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SIMULATIONS OF THE 2004 LAVA FLOW AT ETNA VOLCANO BY THE MAGFLOW CELLULAR AUTOMATA MODEL

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Abstract

Lava flows represent a challenge for physically based modeling, since the mechanical properties of lava change over time. This change is ruled by a temperature field, which needs to be modeled. MAGFLOW Cellular Automata (CA) model was developed for physically based simulations of lava flows in near real-time. We introduced an algorithm based on the Monte Carlo approach to solve the anisotropic problem. As transition rule of CA, a steady state solution of Navier-Stokes equations was adopted in the case of isothermal laminar pressure-driven Bingham fluid. For the cooling mechanism, we consider the radiative heat loss only from the surface of the flow, and the change of the temperature due to mixture of lavas between cells with different temperatures. The model was applied to reproduce a real lava flow occurred during the 2004-2005 Etna eruption. The simulations were computed using three different empirical relationships between viscosity and temperature.

Keywords Mount Etna, Lava Flow, Simulation, Cellular Automata

Introduction

Simulating lava flowing down the slopes of a volcano requires understanding how the thermal and rheological properties of the lava and emission rate out of the crater all vary with time and space (Miyamoto and Sasaki 1998). In order to generate complex trajectories due to the interactions between lava flows and the underlying topography, we need to model the main mechanical features of lava and the way they evolve over time depending on temperature. Another difficulty is to compute the simulation of lava flows at acceptable rates (Del Negro et al. 2005). A number of previous models have been developed dealing with various aspects of flow emplacement and cooling. However, due to the complexity of these processes, most of these models are based on empirically obtained equations for very simple cases, and they are difficult to apply in general conditions. Some of them are intended mainly as an aid to hazard assessment, rather than to analyze flow dynamics (Young and Wadge 1990; Wadge et al. 1994), while others focus on the effects produced by lava flows on composite channel shapes (Macedonio and Longo 1999; Harris and Rowland 2001). Recently, Favalli et al. (2005) have applied a stochastic approach to estimate solely the areas potentially exposed to lava inundation, neglecting both the temperature and rheology of lava. Costa and Macedonio (2005) have instead adopted a generalized set of depth averaged equations, including an energy equation, to describe lava flow propagation on smooth topographies.

An alternative to differential equation methods for modelling very complex phenomena is represented by Cellular Automata (CA), one of the first parallel computing paradigms. Lava flows represent a phenomenon, with features matching the CA paradigms: the system evolution may be described as based on local interactions of their constituent parts. Crisci et al. (1986) were the first to introduce the CA approach in simulating some real lava flows. They designed a three dimensional CA model that was successively reduced to a two dimensional model (Barca et al. 1993) to shorten computation time. However, in this case, the CA transition function was defined introducing some parameters that do not appear in the governing physical equations. 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 of improving the Ishihara's method by considering the self-pressure gradient for simulating lava flows on a flat terrain, and introducing a reduced random space method to eliminate the mesh bias without increasing calculation time. However, when the cooling effect is taken into account, this technique does not solve the cell geometry problem and, above all, leads to non-physical solutions.

Our Laboratory for the Technological Advance in Volcano Geophysics (called TecnoLab) has been developing a different approach of CA for physically based modeling of lava flows. In particular, we developed the MAGFLOW Cellular Automata model to forecast possible lava flow paths and to predict in near real time the evolution of the phenomena during ongoing eruptions (Vicari et al. 2007; Herault et al. 2007). An algorithm based on the Monte Carlo approach to solve truly the anisotropic problem was also included in MAGFLOW. As evolution function of CA, we took a steady state solution of Navier-Stokes equations into account, in the case of isothermal laminar Bingham fluid driven by the effect of self-gravity. In the evolution function, there are parameters that characterize globally the CA model and, therefore, the lava flow through its physical properties. Moreover, MAGFLOW takes into account both the thermal and rheological properties of the lava flow and the effusion rate, providing the propagation time and thickness of the flow, without forget the importance of computation time. The model was validated comparing simulated lava flows with the real ones of 2001 Etna eruption, showing that the code works properly fitting well-constrained eruption data sets (Vicari et al. 2007).

