

A LAVA FLOW SIMULATION MODEL USING A GIS AS A CONTRIBUTION FOR HAZARD ASSESSEMENT AS FOGO ISLAND, CABO VERDE

L. Quental¹, A. Soares² & J.L. Gaspar³

1 - Instituto Geológico e Mineiro, Apartado 7586, 27201-866 Alfragide. E-mail: lidia.quental@igm.pt

2 - Instituto Superior Técnico, Avenida Rovisco Pais, 1096 Lisboa Codex. E-mail: ncmrp@alfa.ist.utl.pt

3 - Deptº de Geociências, Universidade dos Açores, Ponta Delgada. E-mail: jlgaspar@alf.uac.pt

ABSTRACT

A basic model for lava flows simulation is implemented and applied to the Fogo volcano using as a test the April 95 eruption; the objective is to evaluate and control future occurrences. Using the techniques of Cellular Automata (CA), the lava is considered a dynamic system varying in time and space. A digital terrain model (DTM) using discrete cells of 15 meters is created in a Geographic Information System (GIS). A stochastic simulation process is used to establish the lava flow. The set of simulated lava images over time periods, allows evaluation of the uncertainty of spatial dispersion of lava, according to its properties, and elaboration of hazard mapping.

1 • INTRODUCTION

Although rarely resulting on human fatalities (Crandell *et al.*, 1984; Blong, 1984, 1996; Chester, 1993), lava flows may cause social and economic disruptions as the result of damages to structures, production of fires and the cover of productive lands (Duncan *et al.*, 1981). A form of volcanic prediction as a strategy to mitigate their potential hazard consists in the development of lava flows simulation models, allowing the elaboration of eruptive scenes.

Lava flow modelling is usually based on two distinct approaches: i) Analytical models based on transport equations (Dragoni *et al.* 1986; Dragoni, 1989; Baloga & Pieri, 1986; Crisp & Baloga, 1990; Park & Iversen, 1984; Macedonio, 1994) and ii) Numerical models based on discretisation of space in cells in which the dynamic relations of the fluid on those cells are simplified (Crisci *et al.*, 1982, 1986; Barca *et al.*, 1987, 1998, 1993, 1994; Macedonio, 1990; Young & Wadje, 1990; Wadje *et al.*, 1994; Miyamoto & Sasaki, 1997).

The modelling approach used on this work is of the type ii), using the principles of bidimensional Cellular Automata (CA) (Quental & Soares, 1997). CA are mathematical idealisations of a physical systems in which space and time are discrete and physical quantities take on a finite set of discrete values (Wolfram, 1994). Lava flow is visualised as a dynamic system of cells that evolves in space and time, in accordance with determined internal parameters of the cell and a set of rules that controls transition to the neighbour cells. On a digital terrain model (DTM) of Fogo island, created for the effect in a Geographic Information System (GIS), the area is discretised in cells of 15X15m and the transference of lava amongst

them is established by a stochastic process. The model contemplates the conditions imposed by topography, the location of eruptive(s) centre(s), the flow rate, being lava viscosity considered empirically through its effect on lava thickness. The knowledge and mapping data acquired during 1995 eruption are used to test the model.

2 • LAVA FLOW MODELLING

2.1 • CELLULAR AUTOMATA APPROACH

The movement of lava on a well defined topography is generally recognised as having the behaviour of a viscous fluid of Bingham type (Hulme, 1974; Cas & Wright, 1987; Ishihara *et al.*, 1990; Araña & Ortiz, 1993), characterised by a yield stress, which must be exceeded before the lava starts moving. However during installation and cooling, the rheology of lava flows ranges from approximately Newtonian fluids to brittle solids (Barca *et al.*, 1994). Due to the complexity of this process, usually a simplification is done to the physical parameters of the system for simulation purposes.

