THE CATANIA 1669 LAVA ERUPTIVE CRISIS: SIMULATION OF A NEW POSSIBLE ERUPTION

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ABSTRACT

SCIARA (*Smart Cellular Interactive Automata for modeling the Rheology of Aetnean lava flows*, to be read as “shea’rah”), our first two-dimensional Cellular Automata model for the simulation of lava flows, was tested and validated with success on several lava events like the 1986/87 Etnean eruption and the last phase of the 1991/93 Etnean one. Real and simulated events are satisfying within limits to forecast the surface covered by the lava flow. Moreover, improved versions have been adopted in testing other real lava flows of Mount Etna and of Reunion Island (Indian Ocean).

The model has been applied with success in the determination of risk zones in the inhabited areas of Nicolosi, Pedara, S. Alfio and Zafferana (Sicily). The main goal of the present work has been the verification of the effects, in volcanic risk terms, in the Etnean area from Nicolosi to Catania, of a eruptive crisis similar to the event that occurred in 1669, as if the episode would happen nowadays.

Catania has been severely interested in some major Etnean events in history, the most famous one being, namely, the 1669 eruption, involving 1 km^3 of lava during 130 days. The simulation of lava tubes and the usage of different histories within the experiments have been crucial in the determination of a new risk area for Catania. In fact, simulations carried out without the introduction of lava tubes, never involved the city, proving the fact that lava tubes, played a fundamental role in the 1669 Catania lava crisis.

1. INTRODUCTION

In the past, the behaviour of many complex phenomena was investigated only from a qualitative perspective, when the formal models, describing them, were so hard that the main (at that time) computational modality, represented by the integration of differential equations, was impracticable.

Consequently to the development of Computer Science in these years, the applicability limits have been elevated considerably because of the continuous rise of computing power; at the same time researches in Parallel Computing evidenced the relevant potentialities of Parallel Computing models to represent a valid alternative to Differential Calculus in the description of complex phenomena [1].

Cellular Automata (CA) capture the peculiar characteristics (Petitot [2] calls this property acentrism) of systems, which may be seen to evolve according exclusively to local interactions of their constituent parts [3, 4]; they guarantee computational universality, furthermore, modelling main aspects have been widely investigated from a theoretical viewpoint [5, 6].

CA were one of the first Parallel Computing models, they match the parallelism paradigm with the acentrism one and therefore became a powerful tool for modelling natural phenomena, which can be formalised in acentric terms. Conceived in the 1950's to investigate self-reproduction [7], CA have been used mainly for studying parallel computing methods and the formal properties of model systems [3, 8]. However, with the rapid advances in computational resources during the 1980's, CA have become increasingly utilised for more general computer simulation [9].

Applications of CA are very broad, they range from the microscopic and mesoscopic simulation of physical and chemical phenomena, e.g., fluid turbulence [5], Zhabotinsky reactions [9] to the mesoscopic and macroscopic simulation of geological processes, e.g., rock fracturing [10] and lava flows [11, 12].

The forecasting of lava flows was prevailingly limited to qualitative aspects, before the introduction of methods connected to the computer use; in fact, as mentioned earlier, it is almost impossible to solve analytically lava flow differential equations (i.e. Navier-Stokes equations) for real events except for very simple cases.

The use of computational numerical methods, correlated to the solution of differential equation governing lava flows, is however very hard since, if we consider, by example, that particular complexities can arise when lava, while solidifying during emplacement, may range rheologically from approximately Newtonian liquids to brittle solids.

SCIARA (*Smart Cellular Interactive Automata for modeling the Rheology of Aetnean lava flows*, to be read as “shea’rah”) is a CA based model for simulating lava flows. SCIARA was tested successfully and validated on several real Etnean eruptions and has proved to be a reliable model for its application in some fields of intervention for Etnean lavas such as:

a) long term forecasting of the flow direction at various eruption rates and points of emission by locating potential risk areas and permitting the creation of microzonal maps of risk with also a statistical approach (by simulating different lava events);

b) the possibility to follow the progress of an event and predict its evolution;

c) the simulation of the possible effects of intervention on flows for stream deviation, introducing data which represent alterations of the original conditions (e.g., the construction of a canal or embankment, occlusion of a lava canal, etc.).

This paper concerns an application of the previous positive results, in obtaining an instrument that is useful in applications in the field of lava hazard mapping.

The main objective of the present work has been the verification of the effects, in volcanic risk terms, in the Etnean area from Nicolosi to Catania, of a eruptive crisis similar to the event that occurred in 1669, as if the episode would happen nowadays. Several simulations were carried out, using different lava event histories (i.e. different eruptive rates) and with the emplacement of different locations for lava tubes.

The use of different simulations have permitted us to utilize SCIARA from a statistical point of view, giving us the possibility to obtain diverse lava fields in order to individuate major risk areas within the studied area.

The next section illustrates in detail the characteristics of the 1669 Etnean eruption, that is the starting point episode for all the carried out simulations. The third chapter mentions previous methods adopted in the study and simulation of lava flows. In the fourth section we illustrate the basic out lines of the SCIARA CA model while in the fifth we illustrate the most important simulations that were realized for the determination of a new risk area for the city of Catania.

2. THE 1669 ETNEAN ERUPTION

The city of Catania (Sicily, Italy), for its geographical position, has been in the past involved in only two, but devastating, eruptive events caused by Mount Etna, to which base it is located.