The 2004-2005 lateral eruption at Etna volcano provided the first opportunity to verify the ability of our model to predict the path of lava flows while the event was ongoing and to produce different scenarios as eruptive conditions changed. Really, we used the MAGFLOW model while the eruption was under way and the thermal and rheological properties of lava flow outpouring were (and are) unknown. Since the effects of lava viscosity on flow morphologies are well known, the simulations were computed using three different empirical relationships between viscosity and temperature validated on basaltic rocks such as Etna volcano. Results obtained by comparing the three simulated cases with the real event are briefly summarized.

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 values of the cell and the values of neighbors within 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 horizontal 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. This feature 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 (Vicari et al. 2007). It consists of a set of experiments. For each one we consider a cellular automaton that has randomized neighborhood. We define the neighborhood as all cells (i) that are distant from the central cell less than a specified value. Therefore, we count neighbors as those cells whose centers lie inside a circle of a certain radius. The mean values of states of the cells (thickness of lava and quantity of heat) are computed over the set of experiments. With this method, we can get cell geometry free results and can calculate large-scale lava flows with no artificial anisotropy.

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 due to 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). In our simulation code, we assume that the lava flow is a Bingham fluid characterized by yield strength (S_y) and a 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 flux (q) is:

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

where $a = h / h_{cr}$, 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 pressure gradient. This case was introduced by Miyamoto and Sasaki (1997), and Mei and Yuhi (2001). The critical thickness (h_{cr}) depends on the yield strength and the angle of the slope (α), as described:

$$h_{cr} = \frac{S_y}{\rho\, g\left(\sin\alpha - \frac{\partial h}{\partial x}\cos\alpha\right)} \approx \frac{S_y\sqrt{\Delta z^2 + \Delta x^2}}{\rho\, g\left(\Delta z - \Delta h\right)} \tag{2}$$

where ρ is the density of lava, g the acceleration due to gravity, Δz the difference in height between two cells, and Δh the thickness increase in the cell. Lava moves on when the thickness attains the critical value and the basal stress exceeds the yield strength (Rocchi et al. 2004). The viscosity and the yield strength of lavas depend mainly on the temperature (*T*) (Pinkerton and Stevenson 1992; Harris and Rowland 2001) as below:

$$\log\eta(T) = a + bT \tag{3}$$

$$\log S_y(T) = c + dT \tag{4}$$

Since the dependence of lava viscosity on temperature is one of main factors controlling the flow shape, we used three different empirical relationships (Pinkerton and Norton 1995; Ishihara et al. 1990; Giordano and Dingwell 2003) validated on basaltic rocks such as Etna volcano in order to forecast a reliable path of lava flows. The values of viscosity coefficients (*a* and *b*) are reported in Table 1. The coefficients of yield strength *c* and *d* are fixed respectively to c=13.0997 and d=-0.0089 (Ishihara et al. 1990).

In the same way, it is possible to calculate lava cooling. At any time *t*, the heat content of lava (Q_t) in each cell is carried in accordance with the flow motion. The temperature of the lava in a cell is considered as uniform: vertical temperature variation is neglected. For the cooling mechanism, we consider the radiative heat loss ($\Delta Q_{t,r}$) only from the surface of the flow (the effect of conduction to the ground and convection with the atmosphere is neglected), and the change of heat ($\Delta Q_{t,m}$) due to mixture of lavas between cells with different temperatures, hence:

$$Q_{t+\Delta t} = Q_t + \Delta Q_{t,m} - \Delta Q_{t,r} \tag{5}$$

where:

$$\Delta Q_{t,m} = \left(\sum_{q_i > 0} q_i T_i + \sum_{q_i < 0} q_i T \right) \rho c_v \Delta t \quad (6)$$

and

$$\Delta Q_{t,r} = \varepsilon A \; \sigma \; T^4 \Delta t \quad (7)$$

where T is the temperature of the central cell, T_i the temperature of neighbor cells, q_i is the flux between the central cell (i.e. the cell for which the state variables are updated) and its i-neighbor, c_v the specific heat, ε the emissivity of lava, σ the Stefan-Boltzmann's constant ($5.68 \cdot 10^{-8}$ J m^{-2} s^{-1} K^{-4}) and A is area of the cell. Then, the new temperature from the calculated heat is:

$$T_{t+\Delta t} = \frac{Q_{t+\Delta t}}{\rho \; c_v \; h_{t+\Delta t} \; A} \quad (8)$$

where $h_{t+\Delta t}$ is the thickness. The necessary data to run MAGFLOW are the digital elevation model (DEM) for the volcano, the lava effusion rate at vent, and the physical and rheological properties of lava. At the initial state, the thickness of lava at each cell is set to zero. The lava flow starts discharging at a certain rate from a cell (or more cells) corresponding to a vent. The thickness of lava at the vent cell increases by a rate calculated from the volume of lava extruded during each time interval (of course, the flow rate for each vent can change in time). When the thickness at the vent cell reaches a critical level, the lava spread over the neighbor cells. Next, whenever the thickness at any cell exceeds the critical thickness, the lava flows to the adjacent cells.