The simulation model proposed in this study incorporates the most important parameters that control the lava flows, i.e., topography, vents location and flow rate. Rheology is indirectly considered through the effect of lava thickness in cells, which is defined here by viscosity. The model is based on the formalism of the CA where the evolution of lava flow is determined by a stochastic process. To each cell representing an elementar automaton, a set of transition probabilities for the neighbouring cells is

defined:

$$\text{prob}\{x_0 \rightarrow x_i | T(x_0); L(x_0); S(x_0); T(x_i); L(x_i); S(x_i)\} = P_{x_0}(x_i)$$

The transition of cell x_0 to x_i is conditioned to the set of parameters of the cells: topography T , volume of lava L and viscosity S .

The evolution of a lava flow from a source cell x_0 to a neighbourhood cell x_i is determined by the transition probabilities. Eight neighbouring cells are considered, being the sum of the transition probabilities equal to one:

$$\sum_{i=0}^8 P_{x_0}(x_i) = 1$$

For illustrative purposes, we will consider in this study the conditional transition probabilities taking into account only the topography $T(x_0)$ and volume of lava $L(x_0)$:

$$P_{x_0}(x_i) = \text{prob}\{x_0 \rightarrow x_i | T(x_0); L(x_0); T(x_i); L(x_i)\}$$

The difference of elevation (topography + lava) between the cells x_0 and x_i is:

$$d(x_i) = T(x_0) + L(x_0) - [T(x_i) + L(x_i)]$$

Then, negative values of $d(x_i)$ means that there is a null probability of lava to flow from x_0 to x_i . We can assume the ratio $d(x_i)/dt$, as the transition probability of x_0 to x_i with dt as the sum of the positive values $d(x_i)$:

$$P_{x_0}(x_i) = d(x_i)/dt \text{ being } \sum_{i=1}^8 P_{x_0}(x_i) = 1 \text{ and } dt = \sum_{i=1}^8 d^+(x_i)$$

Note that more complex functions of T and L could be chosen for transition probabilities of the lava. In this case viscosity is considered in the simulation process defining the quantity that remains in the cell.

2.2 • SIMULATION OF LAVA FLOW

The simulation is an iterative process where each iteration, representing a period of time t , is initiated in the source cell x_0 with a volume of lava $L_{t=1}(x_0) = L$.

The algorithm of simulation can thus be summarised in the following sequence of steps:

1 - Calculation of $P_{x_0}(x_i)$ and the cumulative distribution function:

$$F_{x_0}(x_i) = \sum_{j=1}^i P_{x_0}(x_j) \quad F_{x_0}(x_i) = \sum_{j=1}^i P_{x_0}(x_j)$$

2 - Generation of a value u from a uniform distribution law between 0 and 1.

3 - The lava flows from x_0 to cell x_i if:

Once is defined the cell to which lava transits, the balance of masses between the cells x_0 and x_i is calculated: if the difference $d(x_i)$ is greater than the total amount $L(x_0)$ then it means that there is sufficient room in x_i to accommodate the lava and consequently it totally (*) flows to cell x_i , if the difference $d(x_i)$ is greater or equal to $d(x_0)$ the lava stays in an equal level at both cells.

4 - The cell to which lava was transferred becomes x_0 and the steps 1 to 3 are repeated until the spatial evolution of lava at iteration t finishes, which happens, basically, in two situations:

In step 3, if $F_{x_0}(x_i) = 0$, $i = 1, \dots, 8$, it means that there is a null probability for the lava to be transferred to any of the eight neighbouring cells. In this case $x_i = x_0$ and $F_{x_0}(x_0) = 1$, the lava is accumulated in cell x_0 and its spatial evolution finishes for iteration t .

When the amount of lava to be transferred is lower than a minimum value previously defined.

In both situations a new iteration $t+1$ starts with this sequential procedure at source cell x_i :

$$t = t + 1; x_0 = x_i; L_{\text{total}}(x_0) = L$$

The simulation process finishes when the total number of iterations is equal to a maximum determined for each simulation t_{max} by the user, which is equivalent to a given period of time of the eruption.

(*) Except a small portion retained in x_0 equivalent to a viscosity parameter.

2.3 • UNCERTAINTY ASSESSMENT OF LAVA FLOW

The set of images has the same probability to occur given the defined characteristics of topography, source cell locations and viscosity.

