IAEA ANSN / ISSC - REGIONAL WORKSHOP ON "Volcanic, Seismic, and Tsunami Hazard Assessment Related to NPP Siting Activities and Requirements"

Jakarta, Indonesia, 13-17 June 2011

"Volcanic hazards"

(Antonio Costa)

INTERNATIONAL SEISMIC SAFETY CENTRE, NSNI/IAEA

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International Atomic Energy Agency

Lecture 11

Outlines

1 – Introduction

2 – Overview of main hazardous phenomena

3 – Characterization and impact

4 – Models for hazards assessment

5 – Conclusion

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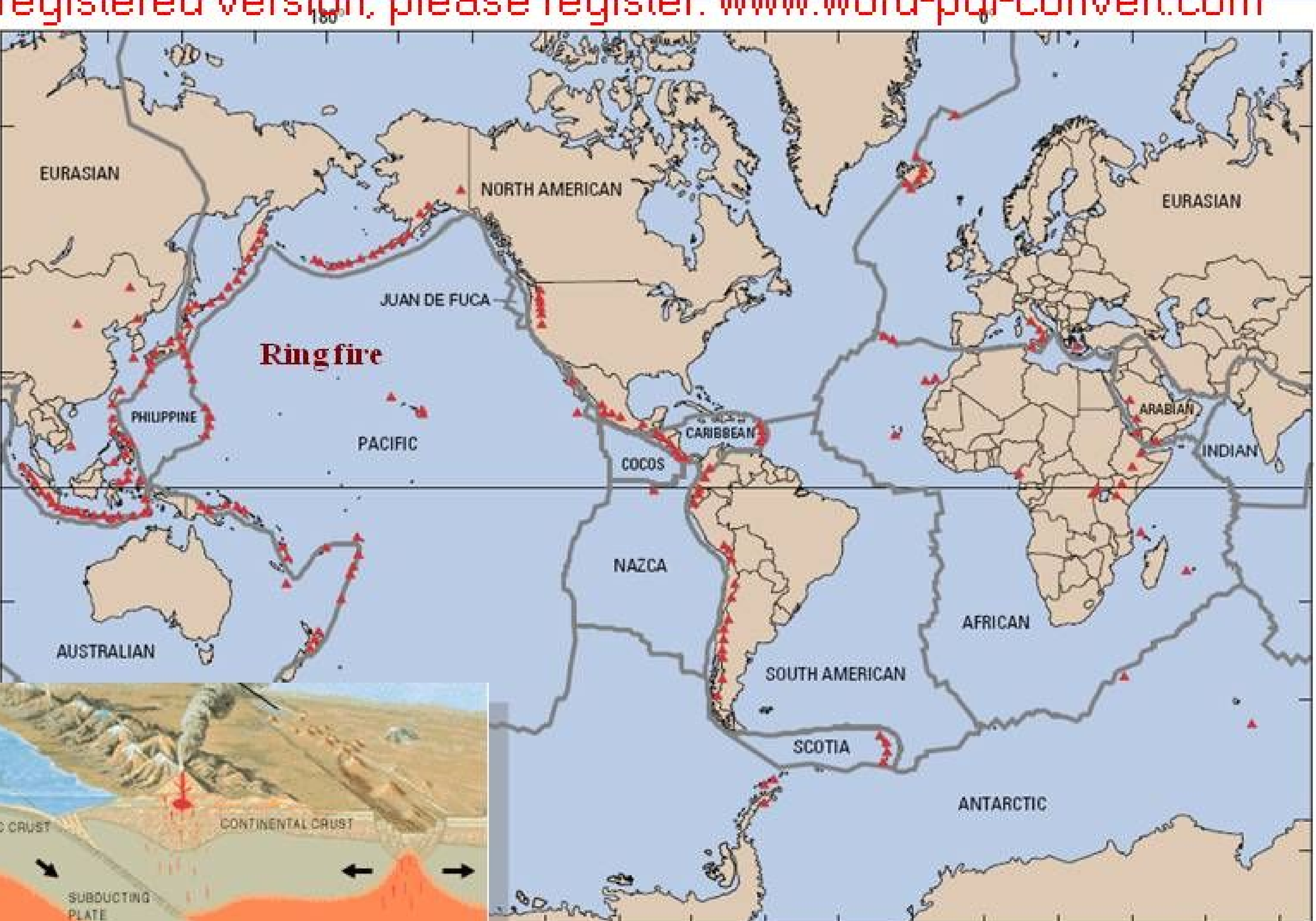
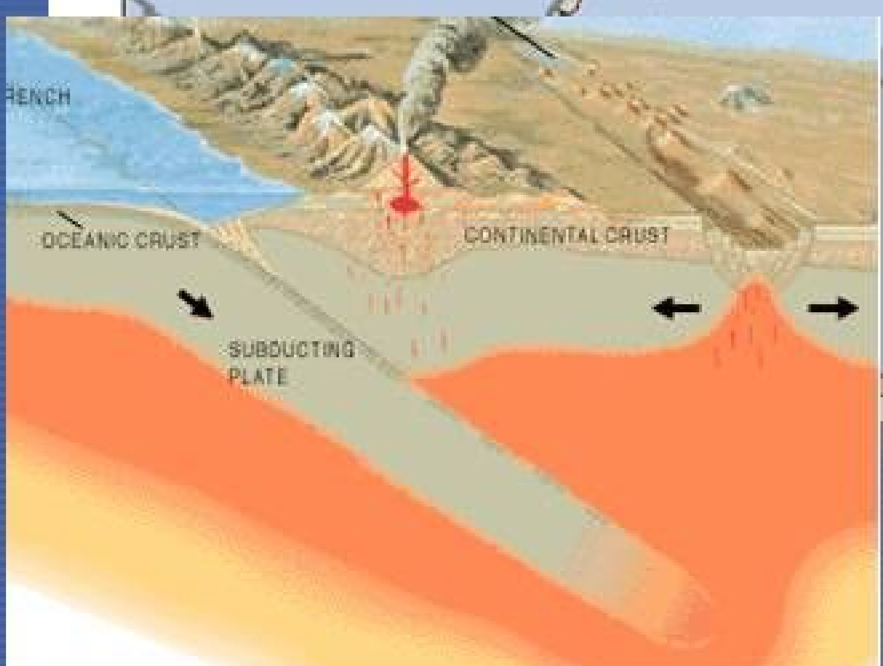
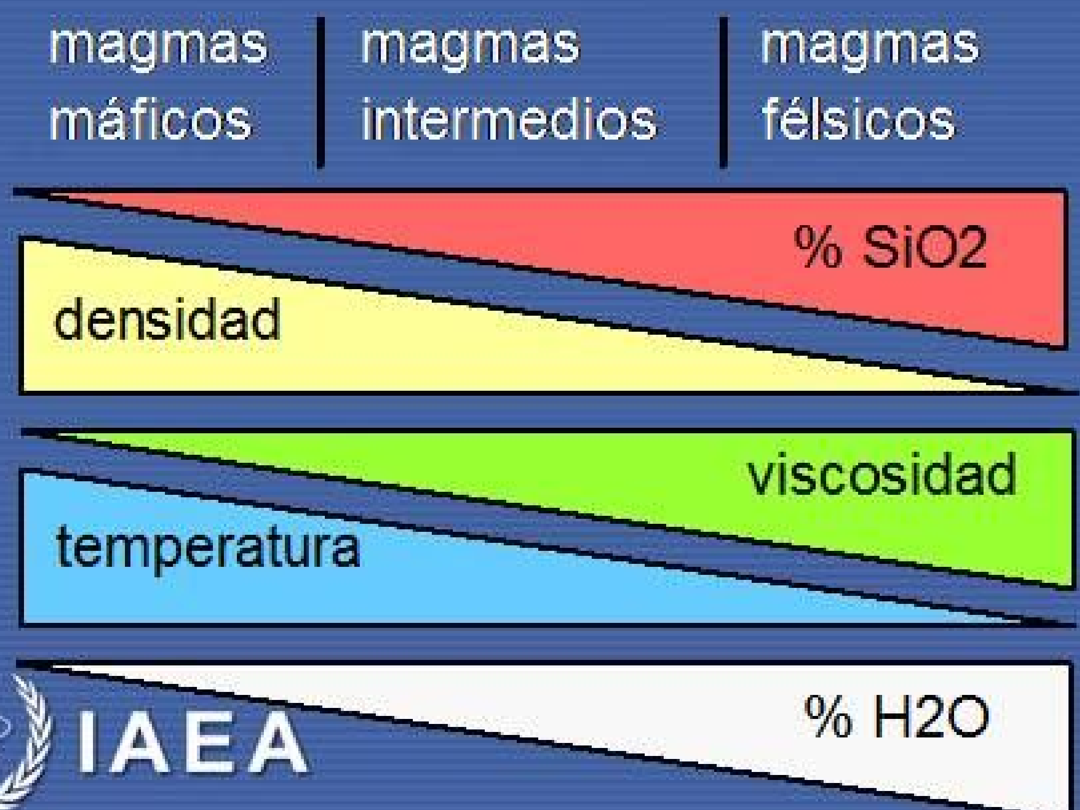
Distribution of active volcanoes (10 ka)





Physical properties of magmas

- Magma: silicate melt + crystals + gas
  - Fraction of silica (SiO_2): 45%-50% (basalts) and 65-70% (rhyolites)
  - Density: between 2200 kg/m^3 and 2800 kg/m^3
  - Viscosity: between 10^2 Pa.s and 10^{12} Pa.s
  - Temperature: between 800ºC and 1300ºC
  - Gas fraction (mainly H_2O): between 0.1% and 7%



§ Magmas evolve and change properties as they cool and degas.

§ Physical properties of magmas control eruptive style.

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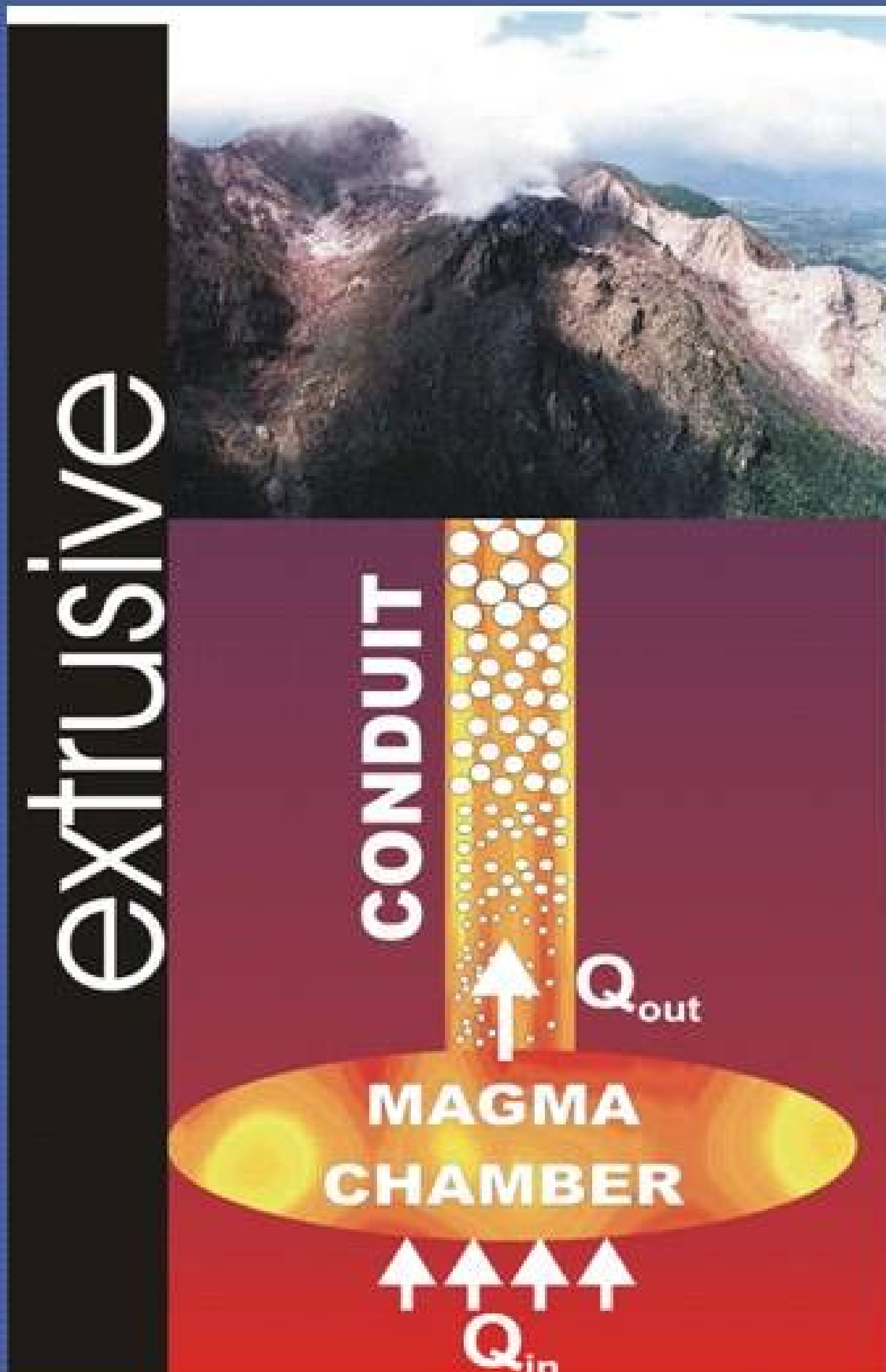
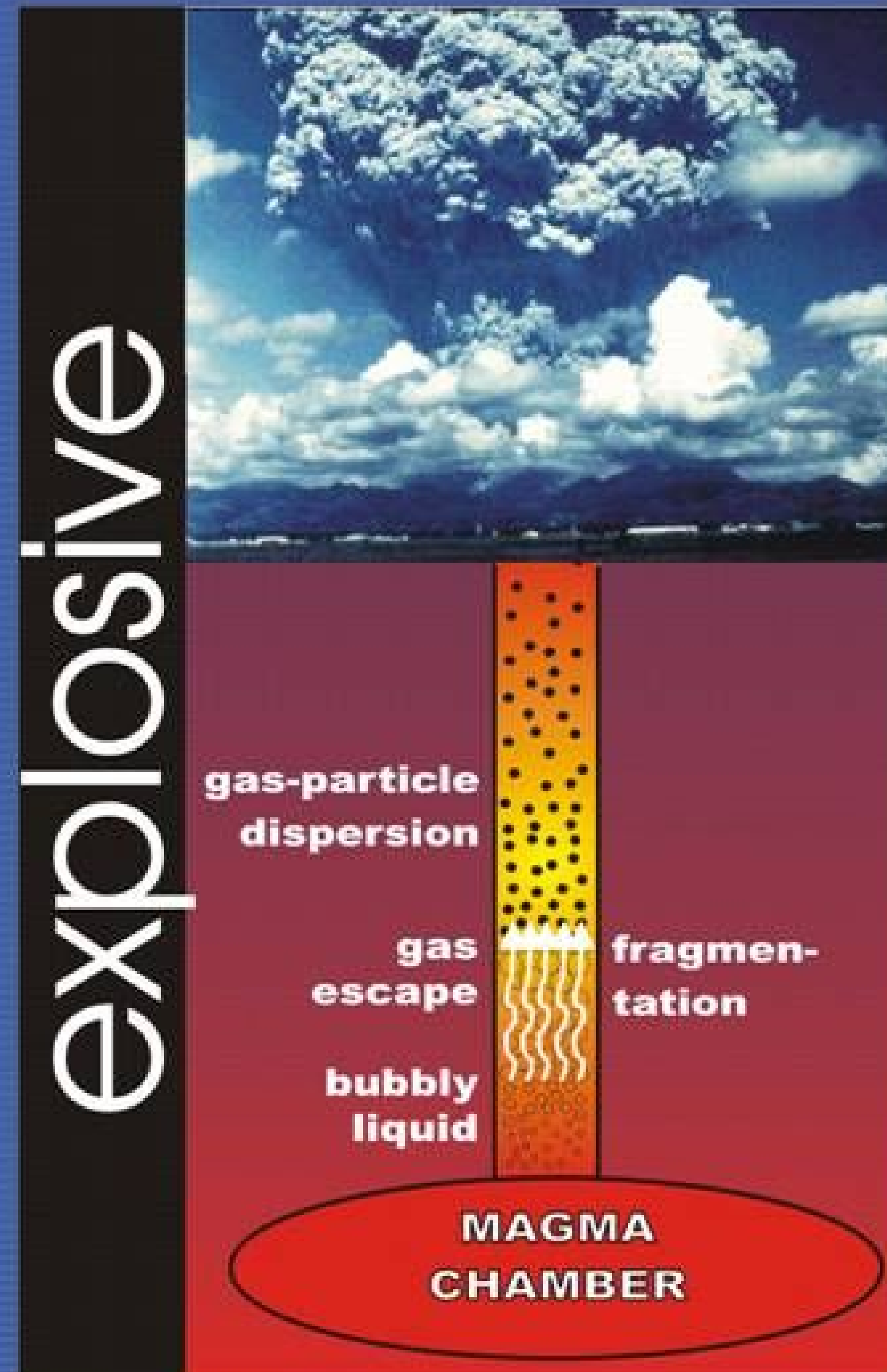
Schematic representation of magmatic systems





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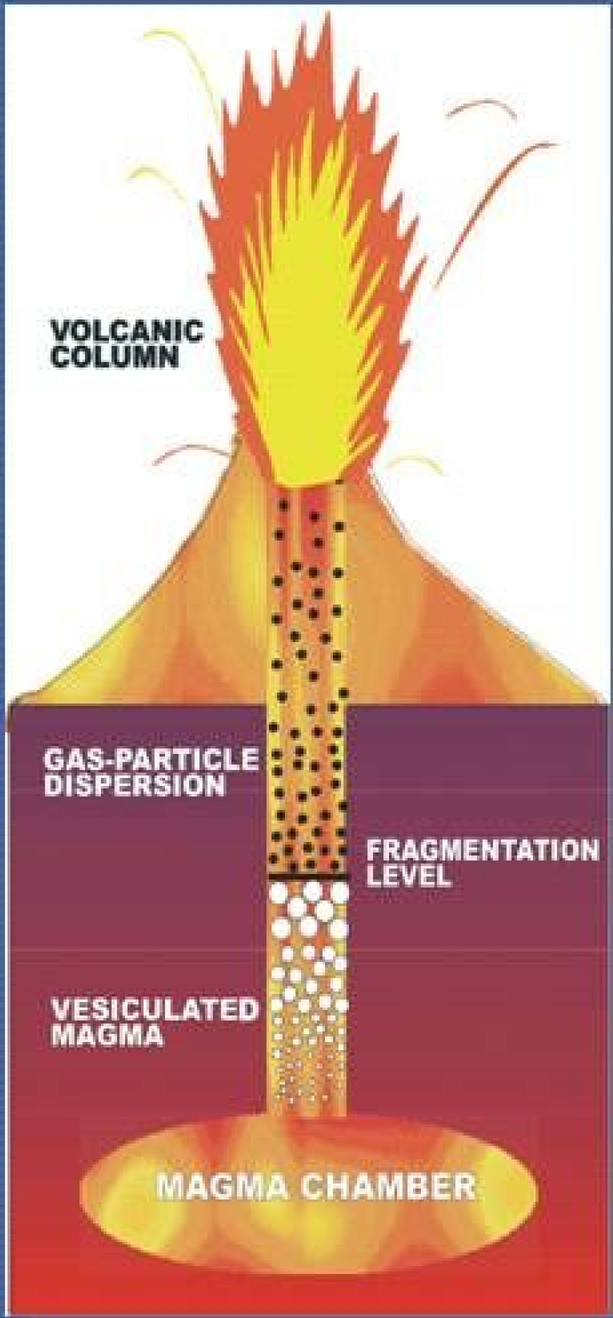
Explosive eruptions

- Magma fragmentation is characteristic of explosive volcanism.
- Typically, viscous magmas (maintain larger fraction of gas).
- Typically, magmas large gas content (or interaction with).
- Generates **pyroclastic material**: bombs, lapilli and ash.
- During the eruption an **eruption column** forms:
  - Mixture of lithics, volcanic gas and pyroclasts.
  - Large columns have three different regions.



Analogy with bottle of Champagne

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Strong explosive eruptions

Umbrella region

Convective region

Jet region

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Shiveluch 2007

Magnitude of an eruption

- It is given by:
  - Volume of tephra (explosive).
  - Volume of lava (effusive).
- "**Volcanic Explosivity Index**" (VEI).

Logarithmic scale for the volume.

- Characteristics defining VEI:
  - Volume
  - Column height
  - Duration of the eruption
- "**Magnitude**". Logarithmic scale of the mass ($M = \log_{10} m - 7$).

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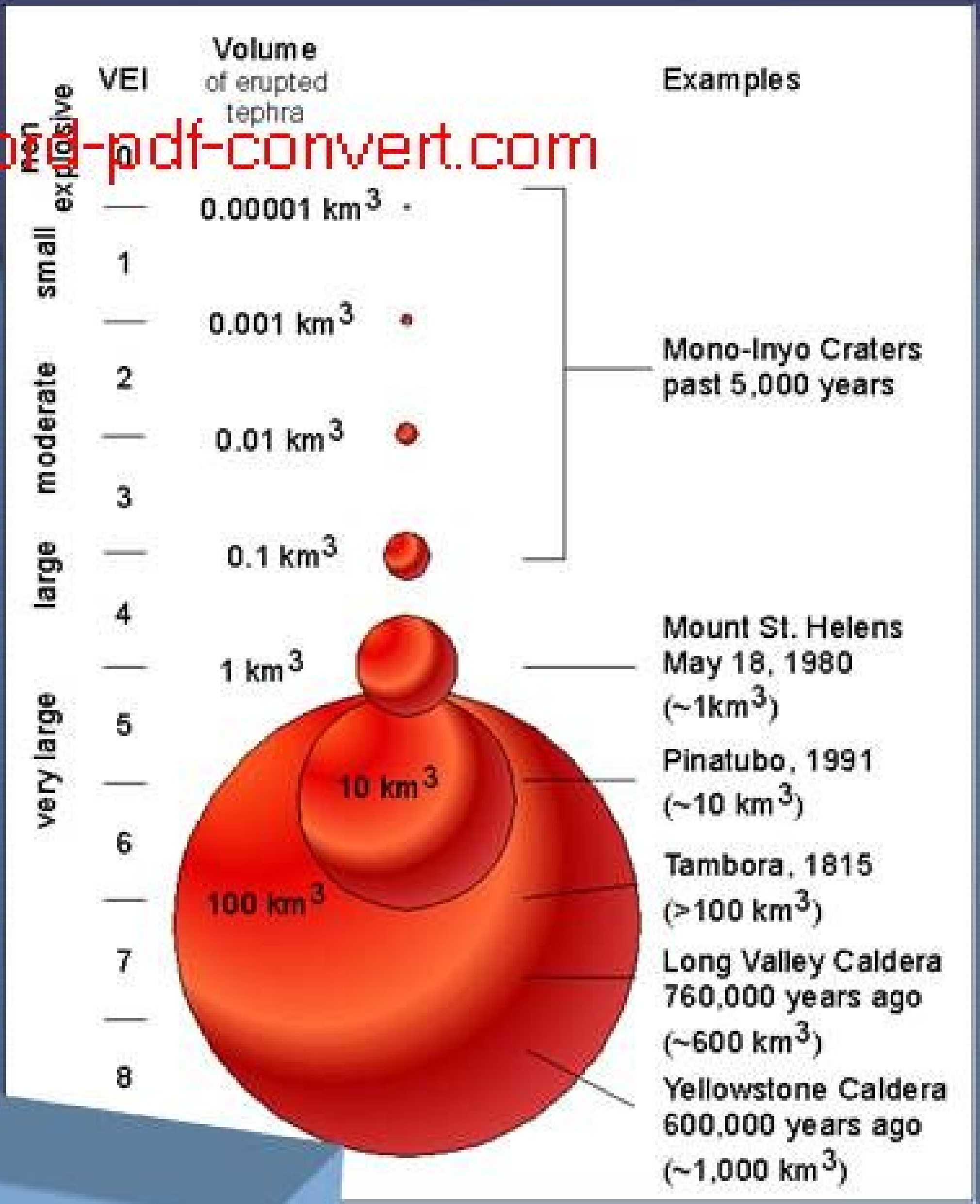
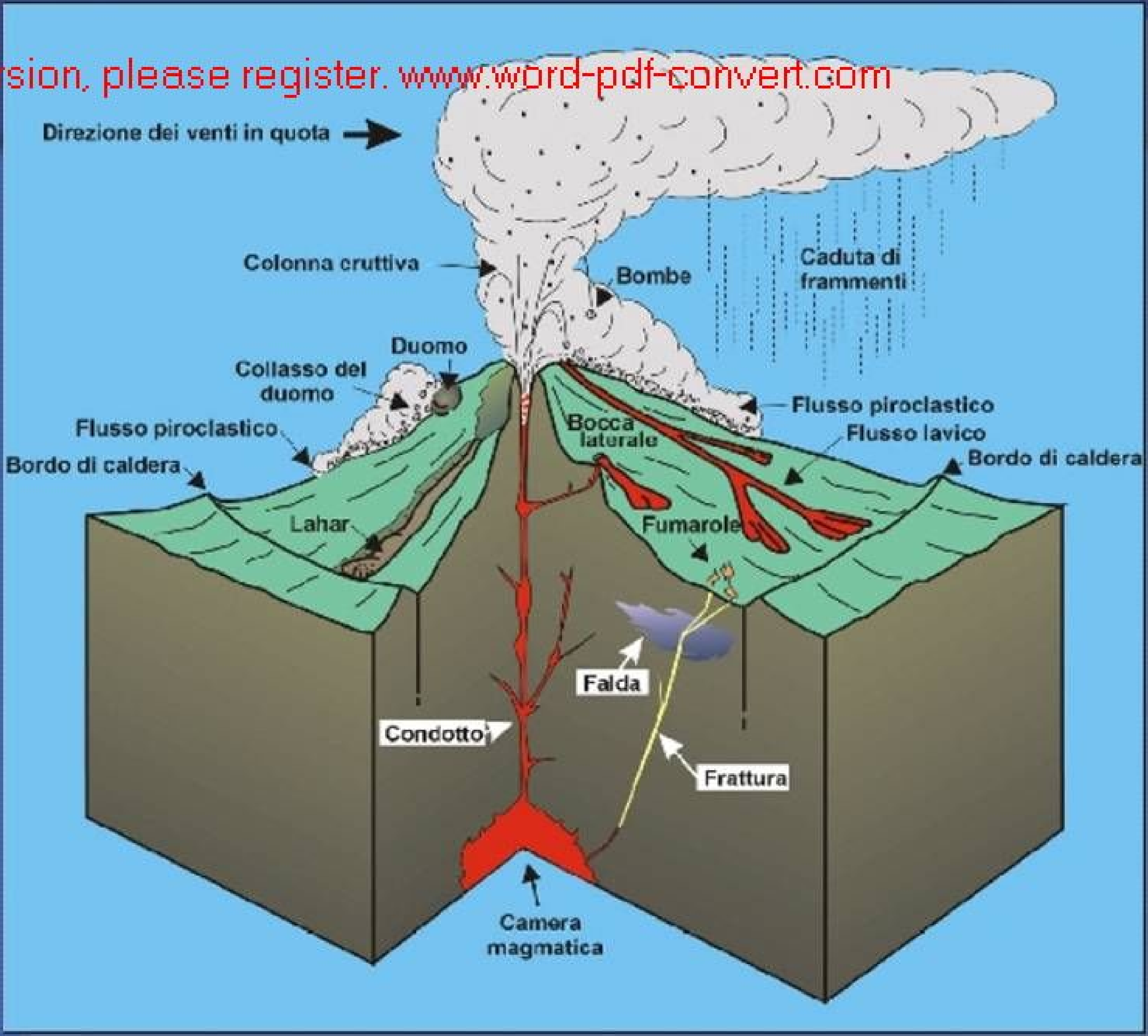