Application to the 2004 Etna eruption

The MAGFLOW model proposed here was applied to reproduce the lava flow occurring during the early phase of the 2004-2005 Etna eruption. Timely predictions of the areas likely to be inundated by lava flows are of major interest to hazard managers during a volcanic eruption. In order to estimate the amount of damage that can be caused by a lava flow, it is useful to be able to predict the size and extent of such flows. Numerical simulation is a good tool to examine such events. With such simulations, one can explore various eruption scenarios and these can specifically be used to estimate the extent of the inundation area, the time required for the flow to reach a particular point and resulting morphological changes. We simulated the effusive activity taking place during the first forty-six days of the eruption, for which some field data for input and comparison are available (e.g. Burton et al. 2005). The eruption was characterized by outpouring of degassed lava from two main vents (vent A at 2620 m; vent B at 2320 m) and a number of ephemeral vents (vent C at 2220 m; vent D at 2130 m; vent E at 2150 m; vent F at 2050 m) within Valle del Bove (INGV-CT 2004a). On 23 October, the lava flow field covered an area of about 0.84 km^2 reaching the maximum length of about 2.5 km and expanding downhill to an elevation of 1670 m (Fig. 1). Field surveys of lava flow thickness allowed to constrain lava volumes between 10.5 and 18.2 x 10^6 m^3.

The simulations were produced taking into account the active phases of each vent. Based on field observations at vents we assumed daily effusion rates for the lava flow ranging from 2.8 to 4.9 m^3/s for the whole period of the simulation (INGV-CT 2004b). As a topographic basis, we used the digital elevation model of the Etna maps with a 1:10000 scale (the spatial grid resolution was $\Delta x = \Delta y = 10$ m). Finally, the typical parameters for Etna lava flows used in the simulations are reported in Table 2 (Kilburn and Guest 1993; Harris et al. 1997).

In order to obtain a reliable forecasting of areas exposed to lava inundation, the simulations were computed with the three different viscosity relationships reported in Table 1. The simulated lava flows after forty-six days of eruption are shown in Figs. 2, 3 and 4. The different colors of the flow are associated with various thickness values. The MAGFLOW model is able to reproduce the behavior of real lava flow and the order of magnitudes of the quantities involved such as thickness or temperature. The comparison between the three simulations shows the strong dependence of the model on the variation of viscosity law (the other parameters are unchanged in the three different simulations). As expected, viscosity plays a significant role in flow morphology: it appreciably affects length, width, area, and thickness. During a simulation, heat transfers at the surface of the lava and inside the flow causes the temperature to decrease, enabling the transition from a low viscosity behaviour to a highly viscous one. When viscosity is low, the lava flows faster, and therefore the flow becomes longer and a slightly thinner, but the width of lava is not greatly affected by viscosity. The simulation with the Giordano and Dingwell (2003) law is rather elongated and canalized in two main branches, and its length is about 25 per cent longer than the real event (Fig. 2). Instead, the simulation with the Ishihara et al. (1990) law reproduces the principal lava body with sufficient precision, but its expansion is slightly shortened downhill and widened eastward compared to that of the actual one (Fig. 3). Finally, we can see that the simulation with the Pinkerton and Norton (1995) law produces the best fit for the extension of the whole lava field (Fig. 4). Although the narrow branches of the lava flow could not be reproduced, the outline of the simulated lava flow almost matched that of the actual one.

Some discrepancies in the inundation area were found at the branches of lava streams and at the margins of main streams. These are largely due to insufficient precision of maps of the pre-eruptive topography and to the size (10 m) of the sampling interval in the horizontal dimension, this being large with respect to the widths of lava streams (Mazzarini et al. 2005). Moreover, it is worth noting that we considered only the main ephemeral vents in the simulations, indeed many secondary ephemeral vents occurred here in the central part of flow field (INGV-CT 2004a; 2004b). Finally, the values of the effusion rate were obtained by few field measurements (the uncertainty associated is unknown). In these conditions, we believe that the results of the simulation, compared with the real lava flow field, can be considered satisfying.