Maps of the probability of each point x to have an amount of lava greater than a given threshold can be drawn with the simulated maps. Let us consider $z^l(x)$ the thickness of point x , in the simulated map l , $l = 1, \dots, NI$ -number of total simulated images of the cell in point

$$I_z^l(x) = \begin{cases} 1 & \text{se } z^l(x) > z \\ 0 & \text{otherwise} \end{cases}$$

x . An indicator variable can be defined for the thickness threshold z :

The probability of each point x to have a thickness of lava greater than z can be computed with the NI

simulated maps.

$$P_z(x) = \frac{1}{N_i} \sum_{i=1}^{N_i} z_i(x)$$

The maps $P_z(x)$ are fundamental tools to calculate the local hazard maps of an eruption with predefined characteristics: source cells location, topography and lava internal properties.

$$F_{X_0}(x_i) > u \geq F_{X_0}(x_i - 1) \text{ for } i=2,4,6,8 \text{ and flows to } x_i \text{ if } F_{X_0}(x_i) > u$$

3 • CASE STUDY

Fogo island in Cabo Verde archipelago consists of a single volcano truncated by a caldera breached to the E (Fig. 1).

The geology of the island is mainly characterised by a thick sequence of basaltic lava flows interbedded with thin layers of pyroclastic deposits, overlying a carbonatite complex (Machado & Assunção, 1965). On the western side of the island the flows are dominantly nephelinitic and they pre-date the formation of the caldera. On the eastern side the flows are basanitic and limburgitic, and they were originated from extrusions that took place after the caldera-forming events (Assunção *et al.*, 1967).

of hawaiian/strombolian-type with variable duration. Within the central volcano caldera a polygenetic basaltic cone (Pico, 2829m), was responsible for the frequent volcanic activity reported since the settlement in the XV century until middle XVIII century. Thereafter eruptive activity has been episodic with quiescent periods varying from a few years to several decades and lava flows have been fed through fissures located on the base of the Pico (Ribeiro, 1960; Torres *et al.*, 1995, 1997). Since 1st quarter of XVIII century the average interval of recurrence is 24.1 years.

The 1995 eruption developed through a fissure NE-SW with explosive and effusive activity within the caldera (Fig. 1, 2). The volcanic activity centred on two boccas after seven of them have been active. The eruptive style at the beginning was hawaiian and on the first two days lava flows travelled approximately 3 km (Figure 2). The total amount of lava for that period was estimated as 2.6 to 5.2x10⁶ m³ and the area covered was 0.86 km² (Wallenstein *et al.*, 1997).

The eruption lasted approximately two months. As result, a village within the caldera was completely destroyed by lava flows. Neighbours villages became inaccessible by road (Gaspar *et al.*, 1995a,b; Ferreira *et al.*, 1997) and more than 4 km² of potential or on use productive lands were covered by lava's (Wallenstein *et al.*, 1997; Costa, 1997).

