INGV

VIRTUAL VOLCANOES

Computer simulations of volcanic eruptions

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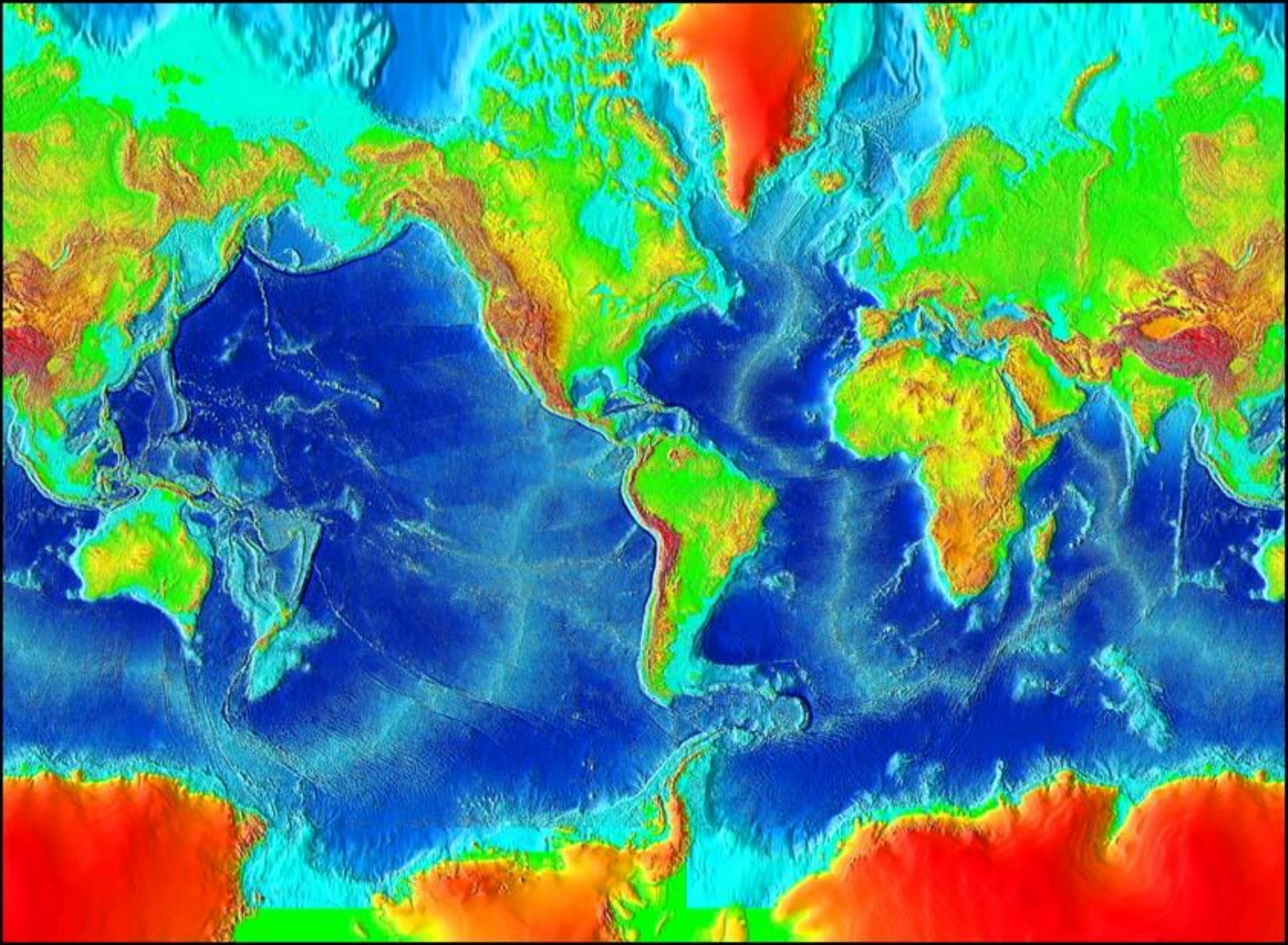
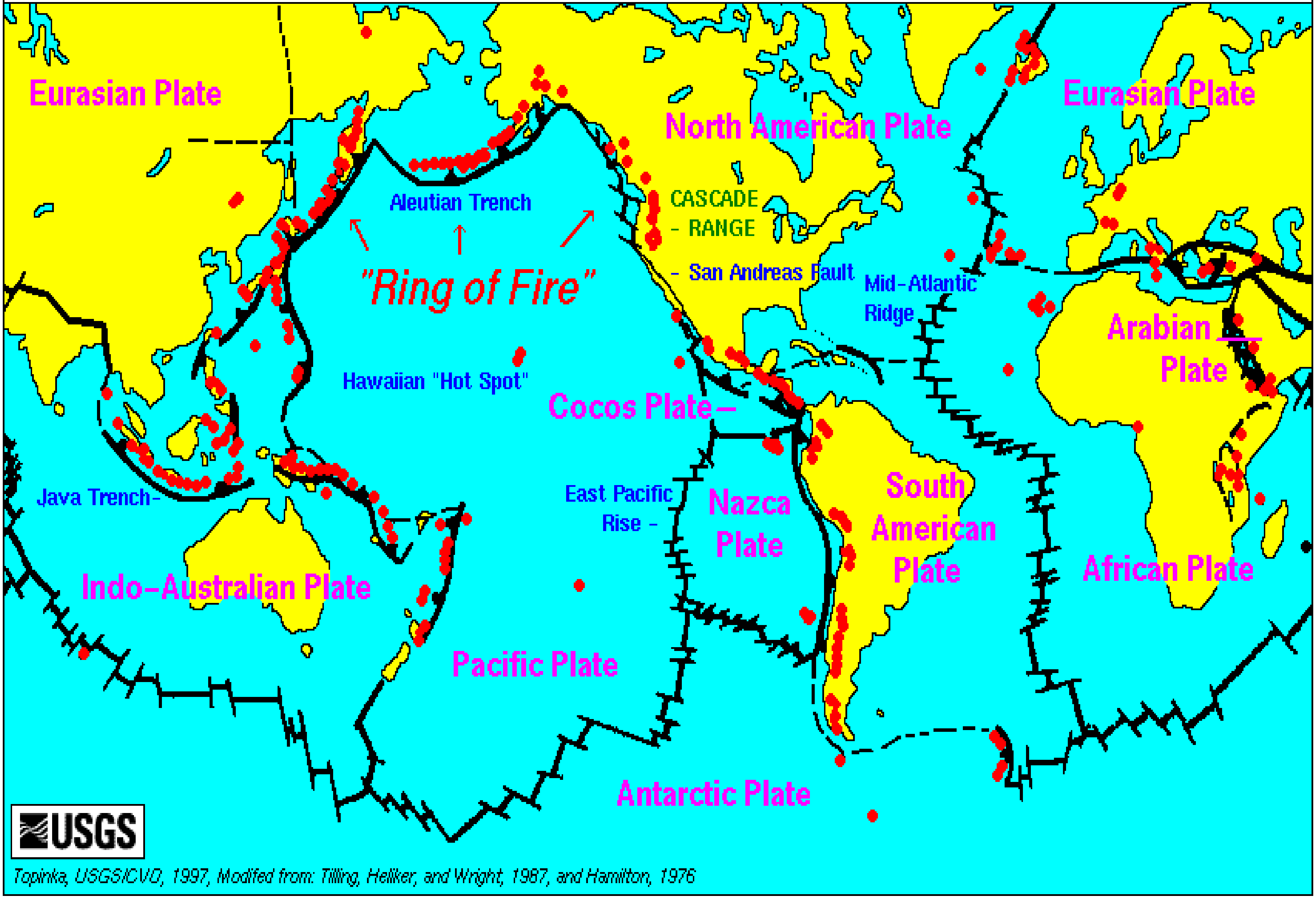
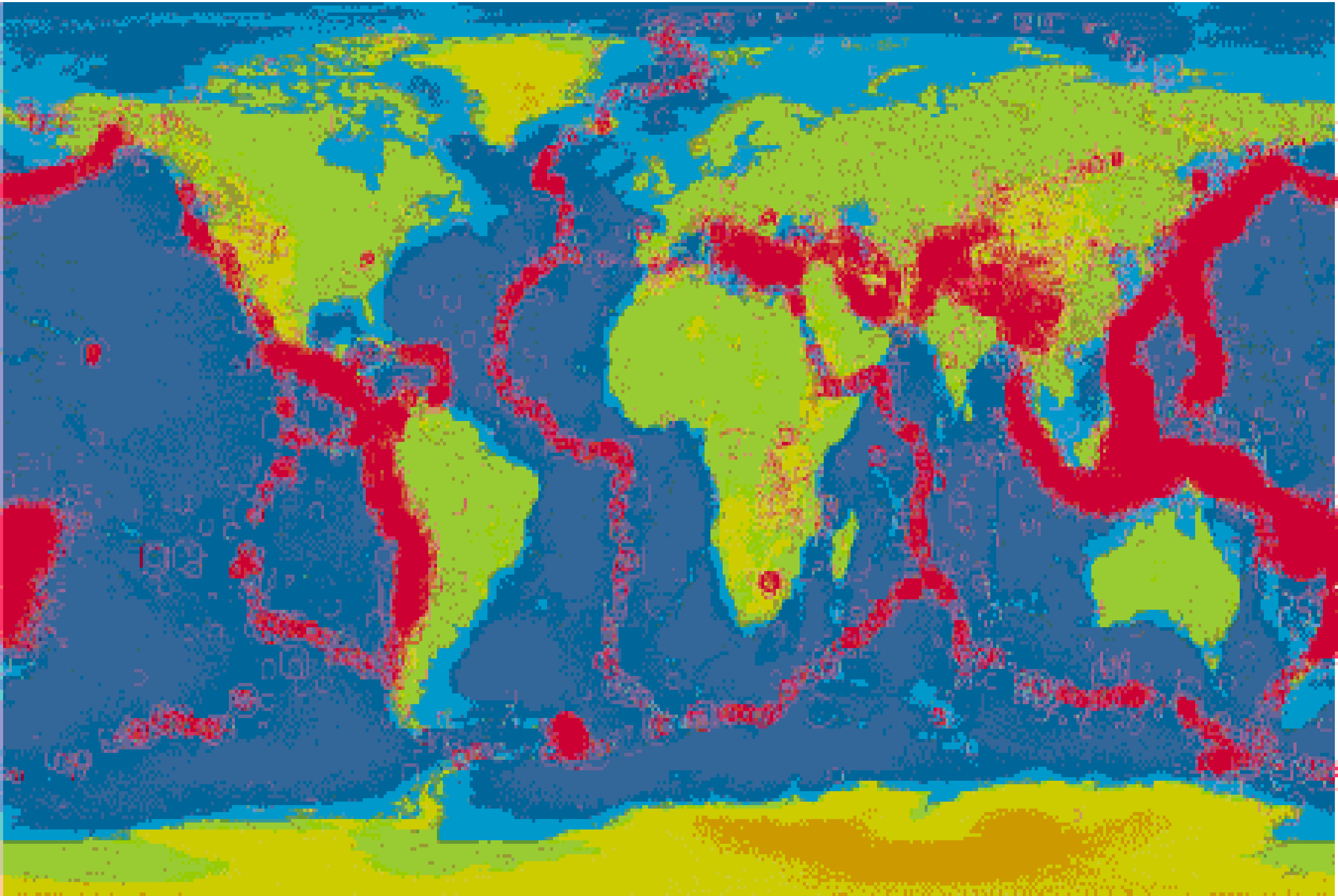


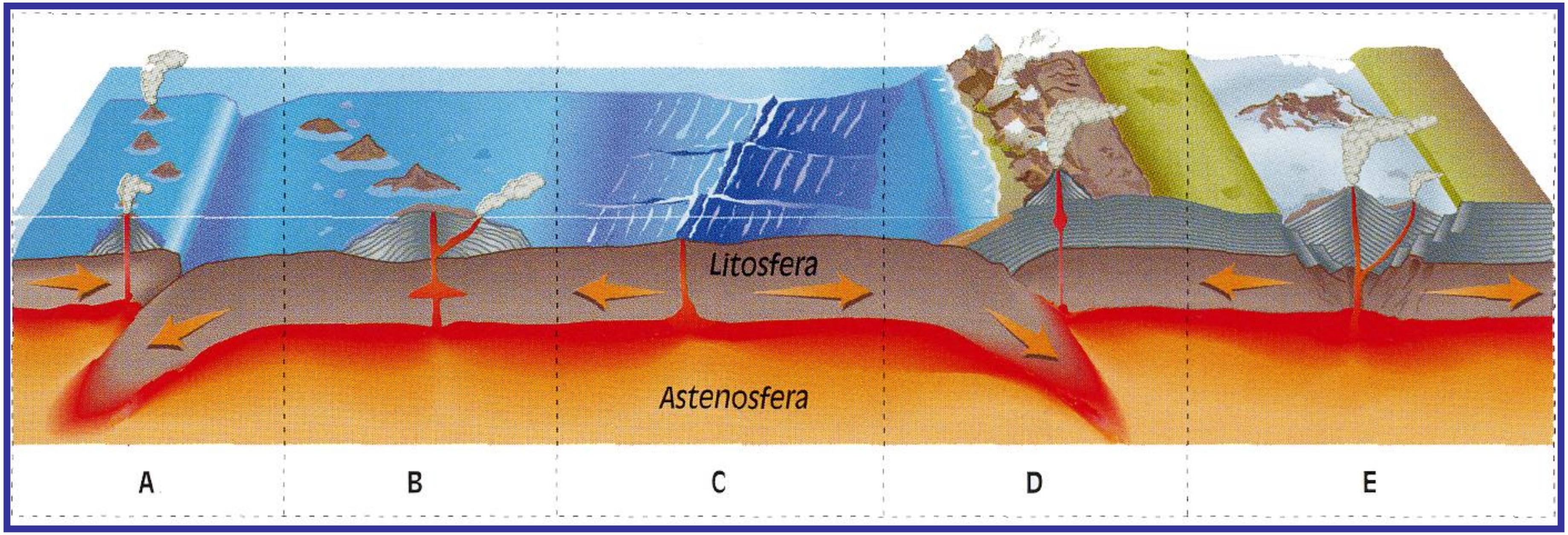
Plate tectonics and distribution of active volcanoes



Distribution of earthquakes on Earth's surface



Geodynamic scheme of volcano types and location



A) Island arc volcanoes (Aleutians, Japan, Indonesia)
B) Hot spot volcanoes (Hawaii)
C) Mid-ocean ridge volcanoes (Iceland)
D) Continental margin volcanoes (North America, Andes)
E) Continental rift volcanoes (East Africa)