Cerro Galán (2 Ma) ca. 2000 km^3, VEI=8

Tambora 1815, ca. 100 km^3, VEI=6

Hudson 1992, ca. 3 km^3, VEI=4

Lascar 1993, ca. 0.2 km^3, VEI=3


Direzione dei venti in quota
Colonna eruttiva
Bombe
Caduta di frammenti
Duomo
Collasso del duomo
Flusso piroclastico
Bordo di caldera
Flusso piroclastico
Bocca laterale
Flusso lavico
Bordo di caldera
Lahar
Fumarole
Falda
Condotto
Frattura
Camera magmatica

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Phenomena associated with explosive volcanism

Phenomenon/distance	Very proximal (~1 km)	Proximal (~ 10 km)	Medial (~ 100 km)	Distal (~1000 km)
Ballistic impact				
Lateral blast				
Pyroclastic flows				
Lahars*				
Ash fallout				
Aerosols (AQ)*				

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* Not necessarily associated with an eruption

1) Ballistic impact

- Very proximal phenomenon with a low risk

Anak Krakatau 2007

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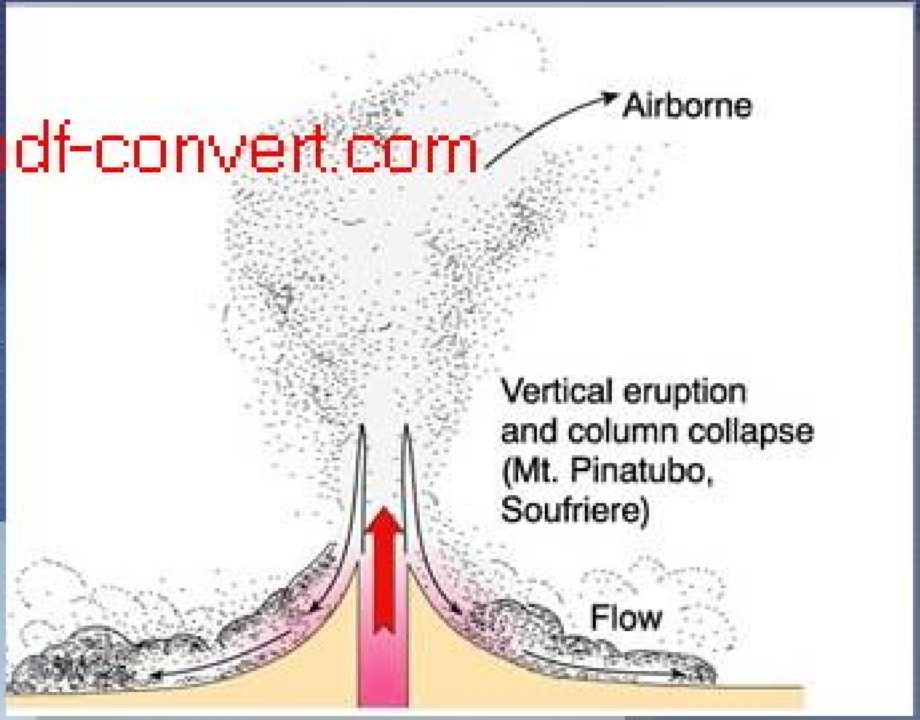
2) Lateral blast

- § Typically due to landslide -
  results in sudden decompression of the magma chamber.

3) Pyroclastic flow

§ Generated from collapse of an eruption column.

§ Dense flow of gas and particles at high temperature often travel at >100 km/h.



4) Lava dome eruption

§ Accumulation of very viscous, crystallized magma typically within the crater. Typically very unstable.

5) Pyroclastic flow (from dome collapse)

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6) Ash fallout (impact and effects)

Damage to human settlements

Pinatubo (Philippines 1991)

Roof collapse from ash loading

Galungung (Indonesia 1981)

Road (and air) traffic disruption

Mt Oyama (Japan 2000)

Respiratory disease

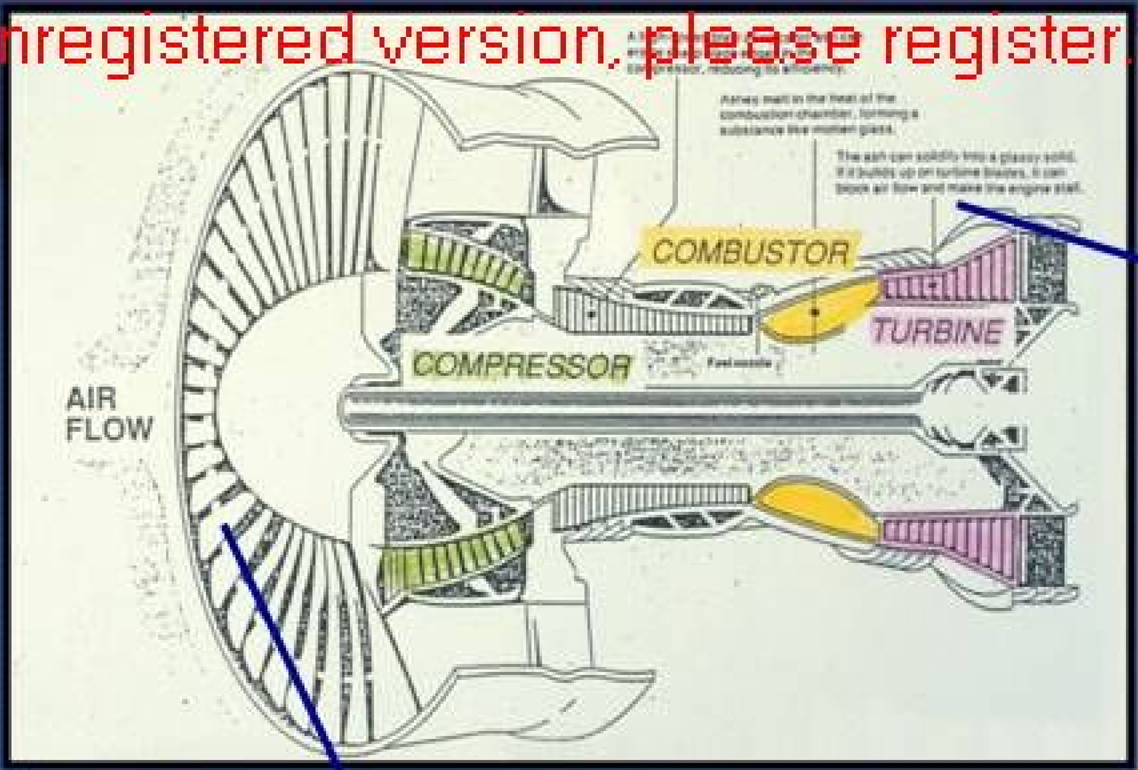
Soufriere Hills (Montserrat 1997)

Damage to cultivated land and livestock

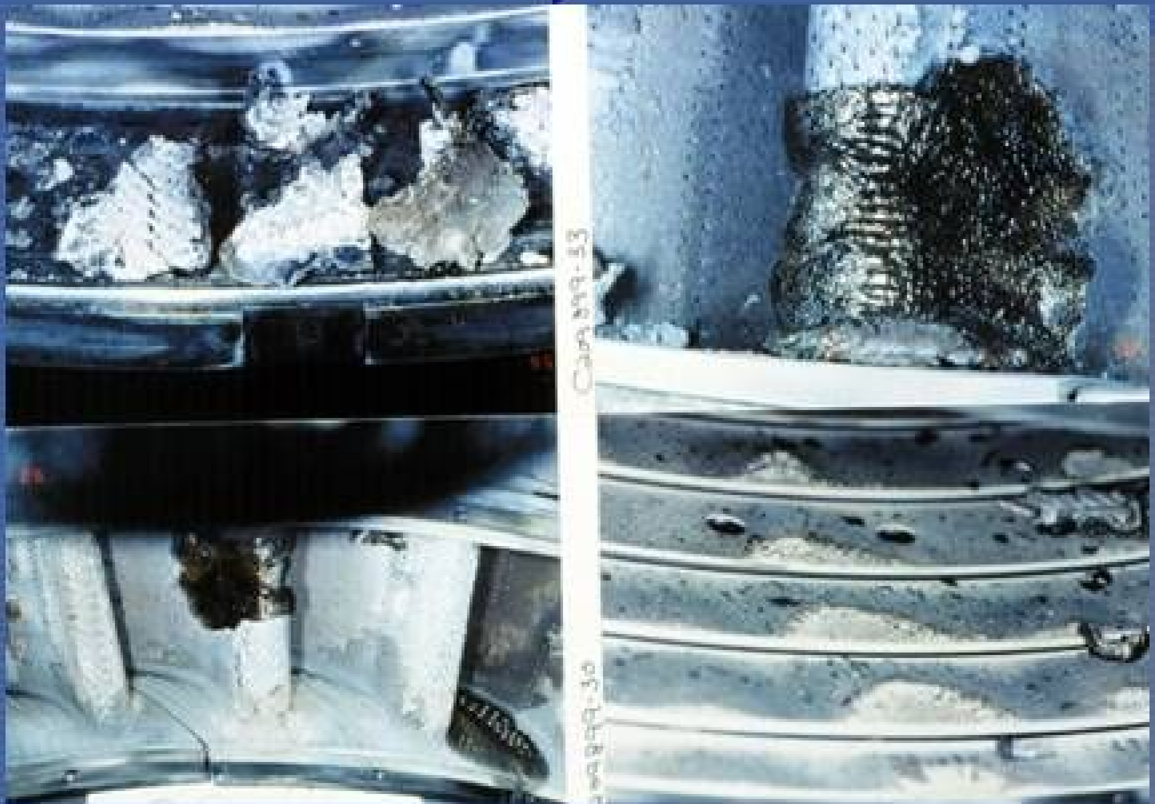
Ruapehu (New Zealand 1996)

Urbinas (Peru 2006)

6b) Threat to aviation (ash)



(courtesy of T. Casadevall)



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7) Lahars

§ Gravitational flow of pyroclastic material and water.

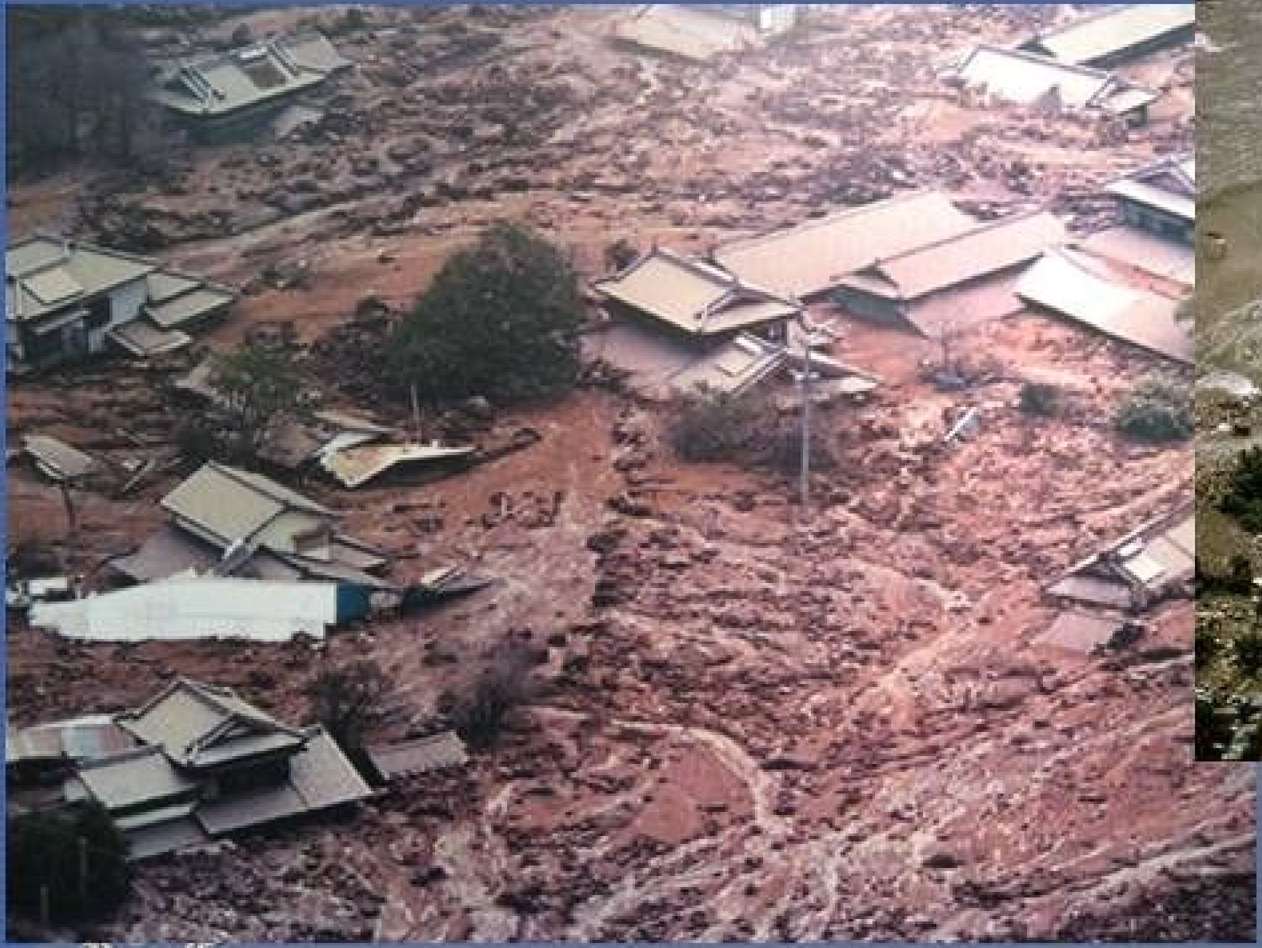
§ Originated from remobilization of tephra deposits:

-Melting of snow and/or glacier (e.g. Nevado del Ruiz 1985; 25000 people killed).

-Collapse of dam/lake.

-Tropical rain (e.g. Pinatubo 1991).

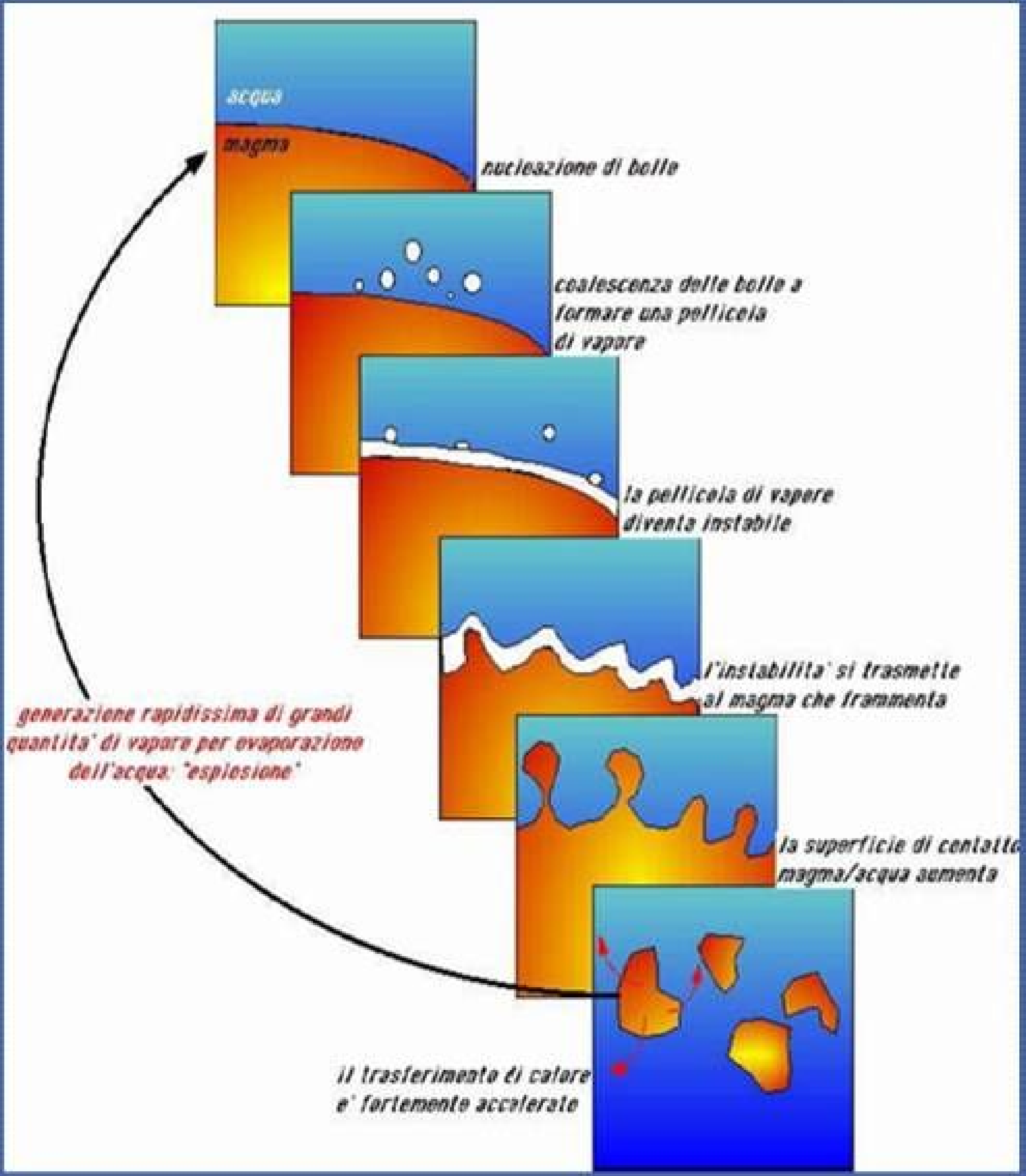
Armero 1985



Uzen 1991

Magma-water interaction

1. Magma-water contact
2. Overheating of water and bubble nucleation
3. Coalescence among adjacent bubbles
4. Formation of a vapour film
5. Film instability
6. Magma fragmentation



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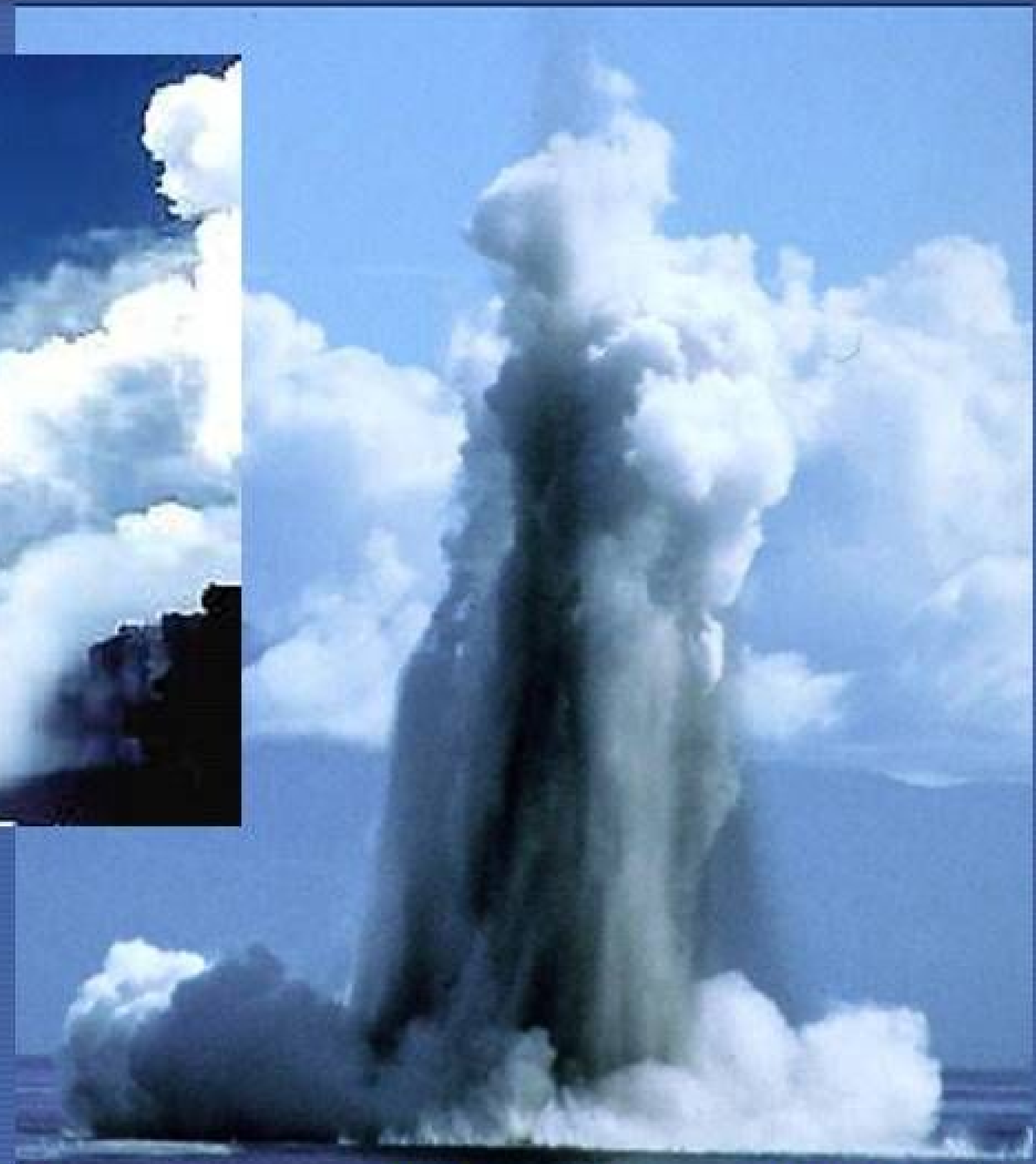
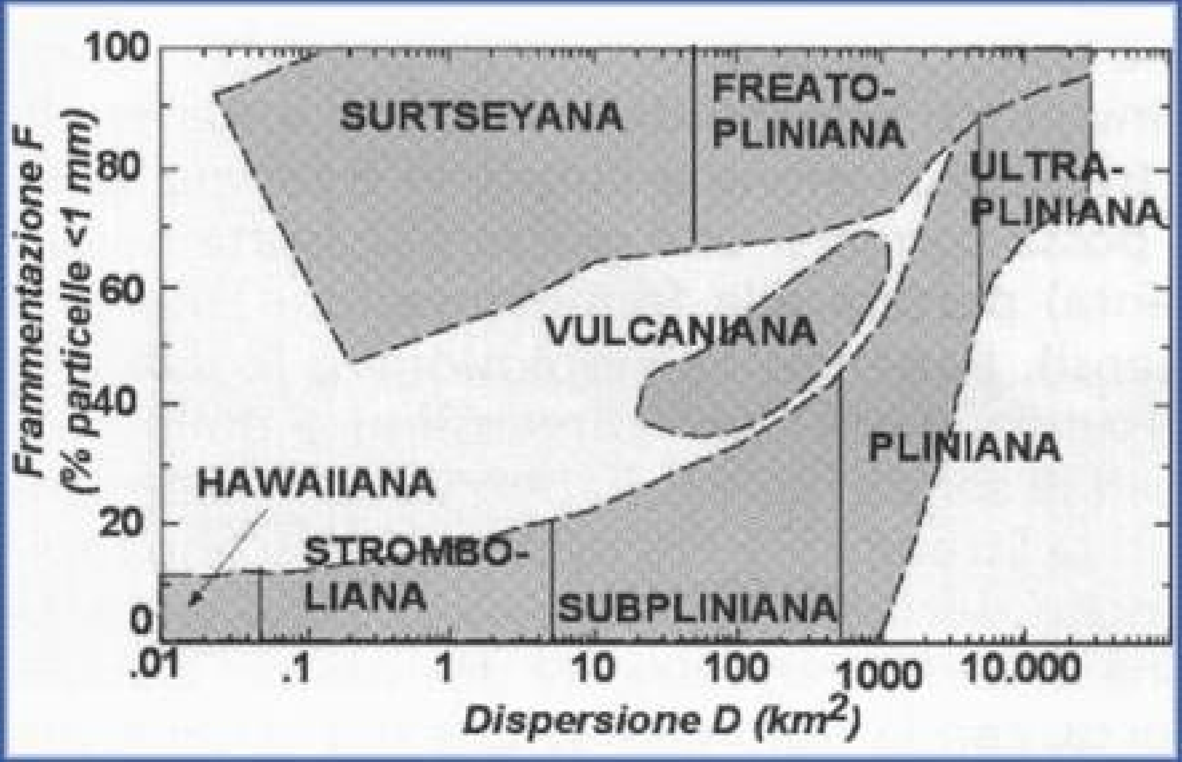
Magma-water interaction