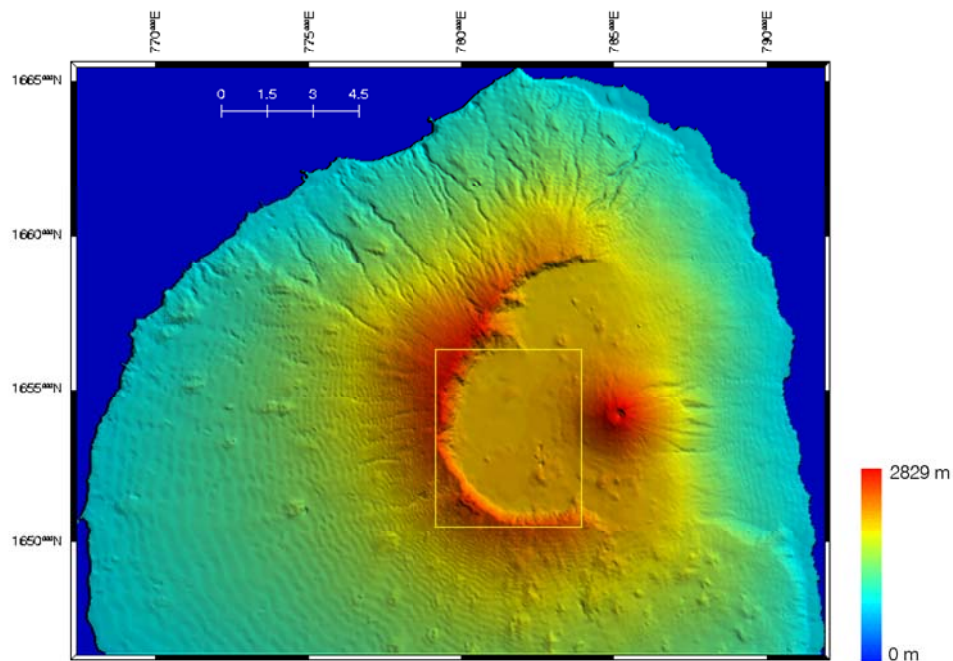


Fig. 1 - DTM of Fogo island, 75.4%, based on S.C.E (1979), UTM projection, International ellipsoid, Local datum Ponto Alto do Sul. Yellow marker is the area of 1995 eruption.

The eruptive story shows explosive and effusive events

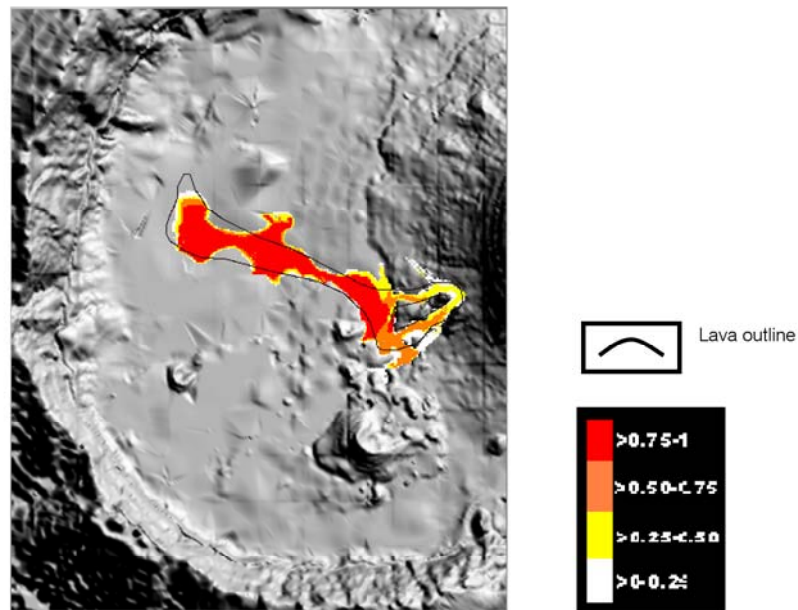


Fig. 2 - Probability map for lava flow. Outline of real lava after Gaspar *et al.* (1997).