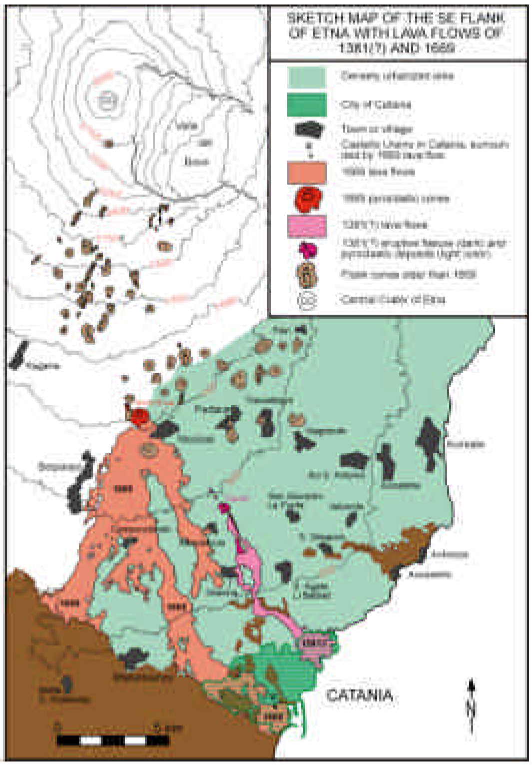


Fig.1 *SE flank of Etna with lava flows of 1669 (www.geo.mtu.edu)*.

The first, which occurred in 1381, seems to have interested the North-Eastern part of the city, even if there is no sufficient documentation on the event. The second one of 1669, of which numerous citations are present, has been instead the most destructive (*Fig.1*).

In the latter, the magma erupted from the South-Eastern flank of the volcano, creating numerous eruptive vents, even at relatively low elevations that, jointly with a *lava tunnel* system, permitted the lava to reach Catania.

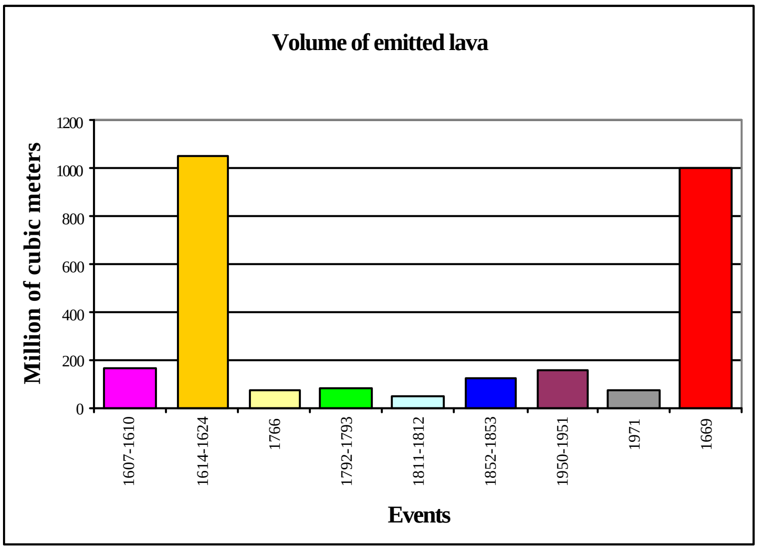


Fig.2 *Volume of lava emitted in major events of Mt. Etna*

The eruptive event of 1669 represents the only circumstance in which lava has reached and destroyed part of the city of Catania. One million cubic meters were produced in only 4 months of the total event duration, an average eruptive rate of $97m^3$/sec, 17,5 Km of total lava field length and a covered area of $37{,}5Km^2$ (*Fig.2*). The fact that the 1669 eruption has been an exceptional event can be noted in the following diagrams that compare characteristics of some major Etnean eruptions.

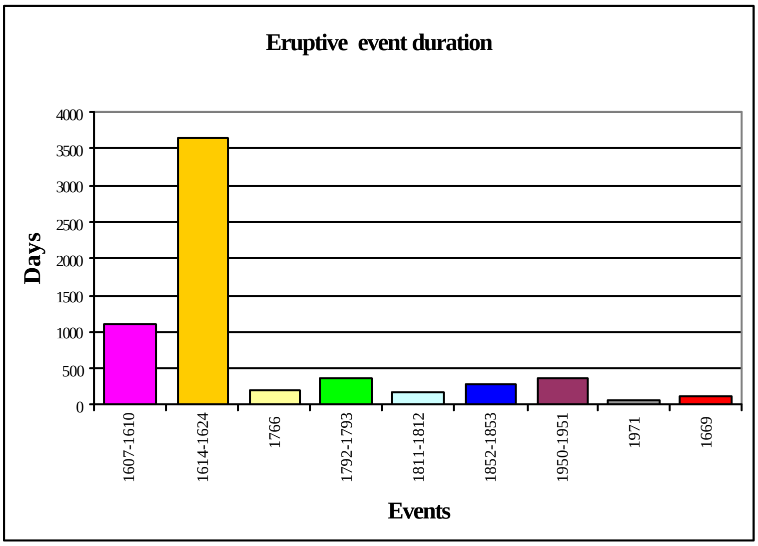


Fig.3 *Duration of major events of Mt.Etna*

In fact, in *figure 2* we can note that only two Etnean events have reached a global lava emission of 1 Km^3 of material, namely the 1614-24 and the one taken into account by us, the 1669 eruption.