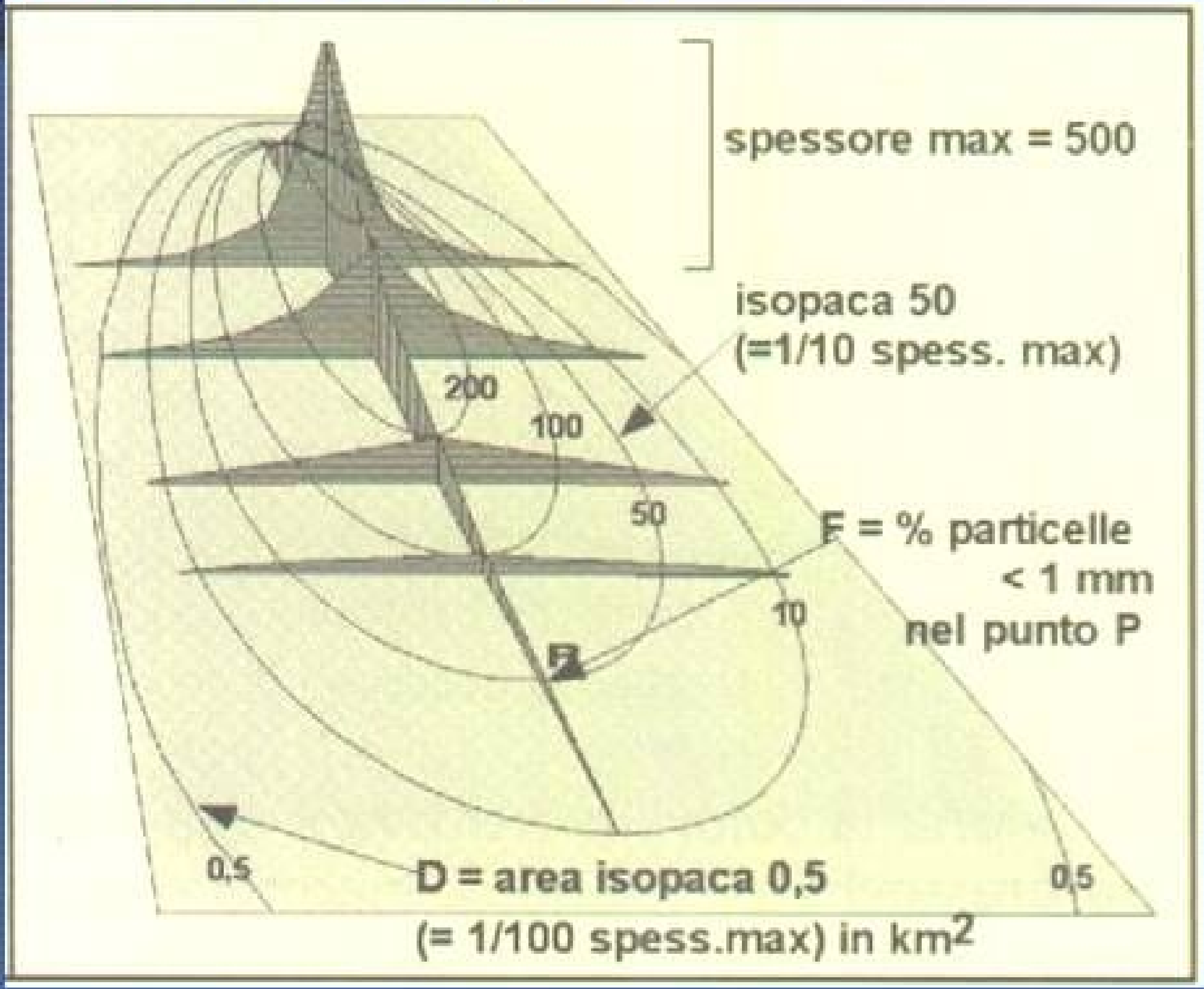
Littoral explosion, Hawaii 1988

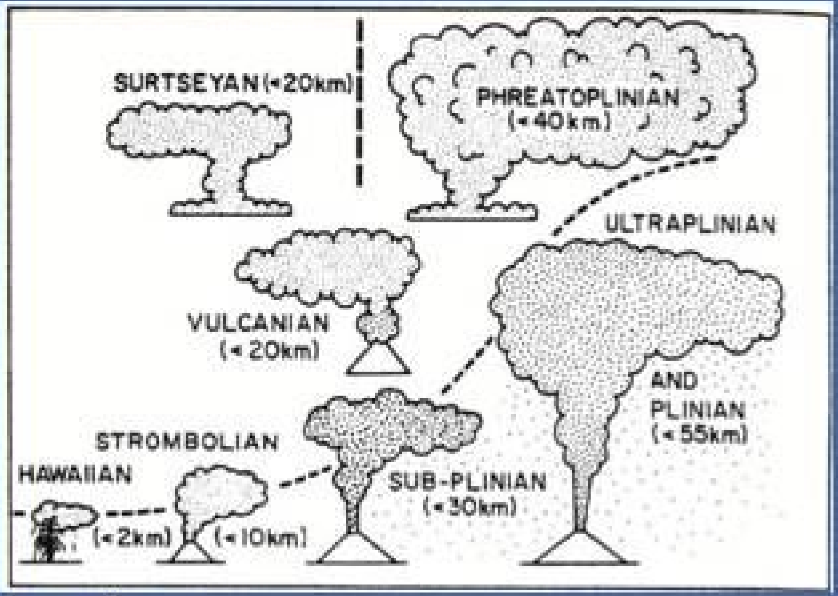


Surtseyan explosion, Kavachi 2000

Classification of explosive eruptions based on dispersion and fragmentation of tephra







Index D: area enclosed by the isopach curve corresponding to 1/100 maximum thickness

Index F: % <1mm at the intersection of the isopach curve corresponding to 1/10 of maximum thickness with the main axis of deposit dispersion

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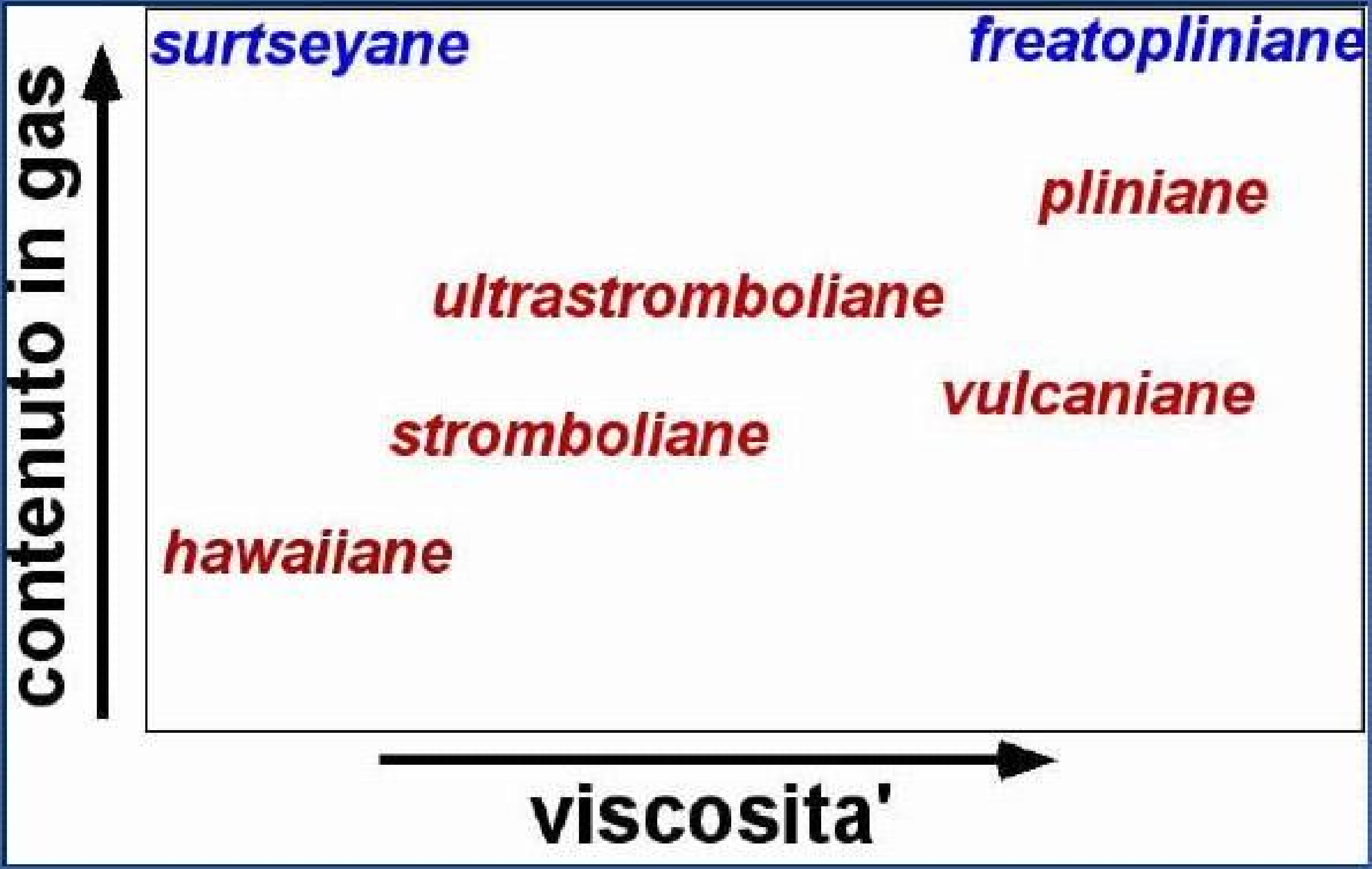
Characteristics of different eruption styles

Attivita' esplosiva	*hawaiiana*	*pliniana*
Viscosita' magma	bassa	alta
Contenuto in gas	modesto	elevato
Tasso eruttivo (intensita')	basso e poco variabile	alto e variabile nel tempo
Livello di frammentazione	superficiale	profondo
Massa totale emessa (magnitudo)	generalmente modesta	spesso enormi



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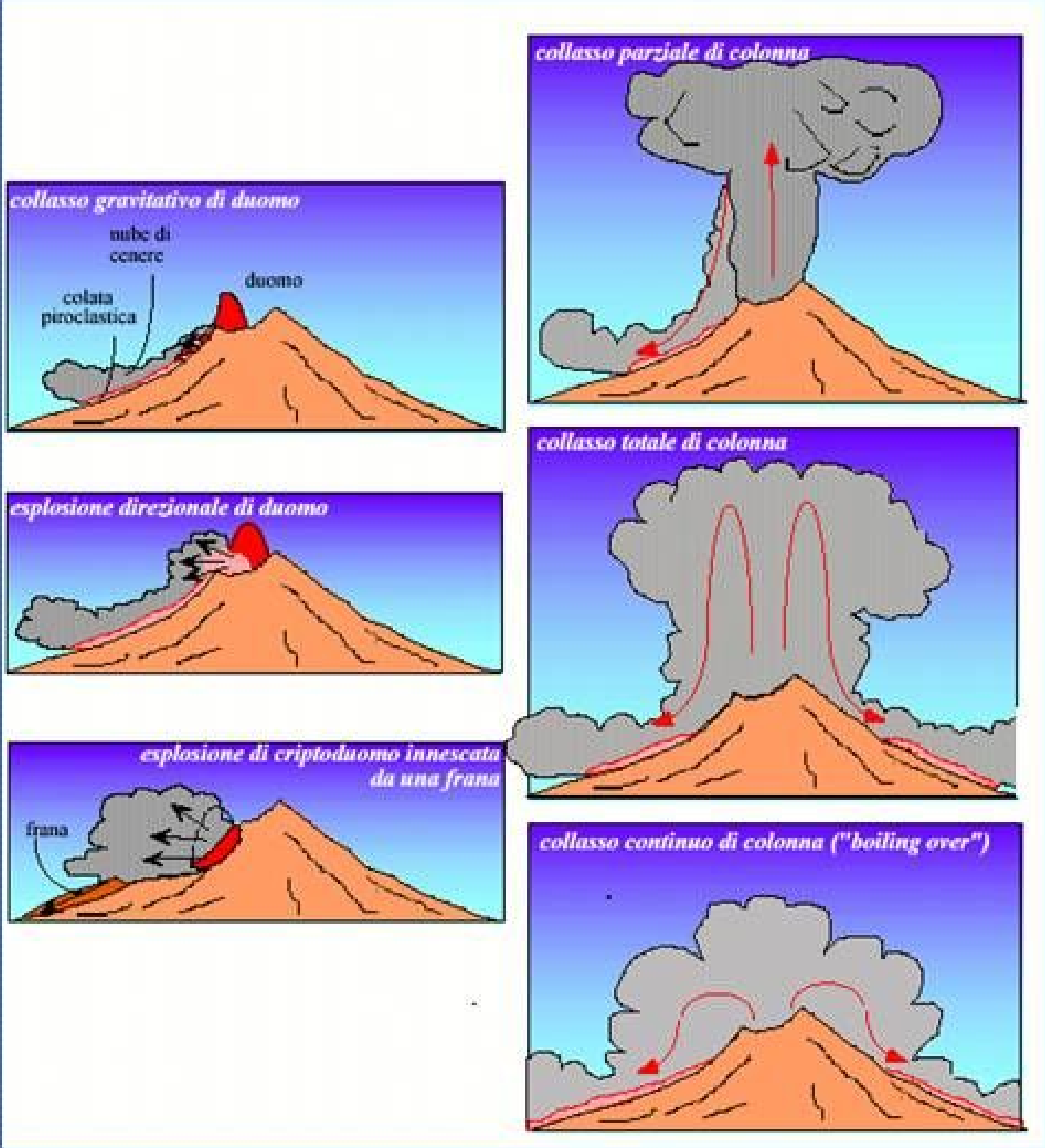
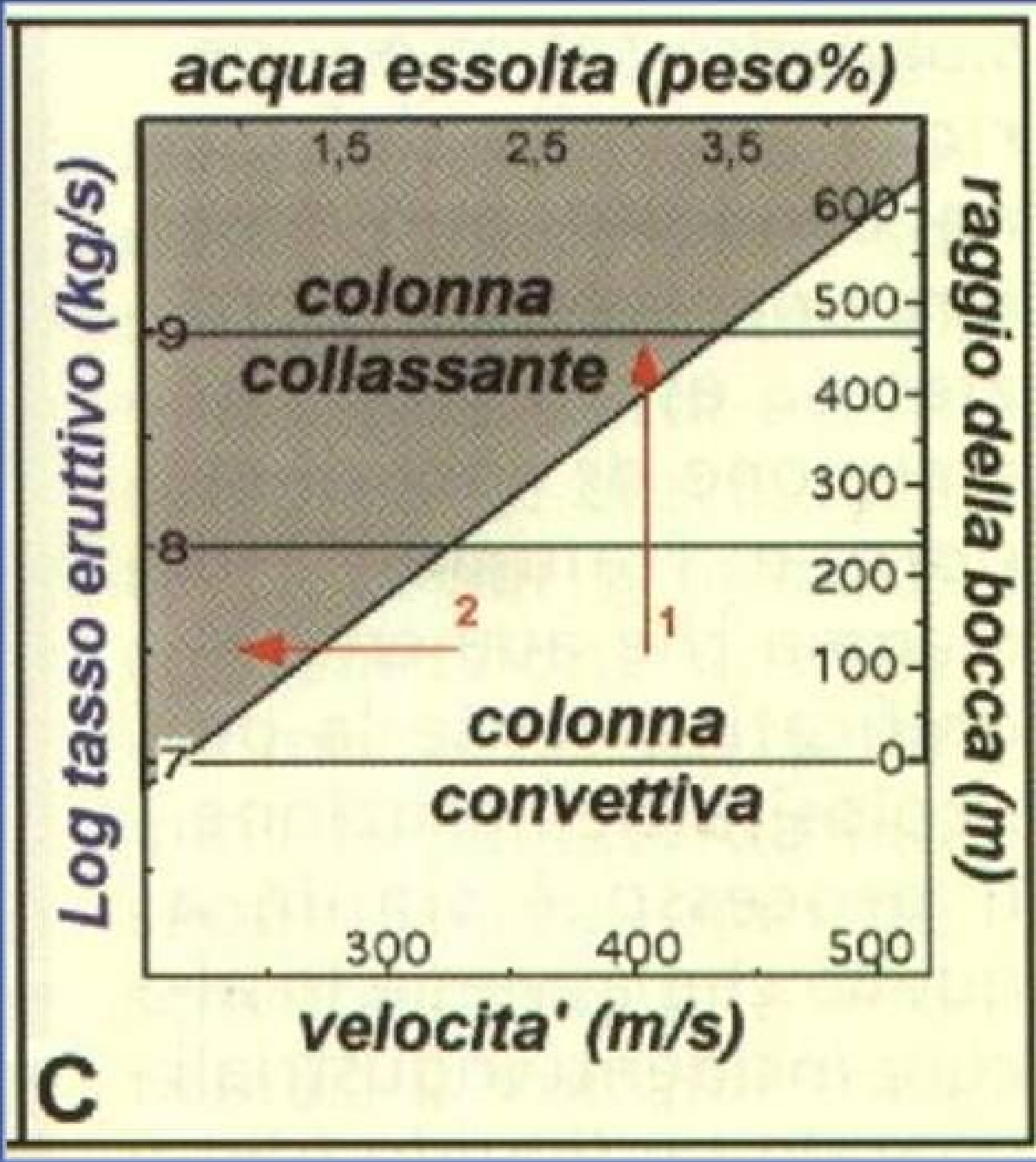
Pyroclastic Density Current (formation mechanisms)





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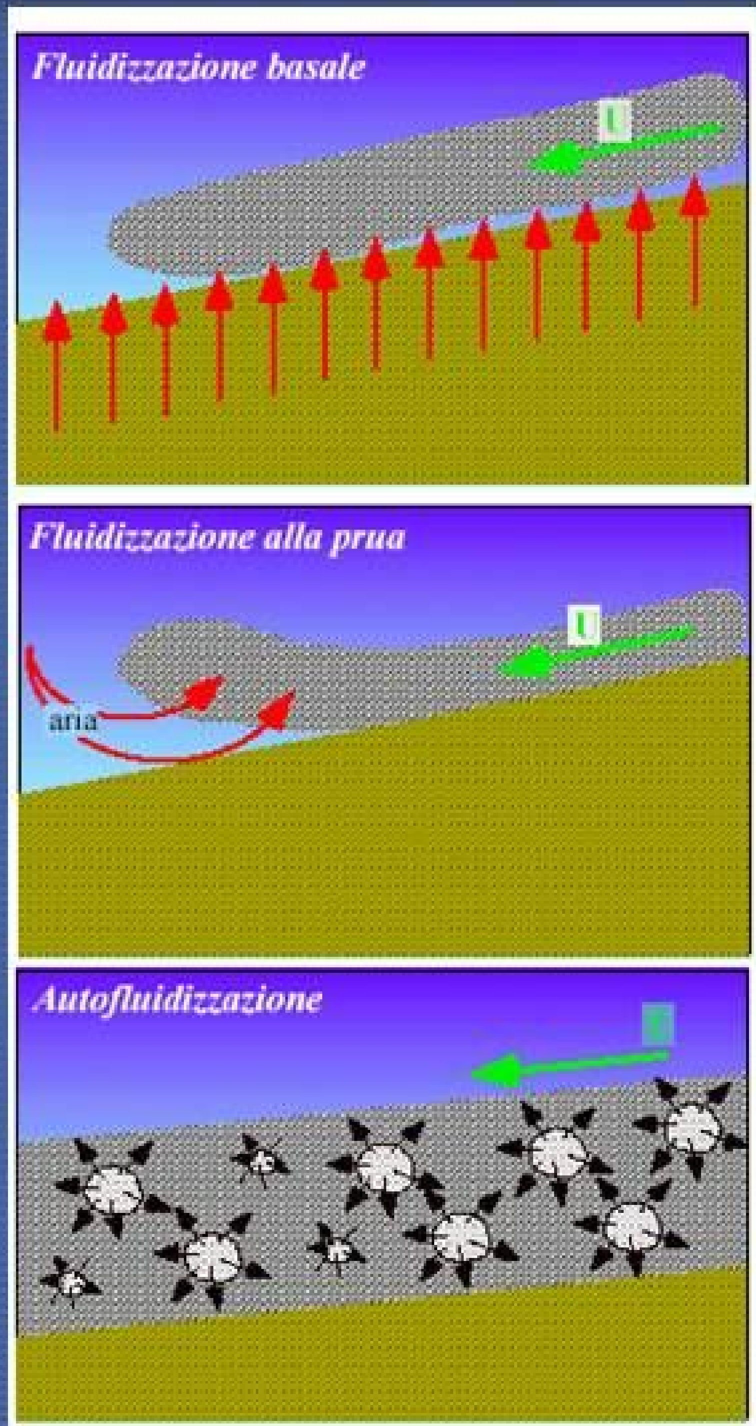
Pyroclastic flows: fluidization



Basal fluidization: Gas is released along the surface where the hot pyroclastic material flows.

Front fluidization: air is ingested from the front of the flow. Air ingestion produces strong fluidization in flow front, and heating of the air causes some of the material to be hurled forward as a low-density, turbulent surge.

Self-fluidization: gas is directly released from single particles of flowing material.

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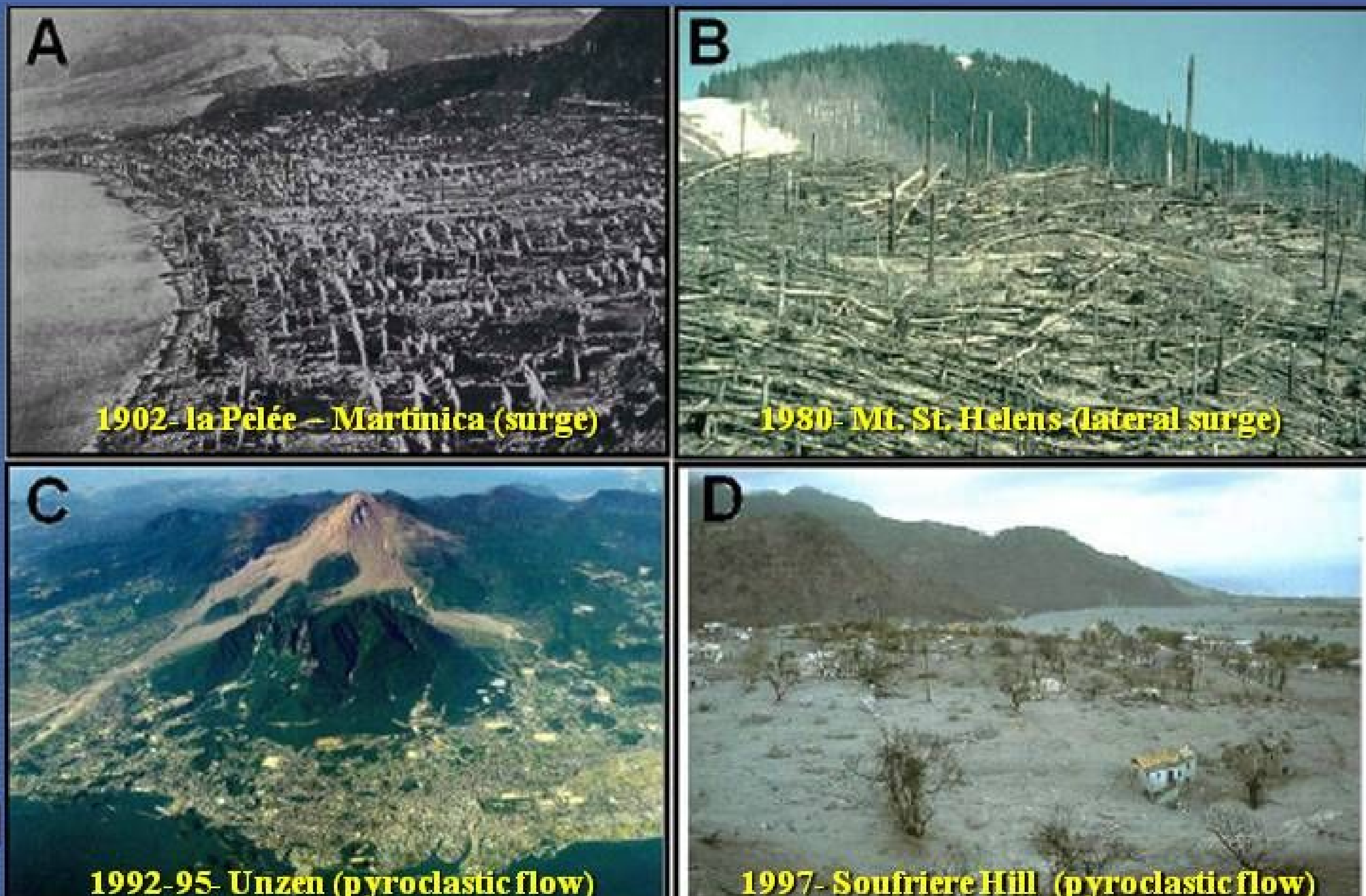
Pyroclastic Density Current (effects)

PDC have devastating effects. They are typically characterized by high velocity (>80 km/h) and high temperature (>200° up to 700°).



