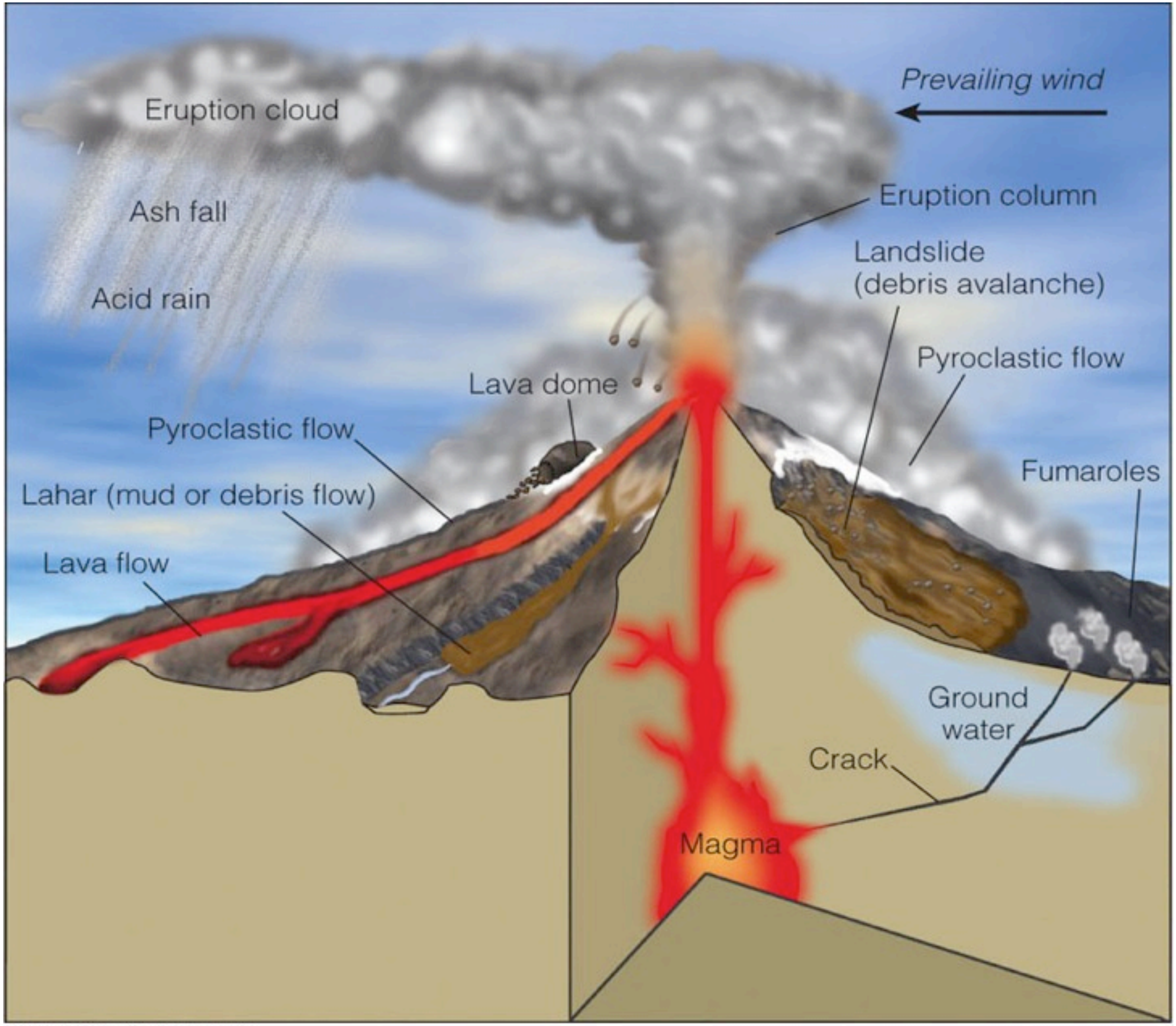
Introduction to Hazard Modeling

Jose L. Palma, University at Buffalo
PASI Workshop, January 2011

Volcanic hazards



Why do we need models?