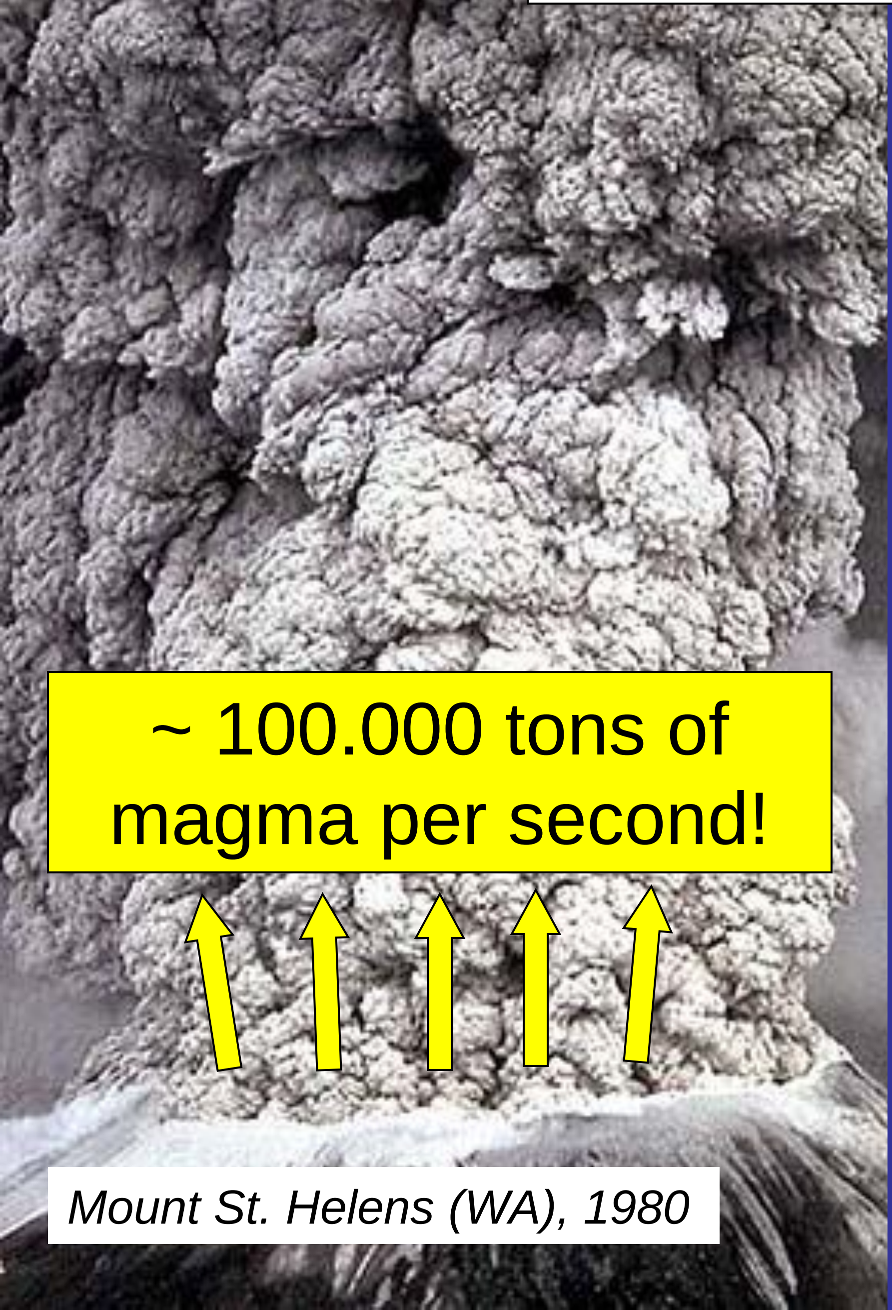
Effusive eruptions

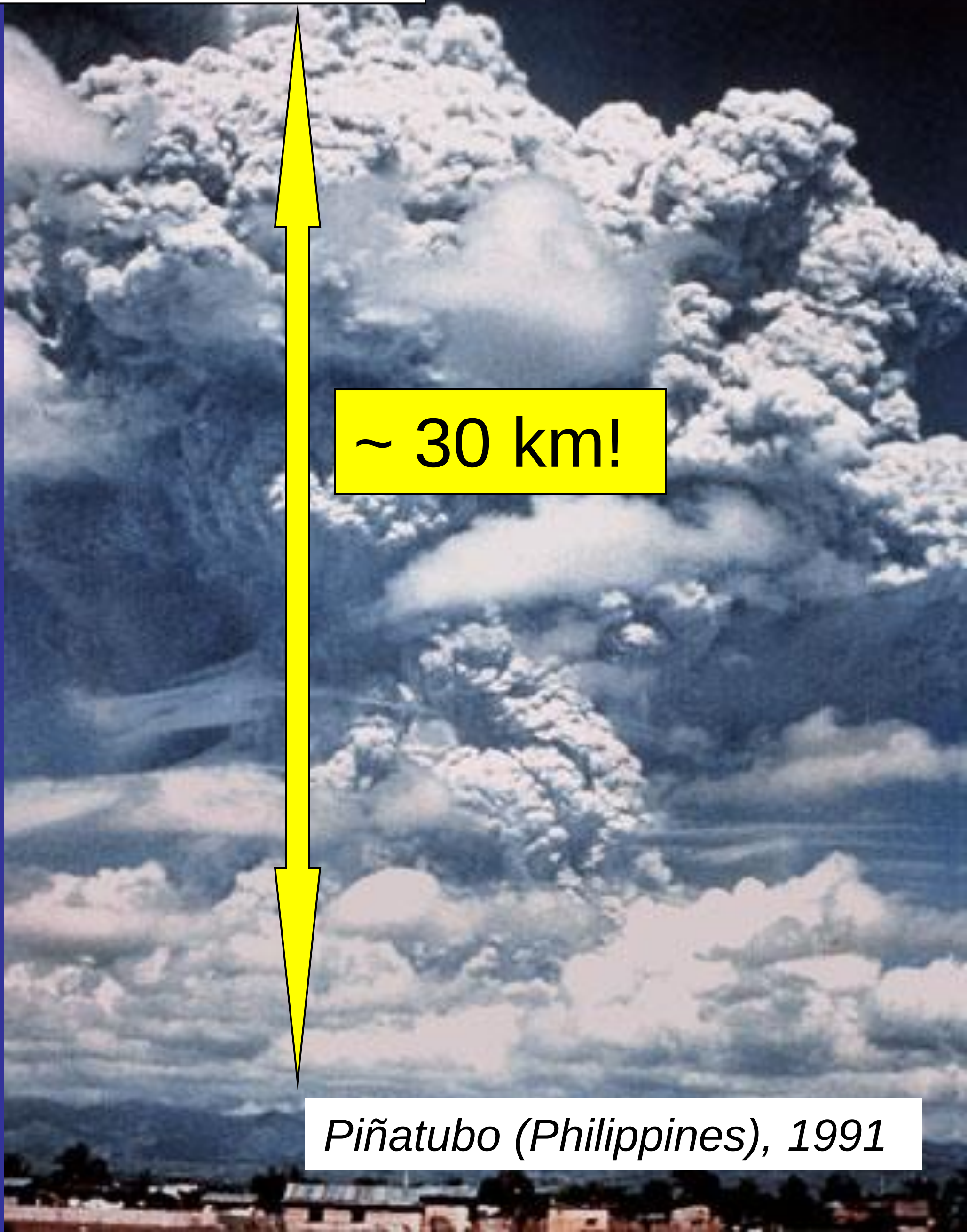
Lava fountains and lava flows at Hawaii

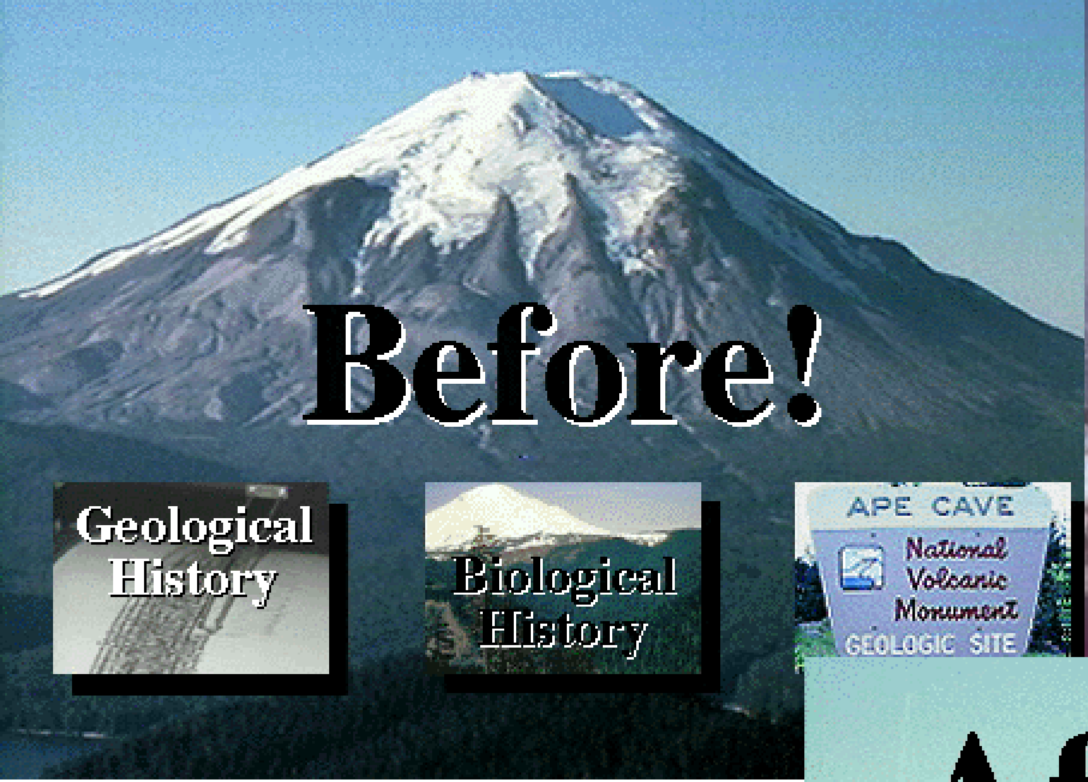

Kilauea volcano, Hawaii

Etna, Italy

Explosive eruptions

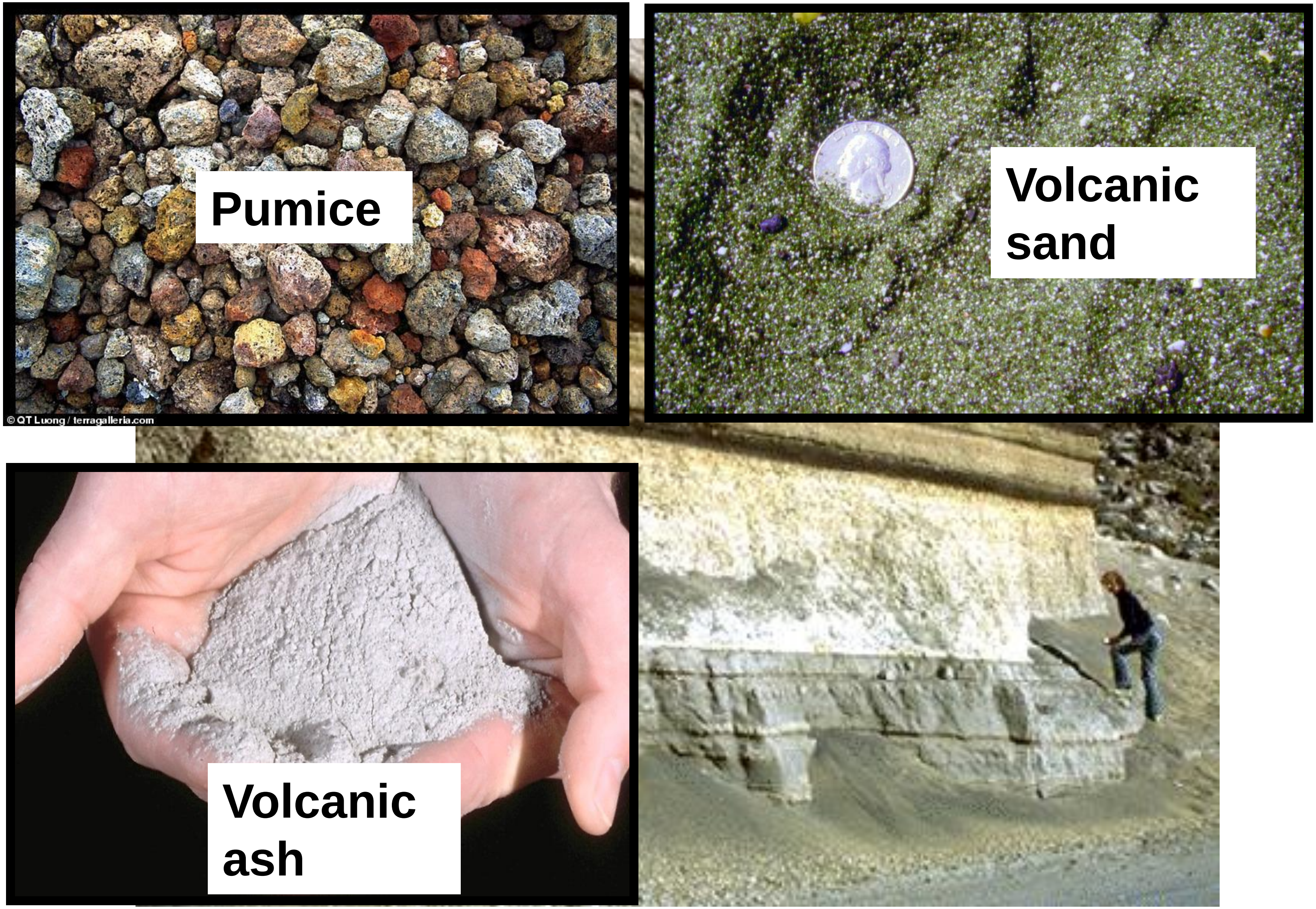




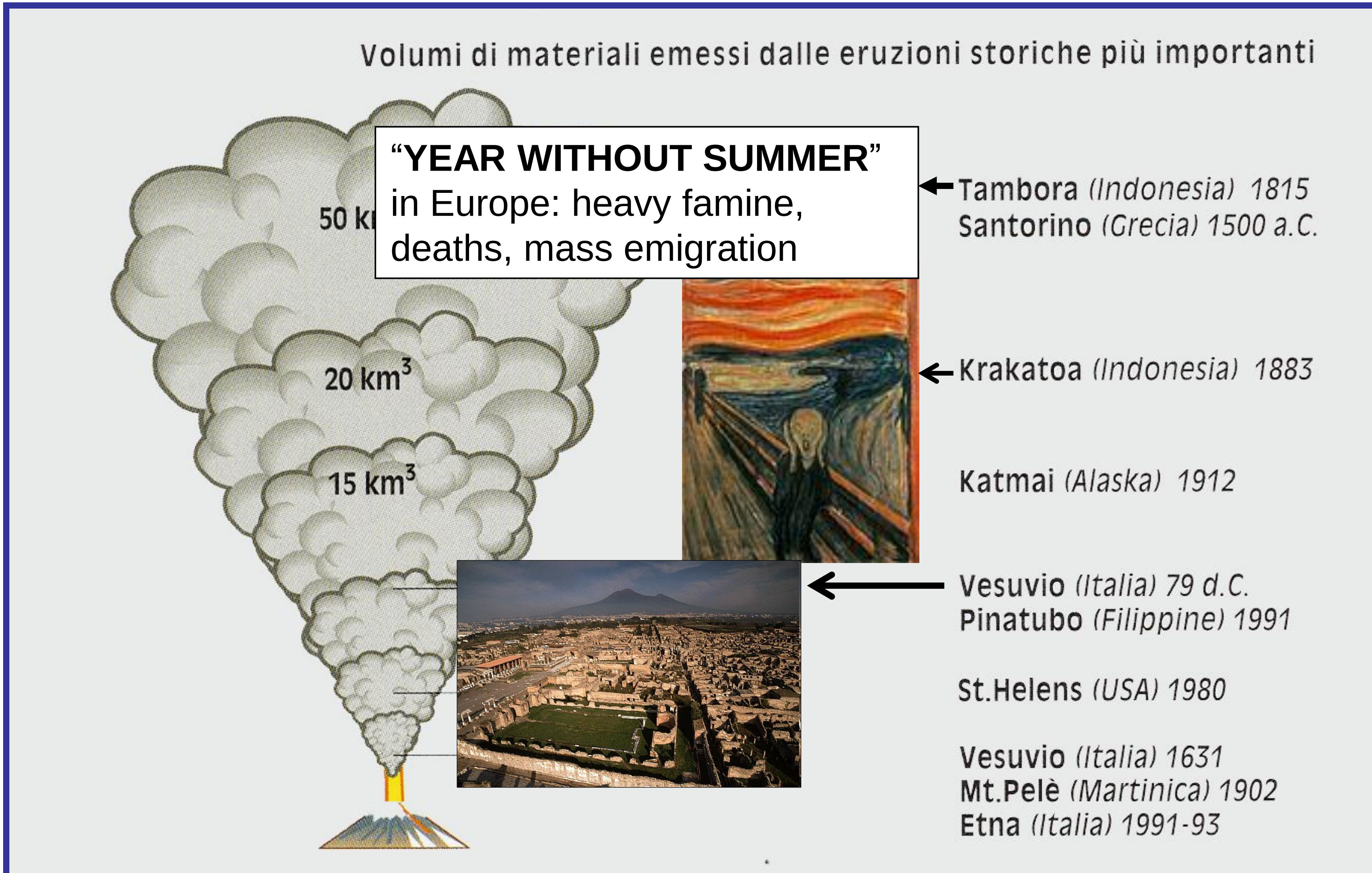


Mount St. Helens, WA (USA), 18 maggio 1980

Fallout from Plinian-type volcanic eruptions



Volume of products from historical eruptions



Comparison between energies from volcanic eruptions, other natural events, and that of the Hiroshima atomic bomb

Event	***Energy (Tons TNT)***	
	Minimum	***Maximum***
Landslide (Stromboli 2002)	100	1000
Tornado	1000	10000
Hiroshima bomb	10000	100000
Eruption of Mt. St Helens, 1980, or of Vesuvio, 1631	**One thousand** times larger than the Hiroshima bomb	
Campanian Ignimbrite eruption, 36 ka BP	**One million** times larger than the Hiroshima bomb	
Impact with asteroid (recurrence 100000 years)	10 billions	100 billions

Naples and Vesuvius (last eruption in 1944)

The active caldera of Campi Flegrei, on the other side of Naples (last eruption in AD 1538)

Popocatepetl volcano and Mexico City

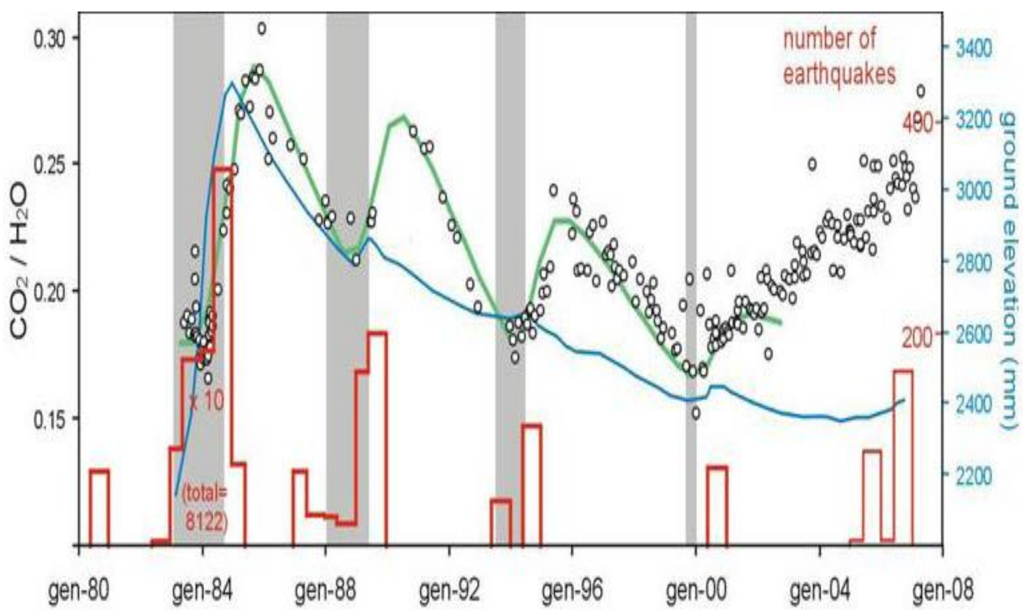
VOLCANO MONITORING

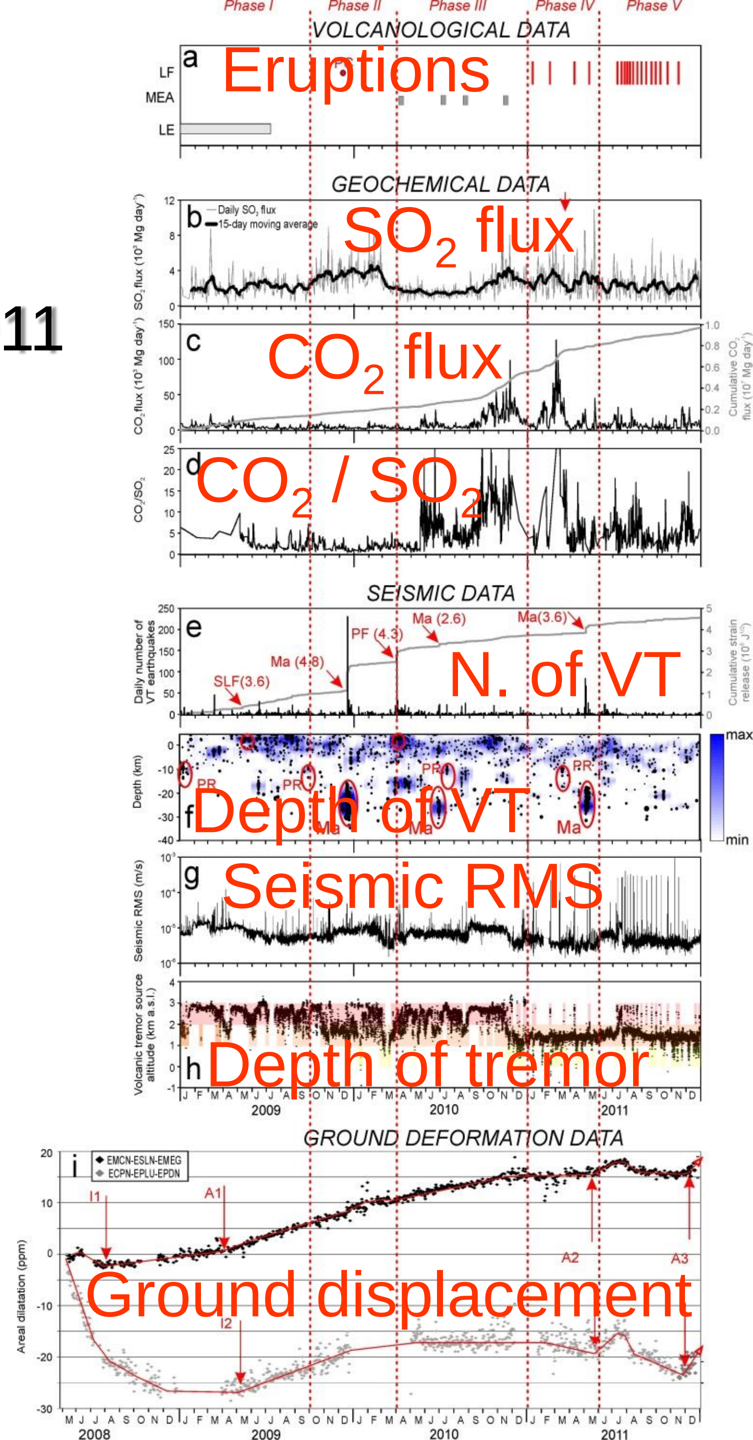
- Short-period and broadband seismic networks
- GPS networks
- Infrasonic networks
- Clinometric networks
- Borehole strainmeters
- Hydrometry
- Tidal gauges
- Gravimetric strations
- Visible light / IR cameras
- Meteorological stations
- Multiparametric geochemical stations (P-T-X, fluxes)
- SAR interferometry, satellite imagery
- ……