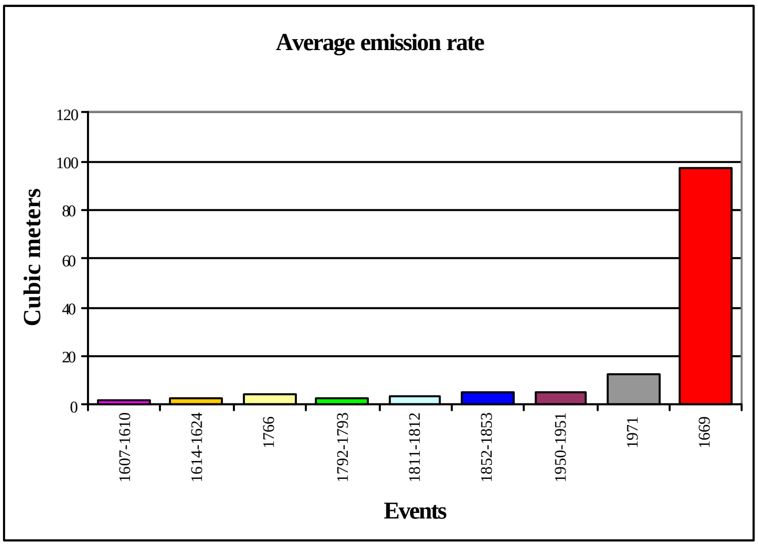


Fig. 4 *Average emission rate of major events of Mt.Etna*

However, in *figure 3*, we can note that in the former eruption the total volume of lava was emitted in about ten years, in opposition to the *four months* of the latter, thus generating a not significant eruptive rate compared with the 97 m^3/s of the lava flow that reached Catania in 1669 (*Fig. 4*).

3. CELLULAR AUTOMATA MODELS FOR LAVA FLOWS

Cellular Automata (*CA*), a paradigm of parallel computing, represent an alternative to differential equations for modelling and simulating complex systems which can be described in terms of local interactions of their constituent parts. Furthermore, *CA* are easily and naturally devisable on parallel computers and can exploit the power of parallelism without significant limits [13].

The forecasting of lava flows was prevailingly limited to qualitative aspects, before the introduction of methods connected to the computer use; in fact, for real events solving analytically lava flow differential equations is almost impossible except in very simple cases.

Anyway, the use of computational numerical methods correlated to the solution of the differential equations governing lava flows is however very hard. As said, they must be particularly complex in order to consider, for example, that lava rheology can range from approximately Newtonian liquids to brittle solids while cooling.

Few computational and numerical flow models have been developed in the past. They are, however, becoming more significant as the available computer power is increasing, especially with new parallel machines.

Crisci et al. [14, 15] and Barca et al. [16] designed three-dimensional *CA* models; the computation costs at that time did not permit to use them for large lava flows and so it was necessary to simplify them in the two dimensional version SCIARA [17, 18, 19, 20]. This *CA* approach, in which space and time are considered discrete, overcomes many of the complexities associated with differential equations and allows features as multiple flow development to be simulated.

Using an approach similar to Cellular Automata, Ishihara et al. [21, 22] started from the Navier-Stokes equations and deduced numerical formulations for discrete space and time intervals; their method, however, cannot be applied to multiple flows or flows, which are extruded intermittently.

Young & Wadge [23] presented a clever simulation code, faster than those cited above, but applicable only to simple flow fronts.

The *CA* model SCIARA, was validated on Etnean lava flows with satisfying results in terms of spatial and temporal evolution of the lava flow path (the 1986 eruption [20], the first and last phase of 1991-92 Etnean eruption [20, 24]).

4.THE *SCIARA* MODEL

The *CA* model SCIARA for lava flows can be intuitively seen as a rectangular region of a plane, partitioned into hexagonal cells of uniform size, each one embedding an identical finite automaton (*fa*). Input for each *fa* is given by the states of the *fa* in the adjacent cells. The state specifies the physical conditions (altitude, lava thickness, flows, temperature, etc.) of the corresponding space portion. At the time t=0, the states of the *fa* are specified according the initial conditions of the phenomenon to be simulated, then the CA evolves changing simultaneously the state of all the *fa* at discrete times, according to the transition function of the *fa*.

The *CA* formal definition, is given by

$$A_{\mathrm{SCIARA}} = (\mathrm{R}, \mathrm{L}, \mathrm{X}, \mathrm{S}, \sigma, \gamma)$$

Where:

- R is the set of hexagonal cells covering the finite region where the phenomenon evolves.
- $\mathrm{L} \subset \mathrm{R}$ specifies the lava source cells.
- The set X identifies the geometrical pattern of cells that influence the cell state change. They are the cell itself, "*Center*" and the "*North-West*", "*North-East*", "*East*", "*South-East*", "*South-West*" and "*West*" neighbouring cells (*Fig.5*):

$$\mathrm{X} = \{\mathrm{Center}, \mathrm{NW}, \mathrm{NE}, \mathrm{E}, \mathrm{SE}, \mathrm{SW}, \mathrm{W}\};$$