1. Predict flow path, runout, speed- before and during eruptions

2. Understand processes, important effects

3. Help interpret past eruptions

Using models to build hazard maps

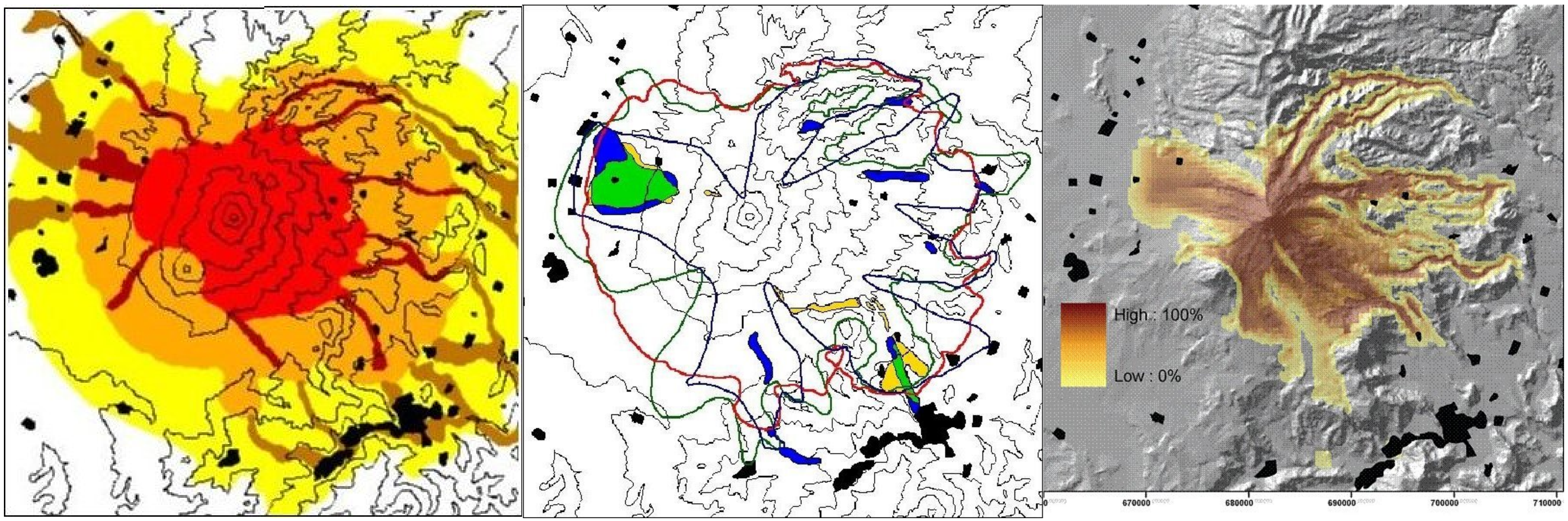


Figure 1.2: Left: This is a hazard map generated by Sheridan et al[121] for Pico de Orizaba, Mexico. Middle: This is a map of deposits and flow outlines from Energy Cone, FLOW2D, and FLOW3D simulations used by Sheridan et al[122] to construct the hazard map on the left. Right: This is a probability of flow depth ≥ 1 [m] that PCQ predicts for an event when all volumes between 5×10^7 and 4×10^8 [m^3] are considered equally likely; the third sub-figure was generated from an ensemble of Titan2D simulations and also appears in Sheridan et al[124].

