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# The 2001 Etnean Crisis: Application Of The "SCIARA" Simulation Model

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# Contents

- Cellular Automata;
- Lava Flow Modelling;
- Quick Model Overview;
- Etnean July 2001 Eruption;
- Simulations & Future Scenarios.

# Lava Flow Modelling



- Lava Flows show complex behaviour;
- Need for Navier-Stokes equations, BUT:
- They are Differential Equations!!!
- Major Complexities arise due to irregular ground topography and because lavas range rheologically from Newtonian fluids to brittle solids.

# Cellular Automata (CA)



- Mathematical tool for modelling natural phenomena;
- Conceived in the 1950s by J. Von Neumann to investigate self-reproduction…
- CA approach involves *locality* (cell state interaction) and *uniformity* (same evolution for each cell);
- CA = discrete time and space (usually square or hexagonal grid).

# CA Applications

- **Enviromental Issues**: Lava Flows, Landslides, Contamination, Bioremediation, Earthquakes, Forest Fires, Soil Erosion, etc…;
- **Bio-medicine**: Immunology system, Cancer cell growth;
- **Industrial applications**: Coffee percolation (ILLY), Tire mixture (PIRELLI);
- **Fluid-dynamics, Traffic, ETC…**

# CA Bibliography


- von Neumann, J., (1966) *Theory of self reproducing automata*. University of Illinois Press;
- Murray, A. B. and Paola, C., (1994), *A cellular model of braided rivers*, **Nature**, *371*, 54-57;
- Malamud B. D. & Turcotte D. L., (2000), *Cellular Automata models applied to natural hazard*, **Computing in Science and Engineering** vol 2 n. 3 pp 43-51;
- Toffoli, T., (1984), *Cellular Automata as an alternative to (rather than an approximation of) differential equations in modeling physics*, **Physica 10D**, 117-127;
- Margolus, N., Toffoli, T., Vichniac, G., (1986) *Cellular Automata supercomputers for fluid-dynamics modelling* Phys. Rev. Lett., 56(10) ,1694-1696;
- Vichniac, G., (1984), *Simulating physics with cellular automata*, Physica 10D, 96-115.


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# Cellular Automata 2



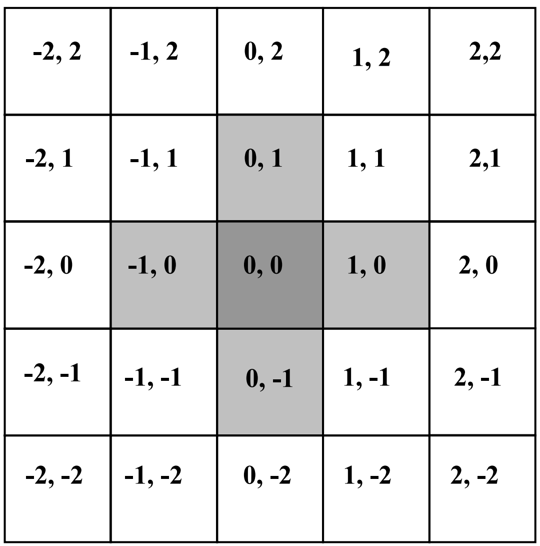
- CA can be seen as a d-dimensional space (i.e. grid), partitioned in cells of uniform size each one embedding an *identical* finite automaton
- Input for *each* cell is given by the *states* (i.e. altitude, temperature, outflows) of the neighbouring cells.
- From time t=0, the CA evolves changing the state at discrete times, according to the *transition function*.

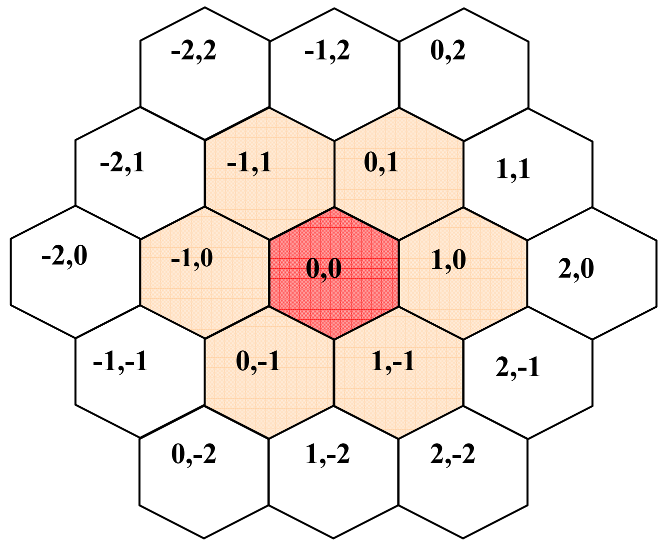
# CA Neighbourhoods



A set of regular square or hexagons cover the finite region where the phenomenon evolves.