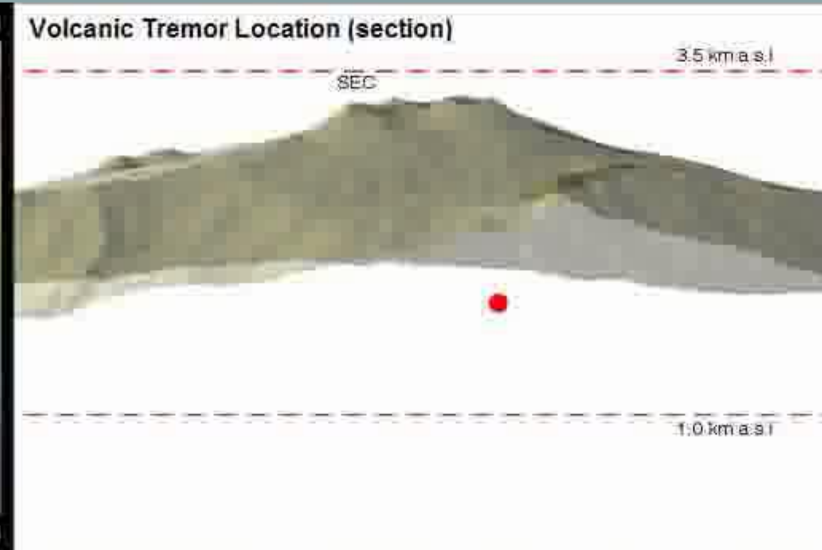
Subset of observations at:

Mount Etna, 2009 - 2011

Campi Flegrei, 1980 - 2008



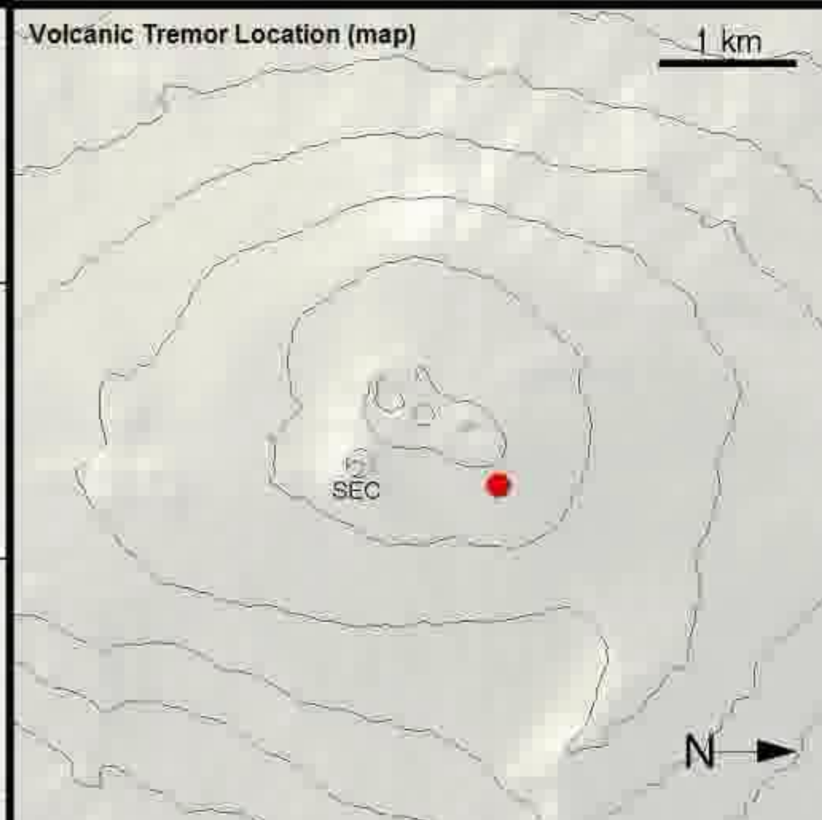




Seismic RMS

Infrasonic RMS

VOLDORAD 2B (agreement INGV - OPGC)



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Physico-mathematical modeling

During last decades the volcanological research has taken advantage of the developments in this technique

The **modelling** studies complement many others, like **stratigraphic** reconstructions from the volcanic deposits, **monitoring** of volcanic activity, **laboratory** investigations, etc.

What is a physico-mathematical model?

It is a virtual representation, in mathematical form, of the dynamics of a system, through the solution of the fundamental equations of physics.

A well-known example is that of meteorological models for weather forecasts

Fundamental equations

1. Mass conservation

   In a closed system, the total mass is constant

   $$[M_T]_{closed} = constant$$

2. Momentum balance (second Newton's law, or law of motion)

   The change in momentum (mass time velocity) of a body is equal to the sum of the external forces acting on the body

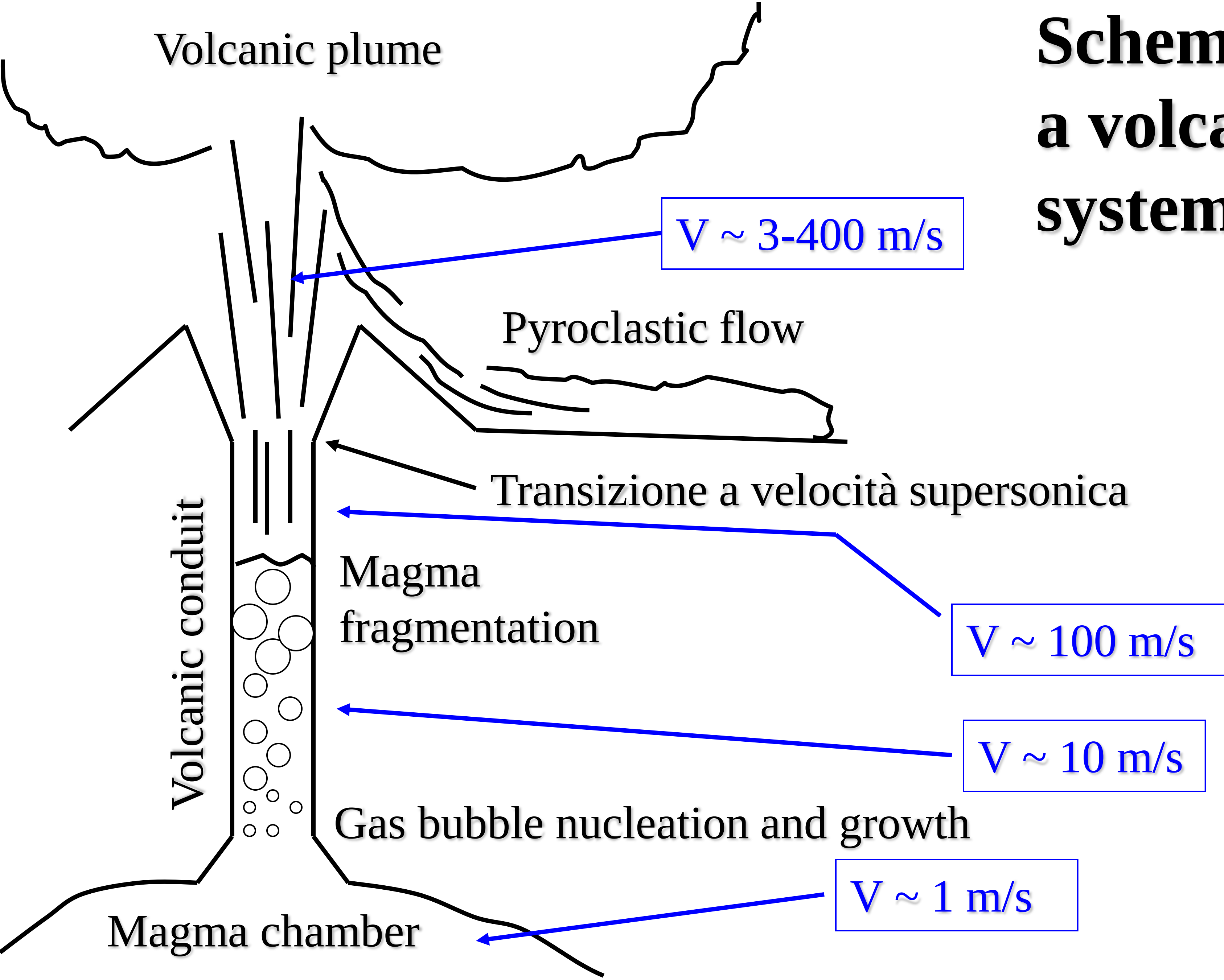
   $$\sum F_e = Ma$$

3. Energy balance (first principle of thermodynamics)

   The change in energy of a closed system is equal to the heat received minus the work done

   $$\Delta E = Q - W$$

Scheme of a volcanic system



Equations used to model the dynamics of volcanic plumes and pyroclastic flows

Mass conservation

Gas phase:

$$\frac{\partial}{\partial t}\varepsilon_g\rho_g + \nabla\cdot(\varepsilon_g\rho_g\mathbf{v}_g) = 0$$

Solid phase:

$$\frac{\partial}{\partial t}\varepsilon_k\rho_k + \nabla\cdot(\varepsilon_k\rho_k\mathbf{v}_k) = 0 \qquad k = 1,2,\ldots N \qquad \varepsilon_g + \sum_{k=1}^{N}\varepsilon_k = 1$$

Momentum balance

Gas phase:

$$\frac{\partial}{\partial t}\varepsilon_g\rho_g\mathbf{v}_g + \nabla\cdot(\varepsilon_g\rho_g\mathbf{v}_g\mathbf{v}_g) = -\varepsilon_g\nabla P_g + \nabla\mathbf{T}_g + \varepsilon_g\rho_g\mathbf{g} + \sum_{k=1}^{N}D_{g,k}(\mathbf{v}_k - \mathbf{v}_g)$$

Solid phase:

$$\frac{\partial}{\partial t}\varepsilon_k\rho_k\mathbf{v}_k + \nabla\cdot(\varepsilon_k\rho_k\mathbf{v}_k\mathbf{v}_k) = -\varepsilon_k\nabla P_g + \nabla\mathbf{T}_k + \varepsilon_k\rho_k\mathbf{g} - D_{g,k}(\mathbf{v}_k - \mathbf{v}_g) + \sum_{k=1}^{N}D_{k,j}(\mathbf{v}_j - \mathbf{v}_k)$$

$$k, j = 1,2,\ldots N$$

Energy balance

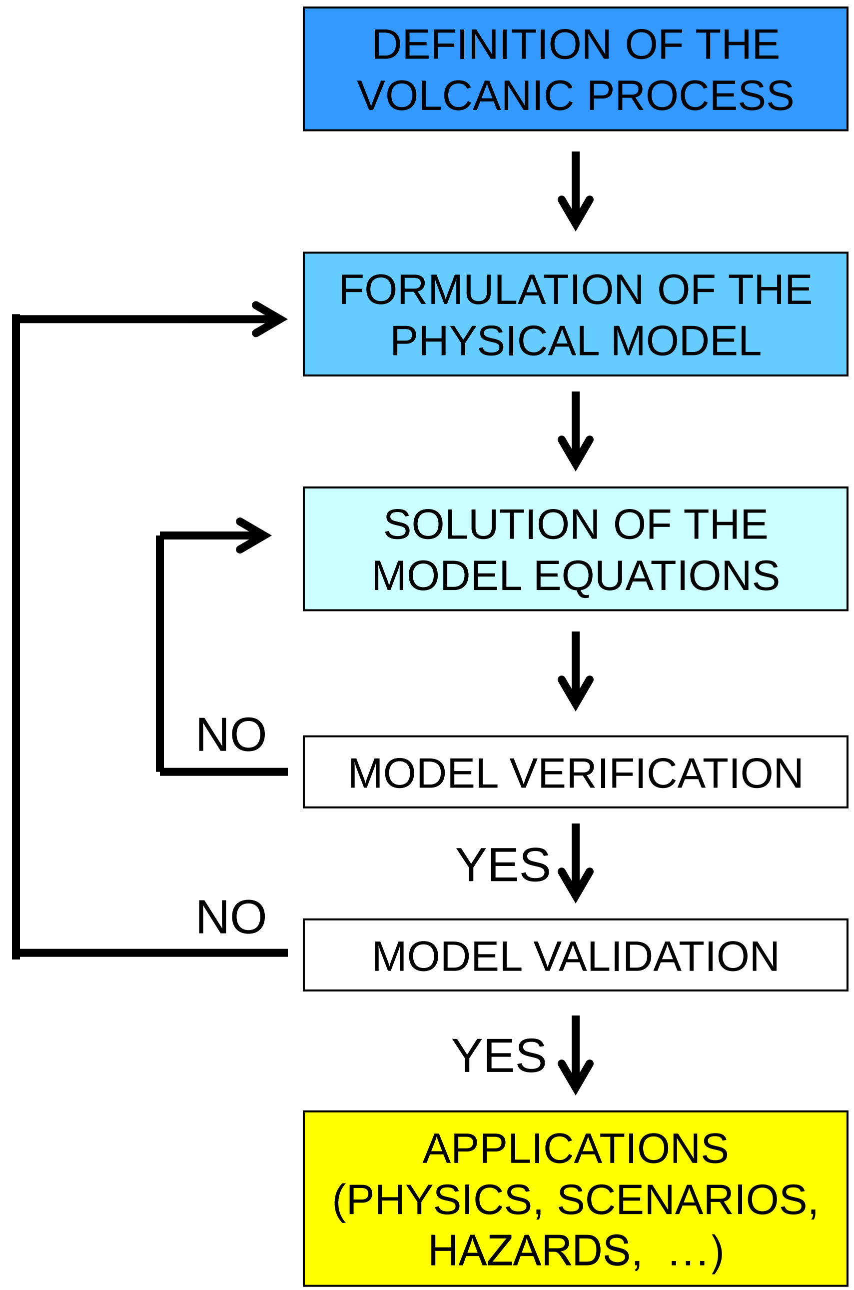
Gas phase:

$$\frac{\partial}{\partial t}\varepsilon_g\rho_g h_g + \nabla\cdot(\varepsilon_g\rho_g h_g\mathbf{v}_g) = \varepsilon_g\left(\frac{\partial P_g}{\partial t} + \mathbf{v}_g\cdot\nabla P_g\right) + \nabla\cdot(k_{ge}\varepsilon_g\nabla T_g) + \sum_{k=1}^{N}Q_k(T_k - T_g)$$

Solid phase:

$$\frac{\partial}{\partial t}\varepsilon_k\rho_k h_k + \nabla\cdot(\varepsilon_k\rho_k h_k\mathbf{v}_k) = \nabla\cdot(k_{ke}\varepsilon_k\nabla T_k) - Q_k(T_k - T_g);\, k = 1,2\ldots N$$

Flow diagram of the modeling approach



USES:

1. Investigate the physics of volcanic processes

2. Foresee volcanic scenarios, forecast volcanic hazards

PROBLEMS

- The transport equations tell us how the relevant physical quantities change at any point in space and any instant of time.