Conclusions

During the 2004-2005 Etna eruption, the MAGFLOW model was used to forecast hypothetical scenarios of diverse evolutionary typologies of the event. That is, while the eruptive event was under way, several enquiries were made to determine the risk of areas becoming inundated. A number of simulations were carried out to answer these issues, which have indicated the possible future scenarios.

The comparison between the real lava flow and the MAGFLOW simulations may be considered satisfactory in relation to the geometric characteristics. Evident differences, such as the greater length and wider extension in the terminal part of the simulated event from that of the actual one can be justified by the topographic inaccuracies and imprecision of the input data. For real case events, the degree of efficiency using MAGFLOW with the aim of hazard assessment and mitigation is closely correlated with the presence of an efficient monitoring system of the event. We can only simulate realistic scenarios with data collected from real events. The potential of the MAGFLOW program depends obviously on the reliability of input data.

Finally, lava flow growth depends on the characteristics of the magma supply system, lava's physical and rheological properties, topography, and on the ambient conditions of the atmosphere (Harris and Rowland 2001). Many of these characteristics can change during an eruption and produce diverse lava flow behaviors. A parametric study on the major computational variables in order to guarantee an adequate resolution of the main large-scale processes and to optimize computer time should be conducted.

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Table captions

Table 1 - Viscosity coefficients

Table 2 - Typical parameters for Etna Lava Flows

Figure captions

Fig. 1 - Fractures and lava flow field map as of 23 October 2004, with inset showing a thermal image of the main structures (see reports of INGV-CT Section available at http://www.ct.ingv.it)

Fig. 2 - Simulated lava thickness of the 23 October 2004 Etna lava flow computed using the relationship between viscosity and temperature as proposed by Giordano and Dingwell (2003) (see inset plot)

Fig. 3 - Simulated lava thickness of the 23 October 2004 Etna lava flow computed using the relationship between viscosity and temperature as proposed by Ishihara et al. (1990) (see inset plot)

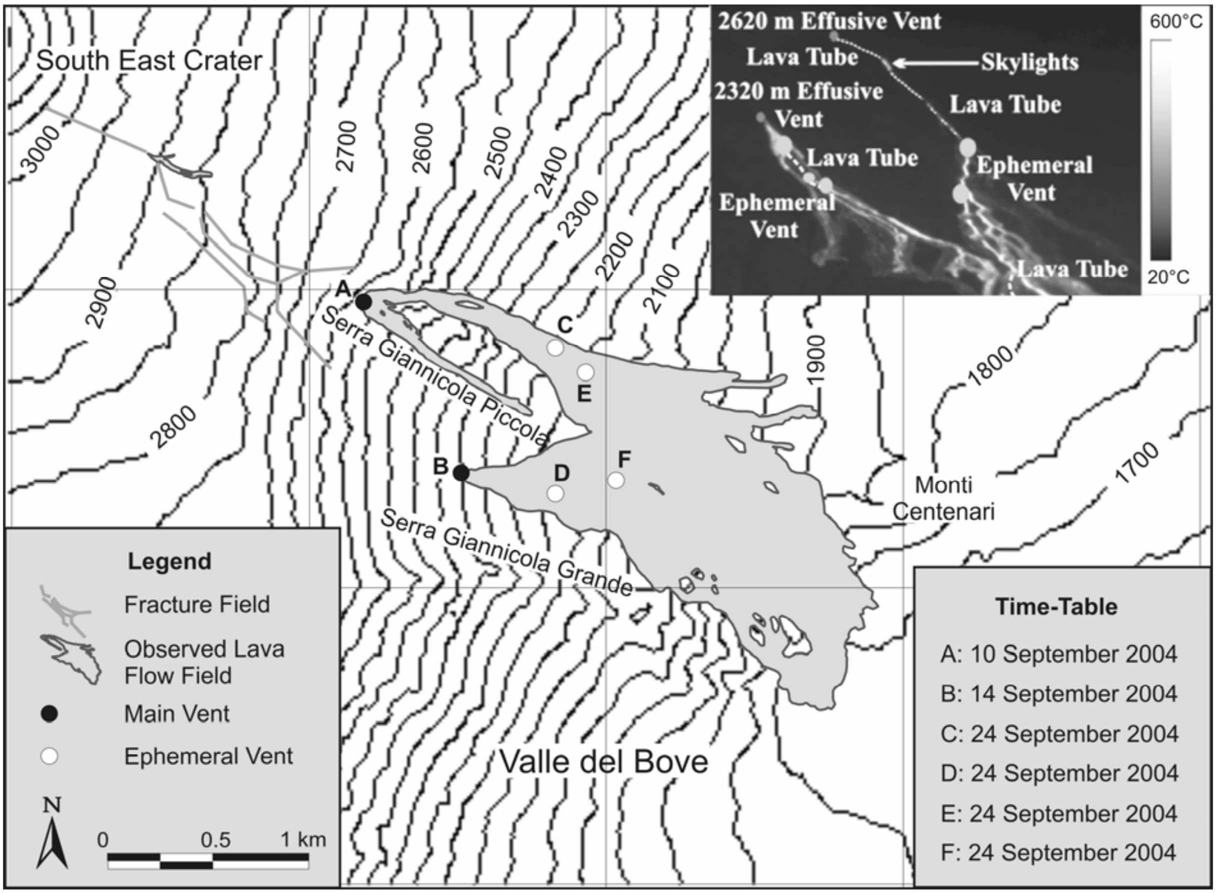
Fig. 4 - Simulated lava thickness of the 23 October 2004 Etna lava flow computed using the relationship between viscosity and temperature as proposed by Pinkerton and Norton (1995) (see inset plot)