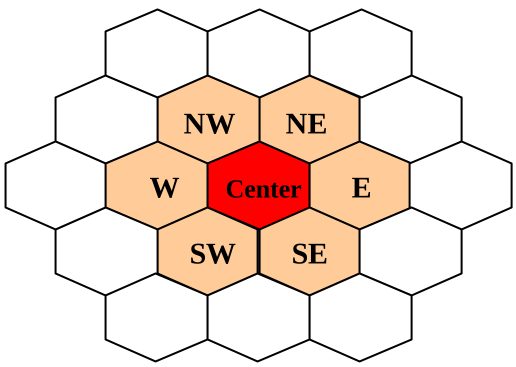


Fig 5 *Hexagonal neighbourhood.*

- The finite set S of states of the *ea*:

$$S = S_a \times S_w \times S_t \times S_T \times S_f^6$$

where

S_a represents the altitude of the cell;

S_t represents a parameter correlated to the lava thickness in the cell;

S_T represents a parameter correlated to the temperature of the lava in the cell;

S_f represents a parameter correlated to lava outflows from the cell toward the six neighbourhood directions.

- $\sigma : S^7 \rightarrow S$ is the deterministic state transition for the cells in R
- $\gamma : S_t \times \boldsymbol{N} \rightarrow S_t$ specifies the emitted lava from the source cell at the time t. In this case the set of natural numbers $\boldsymbol{N}$ represents the time intervals of the *CA*.

At the beginning of time we specify the states of the cells in R, defining the initial configuration of the CA. At each following step the function σ is applied to all cells in R, at the same time the function γ corrects the substate S_h for cells in L, so that the configuration is changed in time and the evolution of the A_{SCIARA} is obtained.

4.1. THE TRANSICTION FUNCTION σ

The A_{SCIARA} states are very numerous compared with the states usually involved in *CA* simulations, which concern mainly microscopic phenomena. Eruptions are macroscopic events, but they can be described with a finite number of states at any approximation. In this case the number of possible altitudes, temperatures and lava thicknesses is large, but finite.

σ could look as a finite-difference approximation method because of its computational characters, but it has a diversity. Here we adopt principles of qualitative physics.

The Navier-Stokes equation for the lava flow are not used here, but in the model we introduce parameters, e.g., the adherence (it rules the viscosity), without direct corresponding in physics, while other parameters, e.g., the temperature, are managed in an orthodox way.

The evolution of the system is due mainly to the “lava outflows” from the lava cell of a single cell toward the neighbour cells and the updating of the cell “temperature”, which are computed by the transition function.

At each step of the CA, the transition function updates the values of all the substates in each cell simultaneously.

The main steps of the transition function for each substate is illustrated in the following, using sentences and formulas to better illustrate the basic outlines of the used algorithms. Moreover, indexes 0..6 indicate for a specified neighbouring the central cell and neighbours “*North-West*”, “*North-East*”, “*East*”, “*South-East*”, “*South-West*” and “*West*” respectively.

4.2 THE S_A SUBSTATE

The cell altitude remains unchanged until lava begins to solidify. When the temperature of the cell in contact with the terrain becomes equal or less than the solidification temperature of the lava, the altitude is increased by the width of such cell.

4.3 THE S_t SUBSTATE

Since the cell dimensions are constant, the amount of lava accumulated in the cells can be described in terms of changes in lava thickness.

The new thickness of the lava cells in the cell at time $t+1$ is given by the thickness at time t, plus the contribution determined by lava inflows from the neighbour cells, minus the contribution determined by lava outflows from the cell toward the neighbour cells at time t.

4.4 THE S_T SUBSTATE

Changes in the cell temperature are modelled as a two-step process to describe changes due to lava motion through a cell and to thermal energy loss from the cell surface.

The first step considers cell inflows and outflows and simplifies the real situation by averaging the temperature *T[i]* of the residual lava *res_lava* in the cell and the incoming flows *fi[i]* of its neighbours.

$$av\_temp = \frac{res\_lava \times T[0] + \sum_{i=1}^{6} \left(fi[i] \times T[i]\right)}{res\_lava + \sum_{i=1}^{6} fi[i]}$$

The second step estimates the temperature drop due to thermal energy losses at the surface. Assuming that losses through the other sides of the cell are small in comparison, the rate of energy loss is approximated by the following formula:

$$T = T_{av} / \sqrt[3]{1 + \left(3T_1^3 \varepsilon\sigma A\Delta t\right) / \rho c V} = T_{av} / \sqrt[3]{1 + \left(T_1^3 pA/V\right)}$$

where ρ is lava density, c the specific heat, V the volume, σ the Stephan-Boltzmann constant, T the absolute temperature of the surface, A the surface area of the cell, and ε is the surface emissivity. Δt ($\Delta t = t_2 - t_1$), the time interval, is the step of the *CA*, $p=3\varepsilon\sigma\Delta t/\rho c$ is the "cooling parameter".

$3\varepsilon\sigma/\rho c$ describes the lava's physical properties, Δt is dependent also on the side cell dimension, p was determined empirically; furthermore, different simplifications have been adopted in order to calculate A/V.

4.5 THE S_F SUBSTATE

The outflow depends on the hydrostatic pressure gradients across the cell, due to differences in altitudes and lava thickness, compared with the correspondent cells, if any, of the neighbouring cells. The effects of variation in lava thickness are accounted for by minimising the total difference of height (cell altitude plus lava thickness of the cell and below cells) between a cell and its six neighbours after each time interval.