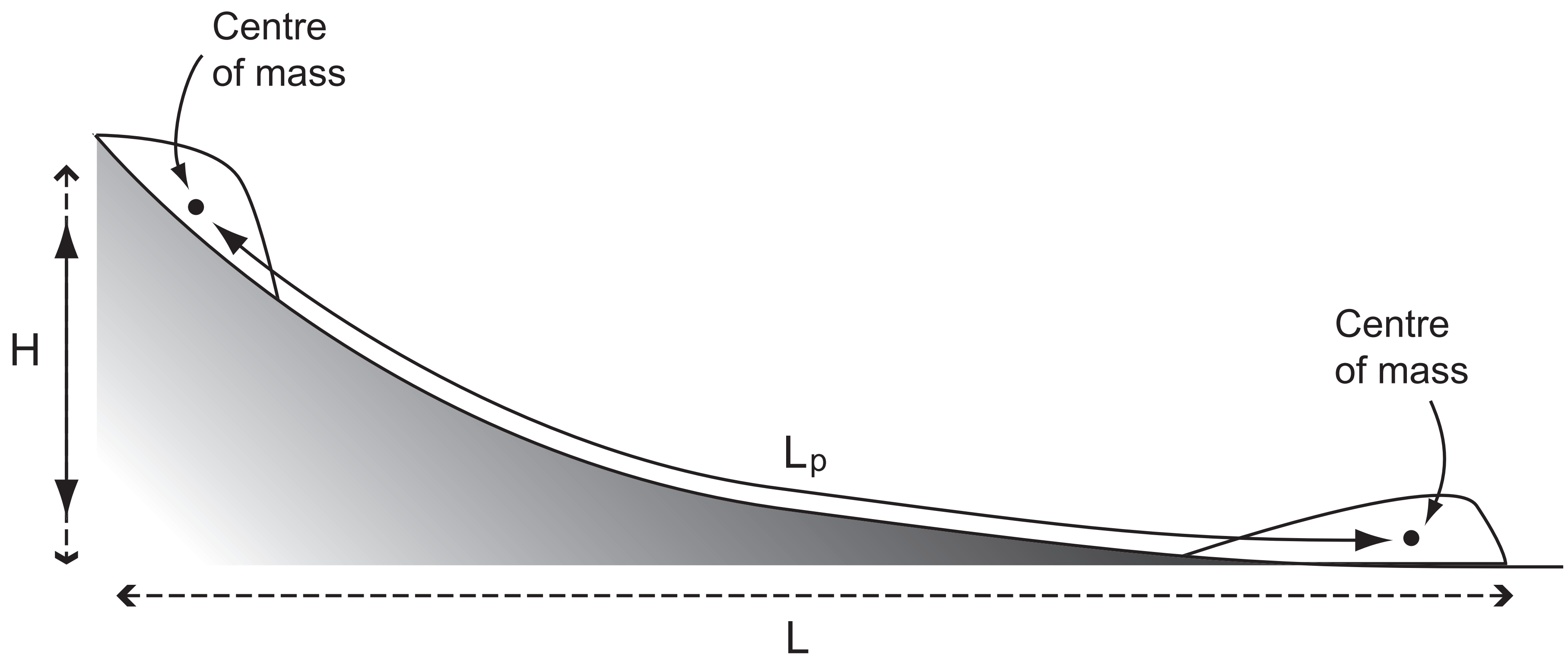
Energy balance

$$E = (U + K) + (C_I - D_I) - F$$

$$(U + K) = E_M$$

$$(C_I - D_I) = I$$

H/L: path-averaged deceleration

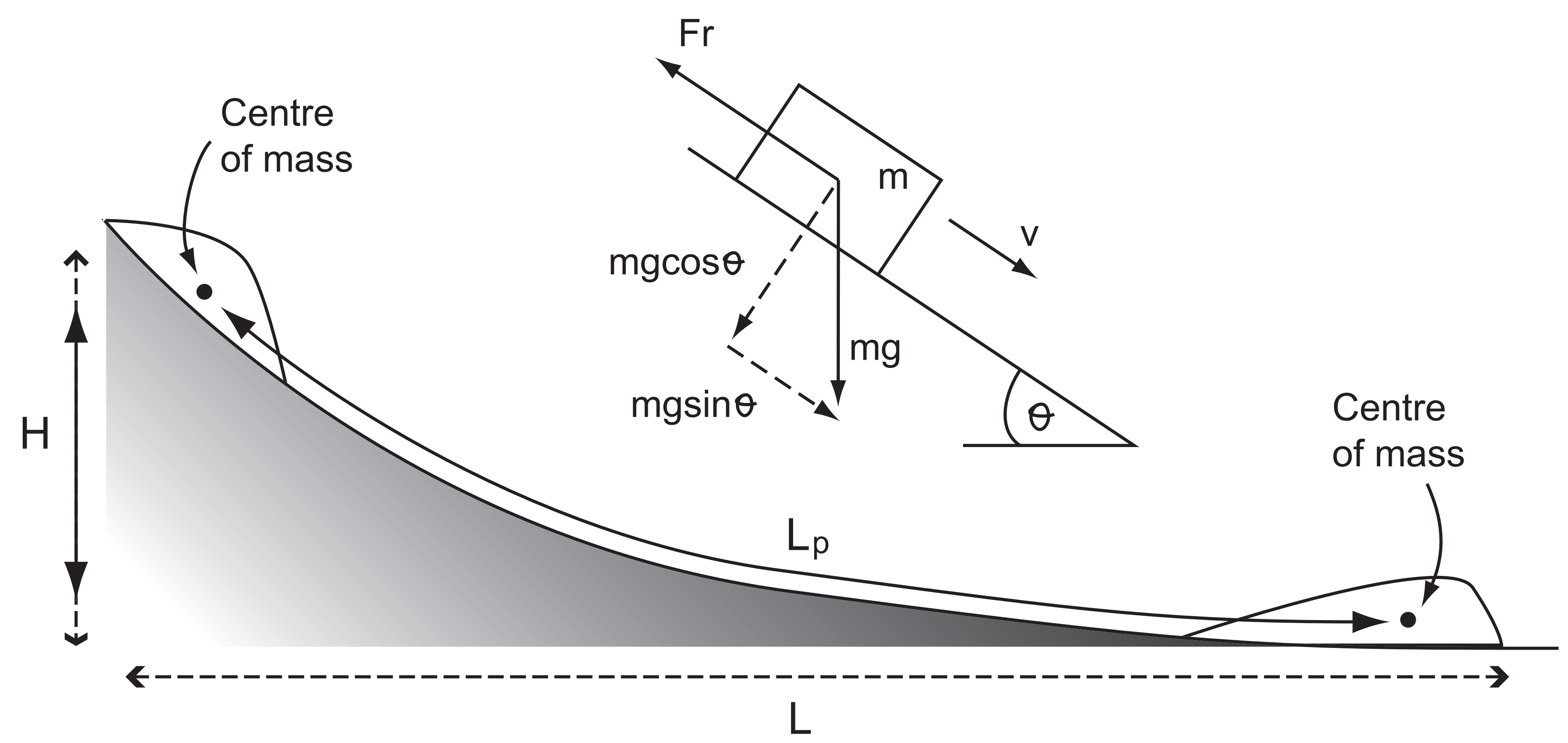


$$mgH = \frac{1}{2}mv^2 + mAL_p$$

$$(v = 0) \Rightarrow \frac{H}{L_p} = \frac{A}{g}$$

H/Lp represents the path-averaged deceleration that causes the loss of mechanical energy of the flow

H/L: rigid body



$$Fr = \mu N = \mu mg \cos\theta$$

$$\mu = \tan\theta = \frac{H}{L}$$

(Coulomb friction model)

