermal camera FLIR,
124 model PM 695, from the OVT, between December 4-6. Around 90 thermal images of the lava
125 flow were taken. Lava overflowed for a period of 5 hours and traveled for about 1.8 km over
126 20 hours with a velocity that decreased progressively with time from a maximal initial value
127 of about 200 m/h (Fig. 3). The thickness of the lava was estimated visually and from
128 topography analysis to be about 3 to 5 meters, and its volume about 10^6 m^3 .

129

130 *Measurement of the lava emplacement*

131 To check the capability of numerical models to reproduce the emplacement of a lava flow, the
132 extension predicted by a model is often compared with the natural extension once the lava
133 comes to rest. However, the model also needs to be checked dynamically to evaluate the
134 adequacy of the model chosen. To follow the evolution of the lava with time we have
135 developed an original photogrammetric approach. After having calculated the position and the
136 orientation of the thermal camera, and the characteristics of the lens, we can calculate the
137 equation of the line that passes through the image of a studied object (P_1 on Fig. 2) on the
138 camera sensor and the centre of perspective of the camera (C on Fig.2). The real position in

139 space of the object (P_2), if it lies on the ground, is located at the intersection between this line
140 and the topography. Each pixel of the lava flow can then be located on the volcano (Fig. 2).
141 The resolution of the thermal camera is relatively low (320x240) and the precision of the lava
142 front location on the volcano ranges between 40-65 m depending on the topographic slope
143 and the distance from the camera. The error is represented on Fig. 3 and is small relative to
144 the 1.8 km extension of the lava.

145

146 *Simulation of the lava flow*

147 The Digital Elevation Model (DEM) used for the simulation was calculated within the
148 framework of the SIGTIERRAS project of the Ecuadorian government, in 2011, some months
149 after the eruption took place. The DEM resolution is 4 m. The 2010 lava is visible on the
150 digital topography and has been removed from the DEM by extrapolating the surrounding
151 topography. The lava is simulated by a constant flux escaping from the lower part of the rim
152 of the summit crater. We assume a constant rate of lava production of about $55.5 \text{ m}^3/\text{s}$ in order
153 to erupt a volume of 10^6 m^3 in 5 hours. The density is fixed at 2200 kg/m^3 .

154 Figure 3 shows a comparison between the position of the lava front with time based on the
155 observation (dots) and the model (lines). 90 thermal images were taken during the eruption
156 but we have used the 10 best images where the lava front can be located unambiguously. The
157 best-fit is obtained for a viscosity of $\eta=4 \times 10^6 \text{ Pa s}$ and a yield strength of $\tau_0=60 \text{ kPa}$ (black
158 thick solid line). The position of the lava front with time is reproduced by the model with an
159 error of less than 50 m, apart from the first dot ($< 100 \text{ m}$). The distance reached by the front at
160 rest is simulated accurately ($< 10 \text{ m}$) even if the lava front is located 100 m to the east of the
161 real front (Fig. 3B), due to small variations in the topography that are not captured by the
162 DEM used. The flow front velocity, the time lava stopped moving and the thickness of the

163 model are all also compatible with the observations (Fig. 3A and B). The area covered by the
164 simulated lava is generally compatible with reality but differs of about 100m close to the lava
165 front and in the middle of the southwest edge (Fig. 3B).

166 To illustrate the sensitivity of the model to the rheological parameters used, Figure 3 also
167 shows curves obtained by varying one of the parameters from the best-fit simulation. The
168 viscosity influences the velocity of the flow (e.g. $\eta=5\times 10^6$ Pa s) while the value of τ_0 controls
169 the thickness and consequently the runout of the lava (e.g. $\tau_0 = 50$ kPa and $\tau_0 = 70$ kPa). A
170 change in τ_0 of 10 kPa changes the runout by approximately 200 m (~12.5%).

171 A critical point for the simulation of some lava flows is the dependence of the results on the
172 DEM resolution. Changing the resolution can slightly change the shape and position of the
173 source. But the main problem comes from the flow capability of natural lavas and models,
174 which is related to lava thickness: for the same lava, a thick flow can move even on a
175 horizontal surface, while a thin flow can come to a stop even on steep slopes. With a low
176 resolution DEM, the small-scale topography that can influence lava emplacement is not
177 reproduced precisely: the simulated flows can spread out more or less than in reality. If the
178 width changes, the thickness changes too and, consequently, the distance reached by the front.
179 Figure 3 shows results obtained with the parameters of the best-fit model on DEMs with
180 resolutions of 8m and 16m. The resolution has a small influence on the emplacement for the
181 initial 1200m, but affects the final position of the front by up to 200m (Fig. 3). Previous tests
182 have shown that the simulation accuracy increases by improving DEM resolution up to a
183 point where changes no longer have much influence on the flow length. Since we detect a
184 large difference between the simulations carried out at resolutions of 4m and 8m, we cannot
185 assert that our best-fit model gives the accurate value of the yield strength τ_0 , and an error of
186 +/- 10 kPa is possible. The strong influence of the resolution change for the lava simulated