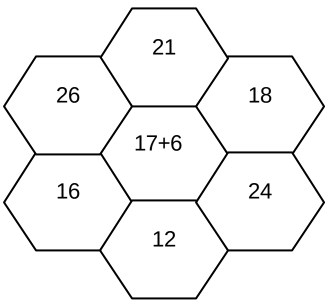
During cooling, a lava rheological resistance is strongly dependent on temperature. The resistance increasing as temperature decreases. Because of complexities inherent in specifying lava rheology and its variation with temperature, we have chosen to model rheological resistance in terms of an "adherence parameter" v, which represents the amount of lava (expressed as a thickness, as discussed above) that cannot flow out of a cell because of rheological resistance. v is assumed to vary with temperature T according to a simple inverse exponential relation $v=ae^{-bT}$, where a and b are constants describing lava rheology. Results from earlier simulations of non-Etnean flows [16, 17, 18] and preliminary studies of Etnean flows, other than the main 1986-87 flow field, suggest that the Etnean examples are reasonably represented by v=0.7m for T=1373°K and v=7m for T=1123°K (the nominal solidus). For these limiting conditions, the constants a and b become 10^9m and $0{,}0154°K^{-1}$ respectively. A further approximation (linear function) was effectively utilised in the simulations.

The lava distribution algorithm is based on the following data: *la* the central cell lava amount, which may be distributed, *z[0]* the height of the central cell minus *la*, *z[i]*, the heights of the neighbours.

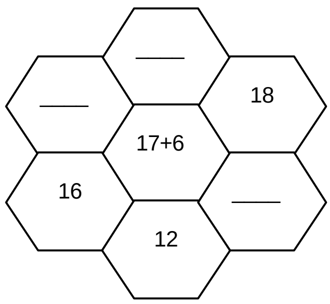
The cells, where the lava cannot flow in, are individuated initially considering the average height given by:

$$av\_height = \left(la + \sum_{i=0}^{6} z[i] \right) / 7$$

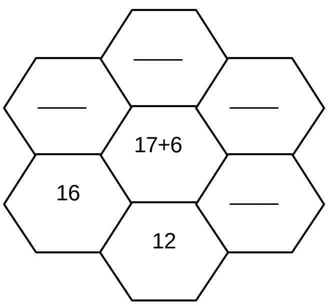
where; *z[i]* greater than *av_height* indicates that lava cannot flow towards *i*; so *i* must be eliminated from the distribution and from *av_height* computations.



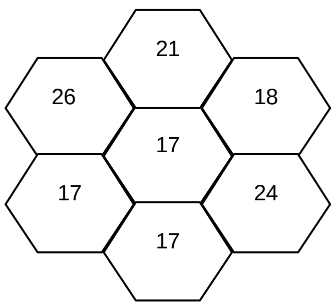
Av_height=140/7=20;
The cells with value higher than av_height ("26";"24";"21") will be eliminated.



Av_height=69/4@17;
the cell "18" will be eliminated



Av_height=51/3=17;
no cell will be eliminated



After distribution.

Fig.6 *Example of an application for the lava distribution algorithm.*

This computation is iterated with the remaining cells, calculating the new *av_height* and eliminating cells with *z[i]* greater than *av_height* until there are no more cells to be eliminated. Then the quantity *av_height-z[i]* for the remaining neighbour cells represents the possible lava inflow to the neighbour cell *i* (*Fig. 6*).

Note that the length of the flow path depends also on the slope, while in the two-dimensional model the "height" is not given explicitly; in this case, a trivial correction is introduced in the previous algorithm in order to account for that problem.

4.6 THE GLOBAL PARAMETERS

In the previous specification of the transition function, parameters that characterise globally the CA appear and, therefore, lava flow in its physical properties. So the model is endowed with a great flexibility which allows the modelling many different types of lava flows.

The global parameters are:

(a) Lava flow temperature at the vent T_V=1373 °K, at solidification T_{sol}=1123°K

(b) Lava adherence at the vent ad_V=3 m and at solidification ad_{sol}=12 m

(c) Cooling parameter, p=5.15e^{-14}

(d) Cell edge length, L=10 m.

The initial and boundary constraints are as follows:

(e) Lava discharge rate.

(f) Ground slope, topography and location of vents.

5. SIMULATIONS

The main characteristics of the lava event, used as initial conditions on the SCIARA model throughout all the carried out simulations, are those that are described in literature and illustrated in several historical witnesses of the 1669 eruptive crisis.

Fig.7 *Investigated area. The red line indicates the principal 1669 fracture*

Our choice has fallen on this event, due to its importance and most of all, because it has been the only eruption that has, in history, interested directly the town of Catania.

The fracture, that is the starting point of the flow, has been positioned *North-West* of Monte Rossi and was oriented towards *NNW (Fig.7)*. The overall emitted magma has been considered equal to 1 Km^3, distributed in 120 days. The vent lava temperature, as well as the lava solidification value (considered as temperature below which the lava is considered not fluid), have been considered respectively equal to 1100°C and 850°C, that are average values of Etnean lavas.

However, values regarding other properties have been varied within a certain range, in order to simulate numerous events with different eruptive histories.

