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Modeling of the 2001 lava flow at Etna volcano by a Cellular Automata approach

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Abstract

The 2D Cellular Automata model, MAGFLOW, simulates lava flows and an algorithm based on the Monte Carlo approach solves the anisotropic flow direction problem. The model was applied to reproduce a lava flow formed during the 2001 Etna eruption. This eruption provided the opportunity to verify the ability of MAGFLOW to simulate the path of lava flows which was made possible due to the availability of the necessary data for both modeling and subsequent validation. MAGFLOW reproduced quite accurately the spread of flow. A good agreement was highlighted between the simulated and observed length on steep slopes, whereas the area covered by the lava flow tends to be overestimated. The major inconsistencies found in the comparison between simulated and observed lava flow due to neglecting the effects of ephemeral vent formation.

Keywords: Lava flow; Etna volcano; Numerical simulation

1. Introduction

Forecasting of lava flow paths on a volcanic edifice requires the development, validation and application of accurate and robust physical-mathematical models able to simulate their spatial and temporal evolution. Methods for modeling lava flows attempt to simulate how the complex interaction between flow dynamics and physical properties of lava lead to the final flow dimensions and morphology observed in the field. The propagation of lava flows produced by volcanic eruptions has been studied through field observations as well as through analytical and numerical modeling (Hulme, 1974; Young and Wadge, 1990; Harris and Rowland, 2001; Costa and Macedonio, 2005; Del Negro et al., 2005). Lava flows consist of an unconfined multiphase and multicomponent stream whose temperature, rheology, and emission rate all vary with time and space. Lava viscosity and yield strength are related to temperature and crystallization. Because it is hard to deal with so many parameters, simplified models have been proposed using some approximations (Wadge, 1978; Huppert, 1982; Pieri, 1986; Crisp and Baloga, 1990). Generally, these methods are based on empirically obtained equations for very simple cases, and they are difficult to apply in general conditions. An alternative approach to standard differential equation methods in modeling complex phenomena is represented by parallel computing paradigms, such as Cellular Automata (CA). The CA are discrete dynamic systems (cells), each of which may be in one of a finite number of states. The states of the cells are synchronously updated according to local rules (the evolution function) that depend on values of the cell and the values of neighbors within certain proximity. In this way, the CA can produce extremely complex structures

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from the evolution of rather simple and local rules (El Yacoubi et al., 2003; Georgoudas et al., in press). Crisci et al. (1986) were the first to introduce the CA approach in simulating some real lava flows. A numerical simulation of lava flows similar to CA was used by Ishihara et al. (1990), who started from Navier–Stokes equations and deduced numerical formulations for discrete space and time intervals. Miyamoto and Sasaki (1997) claimed to improve Ishihara's method by considering the effect of self-gravity, for simulating lava flows on a flat terrain, and the reduced random space technique, to eliminate the strong dependence on the cell geometry and position of the flux induced by the evolution function (anisotropic problem) without increasing calculation time. However, this technique does not eliminate the mesh bias and leads to non-physical solutions when accounting for the cooling effect (Del Negro et al., submitted for publication).

The TecnoLab of INGV-Catania has recently developed a new model based on Cellular Automata, called MAGFLOW, for simulating lava flow paths and the temporal evolution of lava emplacement on effusive volcanoes (Del Negro et al., submitted for publication). The key points of MAGFLOW are:

- two state variables are defined for each cell: thickness of lava and quantity of heat, the other parameters are deduced from these ones;
- the evolution function of the CA is a steady state solution of the Navier–Stokes equations for the motion of a Bingham fluid on a plane subject to a pressure force in which the conservation of mass, both locally and globally, is guaranteed;
- the Monte Carlo approach is adopted to solve the anisotropic flow direction problem.

The 2001 Etna eruption provided the opportunity to verify the ability of MAGFLOW to simulate the path of the lava flow. We will briefly summarize results obtained by comparing the simulated and the real events.

2. Model description

The MAGFLOW model is based on Cellular Automata (CA) in which the states of the cells are the thickness of lava and the quantity of heat. The states of the cells are synchronously updated according to local rules that depend on the cell's own values and the neighbor's values within a certain proximity. In this way, the CA can produce extremely complex structures from the evolution of rather simple and local rules. The evolution function of MAGFLOW is a steady state solution of Navier–Stokes equations for the motion of a Bingham fluid on an inclined plane subject to pressure force in which the conservation of mass is guaranteed both locally and globally. This kind of evolution function induces a strong dependence on the cell geometry and position of the flux, with respect to the symmetry axis of the cell: flows on a horizontal plane spread preferentially in the direction of the mesh (the calculated length of lava flows depends on the relative directions of flow and the mesh). This problem affects the results significantly, and becomes a serious issue especially for calculations of large-scale lava flows. In order to solve this problem we used a Monte Carlo approach. We consider a cellular automaton that has a randomized neighborhood, and define the neighborhood as all cells (i) that are closer to the central cell than a specified value R (Fig. 1). Therefore, we count neighbors as those cells whose centers lie inside a circle of radius R. The mean values of the parameters of the flows are computed over a set of simulations. With this method, it was possible to get cell geometry free results and to calculate large-scale lava flows with no artificial anisotropy. To demonstrate the validity of our method, we computed a two-dimensional flow on a horizontal plane and compared the morphology of the flow spreading with square and hexagonal cells. The results of simulations showed that appropriate flow spreading was obtained using solely square cells (Fig. 2).

Once the MAGFLOW structure was defined, we had to establish the evolution function of the model, or the way in which the cells evolve. Starting from the general form of the Navier–Stokes equations, we used the basic equations governing fluid motion considering the flow driven by the pressure gradient as a result of the variation of flow depth. In this way, it is possible to examine flows on a slightly inclined or horizontal plane (steady state solution of Navier–Stokes equations). Generally, lava flows are modeled as a Bingham fluid. A Newtonian fluid will begin to flow as soon as a force is applied, while a Bingham fluid will flow only if the applied force exceeds a critical value. In our simulation code, we assume that the lava flow is a Bingham fluid characterized by a yield strength (S_y) and plastic viscosity (η), and that it advances as an incompressible laminar flow. The basic formula to calculate the flux on an inclined plane was introduced in volcanology by Dragoni et al. (1986). They deduced a steady solution of Navier–Stokes equations for a Bingham fluid with constant thickness (h), which flows downward due to gravity. The volumetric flow rate (q) is:

$$q = \frac{S_y h_{\mathrm{cr}}^2 \Delta x}{3\eta}\left(a^3 - \frac{3}{2}a^2 + \frac{1}{2}\right) \qquad (1)$$

where $a = h/h_{\mathrm{cr}}$, h_{cr} is the critical thickness and Δx the distance between two adjacent cells.

Other models based on this formulation were proposed in the past (e.g. Ishihara et al., 1990), but they did not consider the flow driven by the effect of self-gravity. This case was

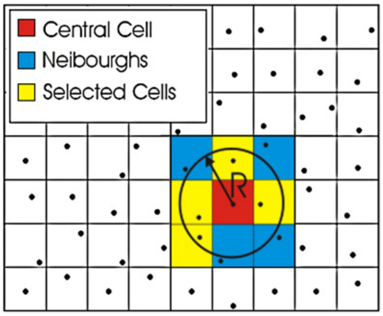

Fig. 1. Scheme of a randomized neighborhood in a cellular automata mesh.