Relationship	***a***	***b***
Ishihara et al., 1990	28.1613	-0.01810
Pinkerton and Norton, 1995	29.4343	-0.01965
Giordano and Dingwell, 2003	25.3496	-0.01677

Table 1 - Viscosity coefficients

Parameter	***Symbol***	***Value***	***Unit***
Density of lava	ρ	2600	kg m^{-3}
Specific heat	c_v	1150	J kg^{-1} K^{-1}
Emissivity of lava	ε	0.9	-
Temperature of solidification	T_s	1173	K
Temperature of extrusion	T_e	1360	K

Table 2 - Typical parameters for Etna Lava Flows



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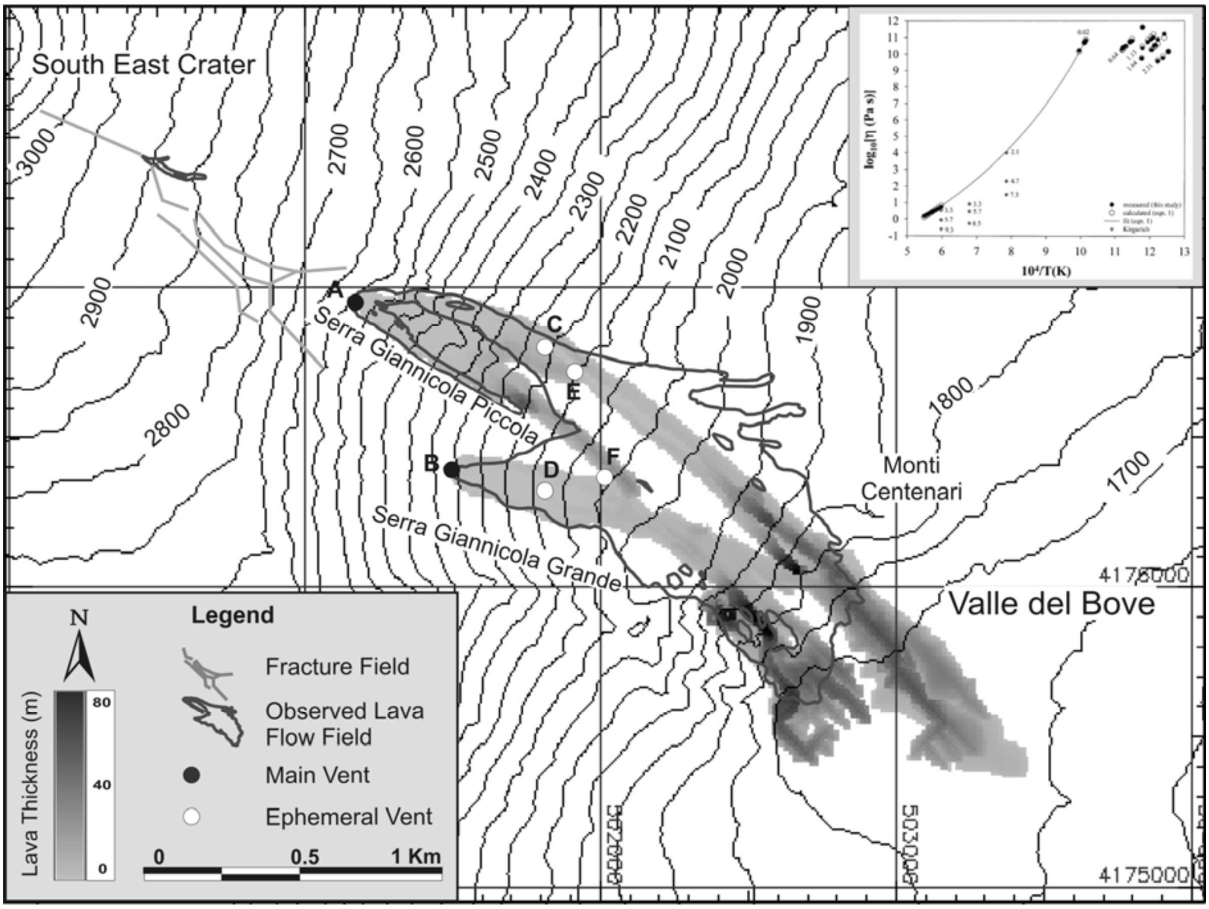