Each simulation has been characterised by a different evolution of the lava emission in terms of daily emitted quantity. Moreover, the rheological parameters have been varied depending on the temperature, thus obtaining different kinds of simulations depending on viscosity terms.

Particular attention has been devoted on the generation and emplacement of ephemeral vents,

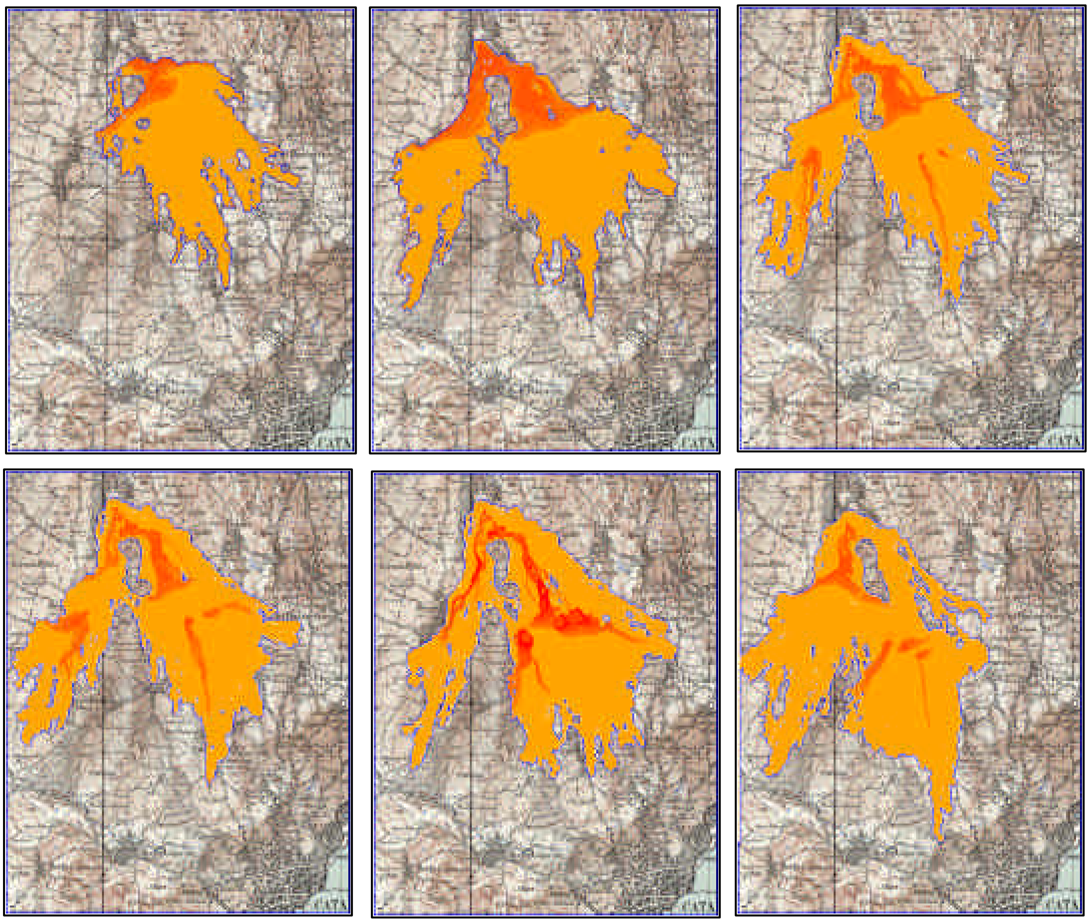


Fig.8 *The first simulations with the emplacements lava vents on the upper part of the lava field.*

which have been crucial for the fact that the lava reached the city.

In fact, due to the relatively high distance between the main fracture and the Catania (ca. 17 Km), no lava episode could of reached the inhabited area without the opening of ephemeral vents downwards, in the valley. Starting from the historical reconstruction of the event, the ephemeral vent location and elevation have been obtained. Considering the fact that the present version of the SCIARA model cannot automatically simulate lava tunnels, these have been considered as ephemeral vents fed by magma, by transferring lava quantities, neglecting any temperature drop, from the main fracture.

In *Figure 8* we started by emplacing lava vents only on the upper part of the lava field, namely in the area of the main fracture of 1669. It can be seen how, in this case, the lava skims the towns of Nicolosi in most cases and, in a fewer ones the town of Belpasso. The volcanic risk for these areas is not negligible: the inhabitants of these two towns have only few hours to intervene on the lava. In any case the city of Catania never gets involved in a lava event. This is mainly due to topographic features and, as said before, by the fact the Etnean lavas usually can travel for more than ten kilometres only if specific factors are present: lava duration, eruptive lava ratio and, most of all, the presence of lava tunnels.