H/L: real data

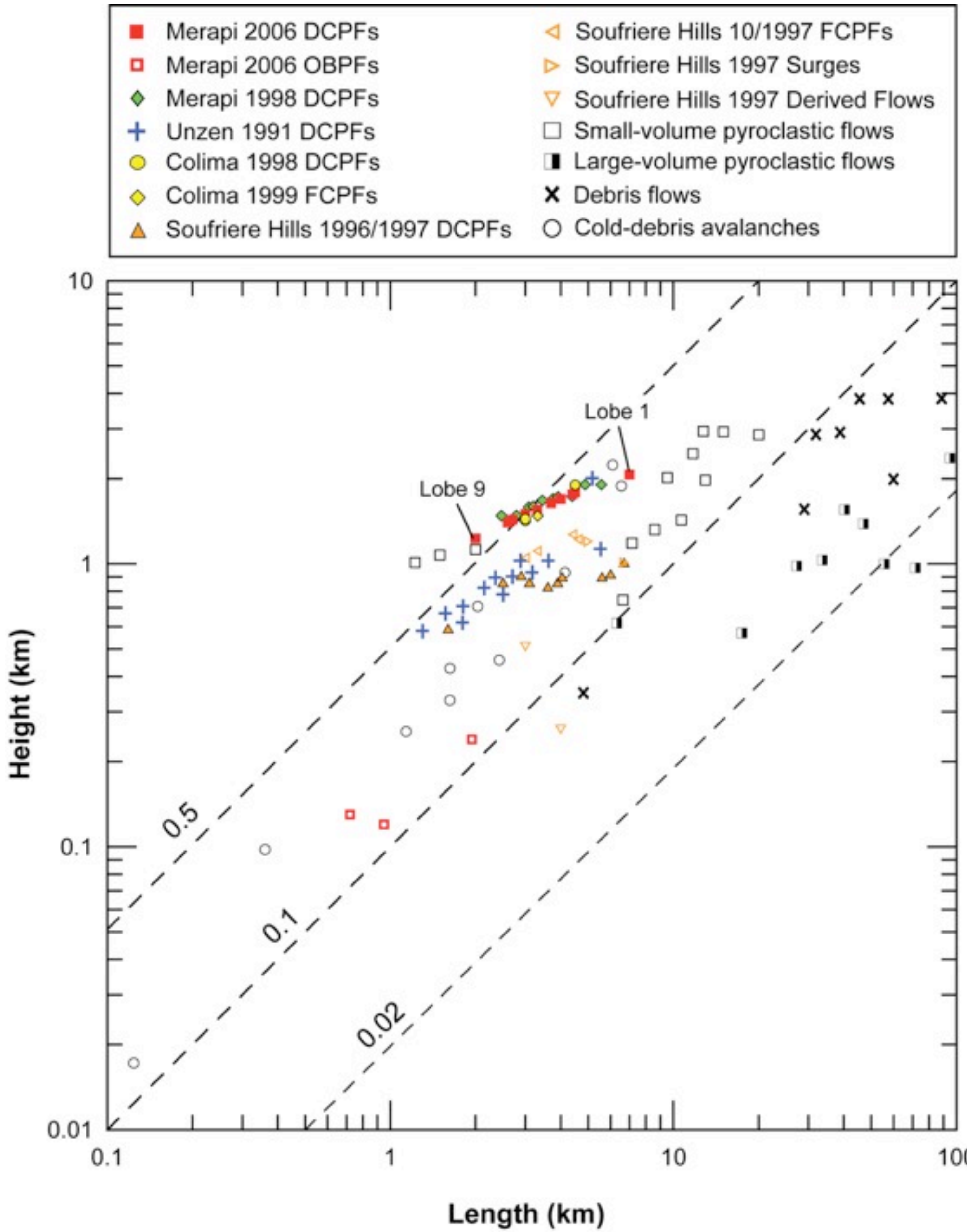


Figure by Sylvain Charbonnier

H/L vs volume

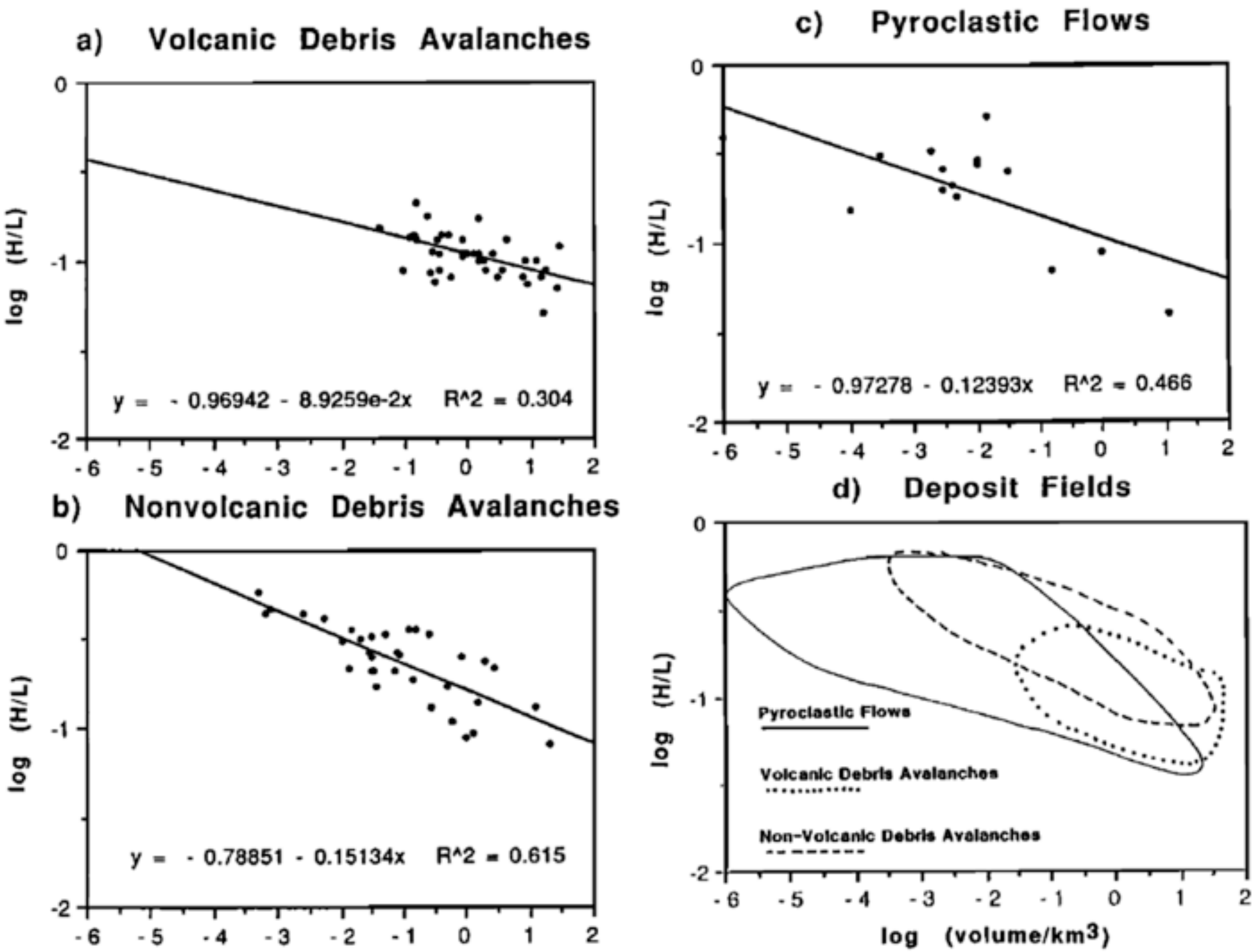