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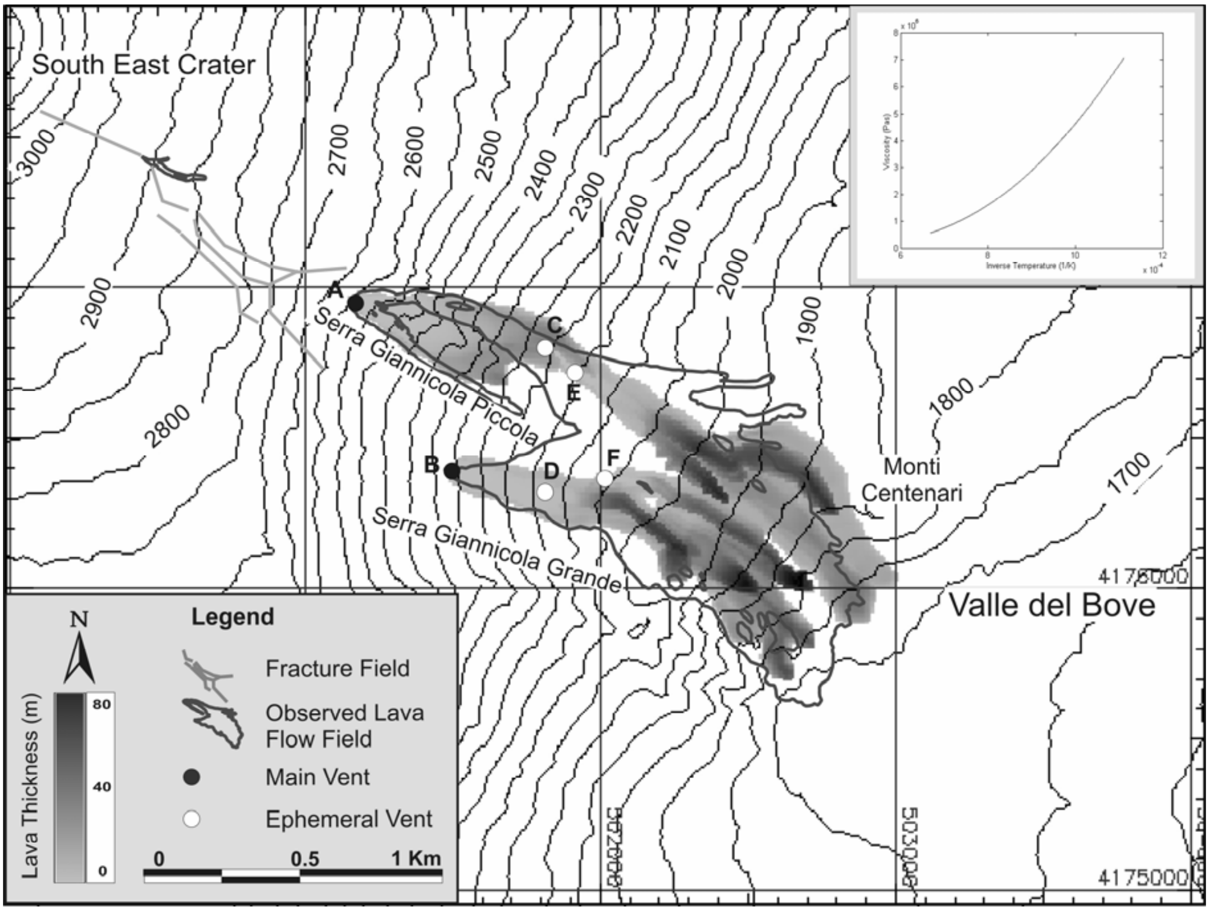