Each square hexagon is individuated by a pair of integers (x,y):



# The SCIARA model

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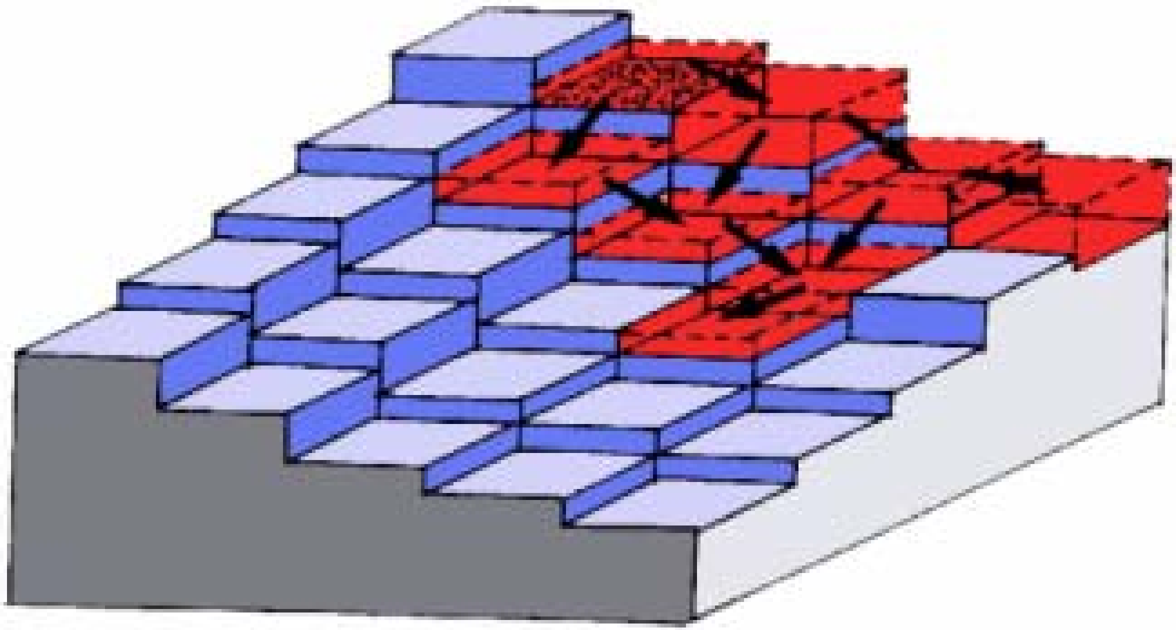
SCIARA is a Cellular Automata based model for the simulation of lava flows

Its possible applications can be:

- The long term forecasting of the flow direction at various eruption rates;
- The creation of microzonal hazard maps through a statistical approach, by simulating different lava events;
- The ability to follow the progress of an event and predict its evolution;
- The simulation of the possible effects of intervention (canals, embankments, etc) on flows for stream deviation.

# Cellular Automata (Flows)





# Lava Simulation Models (by others)

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- Barca, Crisci, Di Gregorio, Nicoletta (1986-89).

  *First approach to the Cellular Automata Model. Three and two dimensional models with discrete time and space, allowing multiple flows;*
- Ishihara et al. (1988, 1989).

  *Starting from Navier-Stokes equations, adopting a space tessellation and discrete time. However, not applicable to multi-flows and/or extruded intermittently flows;*
- Young and Wadge (1990).

  *Cellular Automata approach with simulation of simple advancing lava flow fronts (FLOWFRONT);*
- Miyamoto H. and Sasaki S. (1997)

  *Simulating lava flows by an improved cellular automata method. They solved the problem of spurious symmetries with a probabilistic method;*
- McBirney, A.R., Murase, T. (1984)

  *Study of rheological properties of magmas ;*
- Kilburn, C.R.J., Lopes, R.M.C. (1991)

  *Study of temperature mixing in aa flows.*

# CA States for Lava Flows

The finite states of each cell are:

1. Cell altitude (e.g. 2000 a.s.l) : varies due to lava solidification;
2. Cell lava thickness (e.g. 6 m): varies due to in-coming and out-going lava flows;
3. Cell lava outflows (6) towards neighbouring cells: calculated by minimizing lava heights among neighbours;
4. Cell lava temperature (e.g. 1200 K°): varies by (1) averaging temperature from incoming flows and (2) thermal energy losses at surface.

# Formally speaking! (1)



- The *CA* formal definition, is given by

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

where:

-R = $\{(x, y) | x, y \in \boldsymbol{N}, 0 \leq x \leq lx, 0 \leq y \leq ly\}$ is the set of hexagonal cells in the finite region where the phenomenon evolves.

- $L \subset R$ specifies the lava source cells.

- The set X identifies the geometrical pattern of cells that influence the cell state change.

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

# Formally speaking! (2)

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

$$S = S_a \times S_t \times S_T \times S_f^{\,6}$$

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*.

# Formally speaking! (3)



- 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.