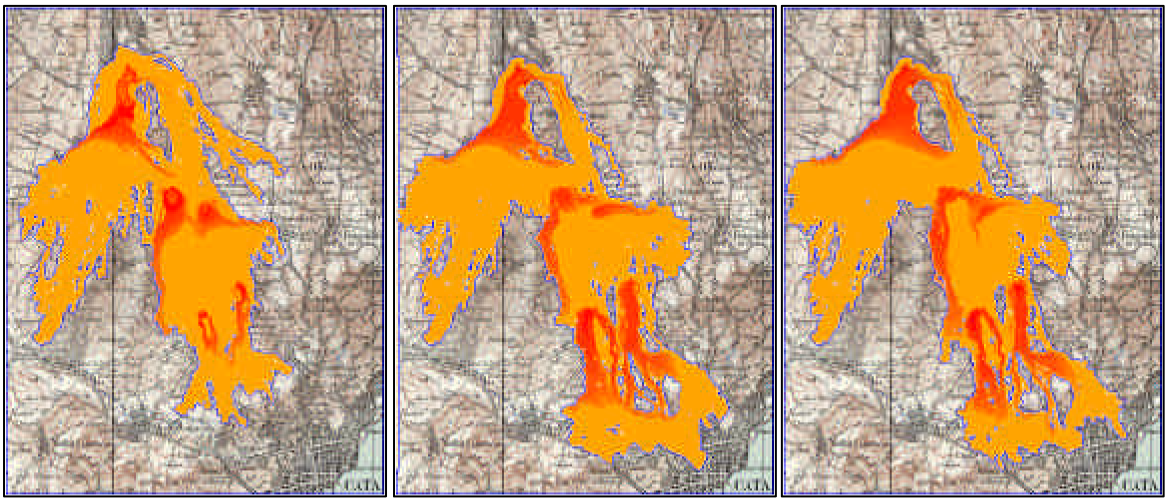


Fig.9 *Simulations with emplacement of lava tunnels in the same place of those of 1669.*

On the other hand, we can see how the emplacement of lava tunnels (*Fig. 9*) in the same place of those of 1669, reduces the safeness of the city of Catania, which is involved in a lava event in some of the simulations that have been done.

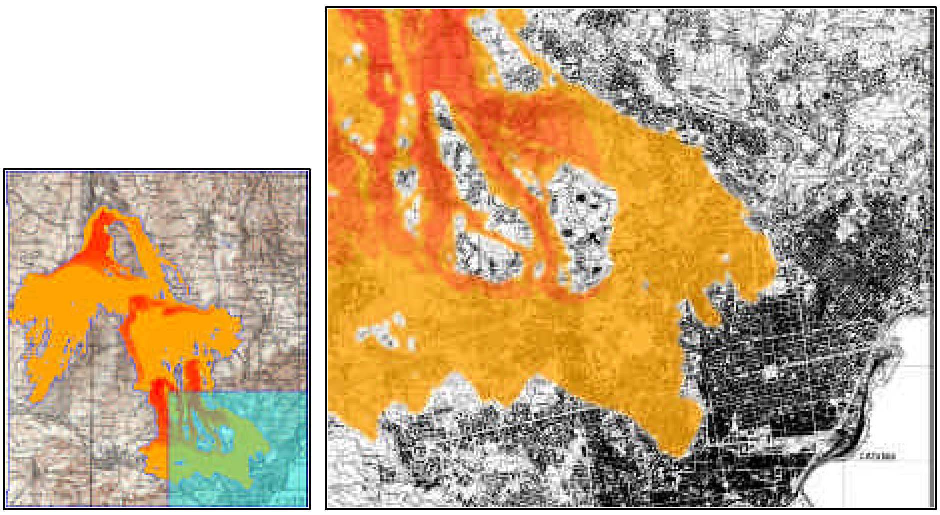


Fig.10 *Close-Up on Catania.*

The *Figure 10* and *Figure 11* shows a close-up of a typical simulation near the outskirts of the city. The possibility to realize zooms of specific areas is a typical feature of the SCIARA program. This characteristic results of extreme importance in supervising a specific event, in order to eventually intervene on the lava flow by individuating the location for the construction of artificial barriers and/or by suggesting local authorities to intercede on the resident populations.