187 here is due to its being channelled into a narrow valley downstream: wide, thick flows are less
188 influence by small variations in topography than thin, narrow flows.

189

190 **Capabilities of the model and future evolutions**

191 The example of the December 4, 2010 lava flow of Tungurahua shows that a simple
192 isothermal approach can be used for simulating some lava flow emplacements. VolcFlow,
193 which is freely distributed and runs on a desktop computer, could be a useful tool for hazard
194 assessments related to lava flows. Each simulation needs about 3 hours of computation time
195 on one 2.6 GHz processor of a desktop computer for the highest resolution (4m) and a
196 calculation domain of 601×501 meshes (~30 mins with an 8m resolution, <2 mins with a 16m
197 resolution).

198 However, it should be stressed that the lava studied was emplaced during a relatively short
199 period of time (about 20 hours) and was relatively thick (3-5 m). Under these conditions, the
200 effect of the cooling and the subsequent rheological changes is probably small, which
201 explains how an isothermal model can reproduce the lava flow emplacement. Future studies
202 need to be systematically conducted to explore the limits of this isothermal approach. There is
203 a real need for quantified observations to objectively evaluate the quality of the different
204 models available and the assumptions made.

205 Cooling and associated rheological changes could also be calculated by VolcFlow (as in the
206 approach of Costa and Macedonio 2005). Indeed, an appealing feature of the code is that it is
207 able to advect any volumetric or surface properties. It can then easily be evolved to take
208 additional balance equations into account, for instance for thermal energy and crystallinity.
209 The cooling and rheological changes of the flow could thus be calculated, as long as the
210 physics operating in the flow is compatible with the depth-averaged assumptions. This is the

211 principal limitation of VolcFlow: the depth-averaged approach cannot take into account
212 complex 3D phenomena such as crust and tunnel formation, or decoupling between the crust
213 and the hot internal lava.

214 The calculation time is currently a few hours, but this could easily be reduced to some tens of
215 minutes by simplifying the numerical scheme. At present, VolcFlow uses a time-consuming
216 numerical scheme to solve the momentum advection (equations 2 and 3) that was designed to
217 be stable with fast, thin flows. Because lava flows are relatively slow, momentum equations
218 are simpler to solve. Thus, if VolcFlow were to evolve further towards the simulation of lava
219 flows, it could be simplified to speed up the calculation time.

220 Two other studies using VolcFlow for lava flow simulation are presented in the book: a
221 benchmarking (Cordonnier et al., 2015) and a damage and evacuation assessment (Latutrie et
222 al., *in review*).

223

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313

314

315 **Figure captions**

316

317 **Fig. 1.** Photographs of the northwest flank of Tungurahua volcano (Ecuador) and of the lava
318 flow studied. This lava flow was emplaced on December 4, 2010 and is contoured with a red
319 line (credit: B. Bernard, IG-EPN). The length of the lava flow is about 1600 m and the slope
320 of the volcano varies from $\sim 40^\circ$ at the crater to $\sim 25^\circ$ at the front of the lava flow.

321

322 **Fig. 2.** The calculation of the position of the front and the extension of the lava flow through
323 time is done by projecting the thermal images onto a 4m-digital topography.

324

325 **Fig. 3. A.** Time evolution of the distance between the lava front and the source (along the
326 slope) during the eruption of December 4th, 2010 at Tungurahua volcano. The observations
327 are shown by the red dots, and the best-fit model by the thick black line. Other lines are
328 simulations done by varying one parameter of the best-fit simulation: yield strength, τ_0 ,
329 viscosity, η , or DEM resolution, dx . Error bars are estimated from the accuracy of the
330 projection techniques. Distances are calculated along the slope, following the position of the
331 front. **B.** X-Y view of the thermal image projected onto the topography. The red dots are the
332 successive positions of the lava front with time, as shown on A. The real lava is in white and
333 yellow. The black line is the simulated lava. **C.** 3D-view of the simulated lava flow once it is
334 at rest.

335

336