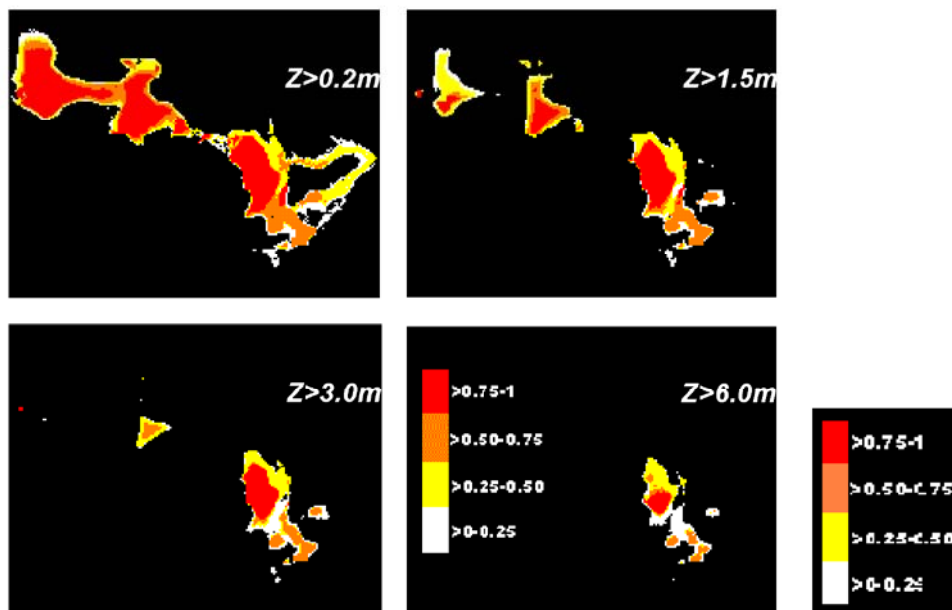


Fig. 3 - Thickness in cells shown by different threshold z values on probability maps.

The two main eruptive boccas were chosen as initial cells x_i .^(a) A xx average value of 30% was chosen after calibration with the outline of real eruption. This is the percentage retained in each cell, which means that only maximum 70% of lava flows from one cell to another.

(a) To define the other parameters a first set of simulations was performed and composed with the outline of real eruption (see Figure 2).

After calibration with the outline of real lava flow we have defined 11000 iterations with a quantity of lava in each iteration = 0.7 xx.

A set of ten simulated images was obtained with the methodology exposed in 3. Based on the 10 simulated images a probability maps P_z were calculated according eq. (6) for a thickness threshold $z=0$ (see Fig. 2). It means the probability of a given point x to have any amount of lava ($z>0$).

The average map Pz show a good match with the real lava outline. After this calibration the model can be applied for any other source cells (eruptive boccas) to preview hazard scenarios.

For illustrative purposes we have calculated probability maps with other thickness thresholds for the same simulated maps. Thus Figure 3 shows probability maps for 4 thickness threshold of lava: $z=0.2m$, $z=1.5m$, $z=3.0m$ and $z=6.0m$ respectively. The red areas represent those with more than 75% to have a thickness of lava greater than 0.2m (Fig. 3a), 1.5m (Fig. 3b), 3.0m (Fig. 3c) and 6.0m (Fig. 3d) after two days of eruption.

5 • FINAL REMARKS

i - The simulation results show a good match with the real lava outline corresponding to the first two days of the 1995 eruption. It validates the model as consistent and consequently can be applied to preview other scenarios assuming identical eruption conditions.

ii - Probabilities maps of Fig. 3 can be extremely important tools to evaluate hazard in other situations. The intersection of these maps with critical infrastructures (main roads, bridges, etc.) allows the development of risk scenarios, being a fundamental tool to preview the impact of future eruptive occurrences and promote adequate mitigation measures.

REFERENCES

ASSUNÇÃO, C.T., MACHADO, F. & SILVA, L.C. (1967) - Petrologia e Vulcanismo da ilha do Fogo. *Garcia de Orta*, 15, p. 99-110.

ARAÑA, V. & ORTIZ, R. (1993) - Riesgo Volcánico. *In: La Volcanología actual* (Martí, J., Araña, V., Eds.), Nuevas tendencias. CSIC, Madrid, 577 p.

BALOGA, S. & PIERI, D. (1986) - Time dependent lava flows. *J. Geophys. Res.*, 91, p. 9543-9552.

BARCA, D., CRISCI, G.M., GREGORIO, S. DI. & NICOLETTA, F. (1987) - Lava flow simulation by celular automata: Pantelleria's examples. *In: Proc. Int. ASME Conf. On Modelling and Simulation*, Vol 4A, p. 9-15, Cairo, Egypt.

BARCA, D., CRISCI, G.M., GREGORIO, S. DI & NICOLETTA, F. (1993) - Cellular Automata methods for modeling lava flows: simulation of the 1986-87 eruption, Mount Etna, Sicily. *In: Active lavas* (Kilburn, C. R. J. & Luongo, G., Eds.), UCL Press Limited. University College London, 374 p.