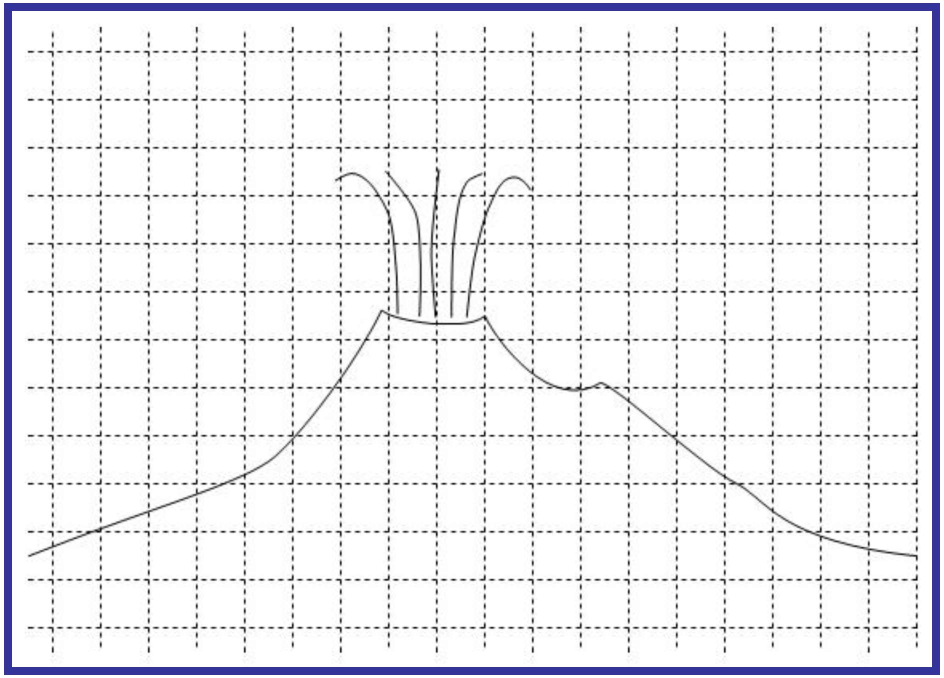
PROBLEM!! Exact solutions to the transport equations are NOT KNOWN.

SOLUTION: we look for approximate solutions (that's what computer simulations do)

PROBLEM!! Computers have a finite memory.

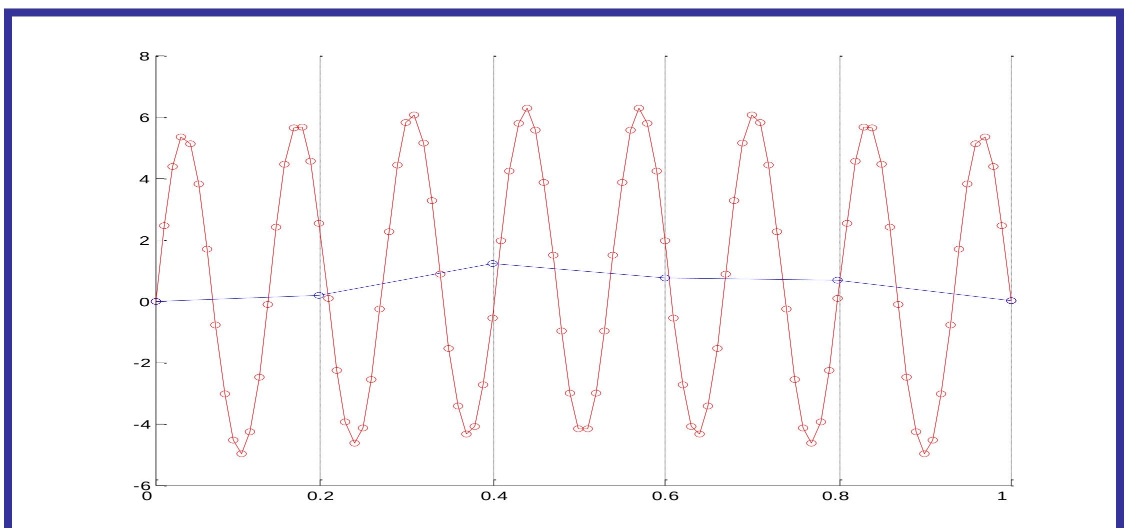
SOLUTION: the solutions are found at only some specified points in space, and only at specified times.

We discretize the space through a grid



Keeping in mind the effects of the approximations we introduce, is crucial in order to correctly understand and use numerical results

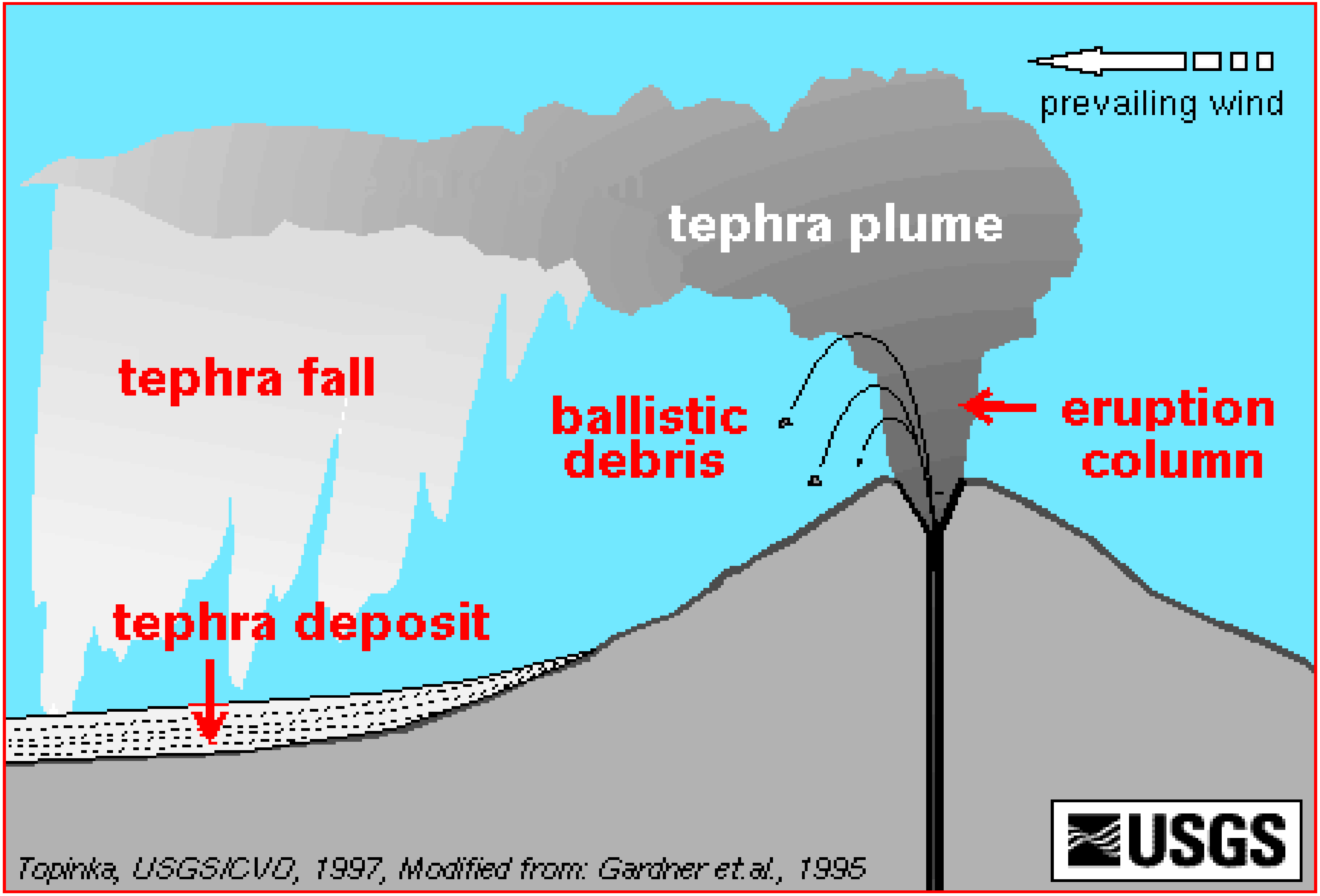
Quantities computed at discrete points on a grid represent a spatial average of that quantity around each point.



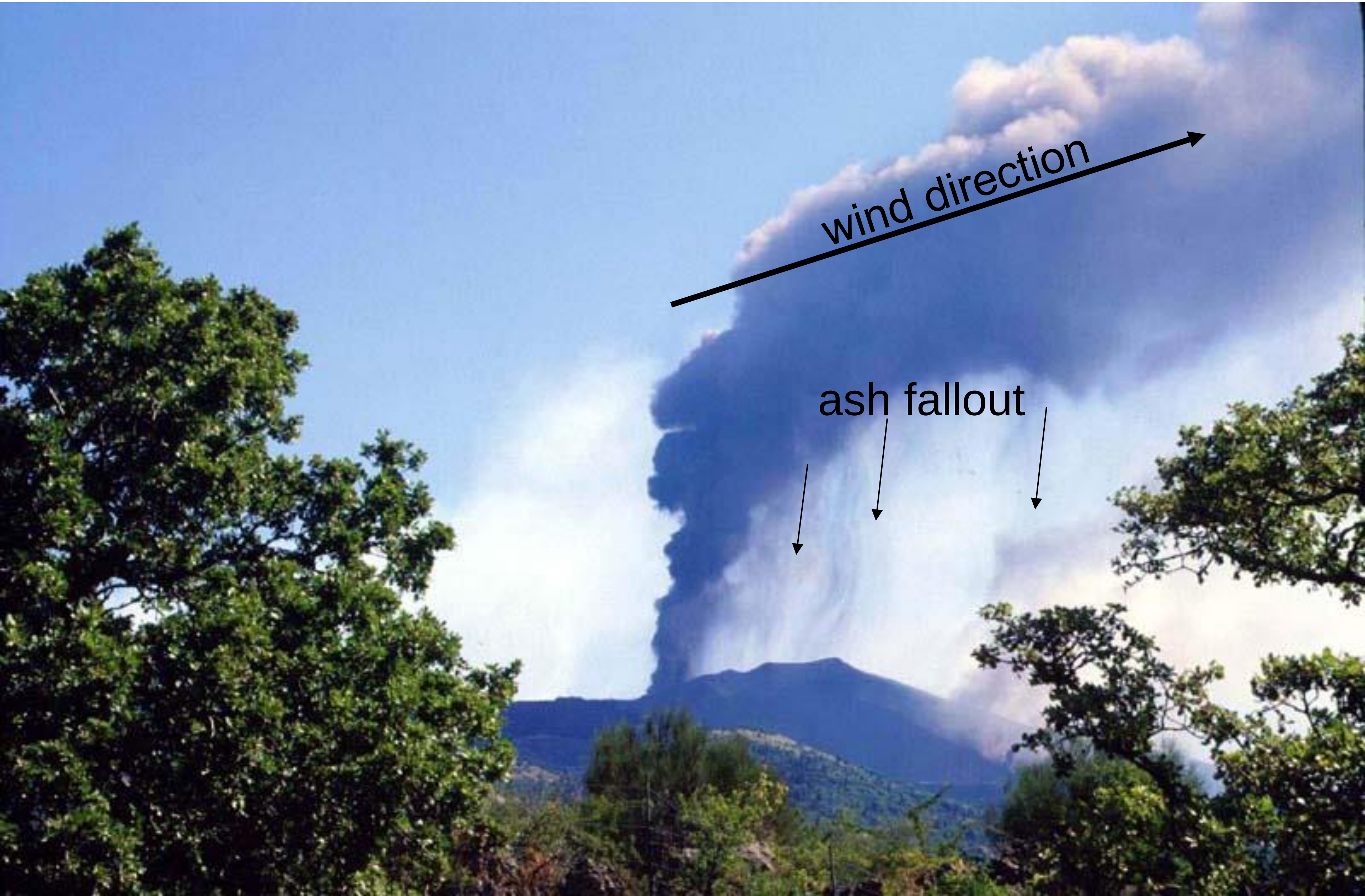
SOME EXAMPLES

1. Ash dispersal

Volcanic tephra fallout



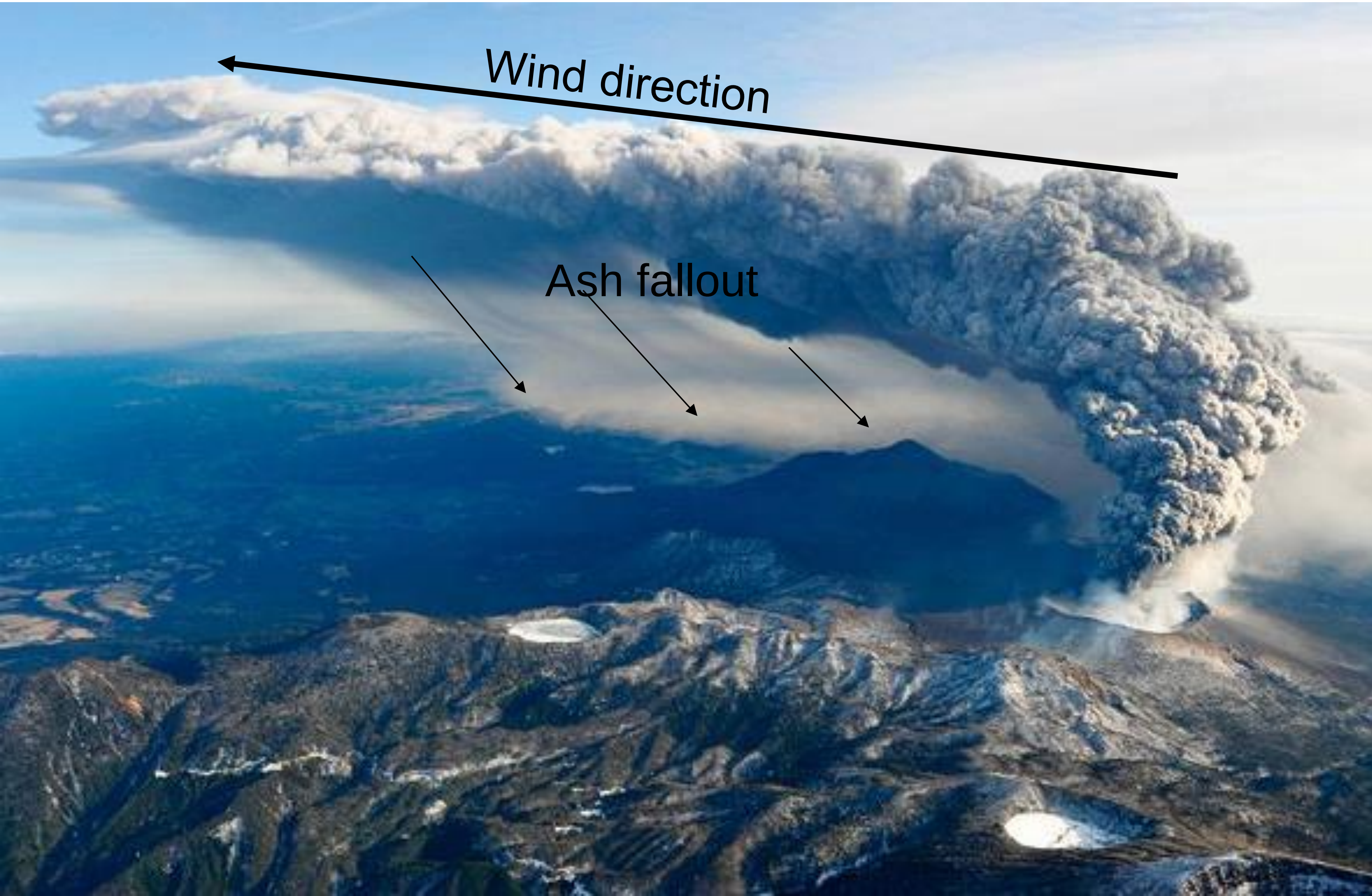
Volcanic tephra fallout, Etna 2001



Even relatively small, effusive eruptions giving rise to lava flows can discharge significant ash into the atmosphere

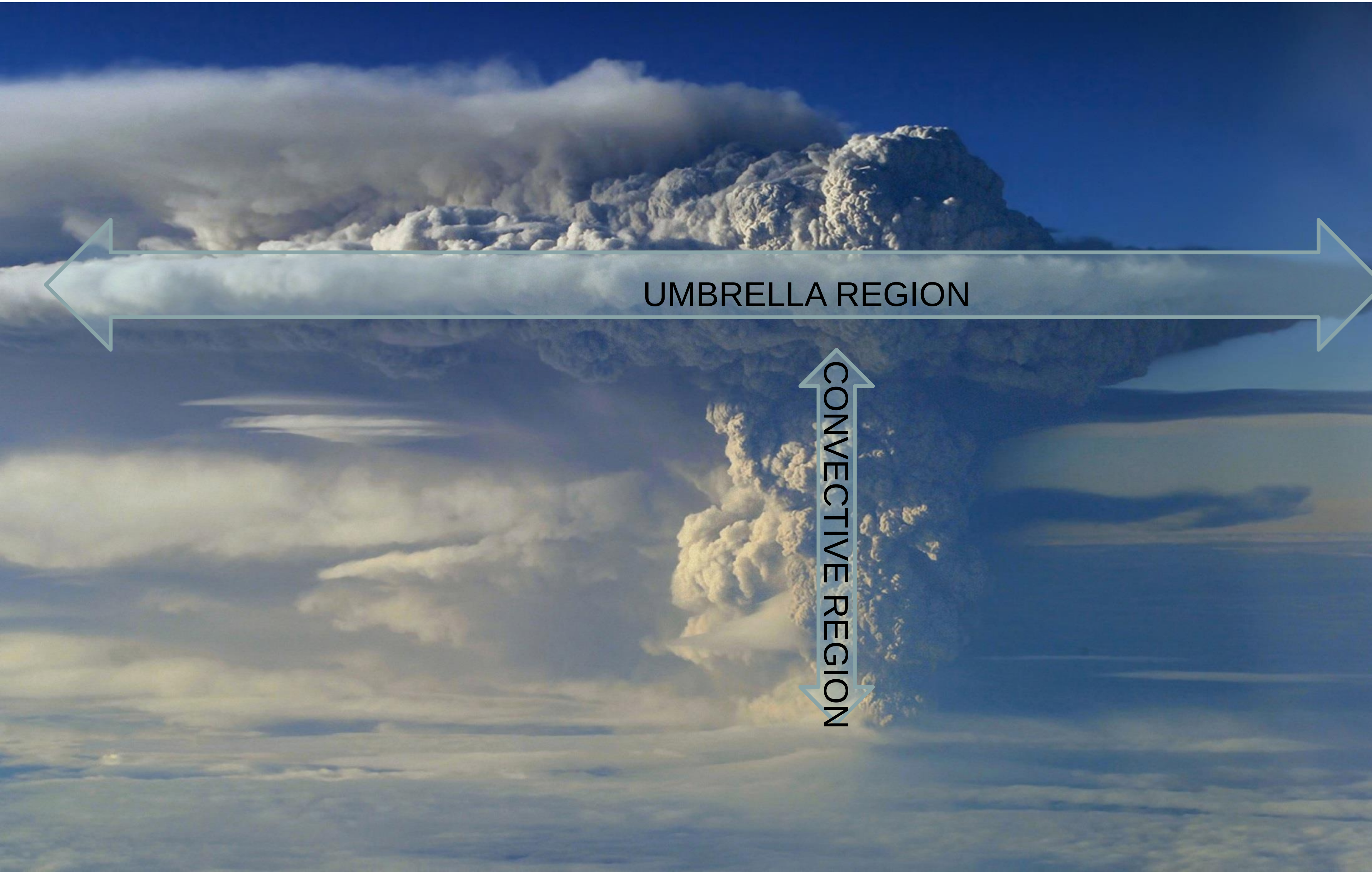
One eruption at Etna, seen from the satellite