# Cell Altitude $S_a$

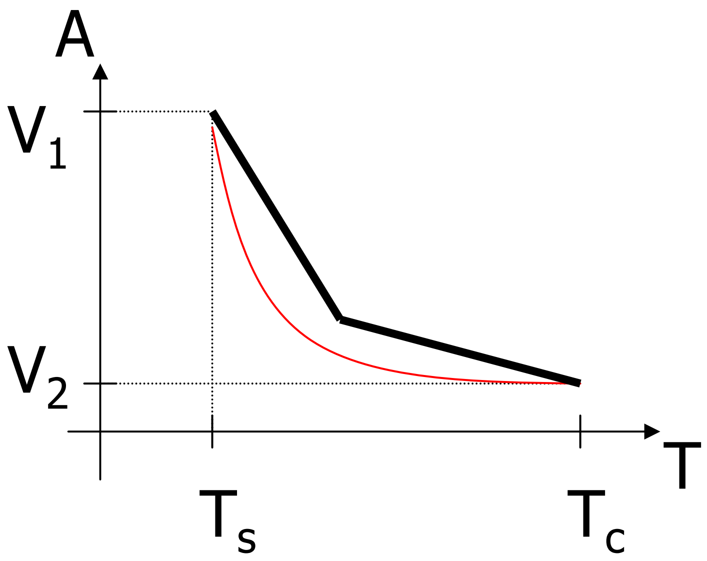


- Cell Altitude at step t+1 is increased by the thickness of lava, once the lava temperature drops to a minimal value so that motion is blocked (*solidification*) (i.e *automatic morphology updating*)
- At the same time the lava thickness of the cell is reset to zero

# The "Adherence Parameter"



Results from earlier simulations on Etnean flows suggest that the Etnean examples are reasonably represented by $v_1$=7 m for $T_s$=1123 K and $v_2$=0.7 m for $T_c$=1373 K




$$v = ae^{-bT}$$

# Temperature drop computation $S_T$



- It is assumed that lava inside a cell can be treated as though thermally well mixed;

- It might seem like a major simplification but, as suggested by Kilburn & Lopes (1991), it *does* yield a characteristic cooling time scale comparable to the typical emplacement times of *aa* flows, **thus**:

- Two step calculation:

  1) Averaging temperature of residual lava inside a cell and incoming lava;

  2) Estimation of temperature drop due to thermal energy losses at the surface

# Temperature

- That is:

1)

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

2)

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

# Cell lava thickness $S_t$



- The value of the lava thickness inside a cell during a CA time-step is computed by *adding* inflows towards the cell, *subtracting* eventually outgoing flows towards neighbouring cells, to the remaing lava inside the cell (adherence)

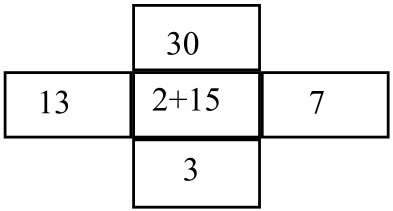
# Lava flows computation $S_f$



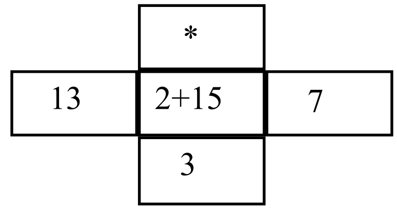
- The outflows depend on the hydrostatic pressure gradients among the cells;
- The algorithm is based on the minimisation of the differences of heights between neighbouring cells
- Moreover, the lava rheological resistance depends on temperature (resistance *increases* as temperature *decreases*) (McBirney & Murase, 1984);
- We have chosen to model rheological resistance in terms of an adherence parameter, which represents the amount of lava remaining in a cell at each step.

# Minimisation algorithm (outline!)

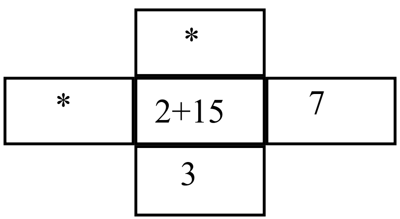
- The outflow from a cell is calculated by minimizing the differences of heights between the neighbouring cells.



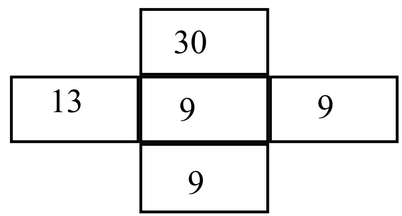

av_height = 70/5 =14
neighbour cell 1 is eliminated




av_height = 40/4 =10
neighbour cell 3 is eliminated




av_height = 27/3 = 9
no cell is eliminated




heights after the lava distribution

# Global parameters

- In the transition function intervene parameters which characterize globally the CA and therefore the lava flow in its physical properties:
  1. Cell dimension (5m);
  2. Cooling parameters;
  3. Lava emission and solidification temperature (1373 K and 1123 K);
  4. Lava adherence at vent (e.g. 0.7m);
  5. Lava adherence at solidification (e.g. 7m);
- Constraints are:
  1. Topography and location of the vents;
  2. Lava discharge rate.
- examples