BARCA, D., CRISCI, G.M., GREGORIO, S. DI & NICOLETTA, F. (1994) - Cellular Automata for simulating lava flows: a method and examples of the Etean eruptions. *Transport Theory and Statistical Physics*, 23, p. 195-232.

BLONG, R. J. (1984) - *Volcanic hazards. A sourcebook on the effects of eruptions*. Academic Press, 424 p.

BLONG, R. J. (1996) - Volcanic Risk Assessment. *In: Monitoring and Mitigation of Volcano Hazards* (Scarpa/Tilling, Eds.), Springer-Verlag.

CAS, R. A. F. & WRIGHT, J. V. (1987) - *Volcanic successions: modern and ancient*. Allen & Unwin Publishers, Lda., 529 p.

CHESTER, D. (1993) - *Volcanoes & Society*. University of Liverpool. Edward Arnold, London.

CRANDELL, D., BOOTH, B., KAZUMADINATA, K., SHIMOZURU, D., WALKER, G. & WESTERCAMP, D. (1984) - *Source-book for volcanic-hazards zonation*. UNESCO, France, 97 p.

CRISCI, G.M., GREGORIO, S. DI, PINDARO, O. & RANIERI, G. (1986) - Lava flow simulation by a discrete celular model: first implementation. *Int. Journal of Modelling and Simulation*, 6, p. 137-140.

CRISCI, G.M., GREGORIO, S. DI, & RANIERI, G. (1982) - A celular space model of basaltic lava flow. *In: Proc. Int. Conf. Applied Modelling and Simulation 82*, Paris, France, Vol. 11, p. 65-67.

CRISP, J. & BALOGA, S. (1990) - A model for lava flows with two thermal components. *J. Geophys. Res.*, 95, p.1255-1270.

CORREIA, J., ARAÚJO, M. G. M. & NASCIMENTO, J. (1997) - Impactos sócio-económicos da erupção de 1995 da ilha do Fogo. *In: A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde*. (IICT, Ed.), Lisboa.

COSTA, F. (1997) - Indicadores geomorfológicos de risco vulcânico na Chã das Caldeiras (Ilha do Fogo, Cabo Verde). *In: A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde*. (IICT, Ed.), Lisboa.

DRAGONI, M., BONAFEDE, M. & BOSCHI, E. (1986) - Downslope flow models of a Bingham liquid: implications for lava flows. *J. Volcanol. Geotherm. Res.*, 30, p. 305-325.

DRAGONI, M. (1989). A dynamical model of lava flows cooling by radiation. *Bull. Volcanol.*, 51, p.88-95.

DUNCAN, A., CHESTER, D. & GUEST, J. (1981) - Mount Etna Volcano: Environmental impact and problems of volcanic prediction. *The Geographical Journal*, Vol.147, 2, p. 164-178.

FERREIRA, T., GASPAR, J. L., QUEIROZ, G., COUTINHO, R., MOTA GOMES, A. & RAMOS, M. (1997) - Avaliação do risco associado à emanação de gases vulcânicos durante a erupção da ilha do Fogo (Cabo Verde). *In: A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde*. (IICT, Ed.), Lisboa.

GASPAR, J. L., FERREIRA, T., COUTINHO, R., QUEIROZ, G., BOTELHO, S., FRAGOSO, F., MOTA GOMES, A., RAMOS, M., DELGADO, J. & AZEVEDO, N. (1995a) - *Riscos para a saúde pública associados à erupção de 2 de Abril de 1995 na ilha do Fogo (Cabo Verde)*. Departamento de Geociências da Universidade dos Açores, Maio 1995.

GASPAR, J. L., WALLENSTEIN, N., QUEIROZ, G., FERREIRA, T., COUTINHO, R. & MOTA GOMES, A. (1995b) - Resumo da actividade vulcânica registada na ilha do Fogo (Cabo Verde), nos menses de Abril e Maio de 1995. Universidade do Porto, Faculdade de Ciências, Museu e Laboratório Mineralógico e Geológico, *IV Congresso Nacional de Geologia*, Memória nº4, p.1005-1007.