Volcanic plume and tephra fallout, Merapi, Indonesia



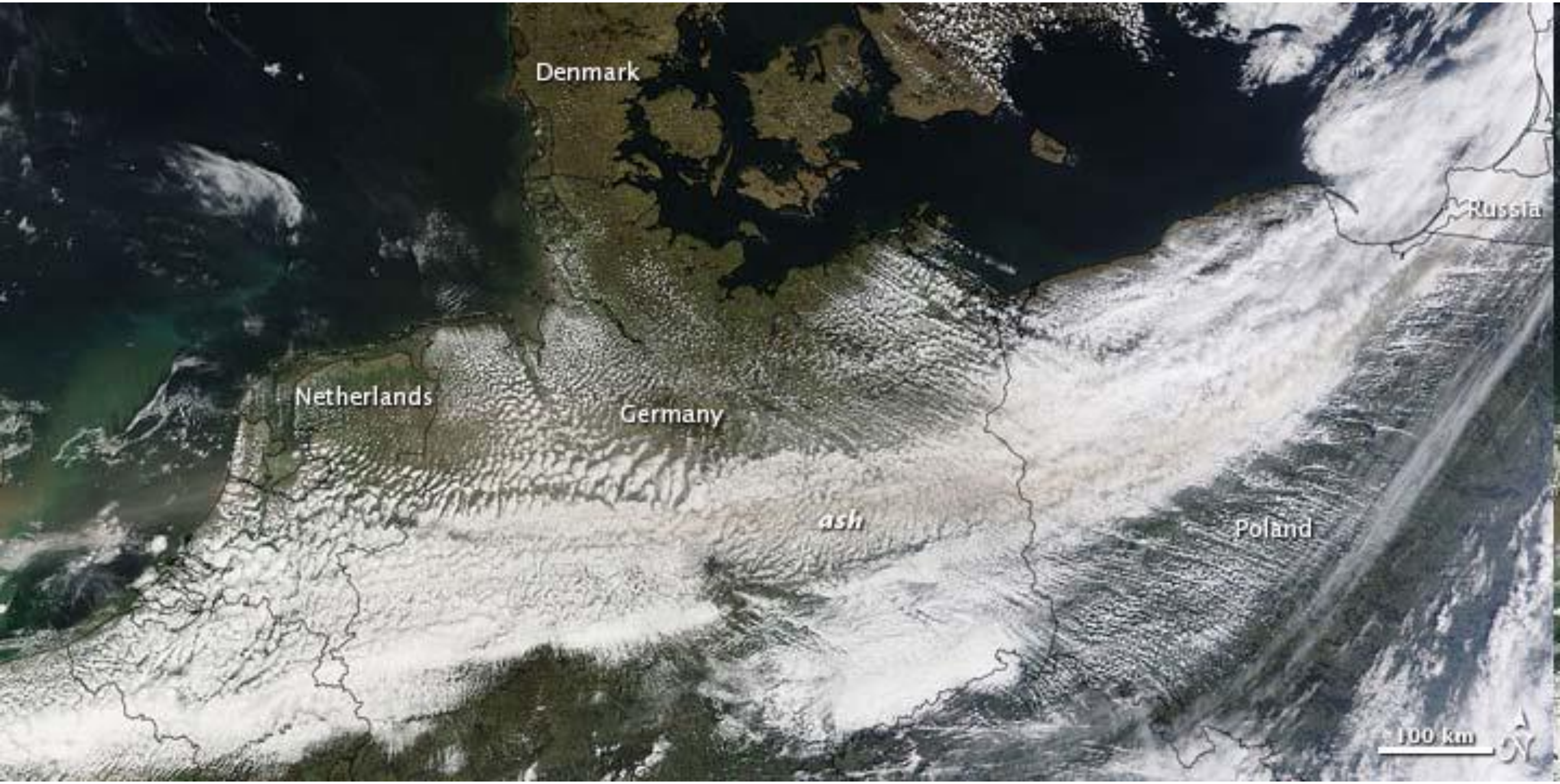
Volcanic columns

Volcanic columns



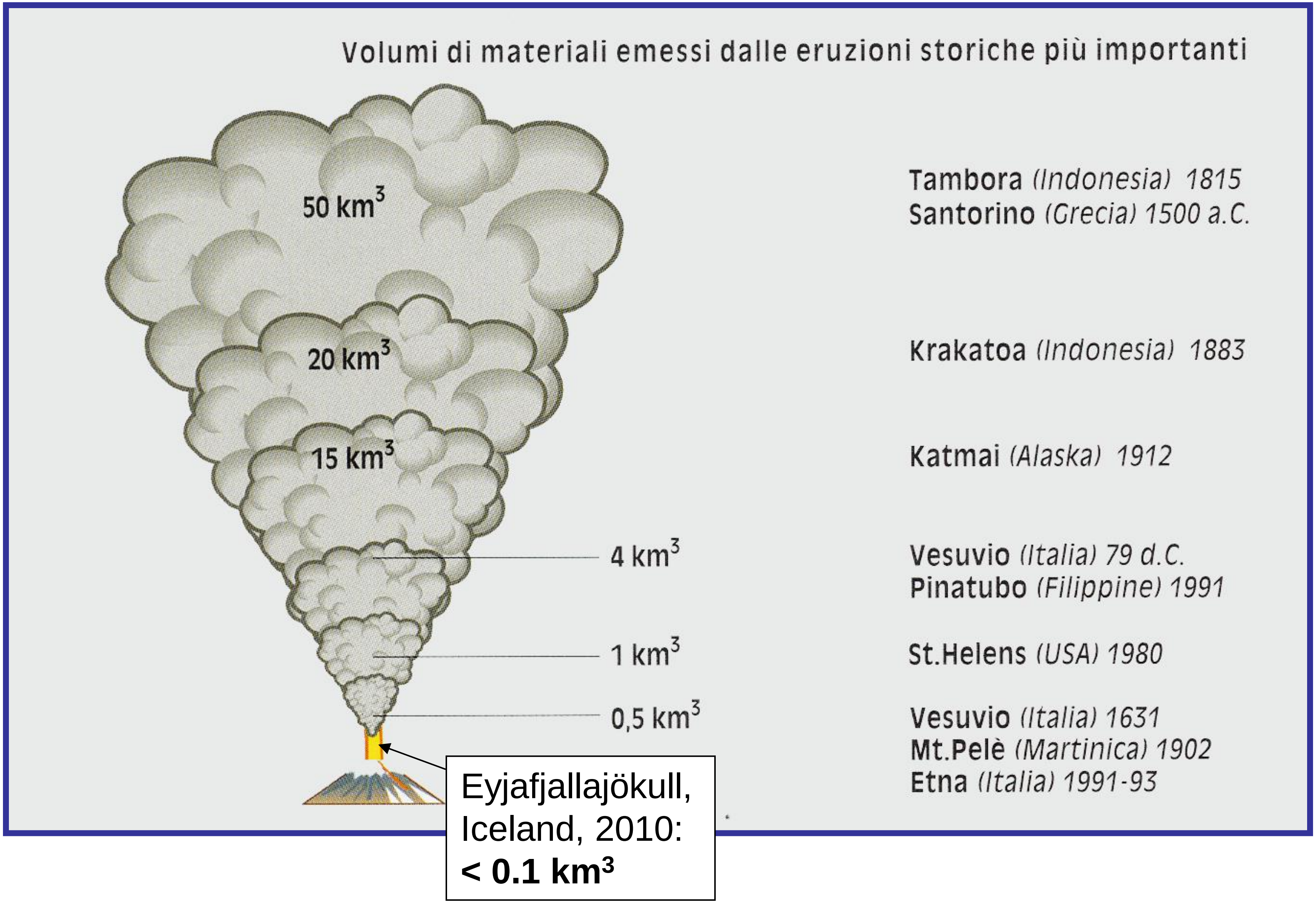
The eruption of Eyjafjallajökull, Iceland, in 2010

The ash plume from Eyjafjallajökull on Northern Europe, March 2010



The air traffic was shut down for days, with an economic loss of **one billion of euros per day**

Volume of products from historical eruptions



Ash fallout from Plinian-type volcanic eruptions

Piňatubo volcano , Philippines, 1991

Effects of volcanic ashes

Effects of volcanic ashes

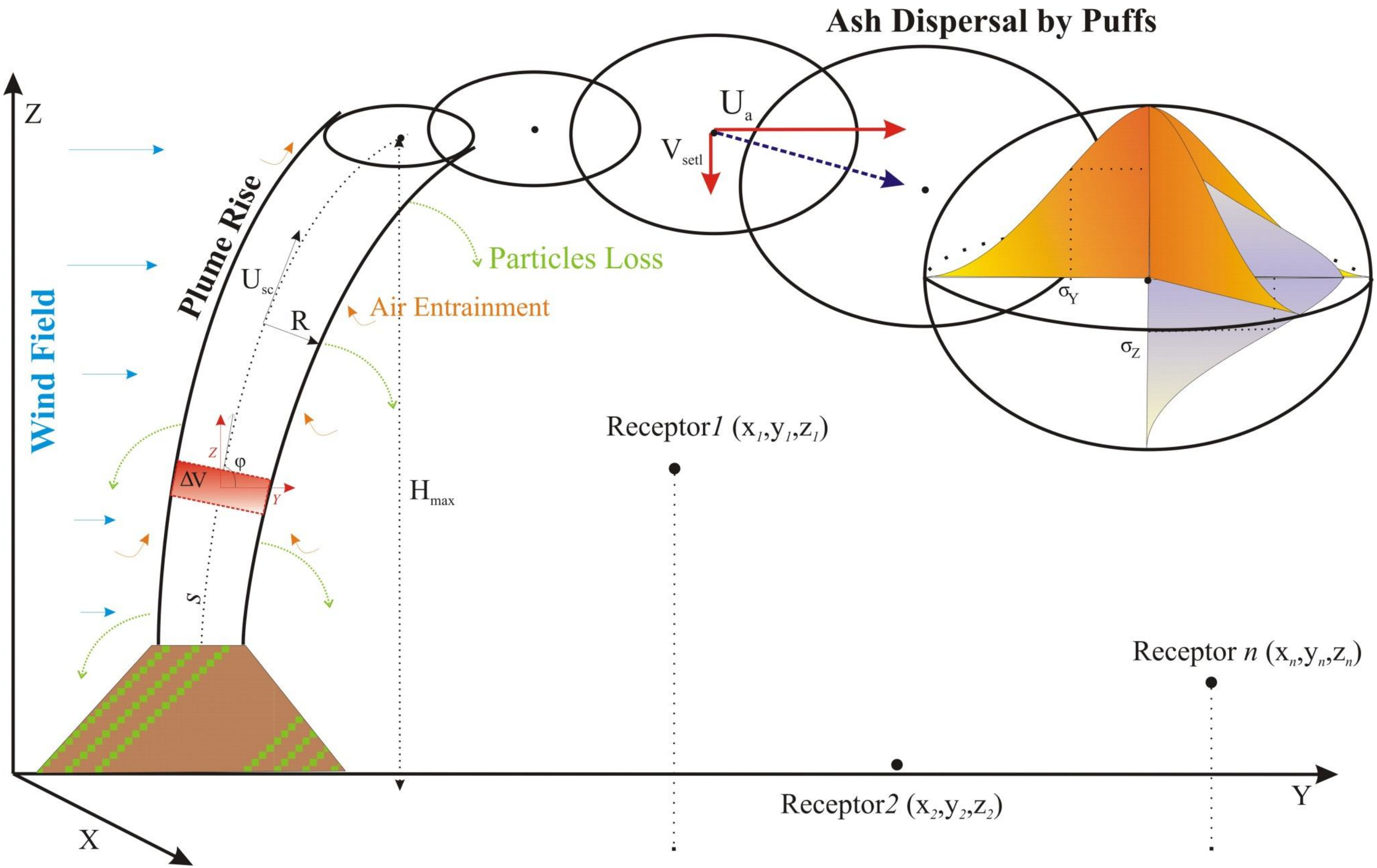
Collapse of structures under the load of volcanic ash

Removal of volcanic ash from roofs

Removal of volcanic ash from roofs

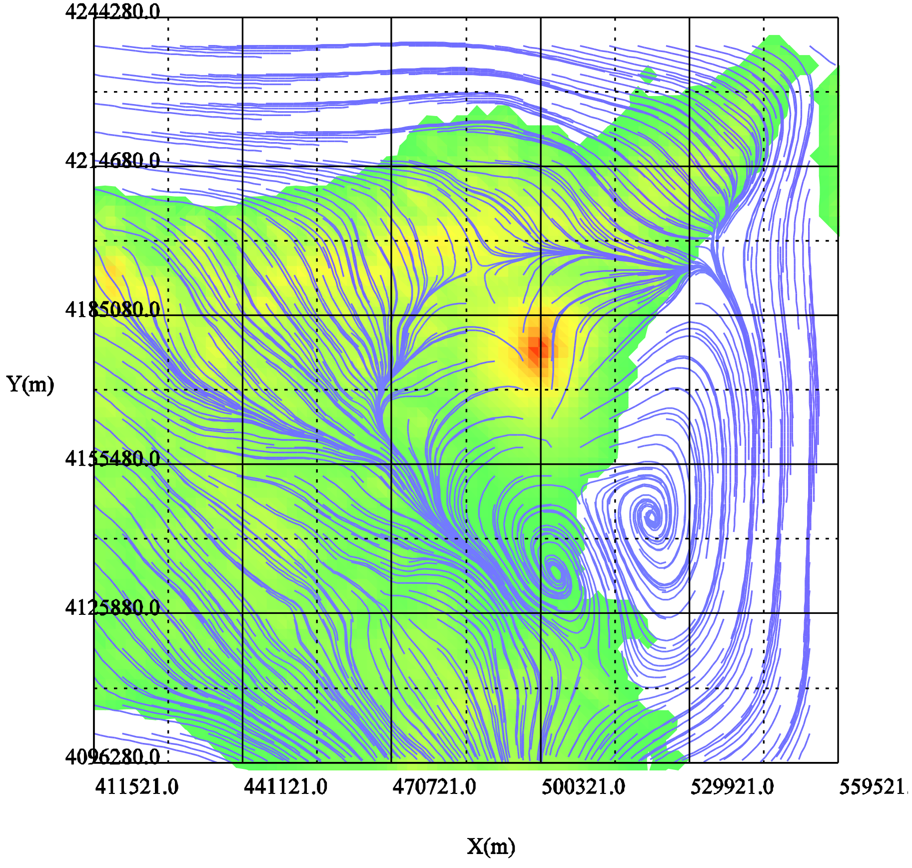
Ingestion of volcanic ash may kill animals