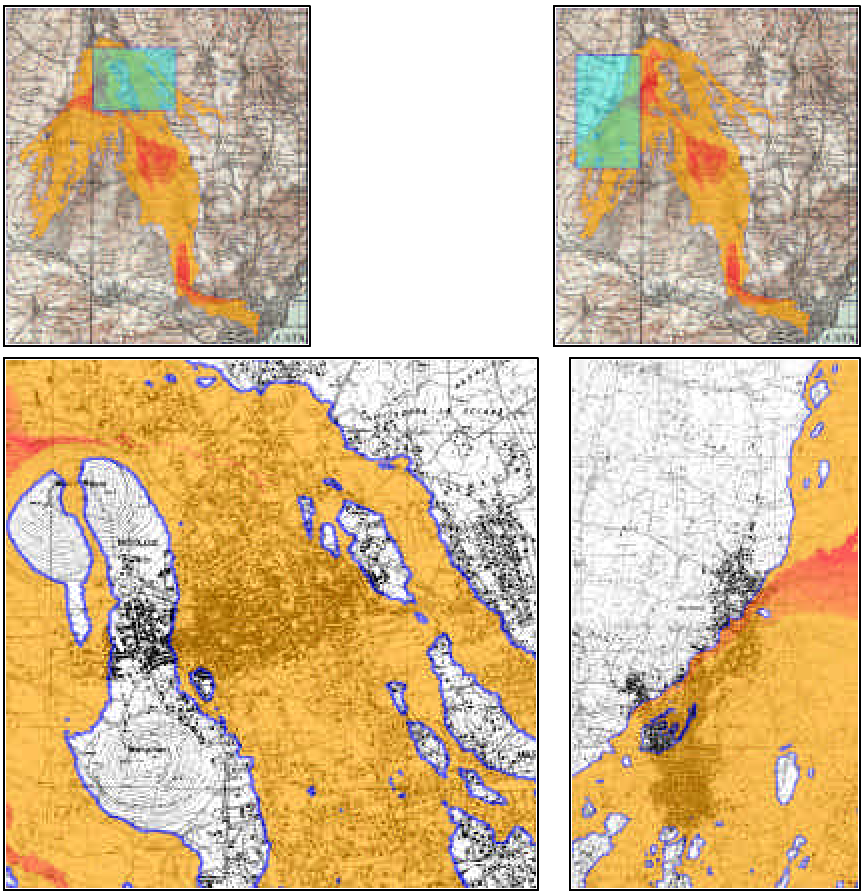


Fig.11 *Close-Up on Nicolosi and Belpasso.*

It is worth to note that we can obtain a lava flow that is similar to the 1669 one, if we vary opportunely some parameters (*Fig 12*).

In fact, by utilising parameters within a certain range of those devised in the validation of the model (namely the 1991-93 Etnean eruption and the 1986/87 one) we have obtained an analogous event of that of the 1669 eruption. The major differences are due to the fact that the simulations were carried out on the *present* morphology, that is obviously different from the original one, for the presence of old lava emitted in the 1669 event.

The analogies are of extreme importance within the general study framework. In this case, SCIARA can be used to study, as said, possible effects of intervention on flows for stream deviation, introducing data which represent alterations of the original conditions, construction of a canal or embankment, occlusion of a lava canal, to protect inhabited areas, electric lines, roads, aqueducts, industries, historical sites, churches and all that concerns civil protection. In such way, the model can be used for the reduction of the hazard for the city.

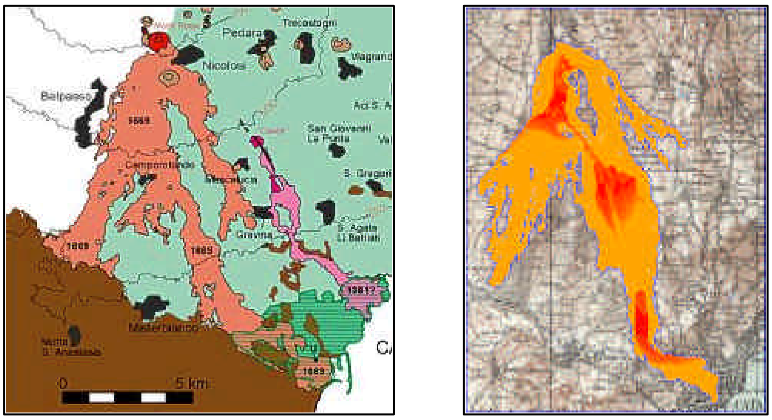


Fig.12 *Real and simulated event comparing.*

6. CONCLUSIONS

A detailed hazard map has been obtained by overlapping all the simulated lava events (32) (*Fig.13*). In such way, four major zones have been individuated, which indicate the hazard of the relative area. The first represents the area where at most 25% (*yellow area*) of the simulated events have been interested, the second indicates those from 25% to 50% (.*green area*), the third the ones from 50% to 75% (*blue area*)and the last one where the lava concerned the area in at least 75% (*red area*).

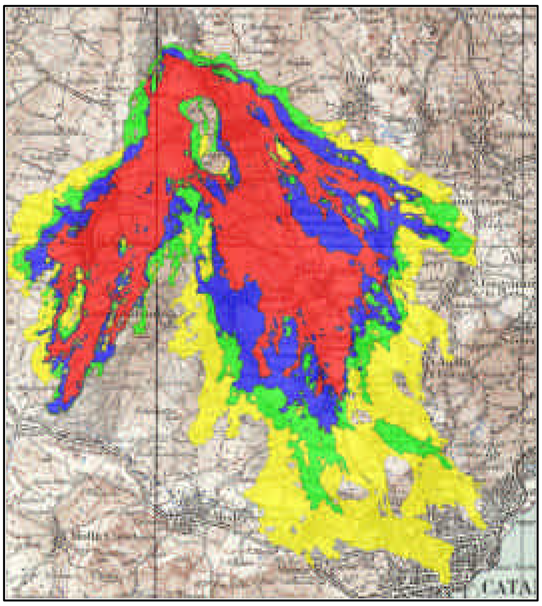


Fig. 13. *Risk map for the Catania area.*

Of course this last area represents the area that has the most elevated degree of hazard in the case of a lava event similar to the 1669 one.

Anyhow, we can note that the city of Catania is only marginally interested by lava flows from the obtained hazard map, and only by those generated by the presence of ephemeral vents located at a relatively low altitude.

Conversely, the towns of Nicolosi, Belpasso and Mascalucia seem to be in most cases at a high degree of hazard since more than 75% of all the events involve the inhabited areas. This is due to the fact that these areas are in a not favourable geographic position, and are not protected by any evident morphological barrier.

The final risk map (*Fig. 13*) can be moreover enlarged and fitted on a more detailed map, thus obtaining a more precise indication for the peril of the investigated area, like the ones of *figures 9* and *10*.

It is worth to note that the obtained results represent a valid assessment even if the number of carried out simulations is relative low (32) for a statistical study. Nonetheless, the results could be quantitatively more significant when more simulated events (ca 100), with different eruptive histories, will be carried out.

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