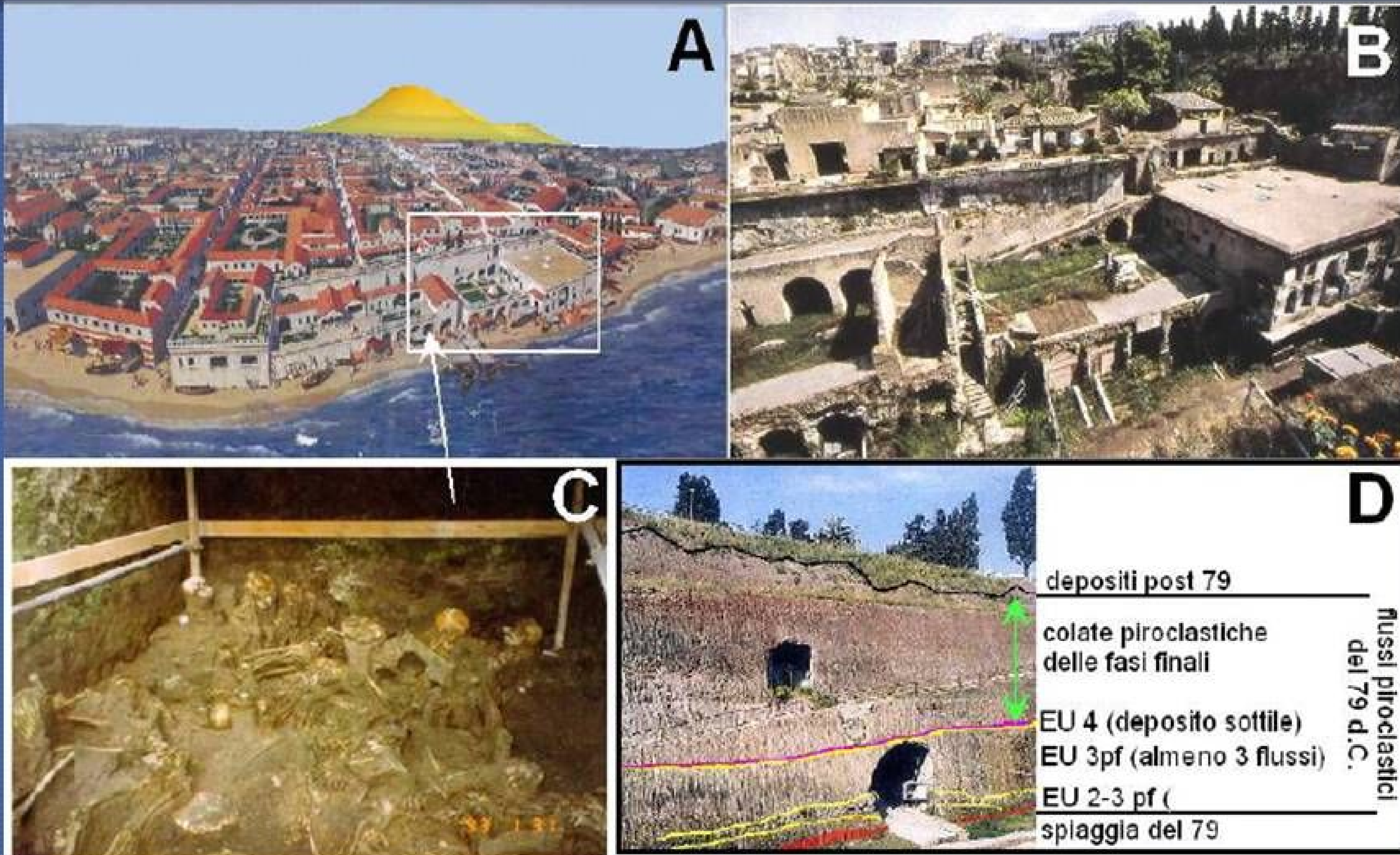
A: 1902- la Pelée – Martinica (surge)

B: 1980- Mt. St. Helens (lateral surge)

C: 1992-95- Unzen (pyroclastic flow)

D: 1997- Soufriere Hill (pyroclastic flow)

Vesuvius 79 AD – destruction of Pompei & Herculaneam



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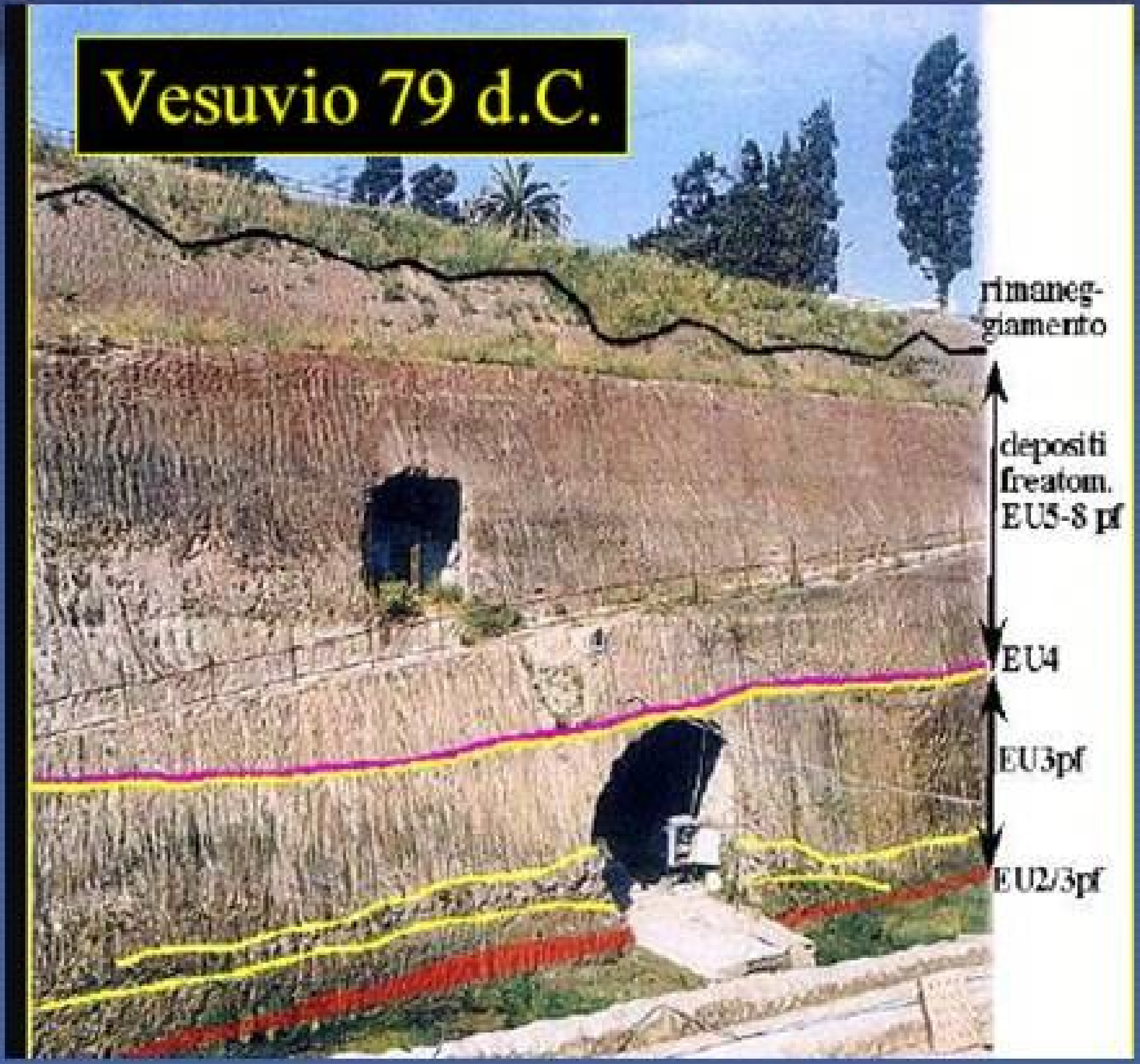
Vesuvio 79 d.C.
rimaneg-
giamento
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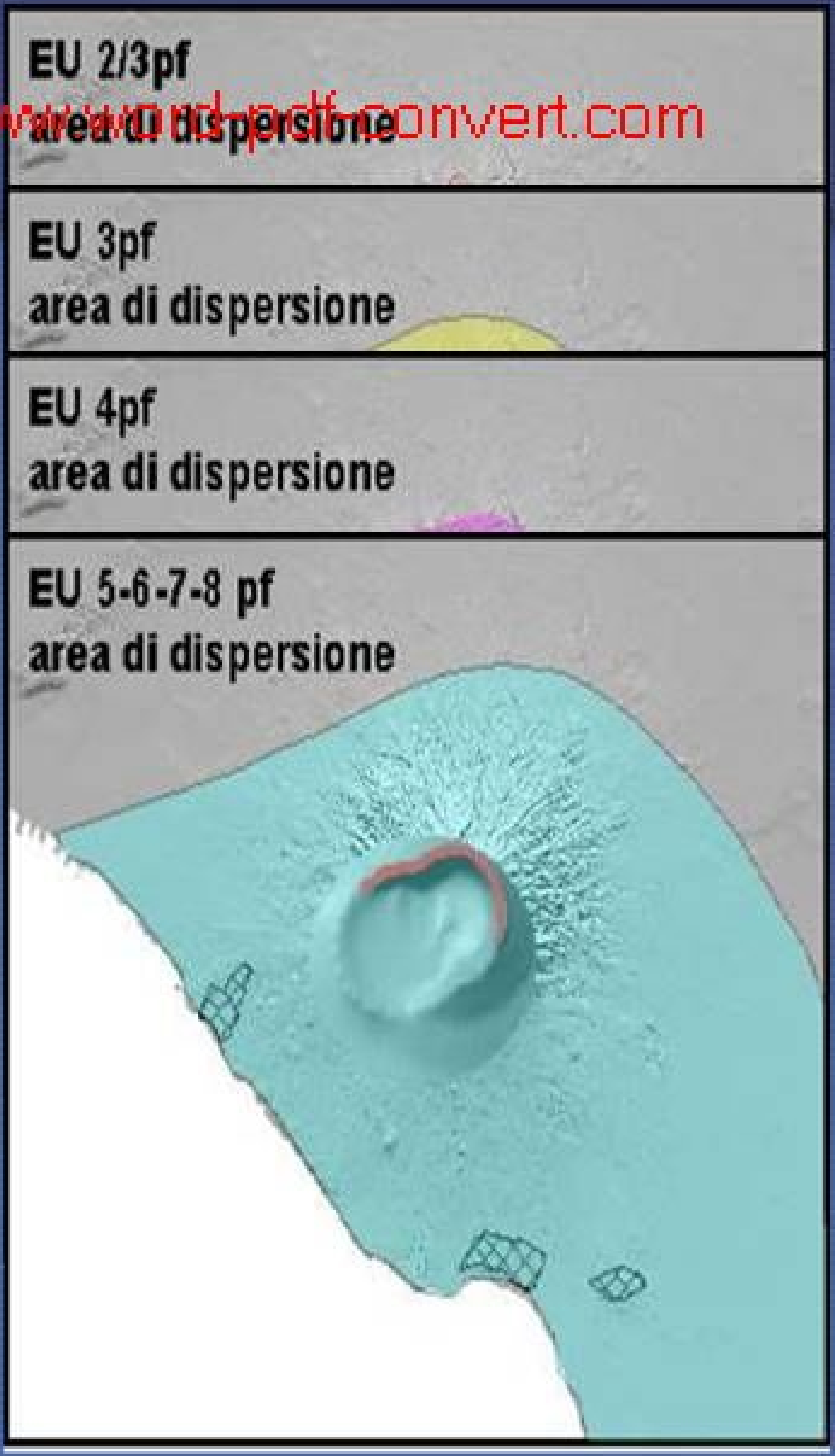
EU5-8 pf
EU4
EU3pf
EU2/3pf


EU 2/3pf
area di dispersione
EU 3pf
area di dispersione
EU 4pf
area di dispersione
EU 5-6-7-8 pf
area di dispersione

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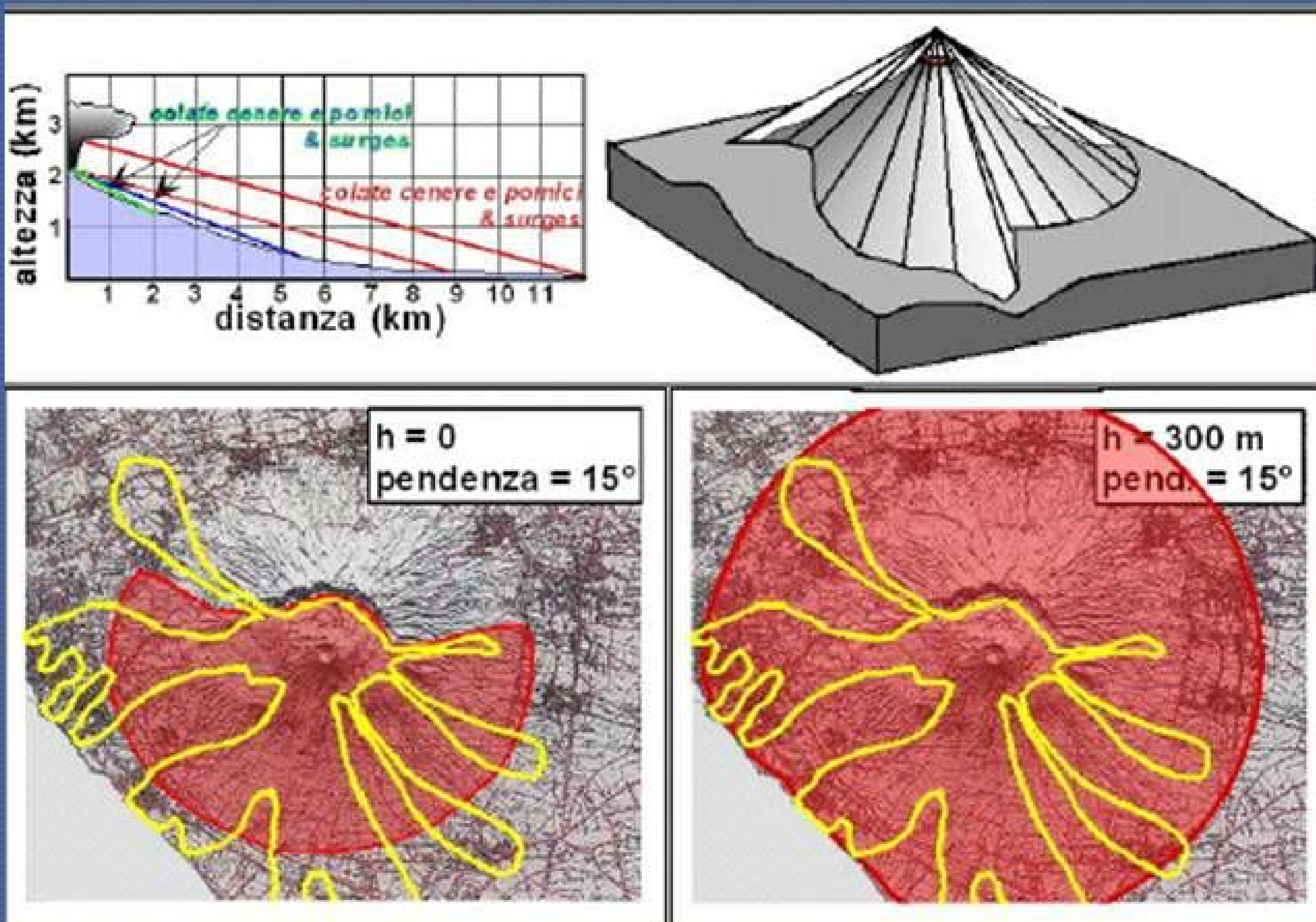
Energy line method (Energy cone)



- The principle is that the height of the starting point of the flow (H) ratios to the length of the runout (L) as a type of friction parameter termed the Heim coefficient (μ).
- The inclination of the energy cone is an angle defined by arctan(H/L).
- The vertical distance (h) between ground surface and energy cone provides a means to estimate of the flow velocity.
- Flow stops where energy line intersects topography.

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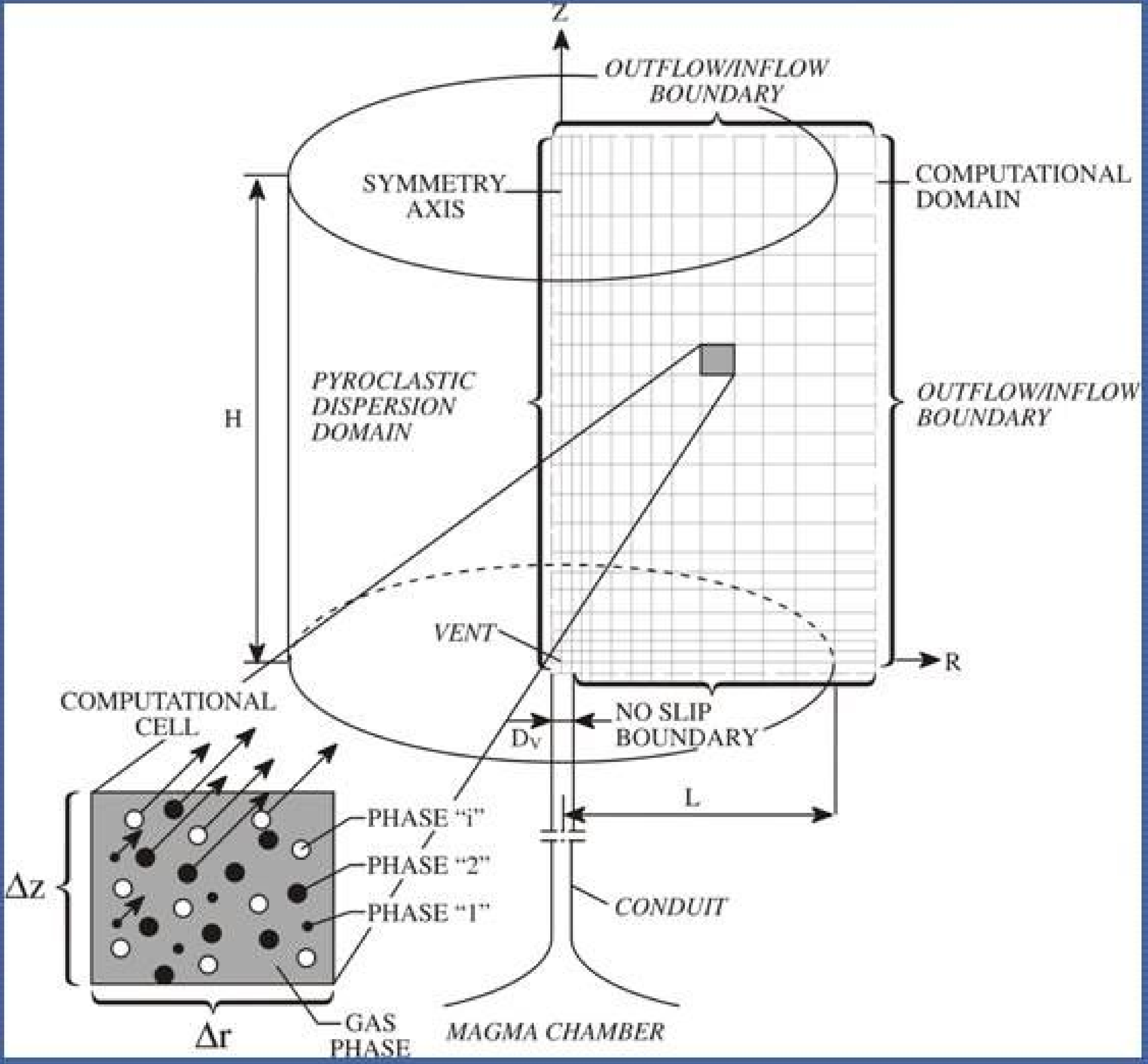
Multiphase 2D-3D models (e.g. Neri et al. 2003)

- Based on transport equations for a multiphase and multicomponent fluid (gas-particle regime)
- Transient
- Bi- (and Tri-) dimensional
- Non-isotermal
- Large Eddy Simulation (LES)
- Constitutive equations based the kinetic theory semiempirical models
- FD or FV methods



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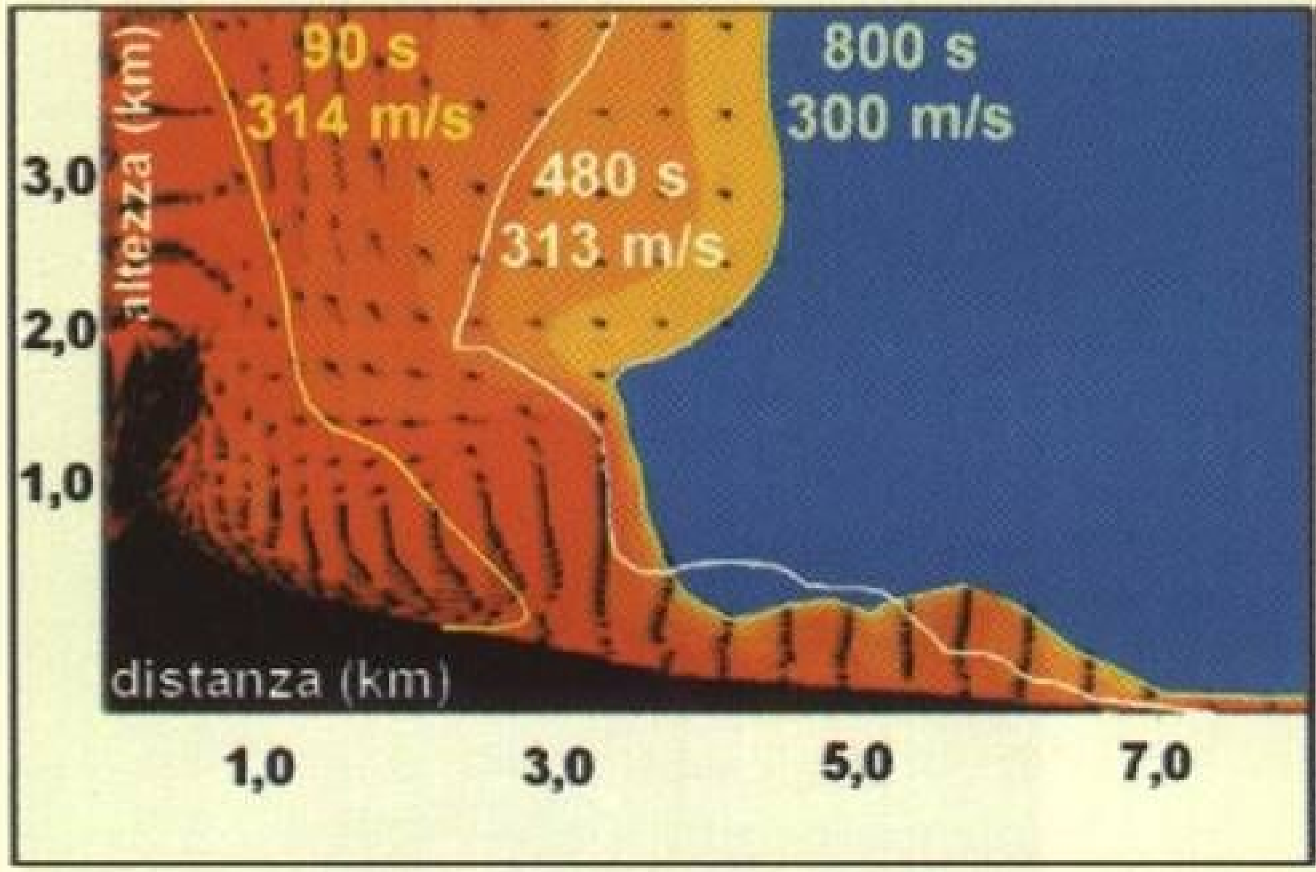
Pyroclastic flows: 2D and 3D numerical simulations



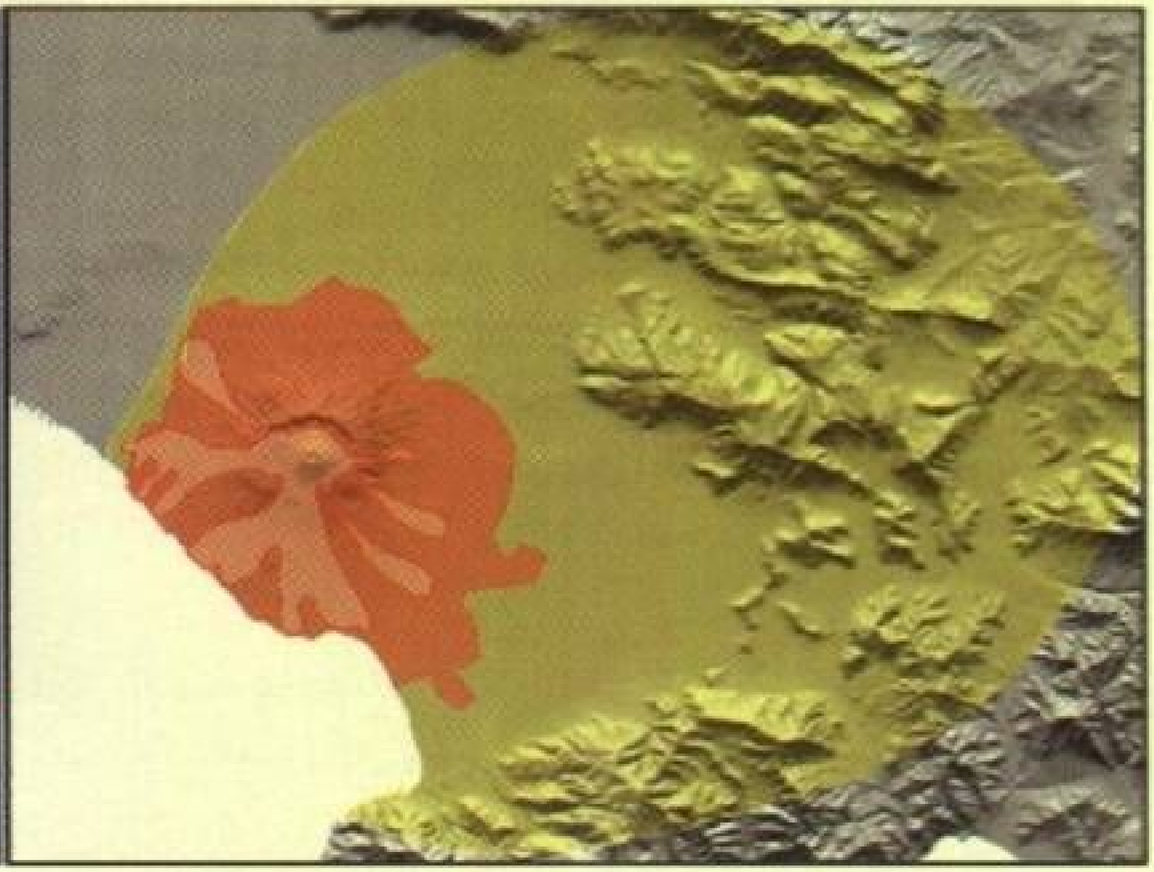


Fig. 3.32 - *A sinistra:* simulazione dello scorrimento di flussi piroclastici generati da collasso di colonna al Vesuvio; è mostrata l'immagine finale della simulazione dopo 800 secondi (sono anche indicati i profili della nube e le velocità di scorrimento dopo 90 e 480 secondi); i colori indicano la concentrazione in volume delle particelle, decrescente dal rosso al giallo (da Todesco et al., 2002). *A destra:* mappa di pericolosità del Vesuvio relativa allo scorrimento di colate piroclastiche (*rosso*, con indicate le aree coperte dai flussi del 1631) e alla ricaduta di piroclastiti con carico superiore a 300 kg/m^2 (*giallo*) (modificato da Santacroce, 1996).