Physical model of plume rise and ash dispersal

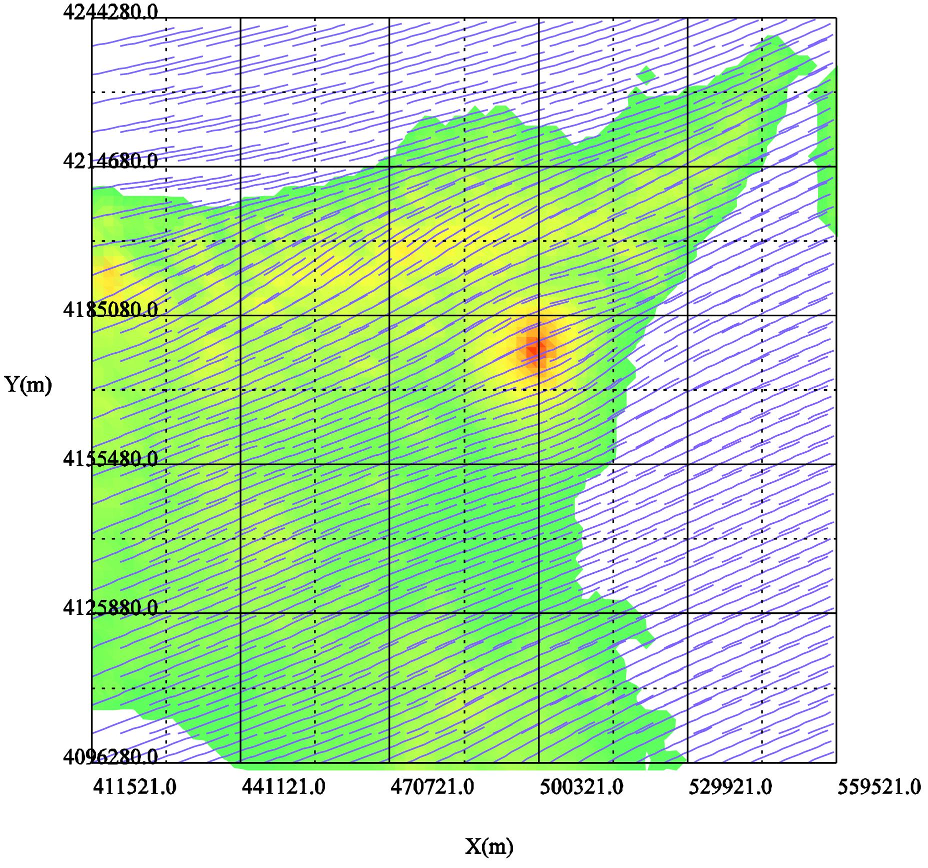


Wind field at different heights

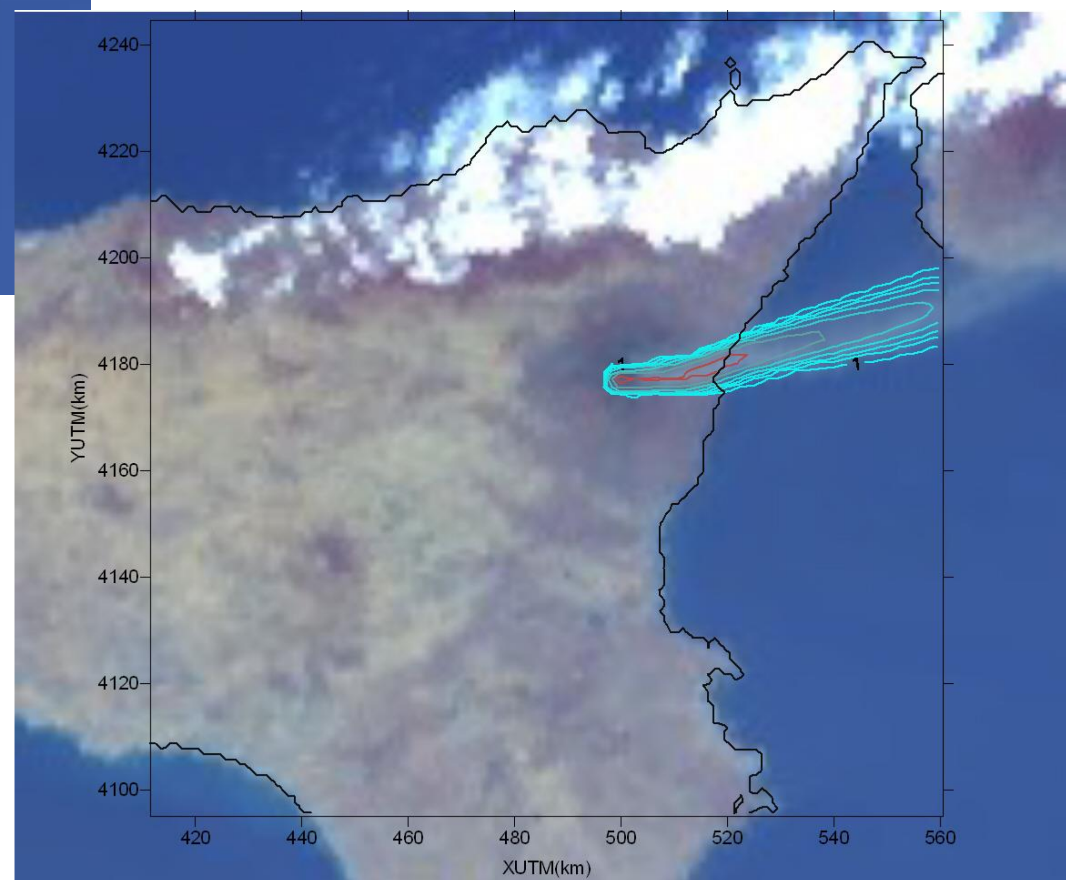
400 m agl



2200 m agl

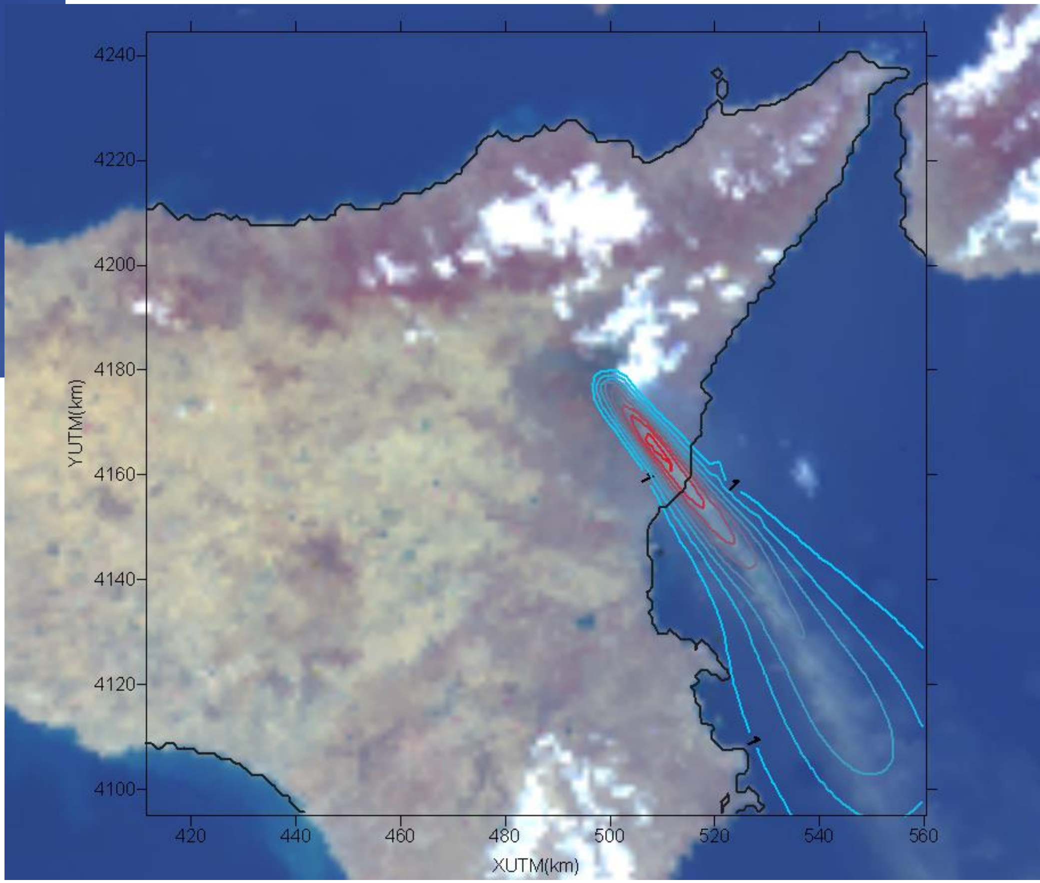


Satellite image



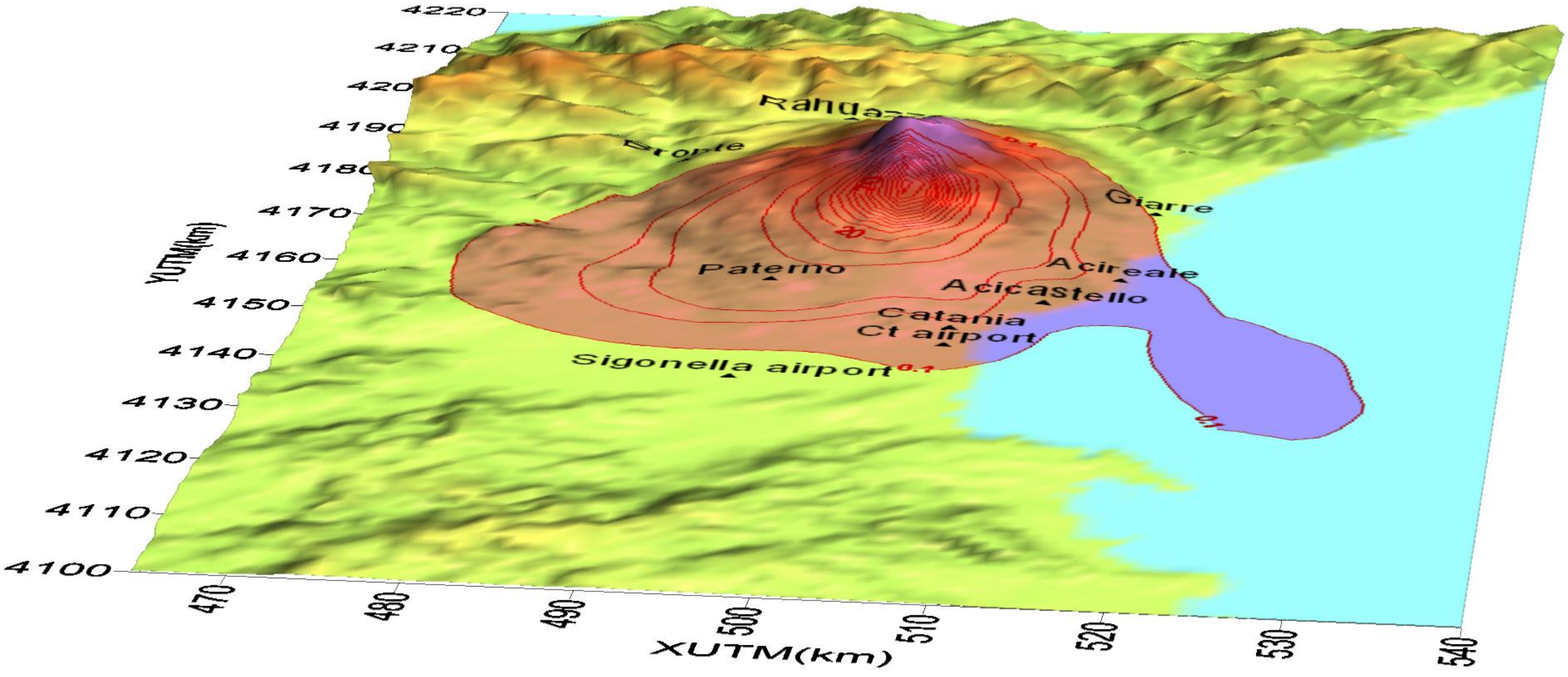
Numerical simulation

Satellite image



Numerical simulation

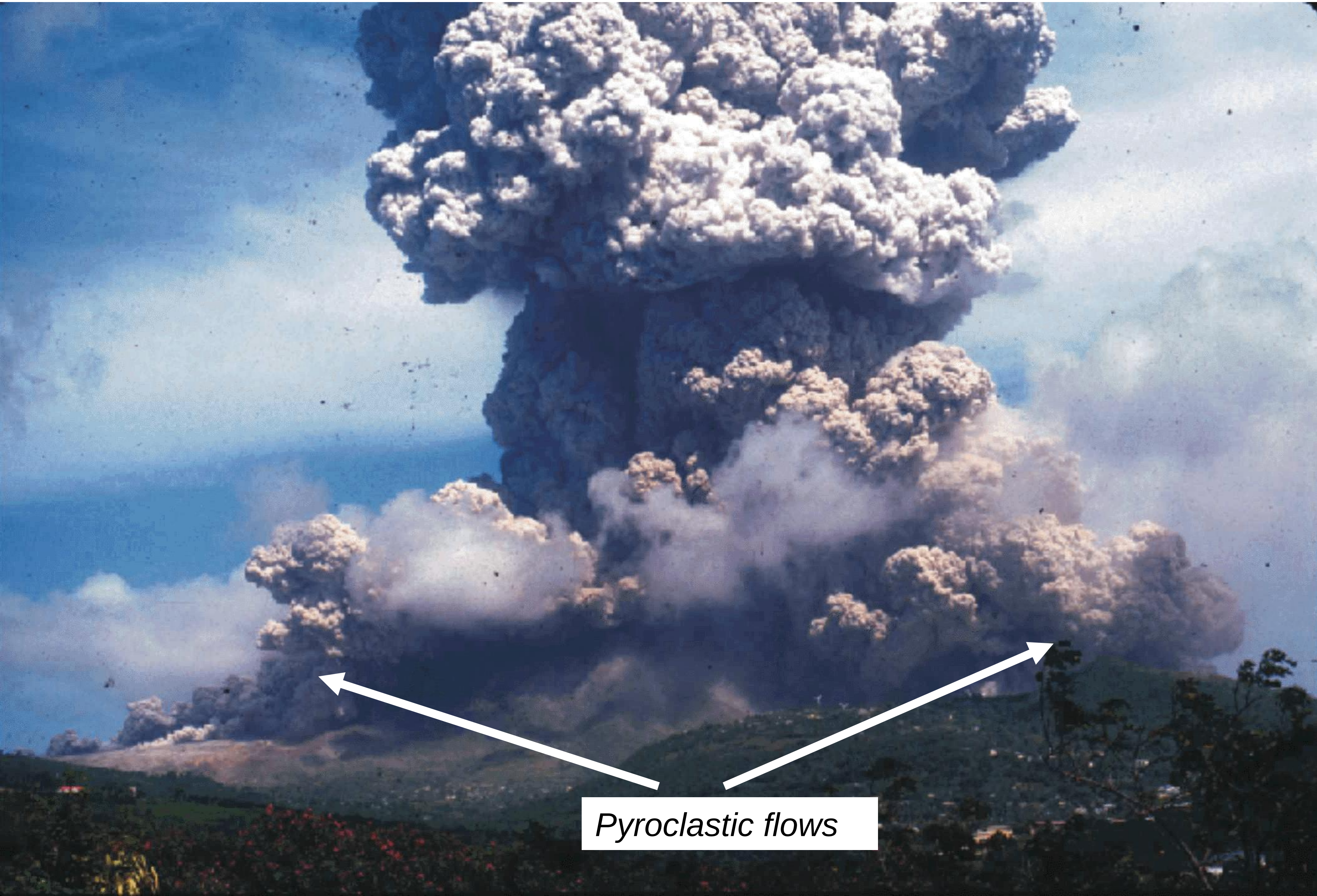
Ground deposit in kg/m^2



SOME EXAMPLES

2. Pyroclastic flows

Soufriere Hills volcano, Montserrat island, Antilles (2001)



Soufriere Hills volcano, Montserrat island, Antilles (2001)

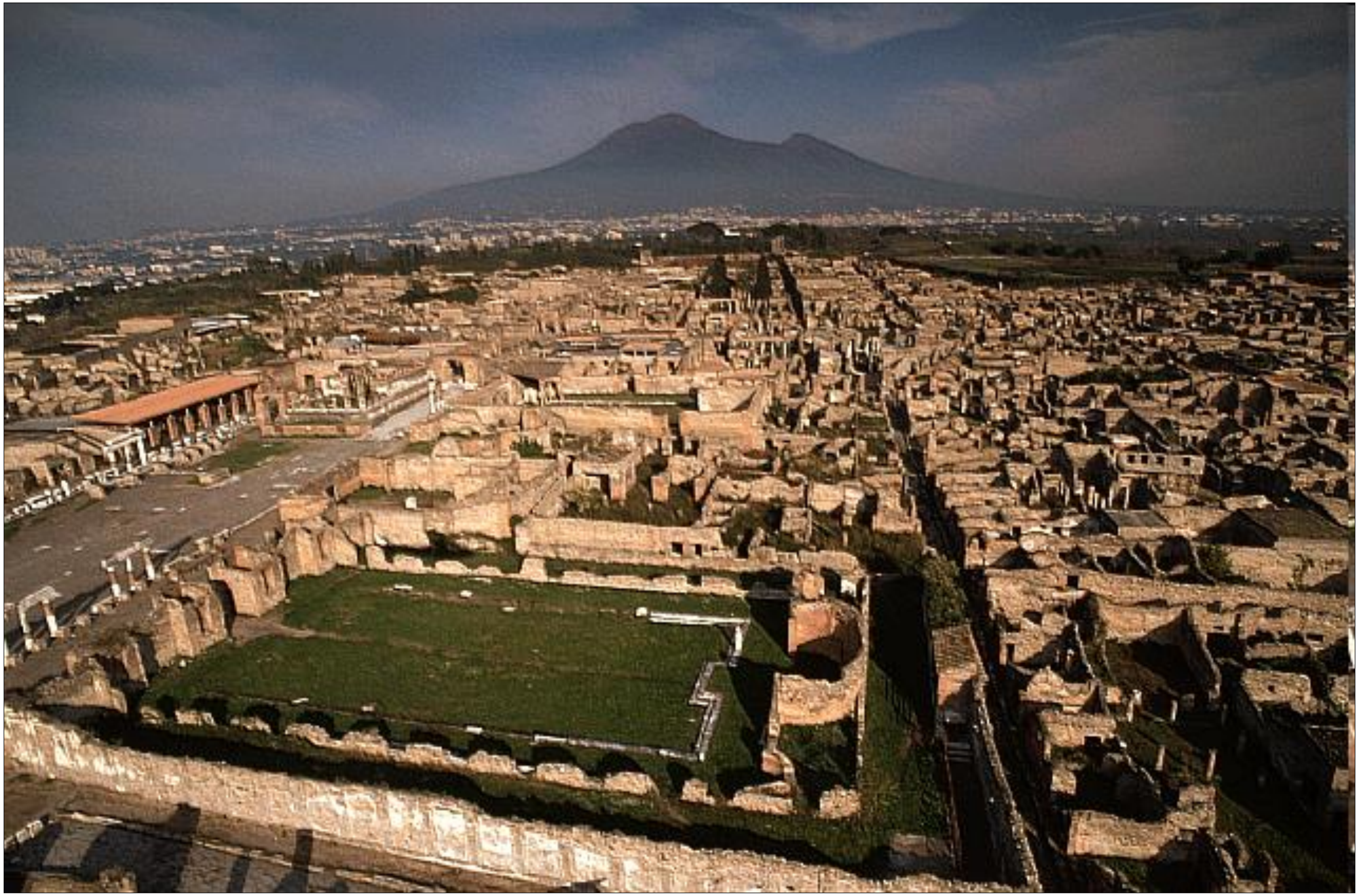
Pyroclastic flows

Pyroclastic flows

Impact of pyroclastic flows on urban areas (Montserrat island)