HULME, G. (1974) - The interpretation of lava flow morphology. *Geophys. J. R. Astr. Soc.*, 39, p. 361-383.

ISHIHARA, K., IGUCHI, M. & KAMO, K. (1989) - Numerical simulation of lava flows on in Japan. *In: Lava flow and domes* (Fink, J.H., Eds.), IAVCEI proceedings in Volcanology, Springer Verlag, New York, p. 174-207.

MACEDONIO, G., PARESCHI, M.T. & SANTACROCE, R. (1990) - A simple model for lava hazard assessment: Mount Etna. *In: Proc. of the International Volcanological Congress, IAVCEI*, Mainz, Germany.

MACEDONIO, G. (1994) - *A 3-dimensional model for lava flows*. CEC Contract EV5V-CT92-0190-Final Report, Comission for the European Community.

- MACHADO F. & ASSUNÇÃO, C.T. (1965) - Carta Geológica de Cabo Verde; notícia explicativa da Ilha do Fogo. *Garcia de Orta*, 13, p. 596-604.
- MIYAMOTO, H. & SASAKI, S. (1997) - Simulating lava flows by an improved cellular automata method. *Computers & Geoscience*, Vol. 23, 3. Pergamon Press, UK.
- ORTIZ, R. (1995) - *Riesgo Volcánico*. Curso de Vulcanología. CSIC, Madrid, 175 p.
- PARK, S. & IVERSEN, J.D. (1984) - Dynamics of lava flow: thickness, growth characteristics of steady two dimensional flows. *Geophys. Res. Lett.*, 11, p. 641-644.
- QUENTAL, L. & SOARES, A. (1997) - Implementação de um modelo de simulação de fluxo de lava num Sistema de Informação Geográfica. Aplicação à ilha do Fogo, Cabo Verde. *In: A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde* (IICT, Ed.), Lisboa.
- RIBEIRO, O. (1960) - A Ilha do Fogo e as suas erupções. *Mem. Série Geográfica I. Minist. Ultramar*, J.I.V., Lisboa.
- S.C.E. (1979) - *Carta da Ilha do Fogo 1:25 000*. Serviços Cartográficos do Exército.
- TOFFOLI MARGOLIS (1987) - *Cellular Automata machines: a New Environmental for Modeling*. MIT Press, Cambridge, MA, 259 p.
- TORRES, P. C., MADEIRA, J., SILVA, L. C., BRUM DA SILVEIRA, A., SERRALHEIRO, A. & MOTA GOMES, A. (1997) - Carta geológica das erupções históricas da ilha do Fogo: revisão e actualização. *In: A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde* (IICT, Ed.), Lisboa.
- TORRES, P. C., MADEIRA, J., SILVA, L. C. & GOMES, M. (1995) - Geologia e Vulcanologia da Erupção de Abril de 1995 da Ilha do Fogo, Arquipélago de Cabo Verde e Formações enquadrantes. *Mem. Univ. Porto*, 4, p. 1019-1022.
- WADGE, G., YOUNG, P.A.V. & MCKENDRICK, I.J. (1994). Mapping lava flow hazard using computer simulation. *J. Geophys. Res.*, 99 (B1) p. 489-504.
- WALLENSTEIN, N., GASPAR, J. L., GUEST, J. & DUNCAN, A. (1997) - Eruptive styles observed during the 1995 volcanic eruption at Fogo island, Cabo Verde. *In: A erupção vulcânica de 1995, na ilha do Fogo, Cabo Verde* (IICT, Ed.), Lisboa.
- WOLFRAM, S. (1994) - *Cellular Automata and Complexity*. Addison-Wesley Publishing Company, 596 p.
- YOUNG, P. & WADGE, G. (1990) - Flowfront: simulation of a lava flow. *Computers & Geosciences*, Vol.16, 8, p. 1171-1191.