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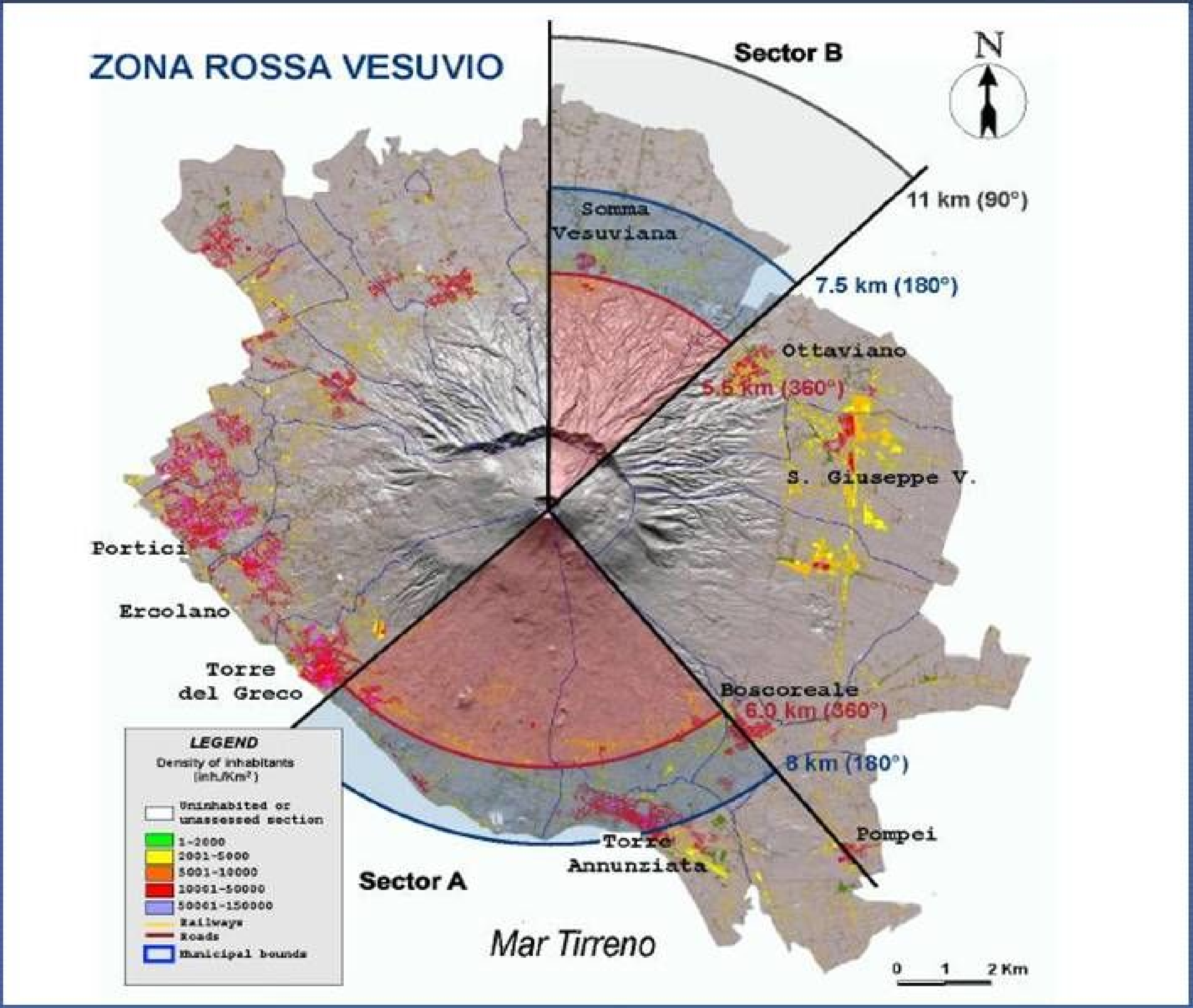
Pyroclastic flows: hazard maps



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Ash transport models

$$\frac{\partial}{\partial t} C_i + \nabla\cdot(\mathbf{U} C_i) - \nabla\cdot(V_{Si} C_i) = \nabla\cdot(\mathbf{K}\cdot\nabla C_i) + S_i$$

Mass variation of a particle class

Advection from MM

Sedimentation term

Turbulence diffusion

Source term

Similar to those used for AQMs but…

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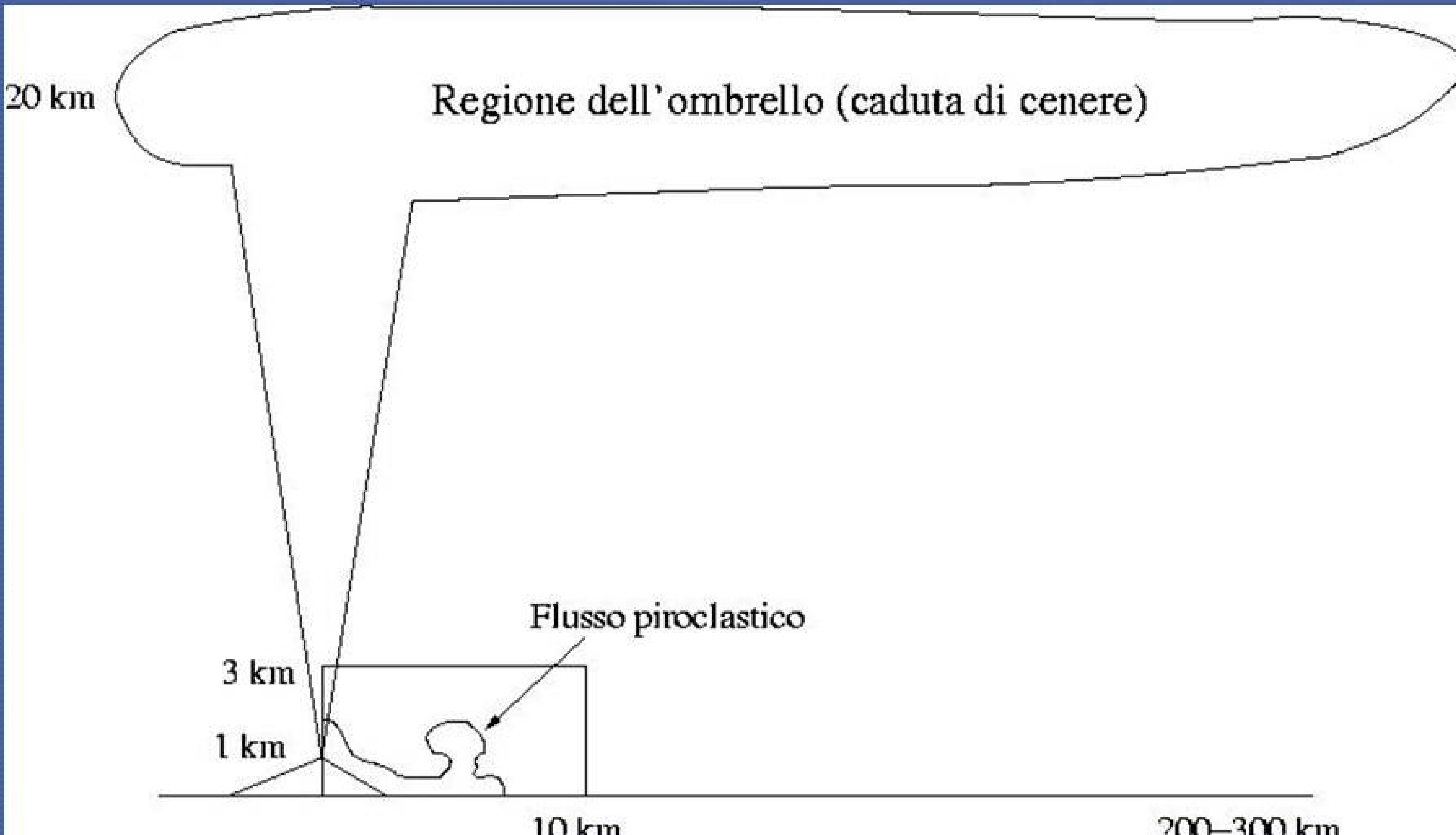
Scale of Plinian eruptions



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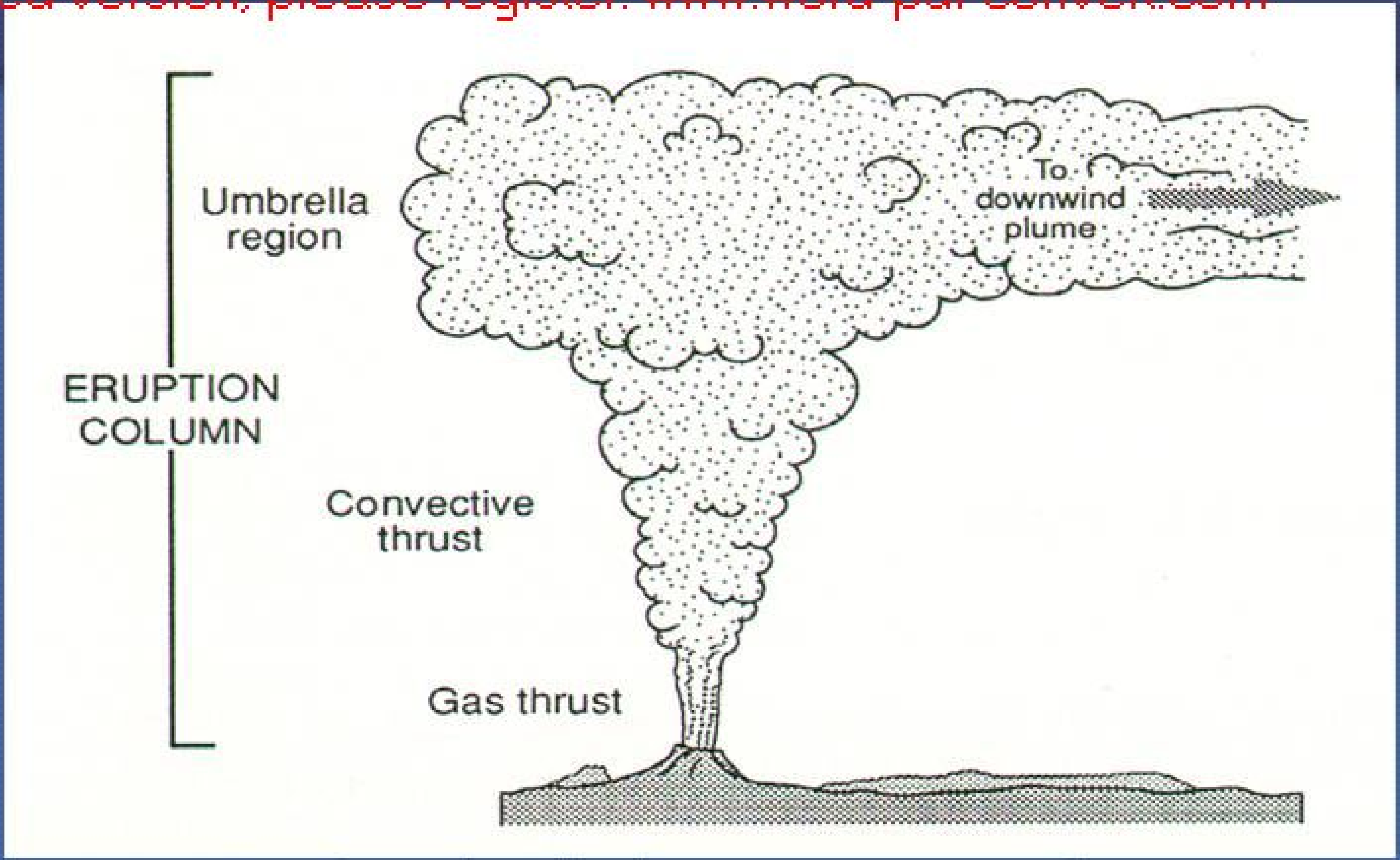
Source term: eruption column



In order to describe the source term we need:

-Column height (direct observations, or Carey & Sparks, 1986 method),

-Mass distribution in the column (empirical, e.g. Suzuki, 1983; BPT, e.g. Bursik 2001)

-MER (BPT, Morton et al, 1956; Wilson & Walker, 1987, Sparks 1997)

-Bulk granulometry (e.g. Bonadonna & Houghton, 2005)

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Particle characterization

	Bombs and blocks	Lapilli	Coarse ash	Fine ash
diameter	> 64 mm	(64 mm, 2 mm)	(2 mm, 64μm)	(64μm, 1μm)
Φ $d(mm)=2^{-\Phi}$	< -6	(-6, -1)	(-1, 4)	(4, 9)
settling velocity	≈ 100m/s	≈ 10 m/s	≈ 1 m/s	< 0.1 m/s
residence time	≈ sec	≈ min	≈ from few hours to few days	few days
distance	proximal ≈ 1km	medium ≈10 km	distal ≈100 km	very distal ≈1000 km

Analytical models

Numerical models

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Ash dispersal models

- **Analytical models:** Based on an analytical solution of the advection-diffusion equation for ash dispersal: e.g., HAZMAP (Macedonio et al., 2005), TEPHRA2 (Bonadonna et al 2005), ASHFALL (Hurst and Turner, 1999). Principal assumption: constant horizontal wind, negligible vertical diffusion. MOSTLY USED FOR SMALL DOMAIN AND STATISTICAL ANALYSIS.

- **Numerical models:** Full 3D time-dependent model for the solution of the transport equation for ash dispersal: e.g., FALL3D (Costa et al., 2006; Folch et al., 2009), VOLCALPUFF (Barsotti et al. 2008)…

  MOSTLY USED FOR LARGE DOMAIN AND REAL-TIME ANALYSIS.

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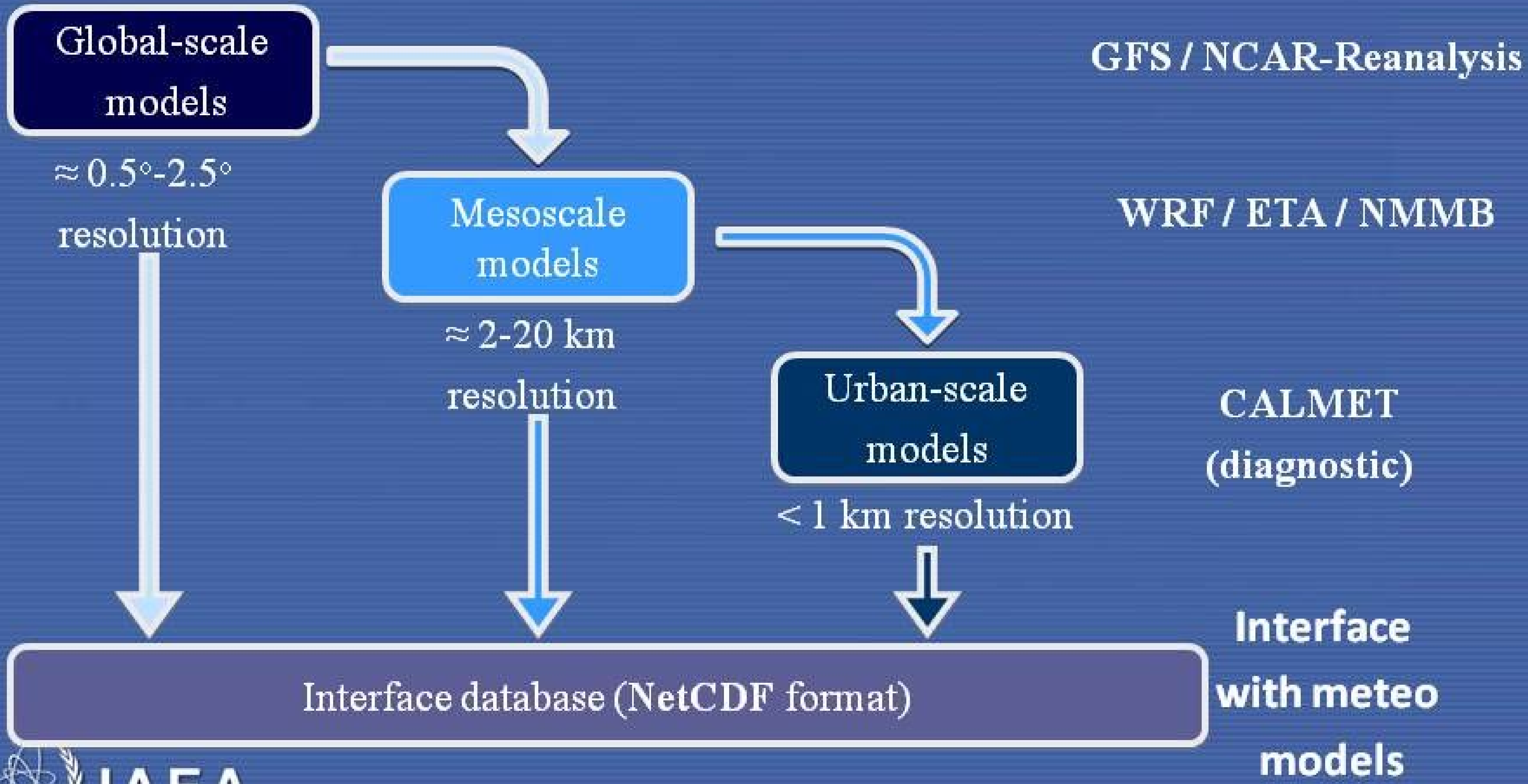
FALL3D (Costa et al., 2006): Model Overview

Multiscale model: it can run at scales from **synoptic** (≈1000s km) to **very local** (≈few km) following an *off-line* strategy with prognostic or diagnostic meteorological models.



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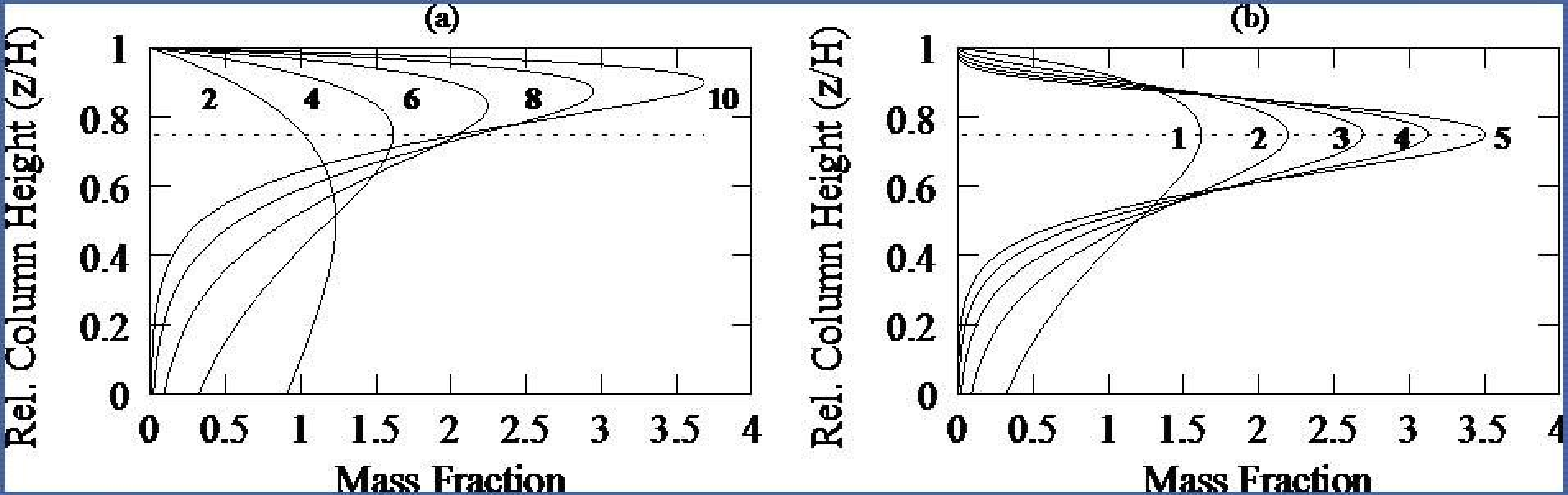
Eruption column (1)

The simplest approaches use empirical parameterization as i) point source or ii) using a mushroom shape function (Suzuki parameterization):

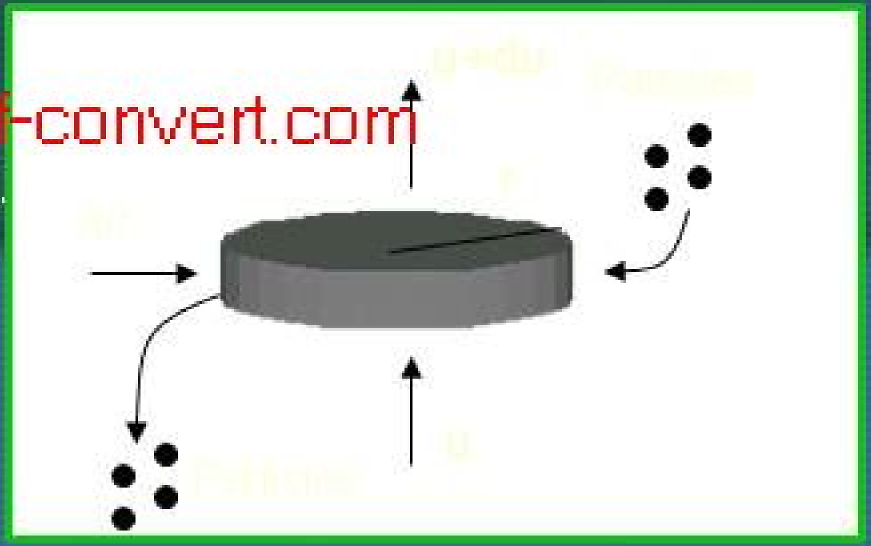
$$S(z) = S_0 \left\{ 1 - \frac{z}{H} \exp\left[A\left(\frac{z}{H} - 1 \right) \right] \right\}^{\lambda}$$

where A and λ are two empirical parameters defining the position of the maximum and the profile sharpness, respectively.



Eruptive column (2): BPT

- **Features**: Quasi-steady, 1D radially averaged [*Bursik*, GRL, 2001].