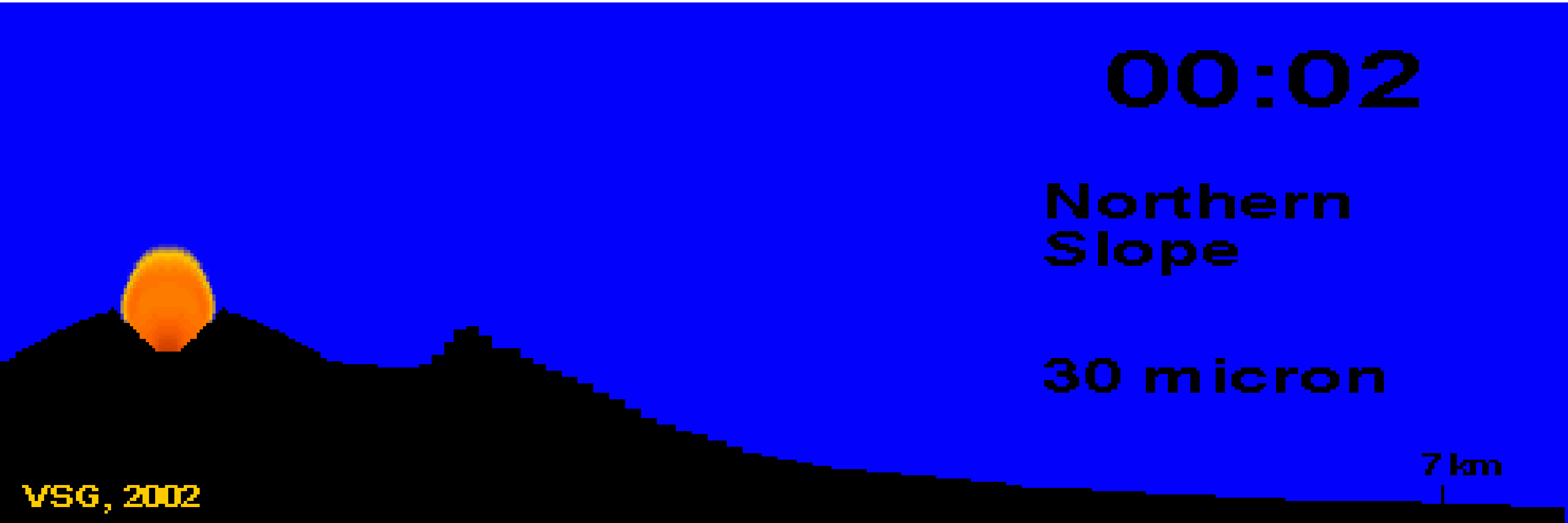
The city of St. Pierre, Martinica, completely destroyed by pyroclastic flows during the eruption 1902 of Mount Pelee (28.000 casualties)

The Roman city of Pompei, destroyed by pyroclastic flows during the A.D. 79 eruption of Vesuvius

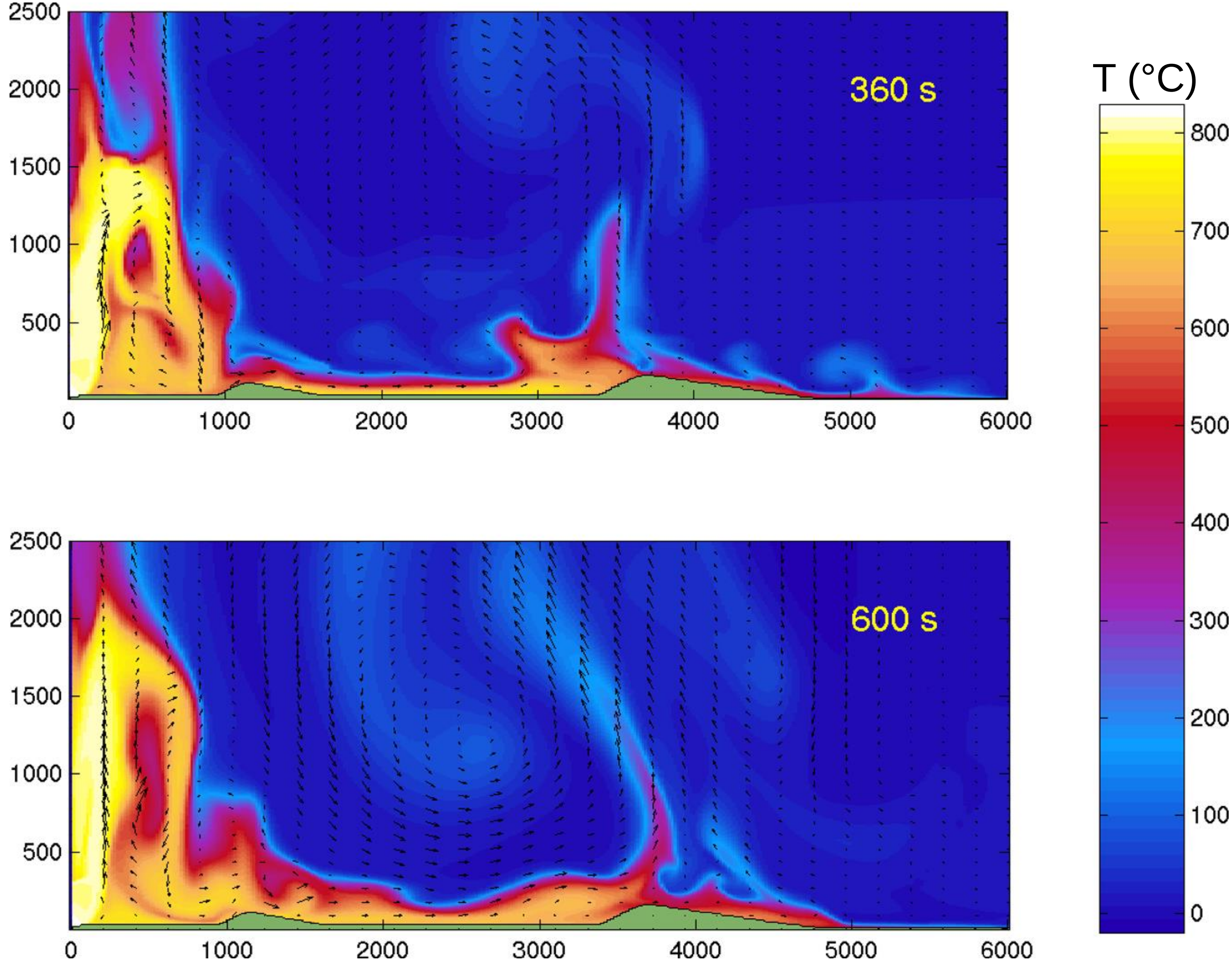


2D numerical simulation of pyroclastic flows

Concentration of particles

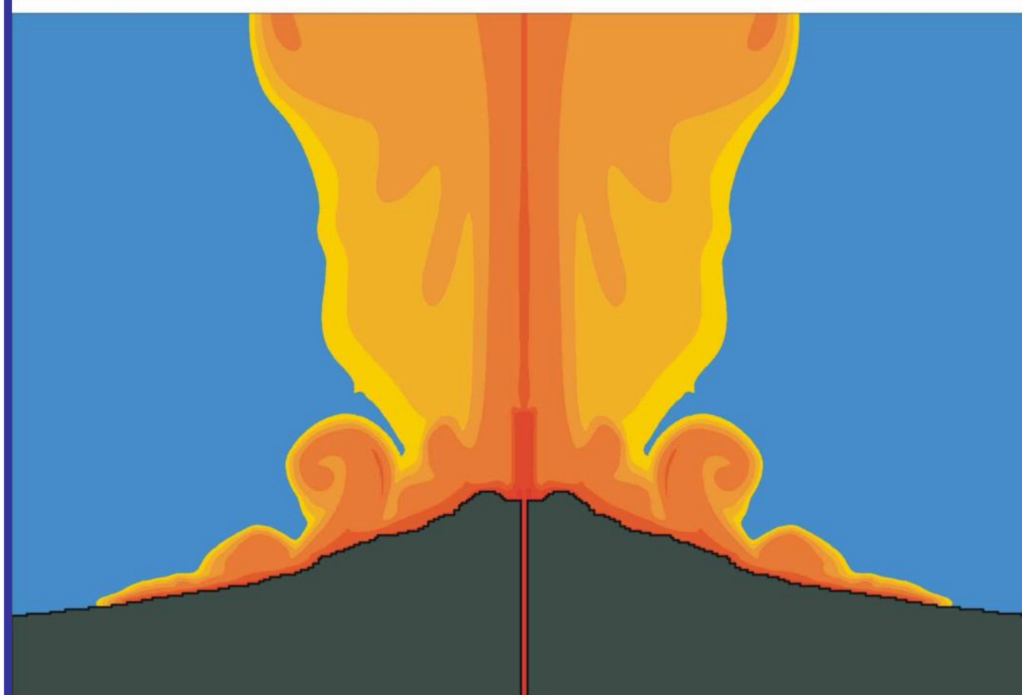


Distribution of temperature (colors) and velocity (arrows) from numerical simulations of pyroclastic flows



Observation…

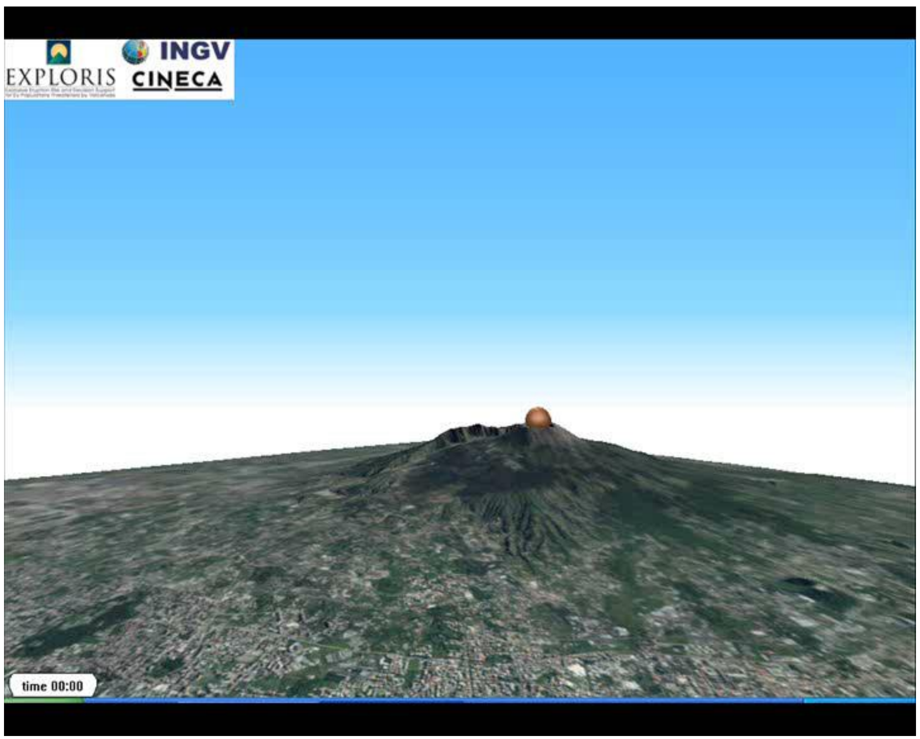
…and prediction



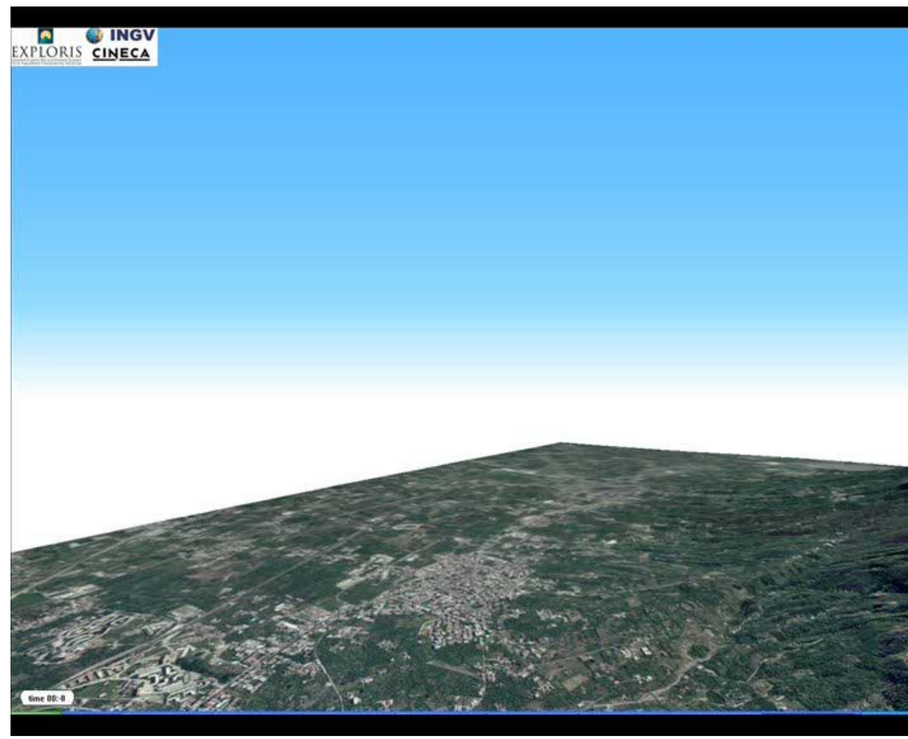
La Soufriere volcano,
Montserrat (Antilles), 2001

3D numerical simulation of pyroclastic flows at Vesuvius

Particle concentration



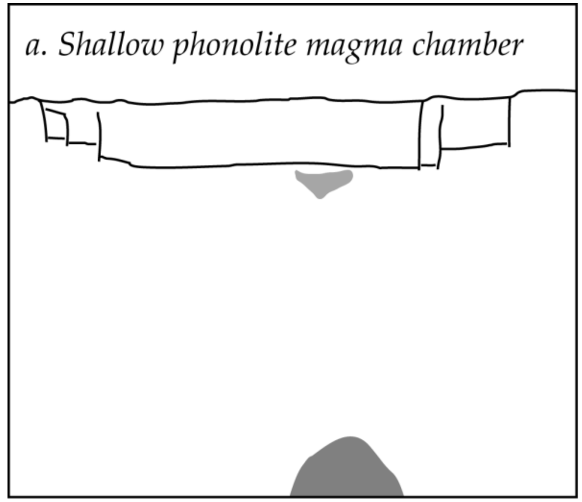
Temperature

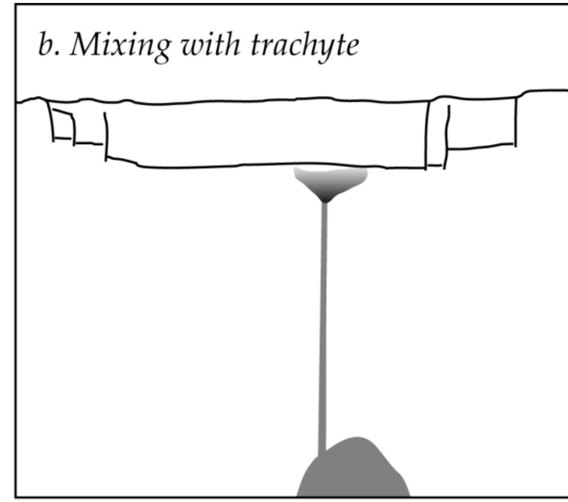


SOME EXAMPLES

3. Underground magma dynamics

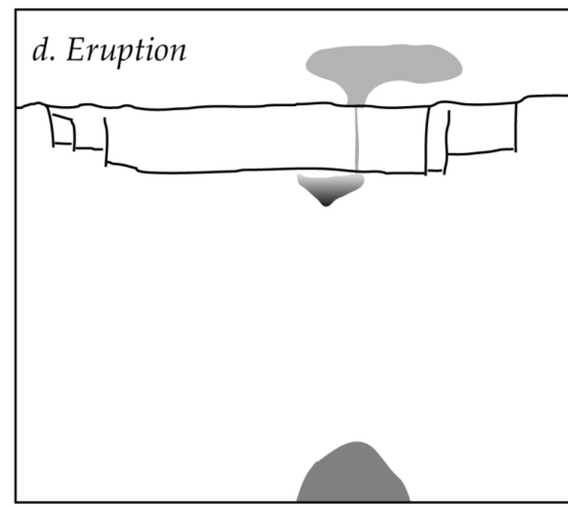
Repeatedly, magma stored in a shallow (a few km) reservoir below the Earth’s surface is reached by magma of deeper origin.

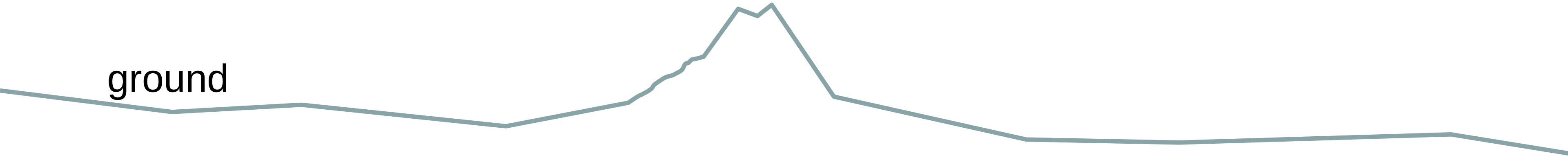




Typically, the deeper magma is rich in gas components

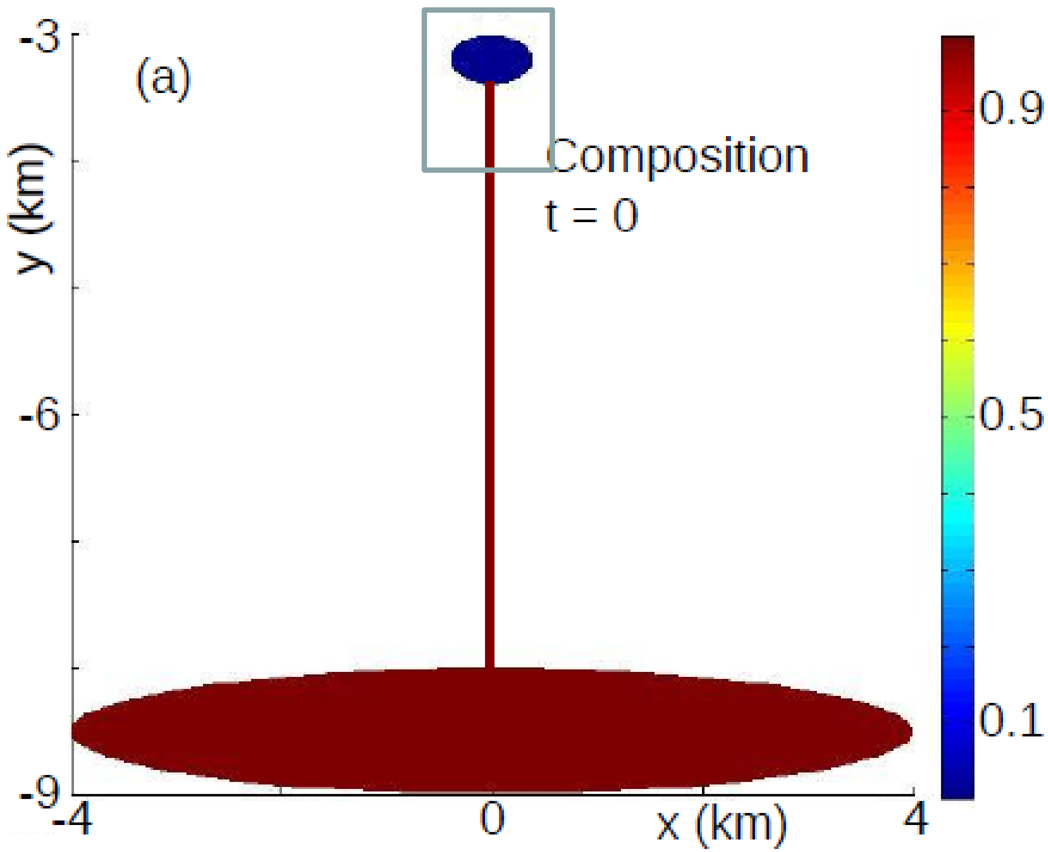
In many cases, that process triggers a new eruption