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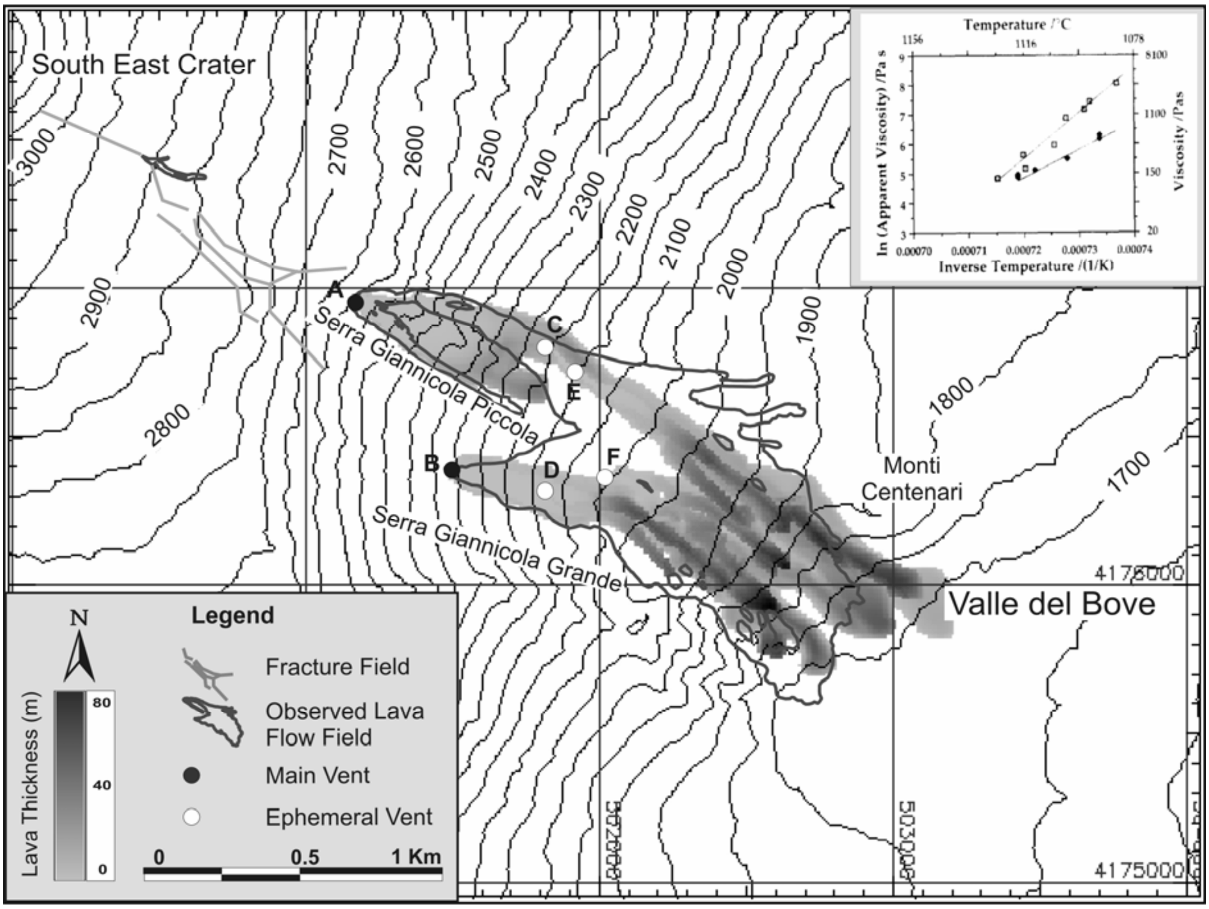

Fig. 4 - Simulated lava thickness of the 23 October 2004 Etna lava flow computed using the relationship between viscosity and temperature as proposed by Pinkerton and Norton (1995) (see inset plot)