MASS:

$$\underbrace{\frac{d}{dz}\left(\pi r^2 \rho u\right)}_{\text{Mass flow}} = \underbrace{2\pi r \rho_a u_e}_{\text{Air}} + \underbrace{\sum_{i=1}^{N} \frac{dM_i}{dz}}_{\text{Fallen particles}}$$

→ Granulometry. **N** particle classes

MOMENTUM:

$$\underbrace{\frac{d}{dz}\left(\pi r^2 \rho u^2\right)}_{\text{Momentum flow}} = \underbrace{\pi r^2 \left(\rho_a - \rho\right) g}_{\text{Buoyancy}} + \underbrace{u\left(2\pi r \rho_a u_e + \sum_{i=1}^{N} \frac{dM_i}{dz}\right)}_{\text{Air plus particles contribution}}$$

ENERGY:

$$\underbrace{\frac{d}{dz}\left[\pi r^2 \rho u\left(c_v T + g z + \frac{1}{2}u^2\right)\right]}_{\text{Energy flow}} = \underbrace{2\pi r \rho_a u_e\left(c_a T_a + g z + \frac{1}{2}u_e^2\right)}_{\text{Air}} + \underbrace{\left(c_p T + g z + \frac{1}{2}u^2\right)\sum_{i=1}^{N} \frac{dM_i}{dz}}_{\text{Fallen particles}}$$

PARTICLES:

$$\frac{dM_i}{dz} = -\frac{\xi}{r u}\left(u_L - f\right) M_i \qquad i = 1:N$$

f Re-entrainment factor $\quad u_L$ Terminal velocity

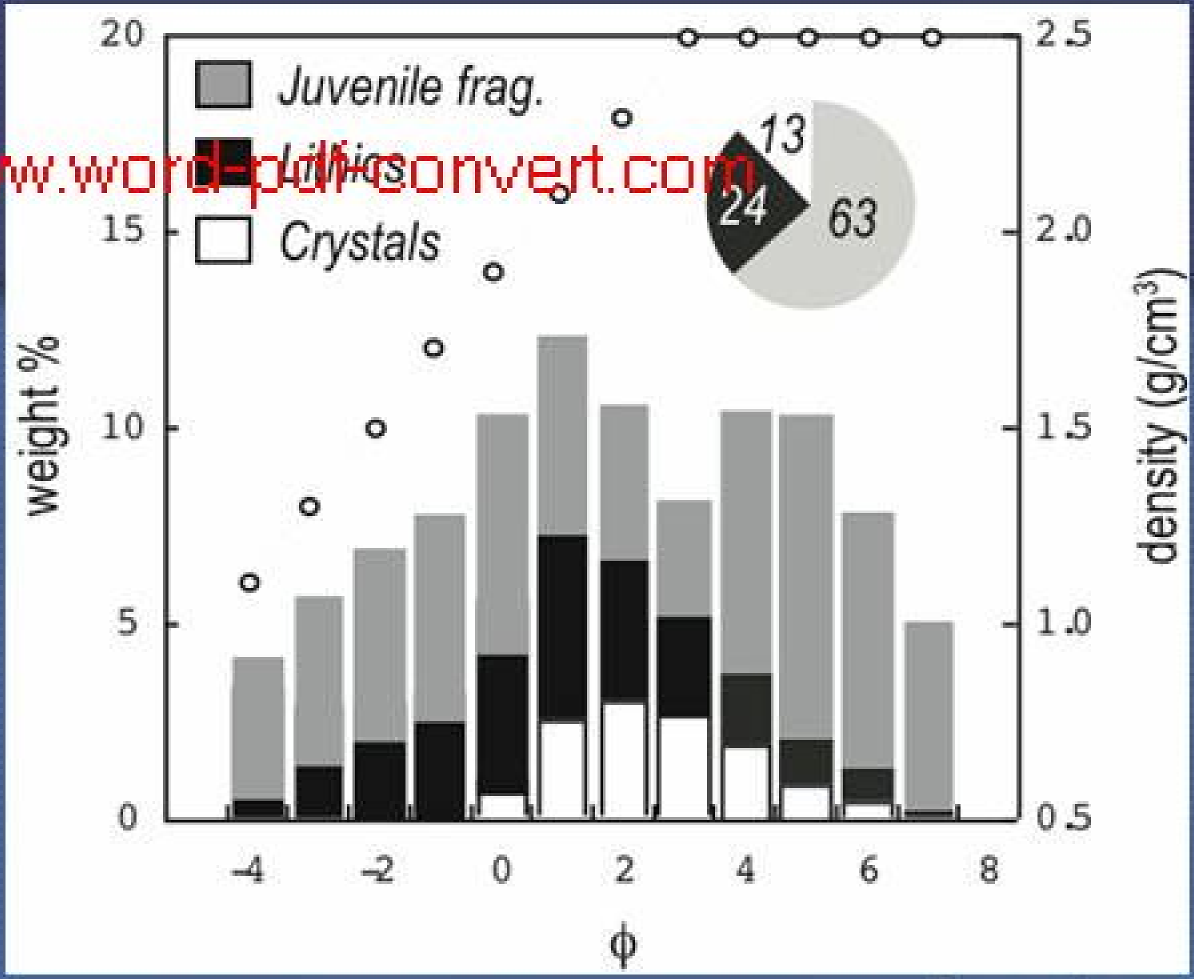
N+3 ODE's to solve for bulk density, temperature, velocity and mass distribution along the plume given the conditions at the vent.

Total grainsize distribution

It handles **multiple classes** of particles

A particle class (bin) is characterized by

- **Size**
- **Density**
- **Shape factor**



d(mm)=2$^{-\Phi}$

Aggregates

Remote Sensing

Φ	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8
d	16 mm	8 mm	4 mm	2 mm	1 mm	0.5 mm	250 µm	125 µm	64 µm	32 µm	16 µm	8 µm	4 µm

Lapilli — 10s km

Coarse ash — 100s km

Fine ash — 1000s km

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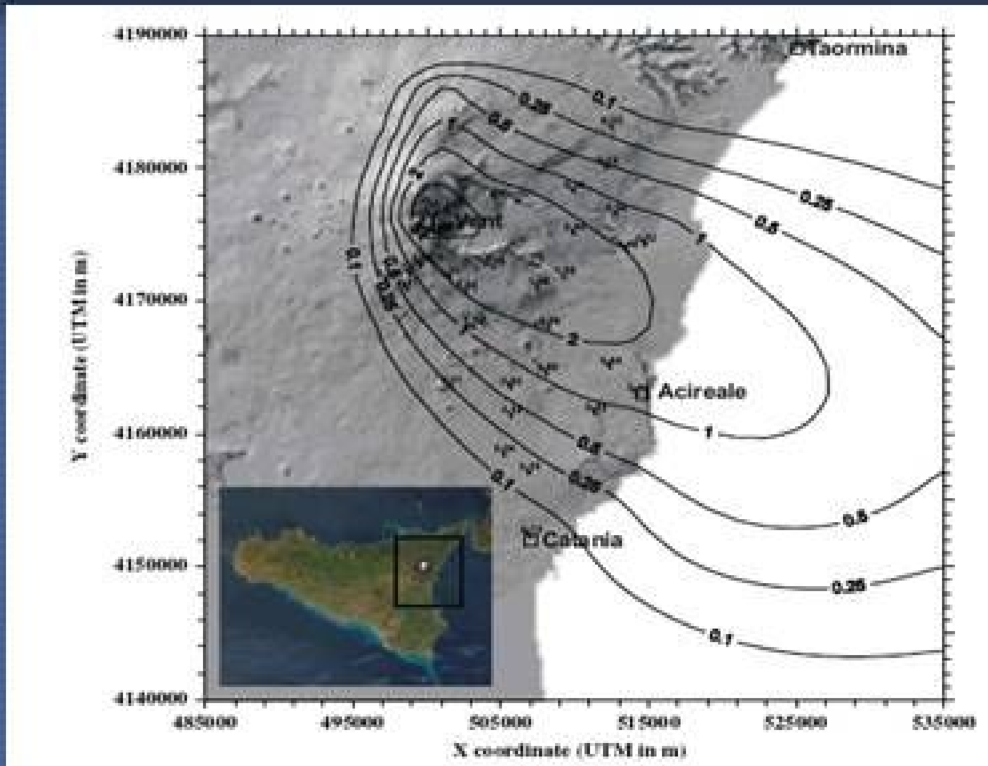
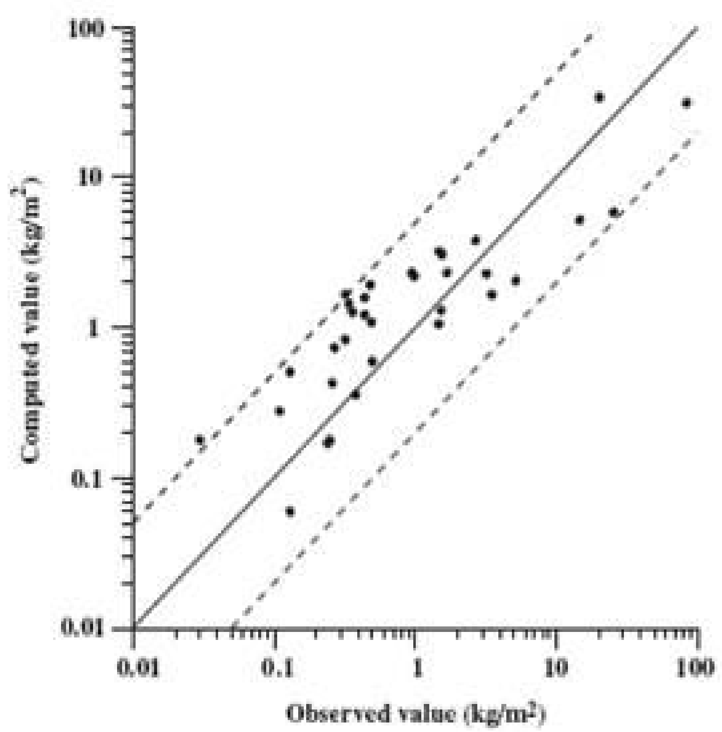
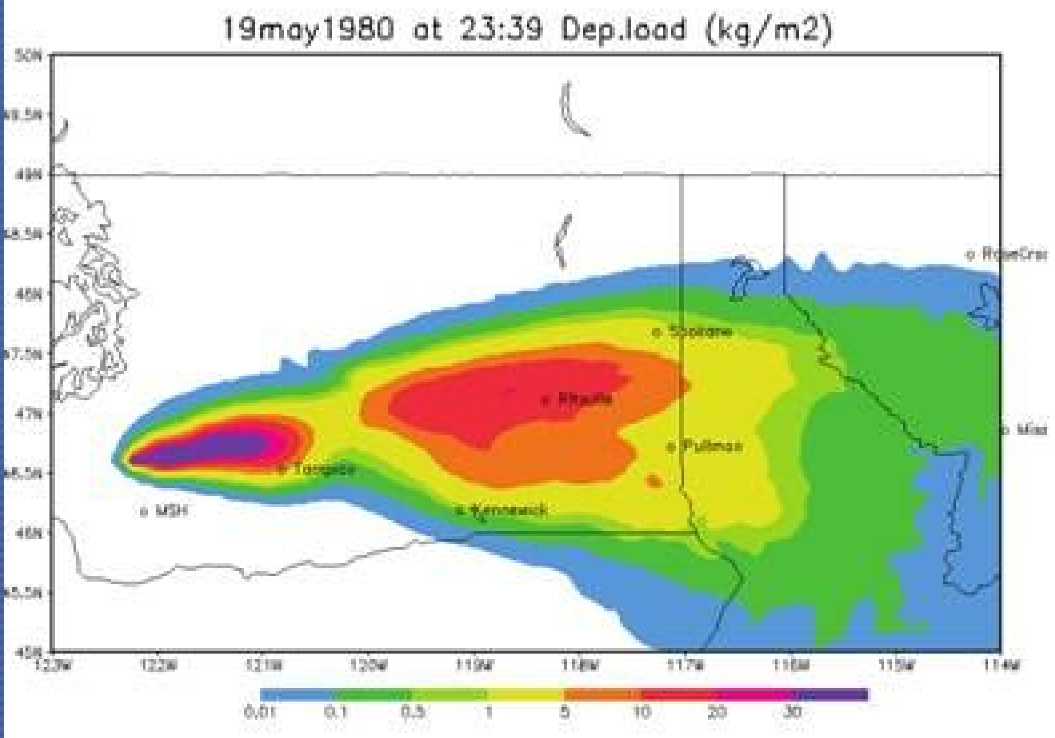
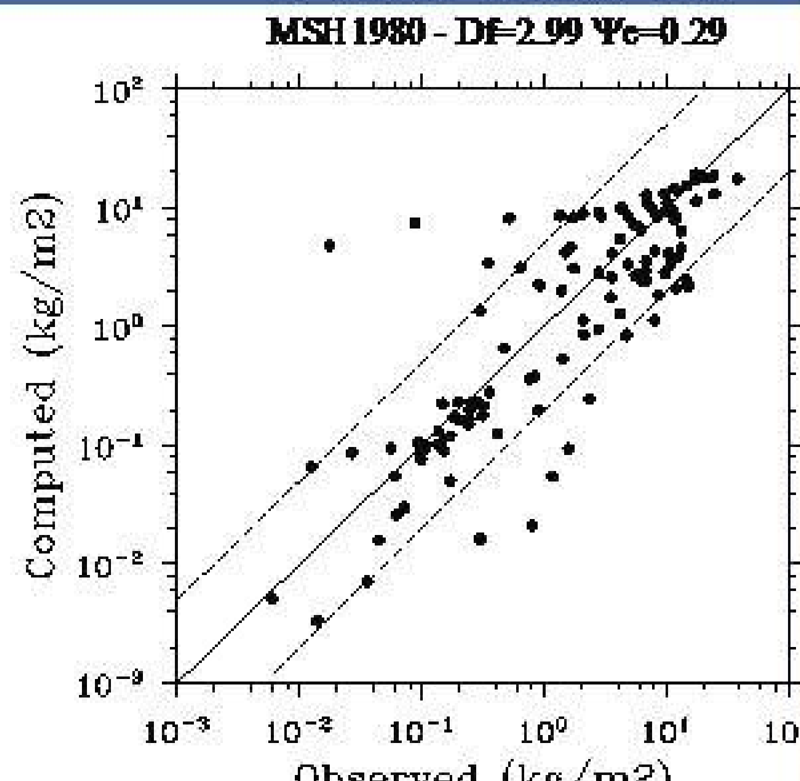
FALL3D: Model Validation vs Observed Tephra Deposits



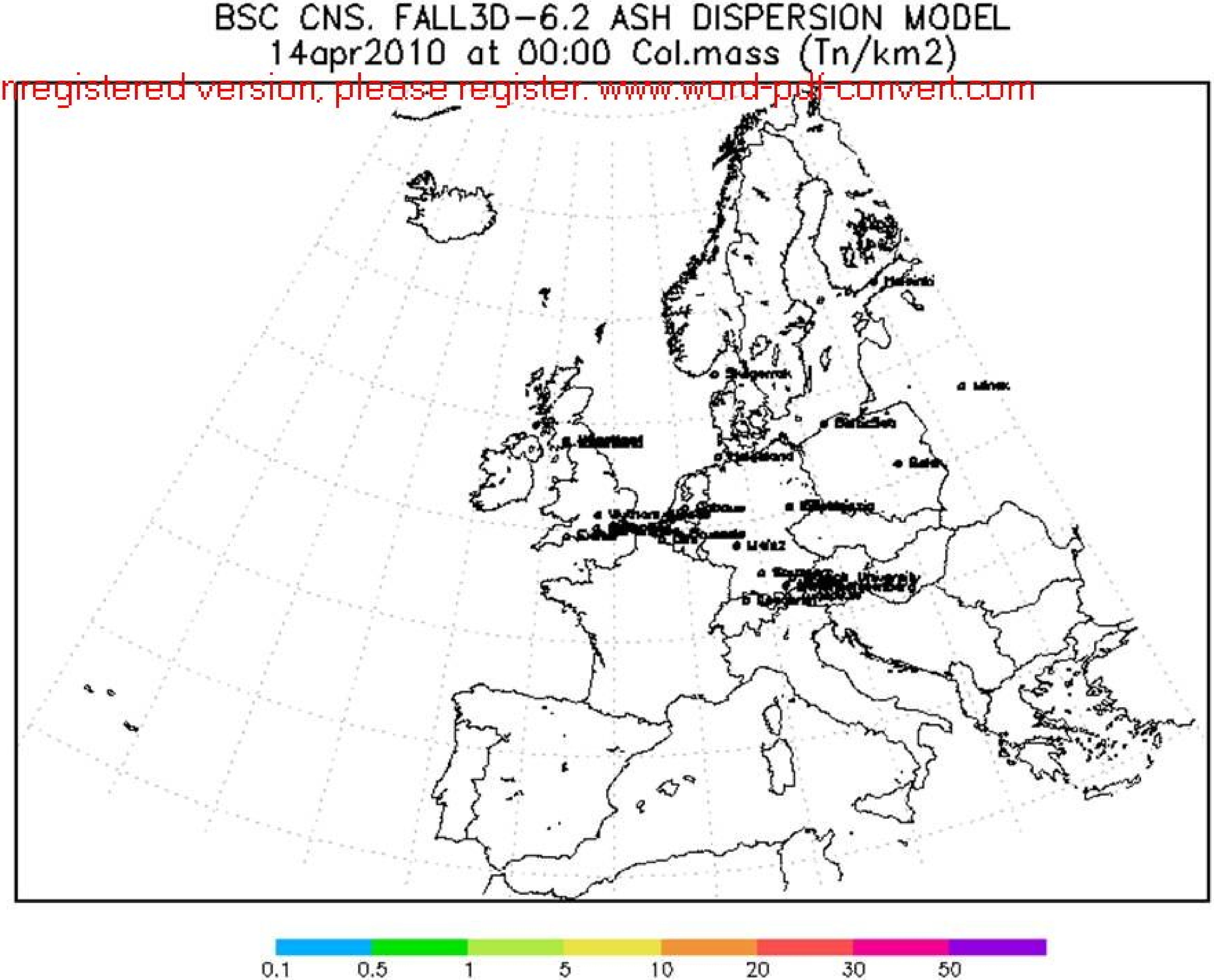


Etna 1998
(short scale)

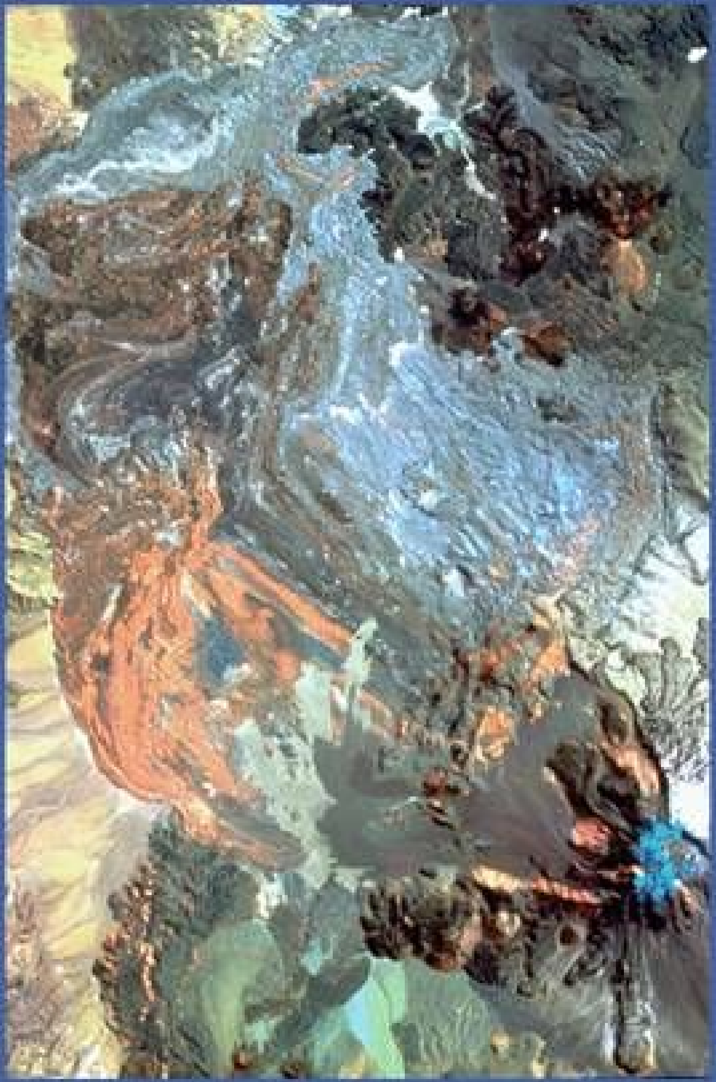




MSH 1980
(large scale)


BSC CNS. FALL3D-6.2 ASH DISPERSION MODEL
14apr2010 at 00:00 Col.mass (Tn/km2)
0.1
0.5
1
5
10
20
30
50

Debris avalanches (dry, granular)



A *debris avalanche* is formed when an unstable slope. Large scale avalanches normally occur on very steep volcanoes.

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Lahar (wet, fluid)

Lahars (mudflows) are debris flows of volcanic material, typically off the slopes of a volcano.

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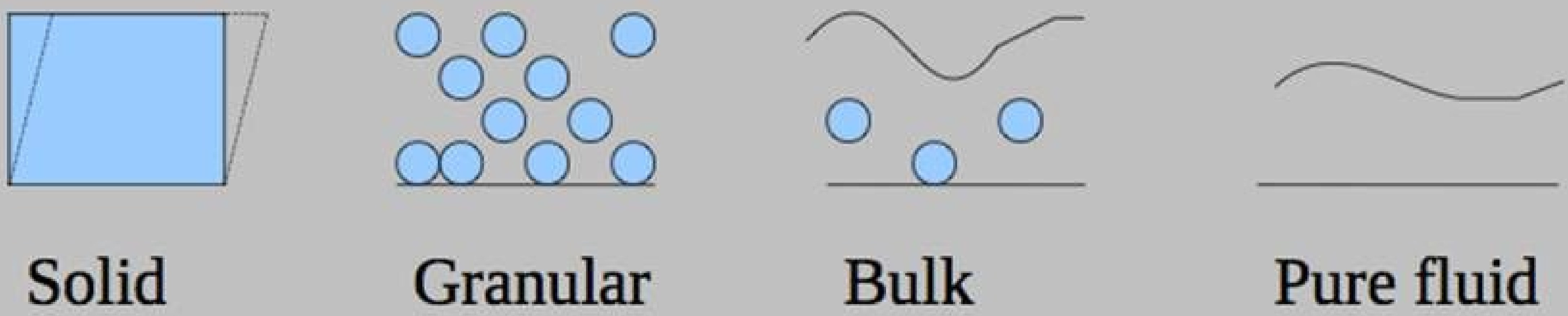
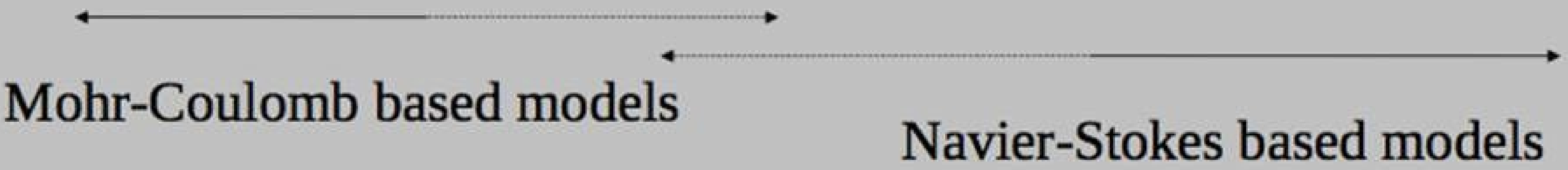
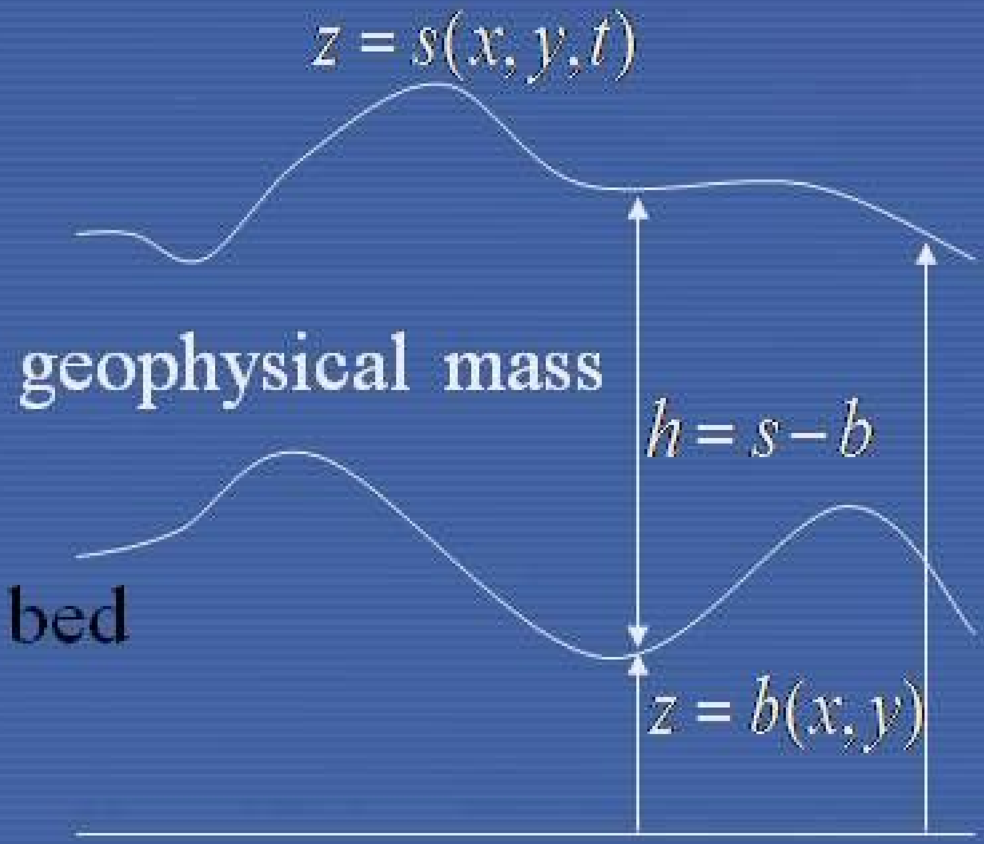
Granular Vs pure fluid



Euler-Cauchy law of motion: $\frac{D(\rho v)}{Dt} = \frac{\partial \sigma}{\partial x_i} + b$



Savage-Hutter approach (generalization of SWE)



Upper free surface:

$F_h(\mathbf{x},t) = s(x,y,t) - z = 0,$

Basal material surface:

$F_b(\mathbf{x}) = b(x,y) - z = 0$

The equations are depth averaged:

$$h\bar{v}_x = \int_b^s v_x dz, \qquad h\bar{v}_y = \int_b^s v_y dz,$$

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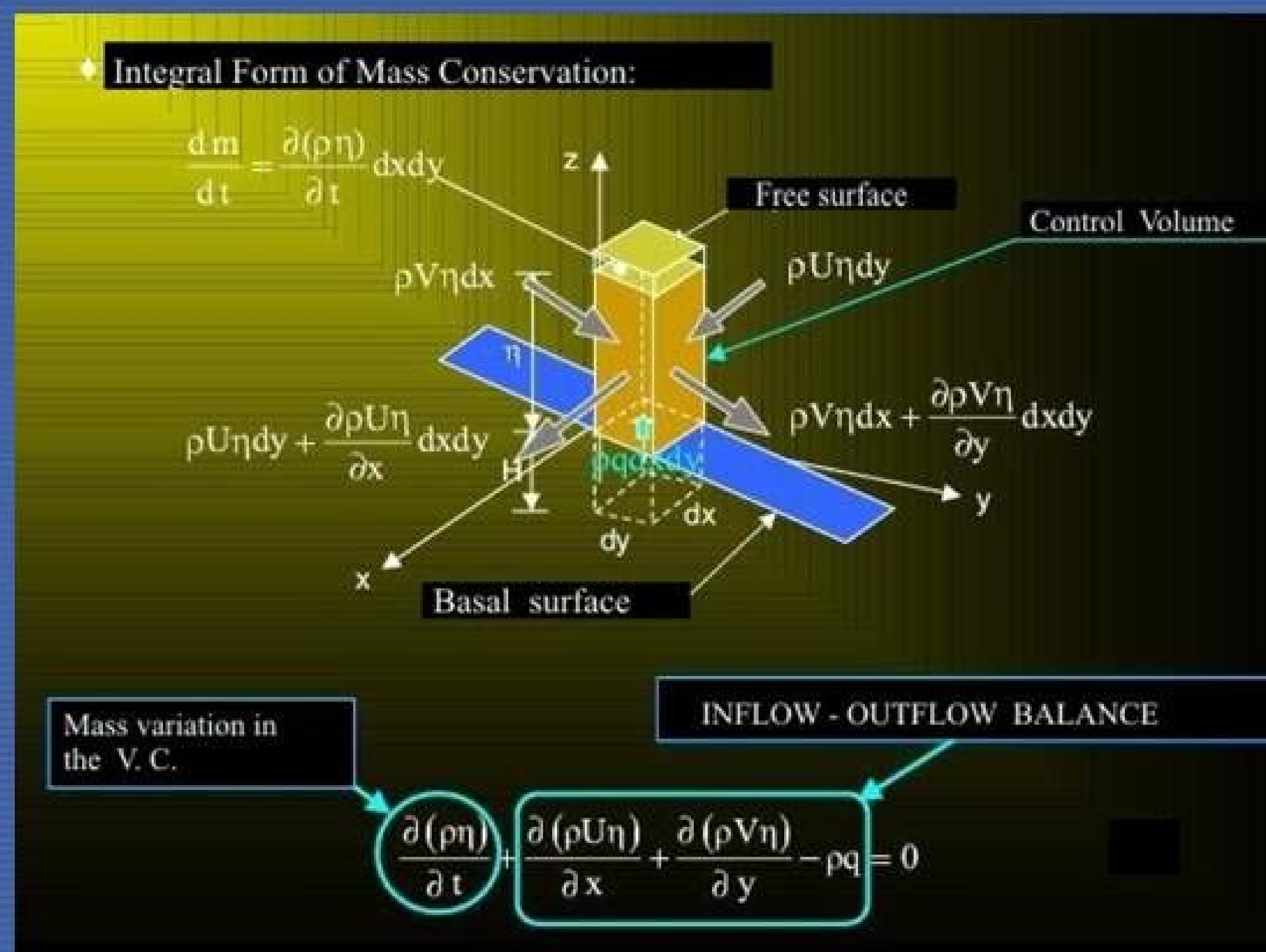
Savage-Hutter approach (generalization of SWE)

Savage-Hutter provide a framework for later, more sophisticated models. The model is based on assumptions:

- Aspect ratio of the flow is small
- Granular flows have Coulomb friction behavior
- Top surface is stress-free
- Top surface and bed surface represented as functions

• $F_h(X,t)=0$ and $F_b(X)=0$



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Titan2D model

2D - depth averaged equations:

$$\frac{\partial h}{\partial t} + \frac{\partial h v_x}{\partial x} + \frac{\partial h v_y}{\partial y} = e_s$$

continuity

$$\frac{\partial h v_x}{\partial t} + \frac{\partial (h v_x^2 + .5 \cdot k_{ap} g_z h^2)}{\partial x} + \frac{\partial h v_y v_x}{\partial y} =$$

x momentum

$$= g_x h + v_x e_s - \frac{v_x}{\sqrt{v_x^2 + v_y^2}} \cdot \left[g_z + \frac{1}{\kappa_x} \cdot v_x^2 \right] \cdot h \cdot \tan(\varphi_{bed}) - \operatorname{sgn}\left(\frac{\partial v_x}{\partial y} \right) \cdot h k_{ap} \frac{\partial h g_z}{\partial y} \sin(\varphi_{\text{int}})$$

1 **2** **3** **4**

1- Gravitational driving force.

2- Momentum due to erosion.

3- Resisting force due to Coulomb friction at the base.

4- Intergranular Coulomb force due to velocity gradients normal to the flow direction.

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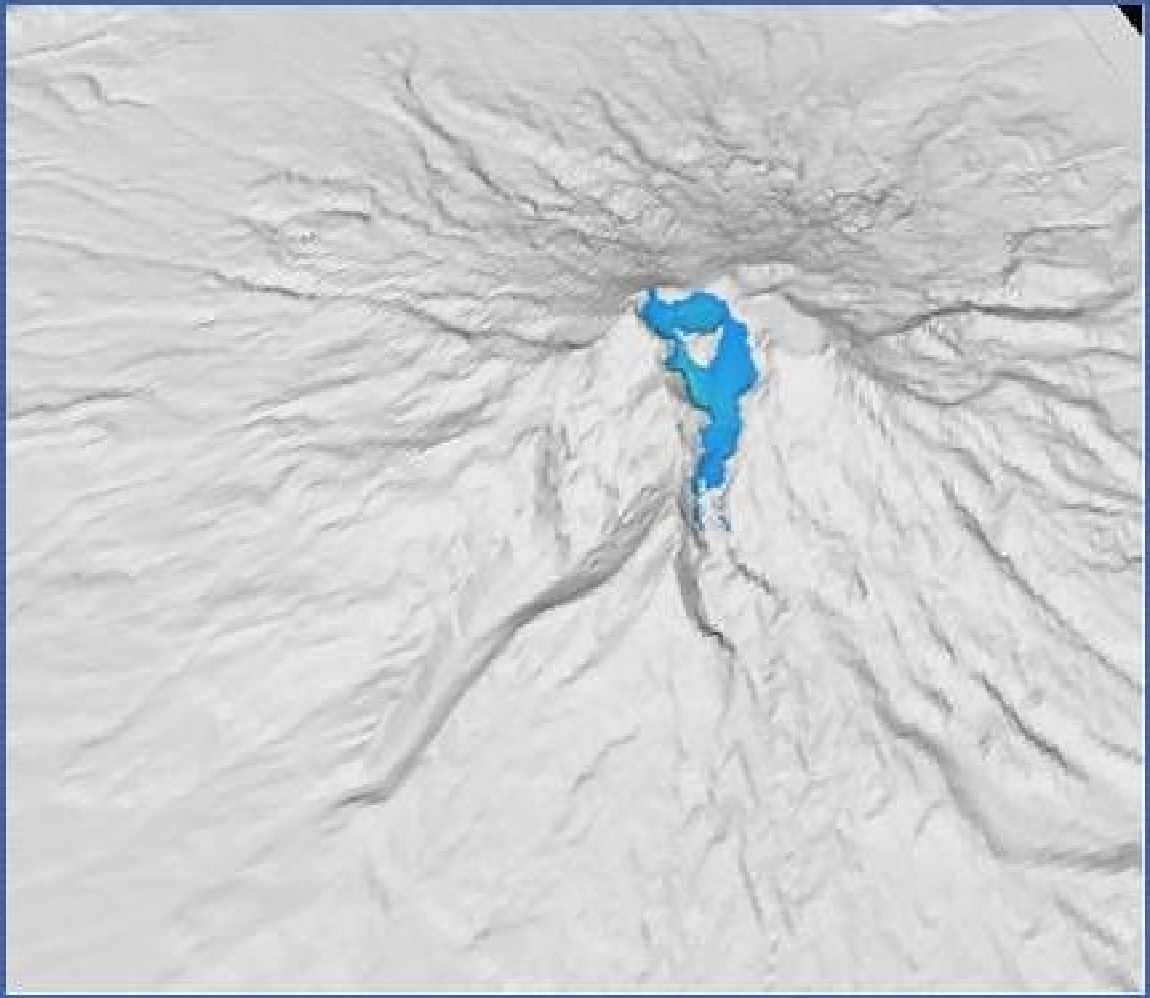
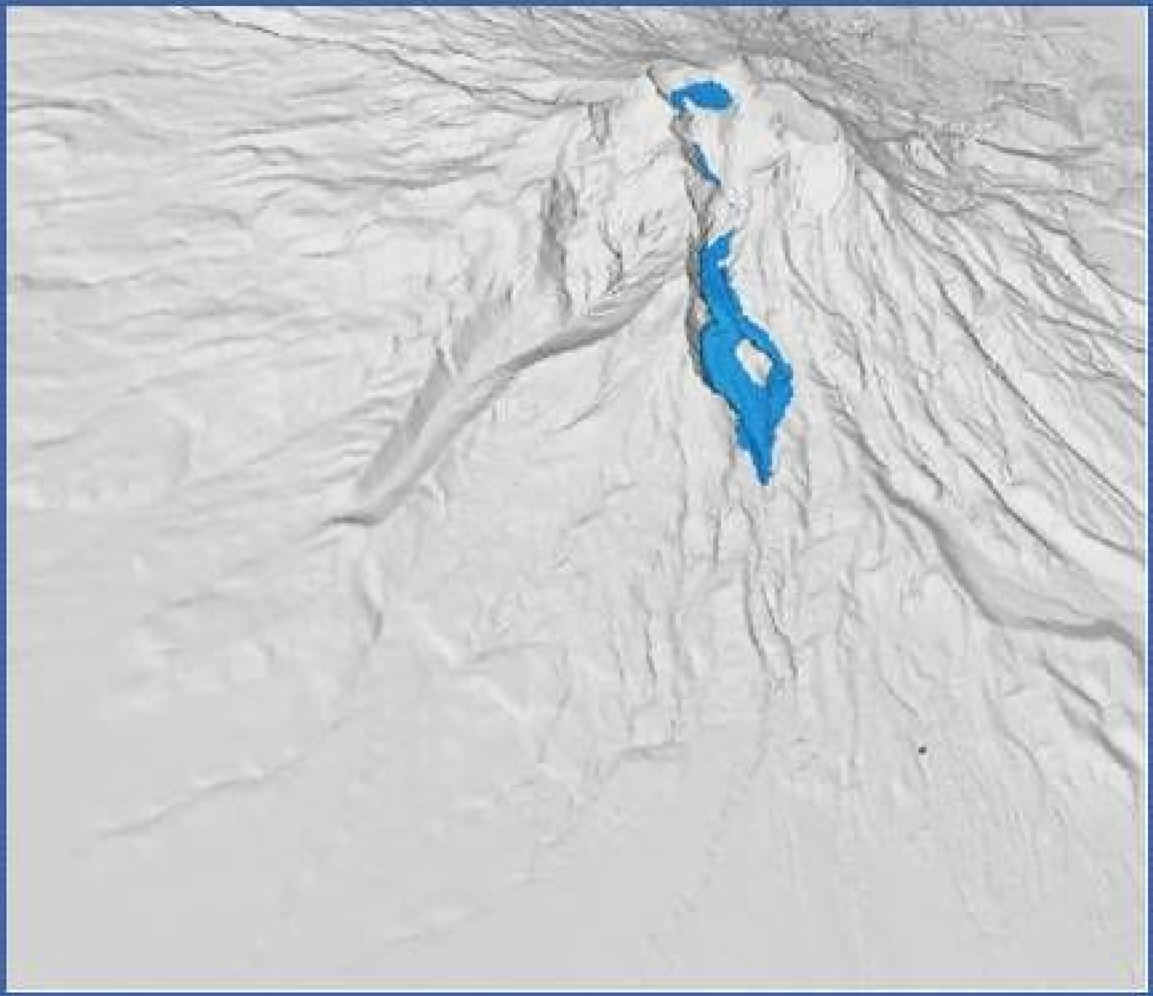
Titan2D model (two-phase generalization)



Dry Model after 20 minutes of flow simulation (Ruapehu, NZ)



Two phase Model after 20 minutes of flow simulation

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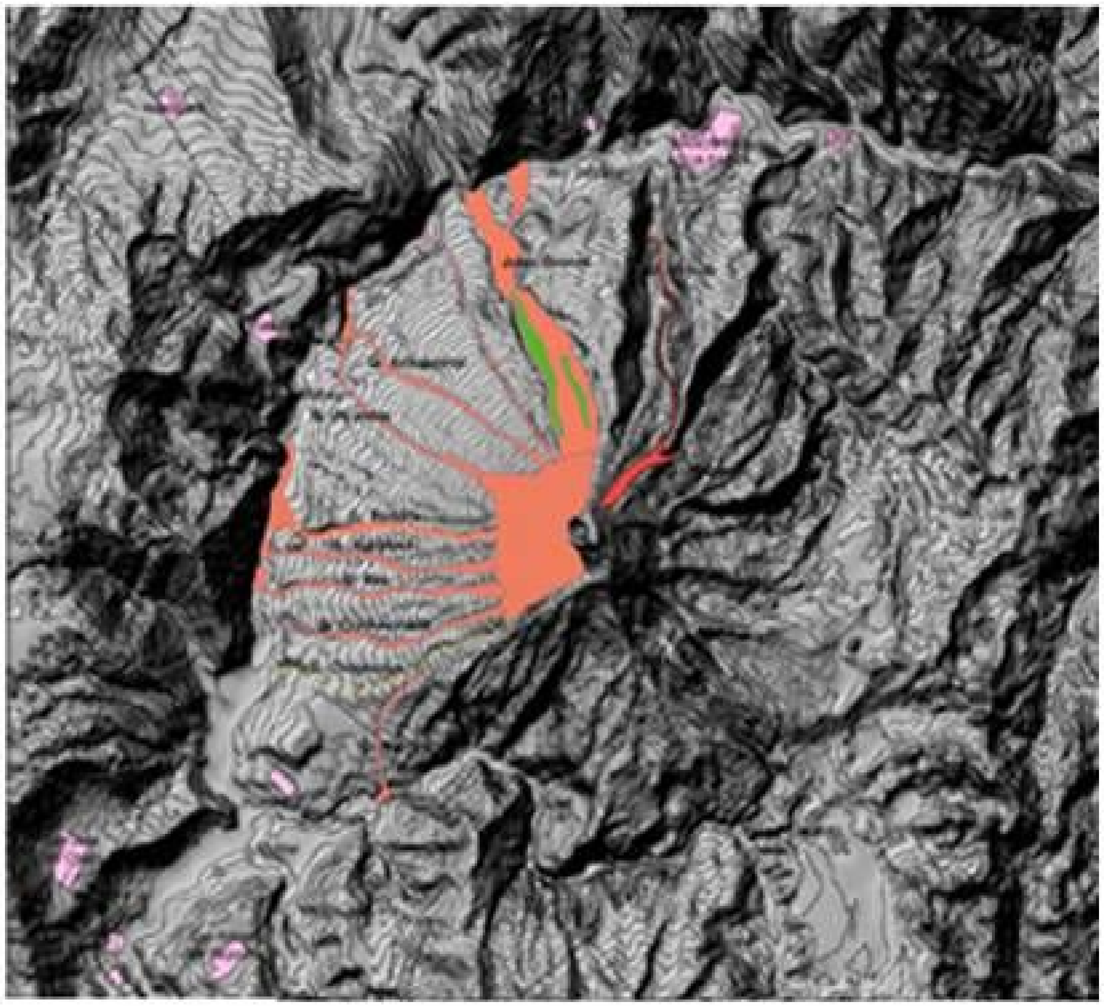
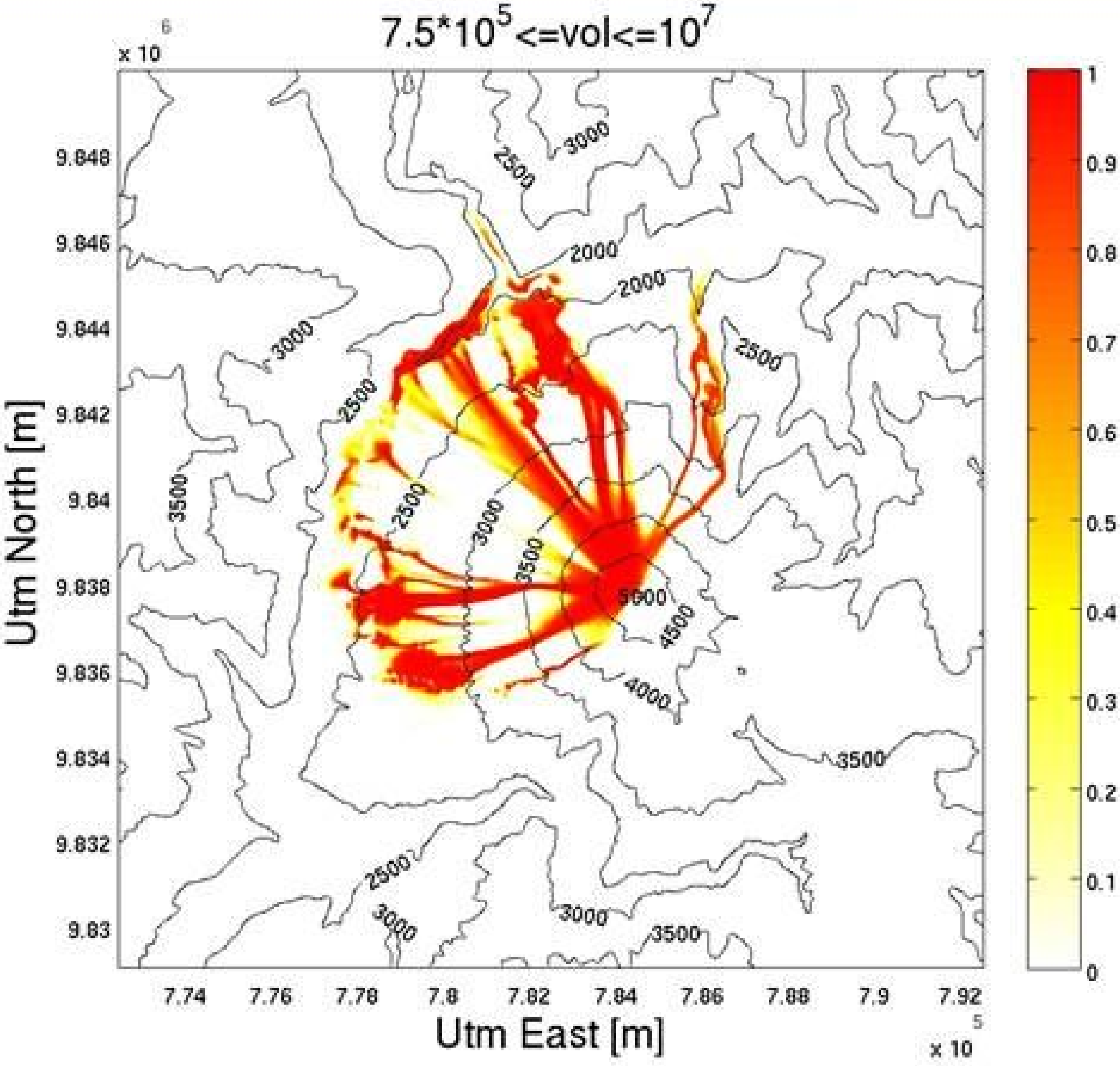
Uncertainty Propagation (probability mapping)

Ability to propagate uncertainty in inputs into estimates on uncertainty in output quantities of interest.

Probability that the cumulative thickness of 12 flows will exceed 0.2 m.



Tungurahua 2006



Effusive Eruptions

Risks and damages related to effusive eruptions require satisfactory models to reliably forecast the lava flow path.

Example of risk mitigation: recent Etna eruptions

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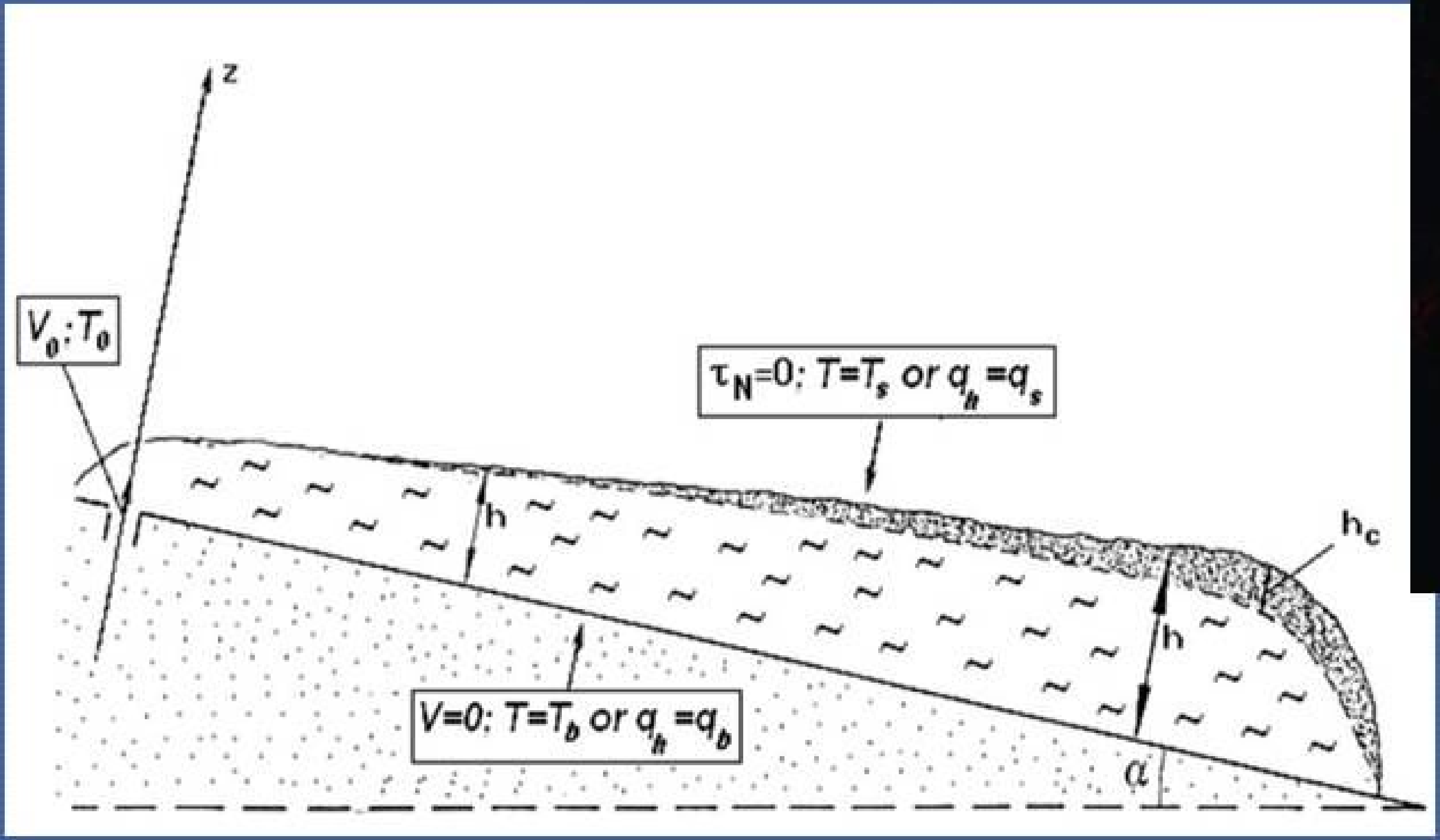
Photos by T.Pfeiffer

Etna eruption damage, 27 October 2002

(foto La Sicilia)

(foto La Sicilia)

Sketch of a lava flow



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Lava flow models

Due to the high complexity of the phenomenon, numerical solution of the 3D conservation equations for real lava flows is often impossible.