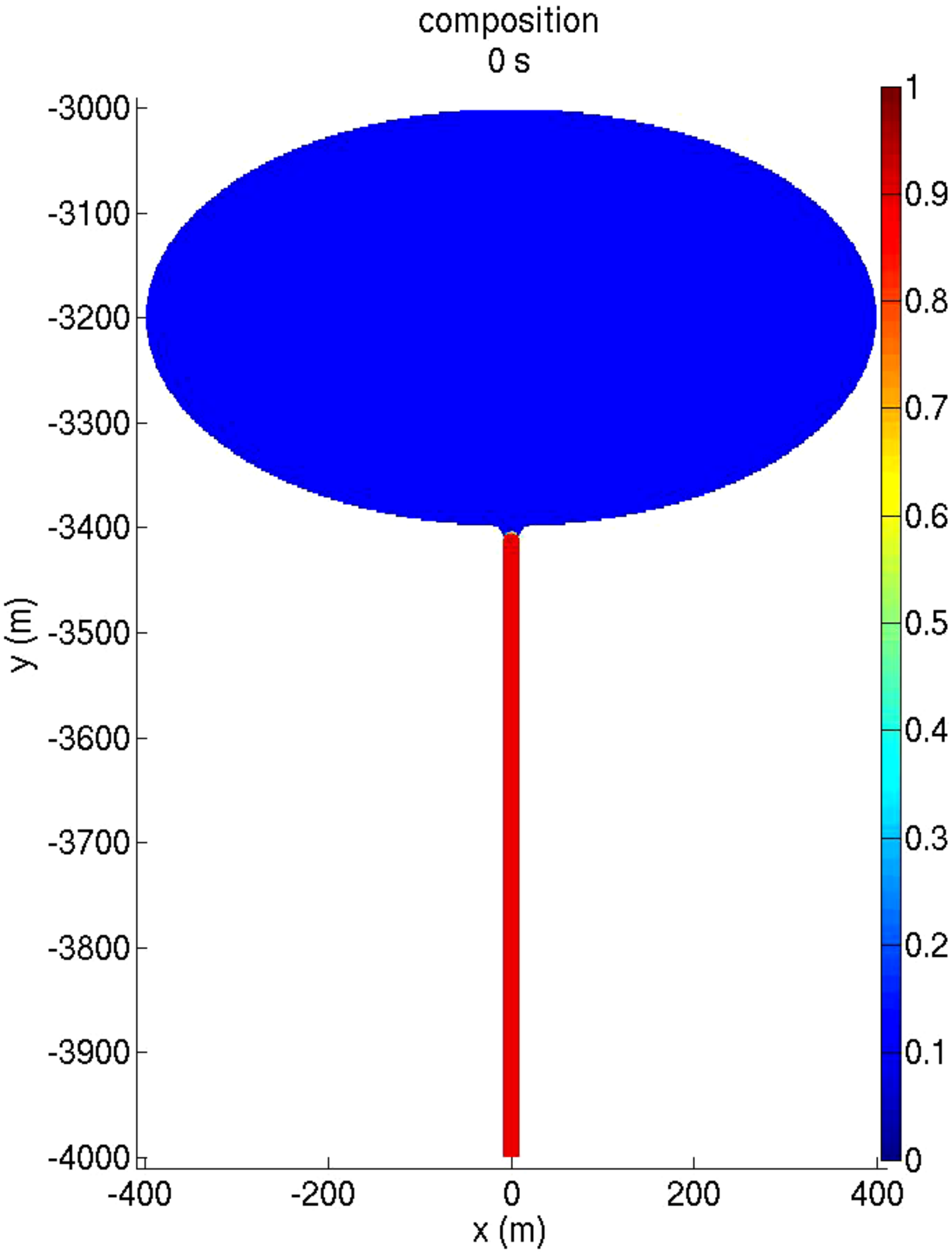


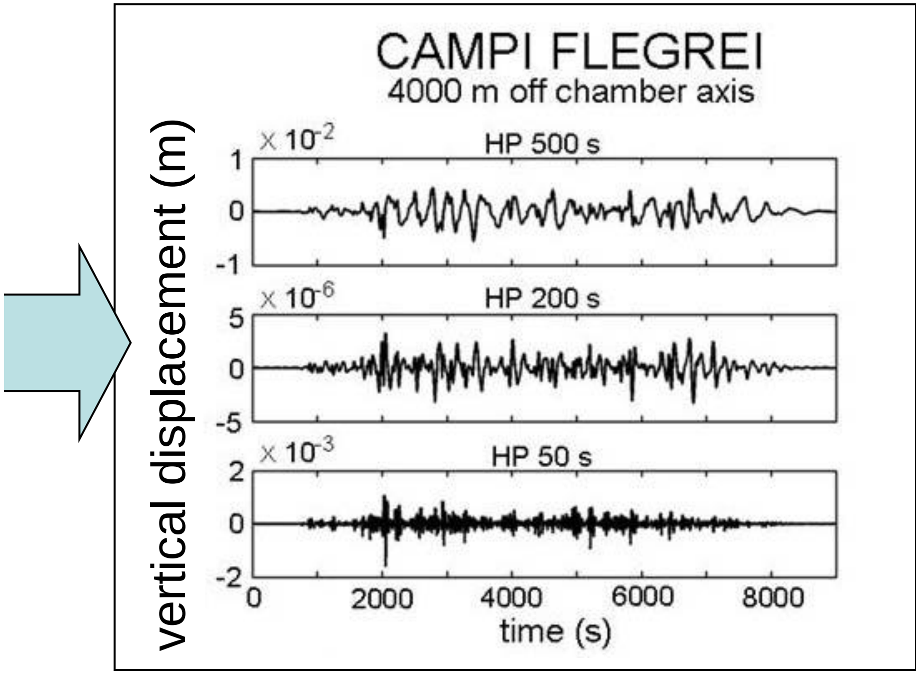
Blue:
composition 1,
partially
degassed
magma

Red:
composition 2,
gas-rich
magma



Dynamics of convection and mixing in underground magmatic systems





What I have presented so far is a **DETERMINISTIC APPROACH** to the investigation of volcanic processes

There are however limitations in the extensive use of such an approach for volcanic hazard purposes:

- We have a limited knowledge of the physics, and most importantly, of the conditions that will characterize the next eruption: **EPISTEMIC UNCERTAINTY**

- The volcanic processes are highly non-linear, meaning that even small fluctuations somewhere may have large consequences on the overall processes: **ALEATORIC UNCERTAINTY**

WE MUST TAKE THESE UNCERTAINTIES INTO ACCOUNT, AND RELY ON A **PROBABILISTIC APPROACH** IN ORDER TO FORECAST VOLCANIC HAZARDS → **VOLCANIC HAZARD IS A PROBABILISTIC CONCEPT**

So, what's the usefulness of deterministic numerical modelling?

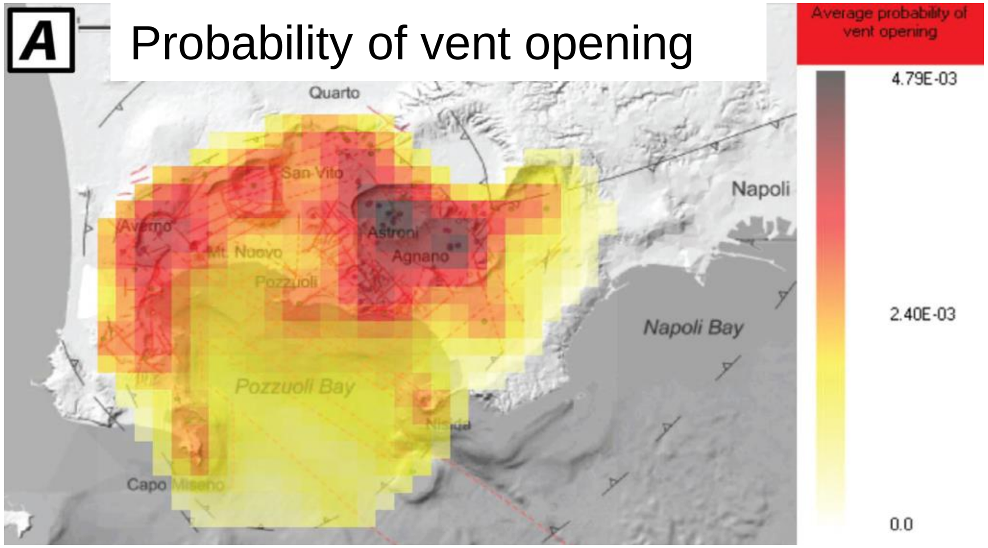
1. We want to know how Nature works → **BASIC SCIENCE**

2. We can relate observed quantities (e.g., seismic, deformation signals) to processes occurring outside direct observation (e.g., in magma chambers) → **VOLCANO MONITORING**

3. We can obtain pictures of how hazardous quantities (T, P, ash concentration, etc.) can be distributed, in time and space, for selected (more likely, or more expected) sets of conditions characterizing a next eruption → **VOLCANIC SCENARIOS**

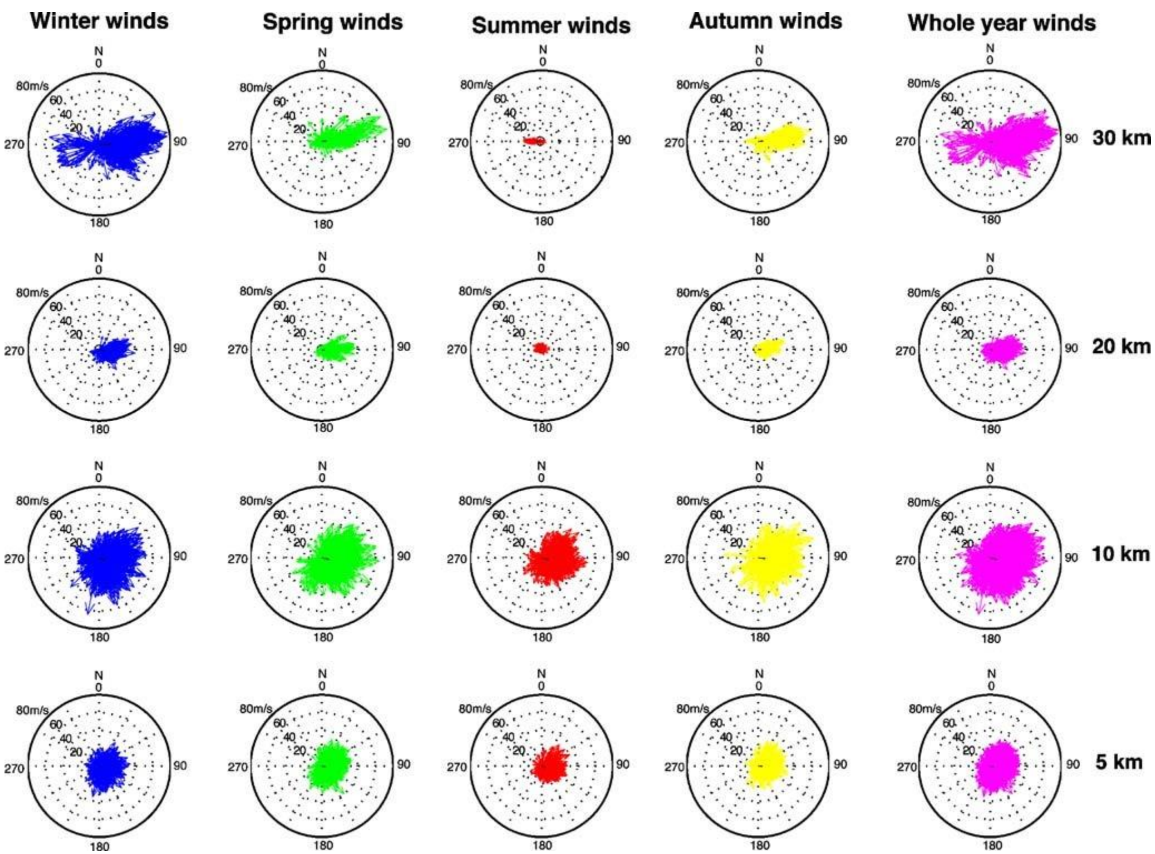
4. We can run the models several times by varying the conditions according to their estimated probabilities, and obtain (probabilistic) **HAZARD MAPS** (limited by computational times)

Probability of vent opening



Probability of eruption size

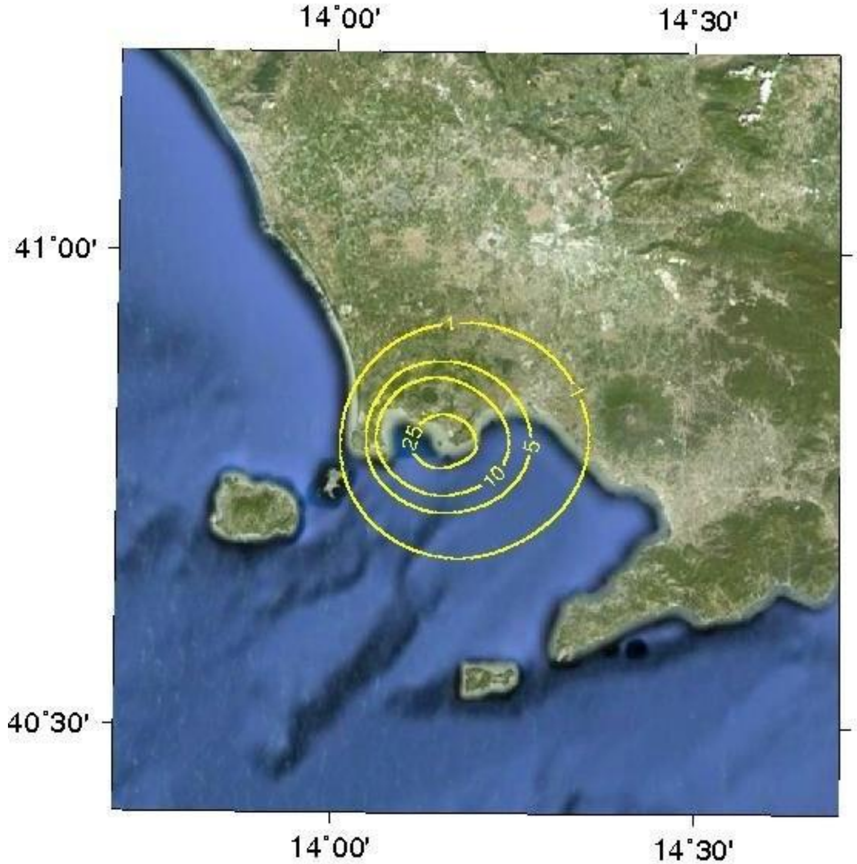
Eruption size	Conditioned probability in %
Effusive	11.9
Small	59.6
Medium	23.8
Large	4.0
Very large	0.7

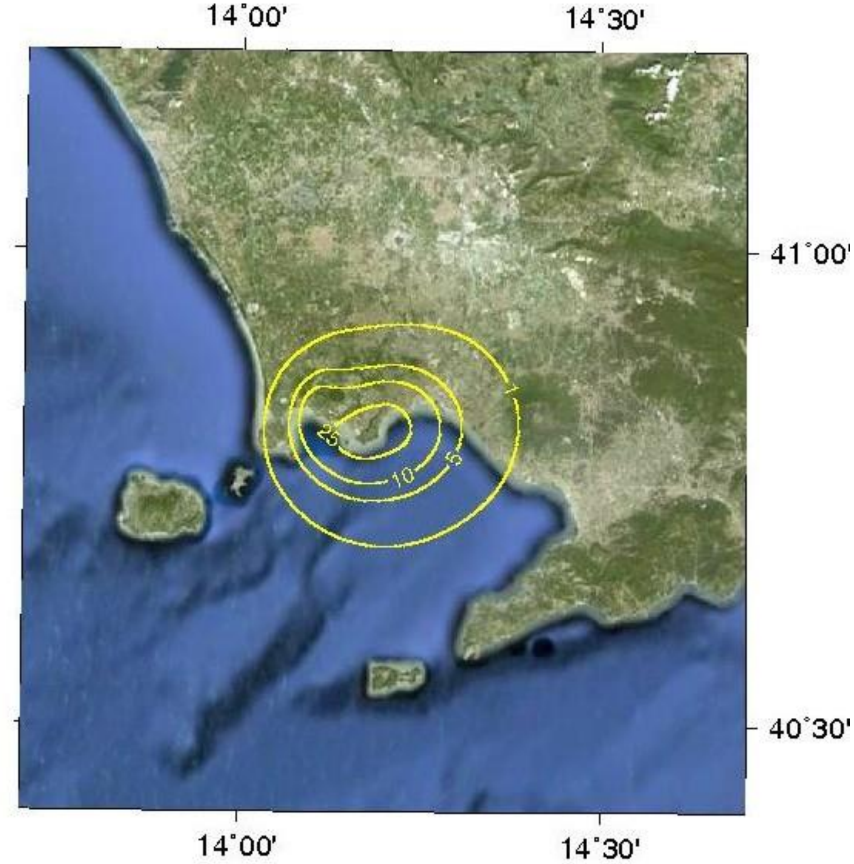


Probability of wind velocity and direction at each different height

One example from Campi Flegrei, Italy

Ash fallout **HAZARD MAPS** for Campi Flegrei, Italy





Probability of overcoming a threshold of 300 kg/m^2 in ash load on the ground.

Left: including vents opening in the sea

Right: exclusing vents opening in the sea

Mount Etna, Sicily, with the city of Catania on the background