To overcome the computational difficulties simplified models are usually adopted, such as:

- Probabilistic maximum slope models (Macedonio et al., 1990)
- Cellular Automata models (Barca et al., 1993)
- Flow front models (FLOWFRONT: Young and Wadge, 1990)
- 2D models based on the Shallow Water Equations (Costa and Macedonio, 2005)

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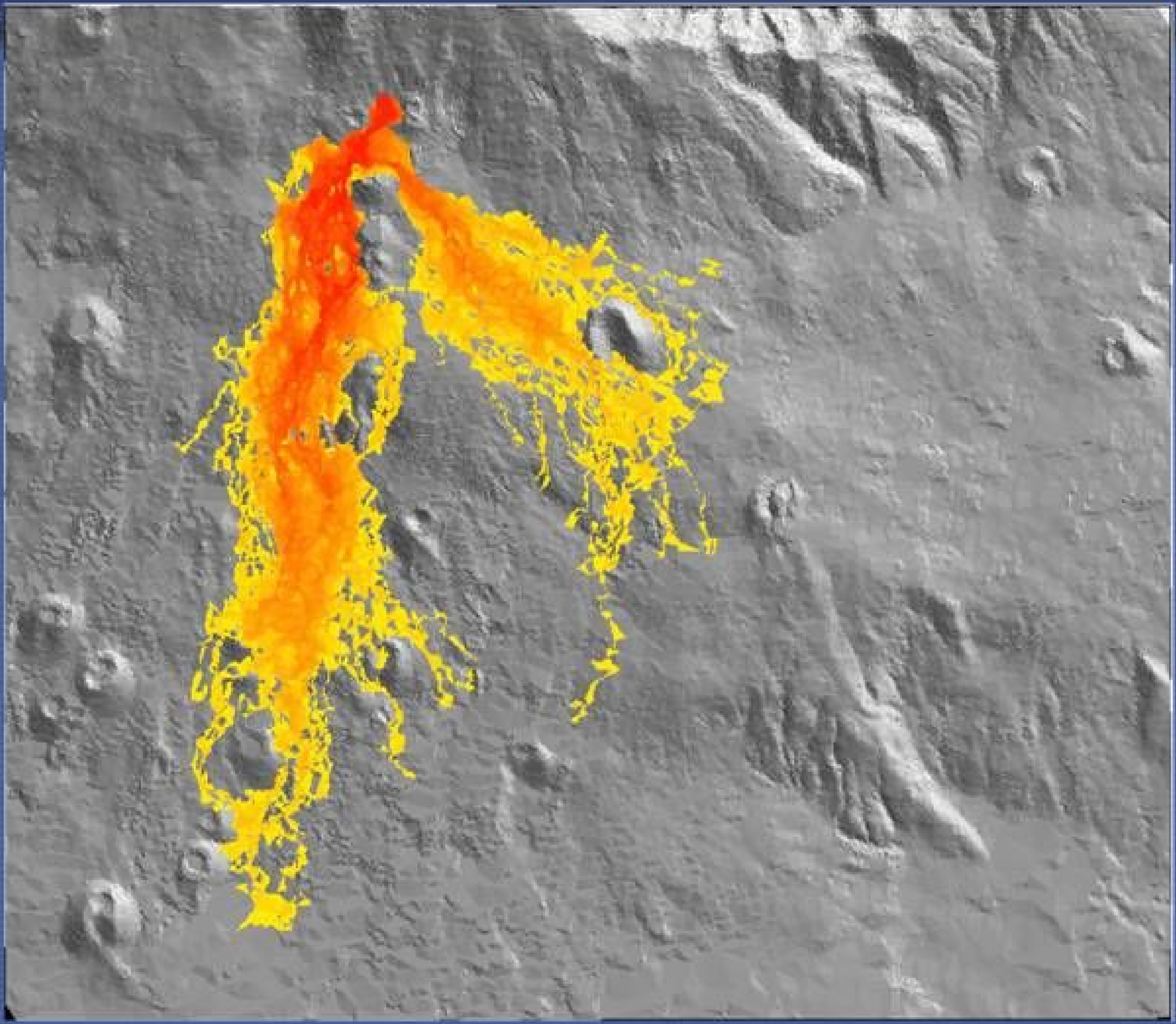
Probabilistic model based on maximum slope



PROBABILISTIC MODELS BASED ON THE MAXIMUM SLOPE

In the model of Macedonio et al. (1990) it is assumed that topography plays the major role in controlling lava flow path. The identification of the different zones potentially invaded by a lava flow is performed by computing the probability of invasion by using a Monte Carlo algorithm. The flow is allowed to propagate along random paths starting from a source point on a topographic map by following a set of propagation rules. The paths cannot propagate upward, whereas the downflow paths are more probable along the maximum-slope direction. Due to the probabilistic character of the propagation rules, the paths may barriers. When several paths are generated, areas with greater probability are crossed many times, whereas areas with lower probability are crossed very seldom. The flow paths have no lateral dimensions and cannot fill basins; when many paths enter a basin, they randomly propagate and spread until they touch the walls of the basin and stop. Therefore, a basin behaves as a sink for the flow paths, and this allows easy recognition of them. Flow rate cannot be specified in the source points and the program does not account for the time. It simply shows which paths are more probable when a fluid is allowed to exit from the source points. It must be noted that this program does not solve physical equations and, for this reason, it allows fast computation of the invaded areas. However, since the results are only the probabilities of fluid invasion without knowing the rheological properties of the fluid, the main application of this model is generating hazard maps when the characteristics of the fluid are not known. The program was used to evaluate the eruptions of Mt. Etna of 1983, 1985, 1987, and 1989 and to evaluate a hazard map

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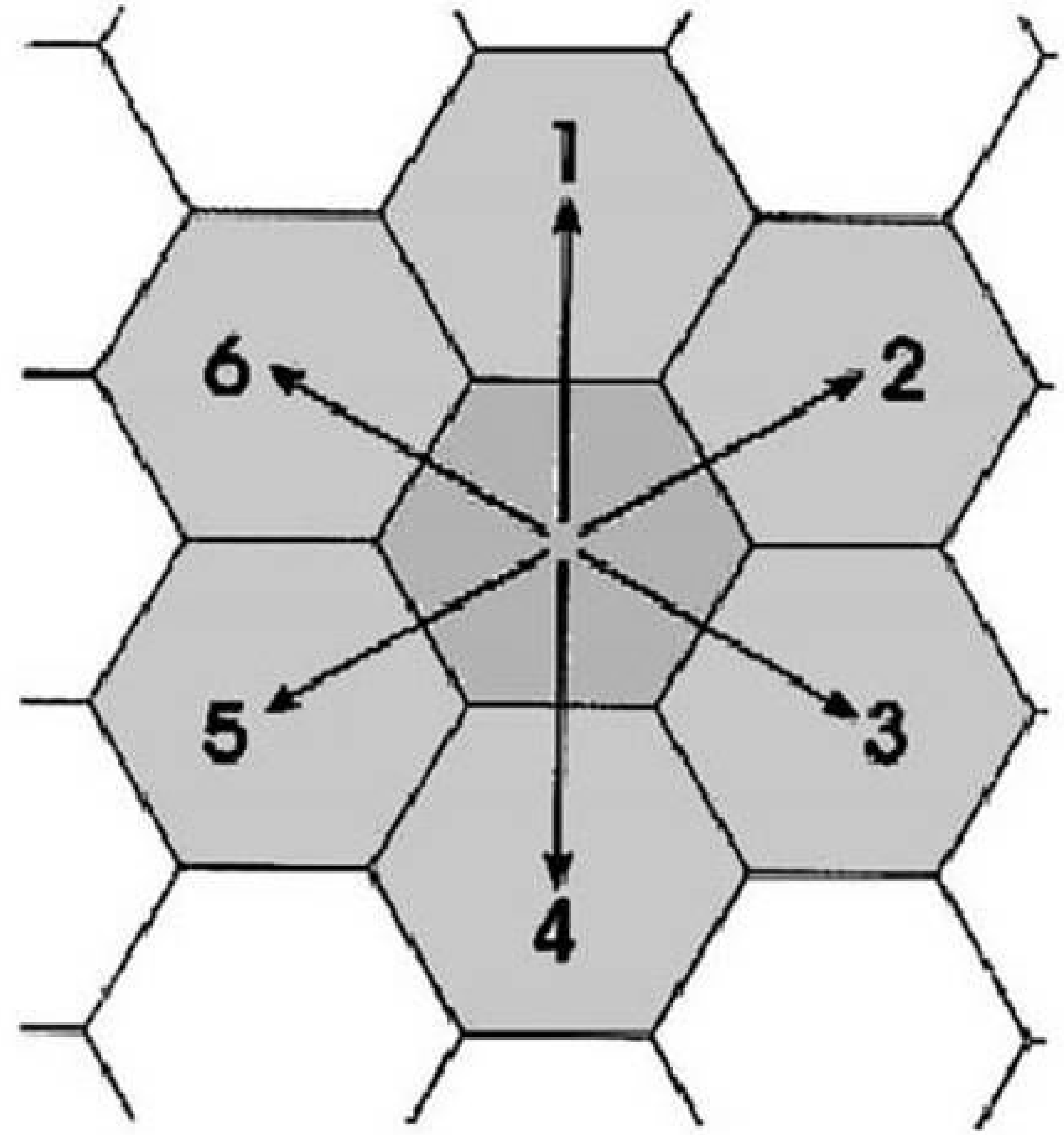
Cellular Automata Models (Barca et al., 1993)

The model assumes the space inhabited by lava flow may be partitioned in terms of discrete volume (cells) to which a set of parameters is associated: (1) altitude of the cell; (2) lava thickness; (3) lava temperature; and (4) four (or six) lava fluxes to and from the neighboring cells (see Fig. 2). These parameters may vary as a consequence of an interaction with a neighboring cell, or because of an imposed global condition that affects all the cells simultaneously (Barca et al., 1993). A set of rules was given for changing a given parameter at each time step. For example, the cell altitude remains unchanged until lava reaches a given temperature and solidifies; at this time the altitude of the cell is increased by the value of lava thickness inside the cell, and the lava thickness is reset to zero. Flows among the cells are allowed as a consequence of the different hydrostatic pressure of the lava among neighboring cells. Lava rheology is accounted for by introducing a minimum lava level below which no flow is possible. This minimum level (adherence parameter) was allowed to vary with the temperature



Depth-averaged equations for lava flows (Costa & Macedonio, 2005)

- $$\frac{\partial h}{\partial t}+\frac{\partial Uh}{\partial x}+\frac{\partial Vh}{\partial y}=q$$ (mass)

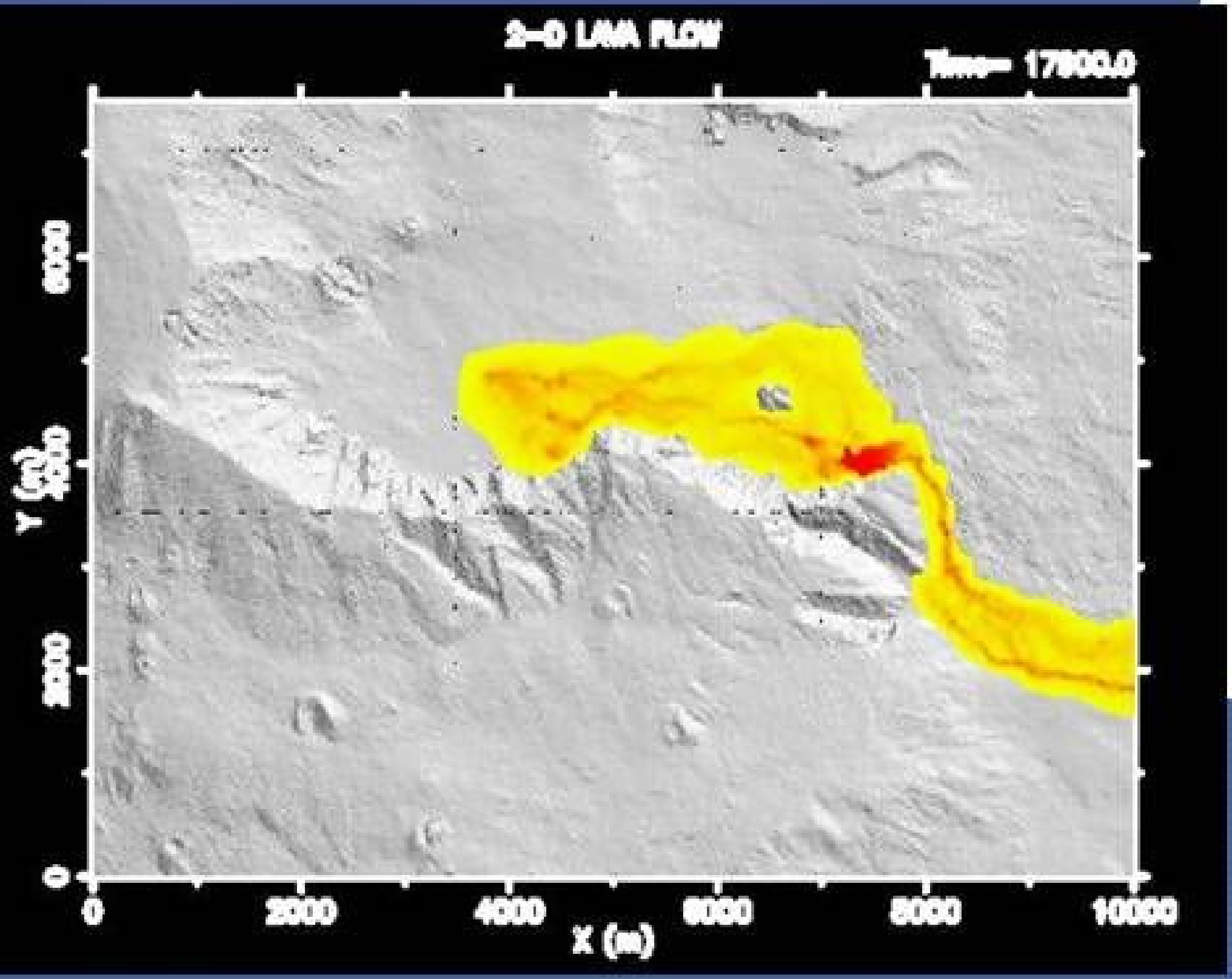
- $$\frac{\partial Uh}{\partial t}+\frac{\partial U^2 h}{\partial x}+\frac{\partial UVh}{\partial y}=-gh\frac{\partial (H+h)}{\partial x}-\gamma U$$ (x-momentum)

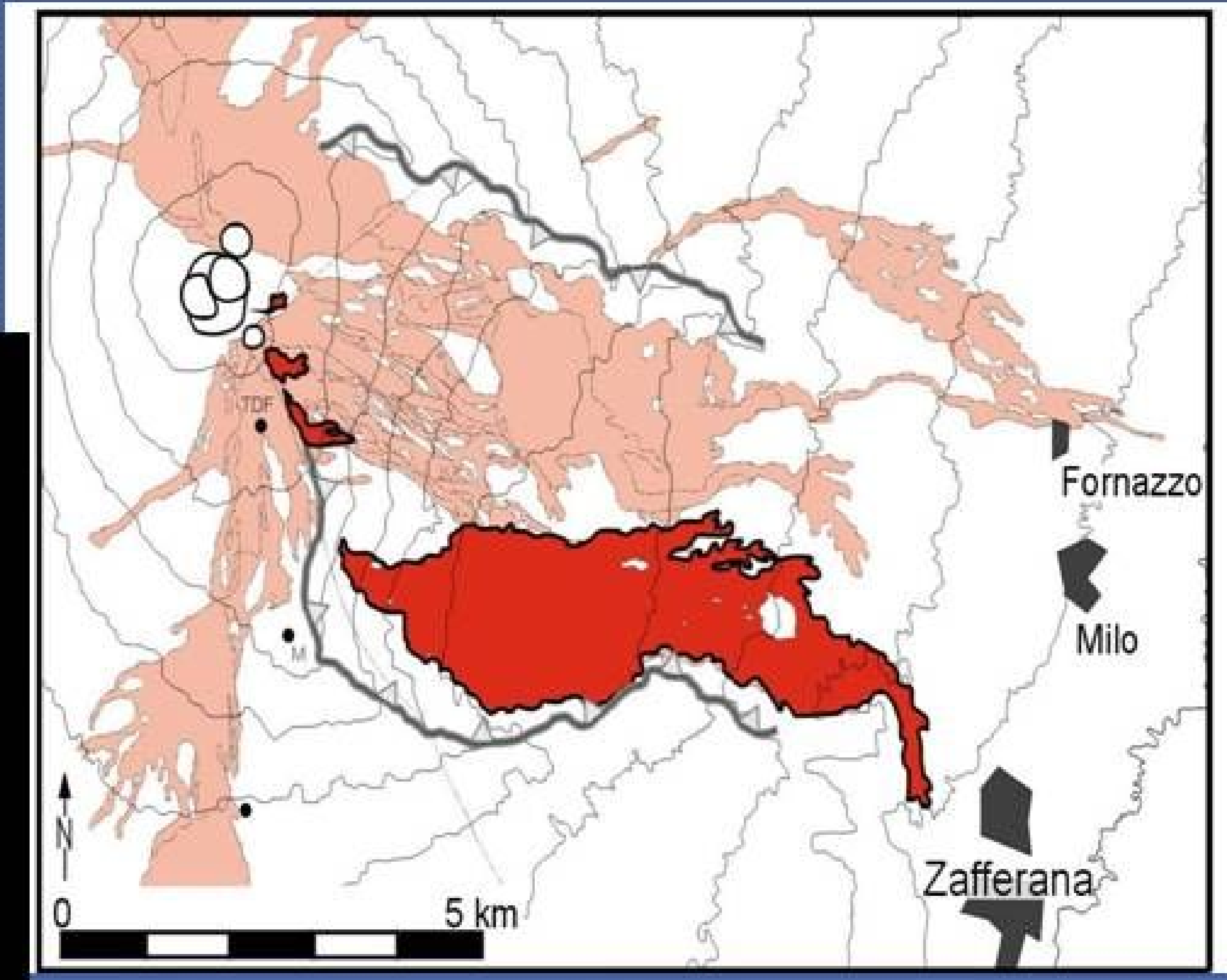
- $$\frac{\partial Vh}{\partial t}+\frac{\partial UVh}{\partial x}+\frac{\partial V^2 h}{\partial y}=-gh\frac{\partial (H+h)}{\partial y}-\gamma V$$ (y-momentum)

- $$\frac{\partial Th}{\partial t}+\frac{\partial \beta UTh}{\partial x}+\frac{\partial \beta VTh}{\partial y}=-E(T^4-T_{env}^4)-W(T-T_{env})-C(T-T_c)+K(U^2+V^2)\exp[-b(T-T_{ref})]$$ (energy)

- Boundary and initial conditions

Comparison with lava flow from 1991-1993 Etna eruption





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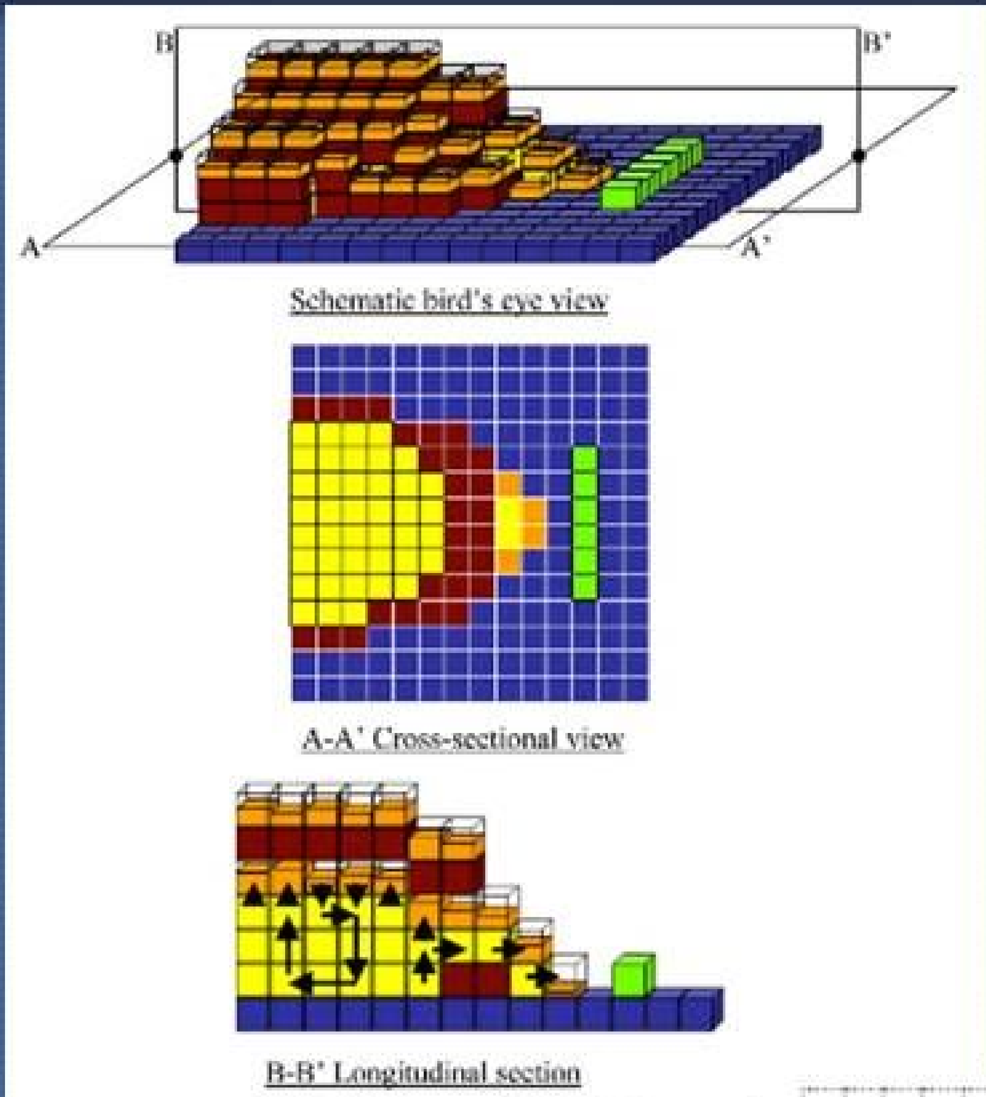
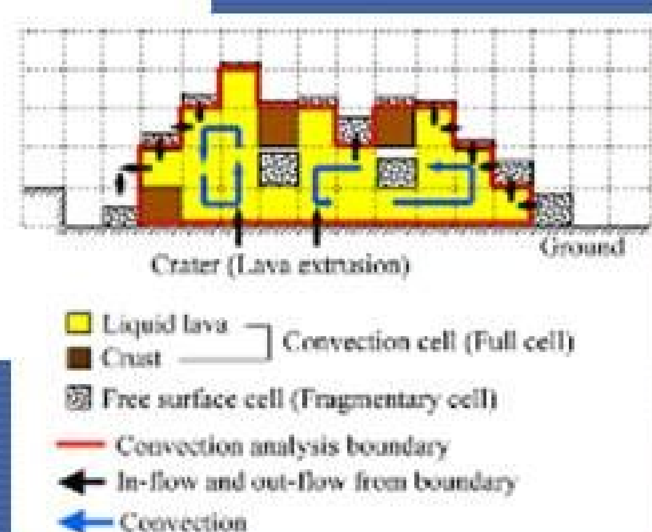
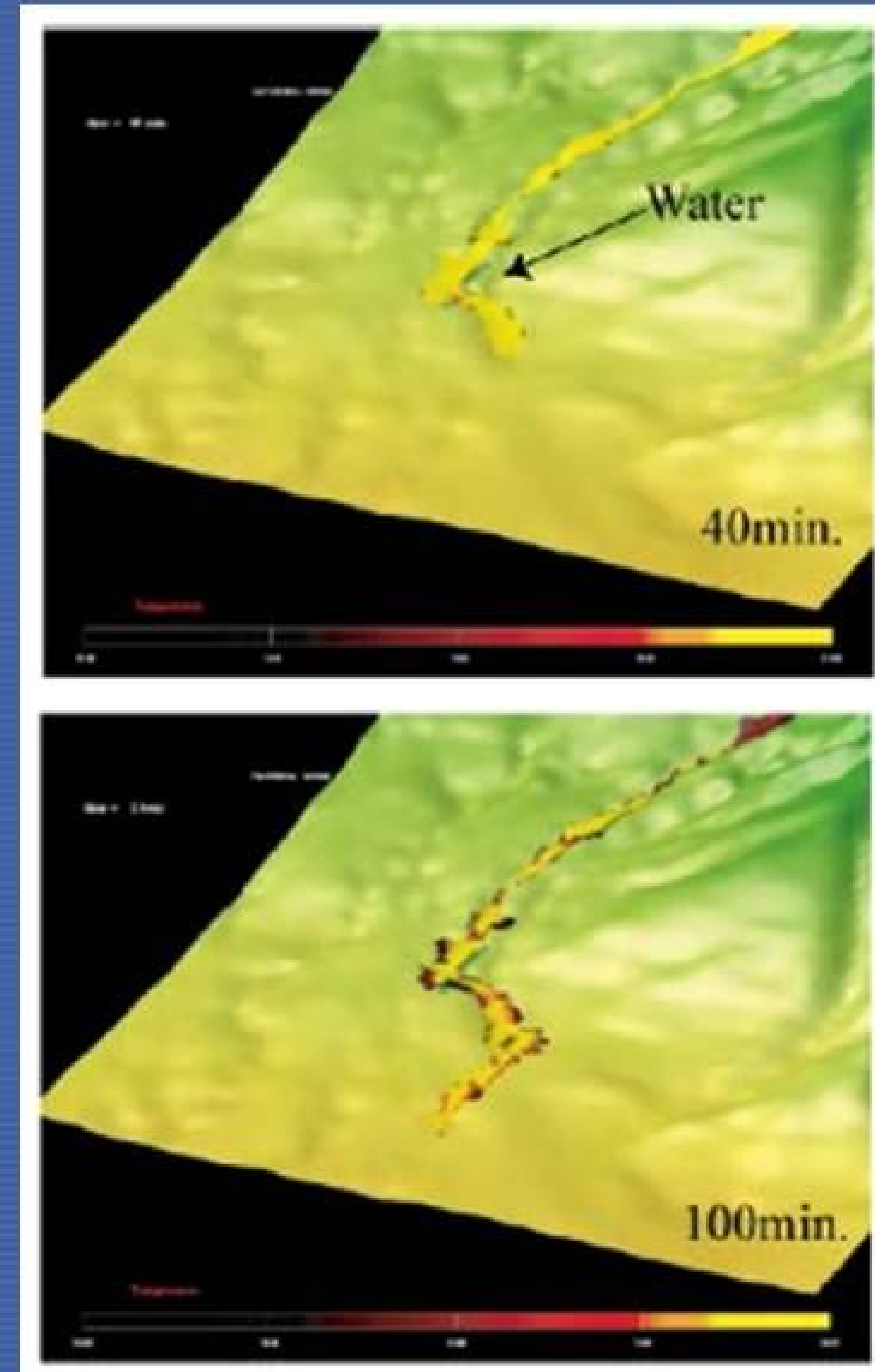
LavaSIM (Hidaka et al. 2005): a lava model for 3D convection, spreading and solidification



Symbol	Form	Cell attribution
(yellow)	Liquid lava	Convection cell
(dark red)	Crust	
(orange)	Liquid lava or crust	Free surface cell
(blue)	Ground	
(green)	Structure (Protection bank, etc.)	





CONCLUDING REMARKS

- Overview of the main hazardous phenomena due to volcanic activity.
- Characterization and impact of hazardous phenomena.
- Probabilistic and deterministic methods for hazards assessment.
- Stress on approaches to account for uncertainties (aleatory and epistemic).
- Example of hazards maps.

International Atomic Energy Agency

Thank you for your attention

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