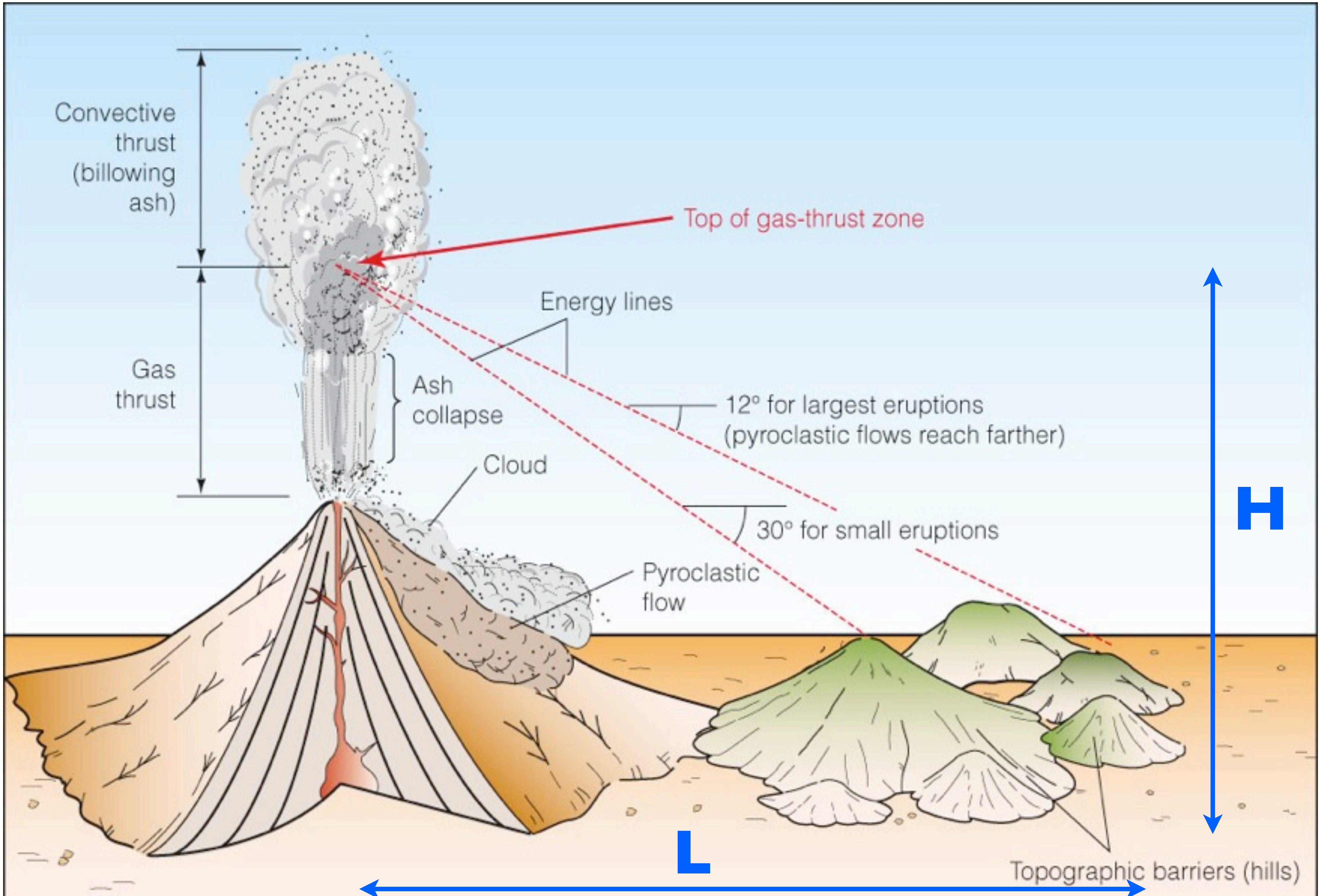


Fig. 2. Log(volume) versus log(*H*/*L*), where *H* is the height descended and *L* is the runout distance. (*a*) Volcanic debris avalanches (*vda*). (*b*) Nonvolcanic debris avalanches (*nvda*). (*c*) Pyroclastic flows (*pf*). (*d*) Deposit fields for all three types of deposits.

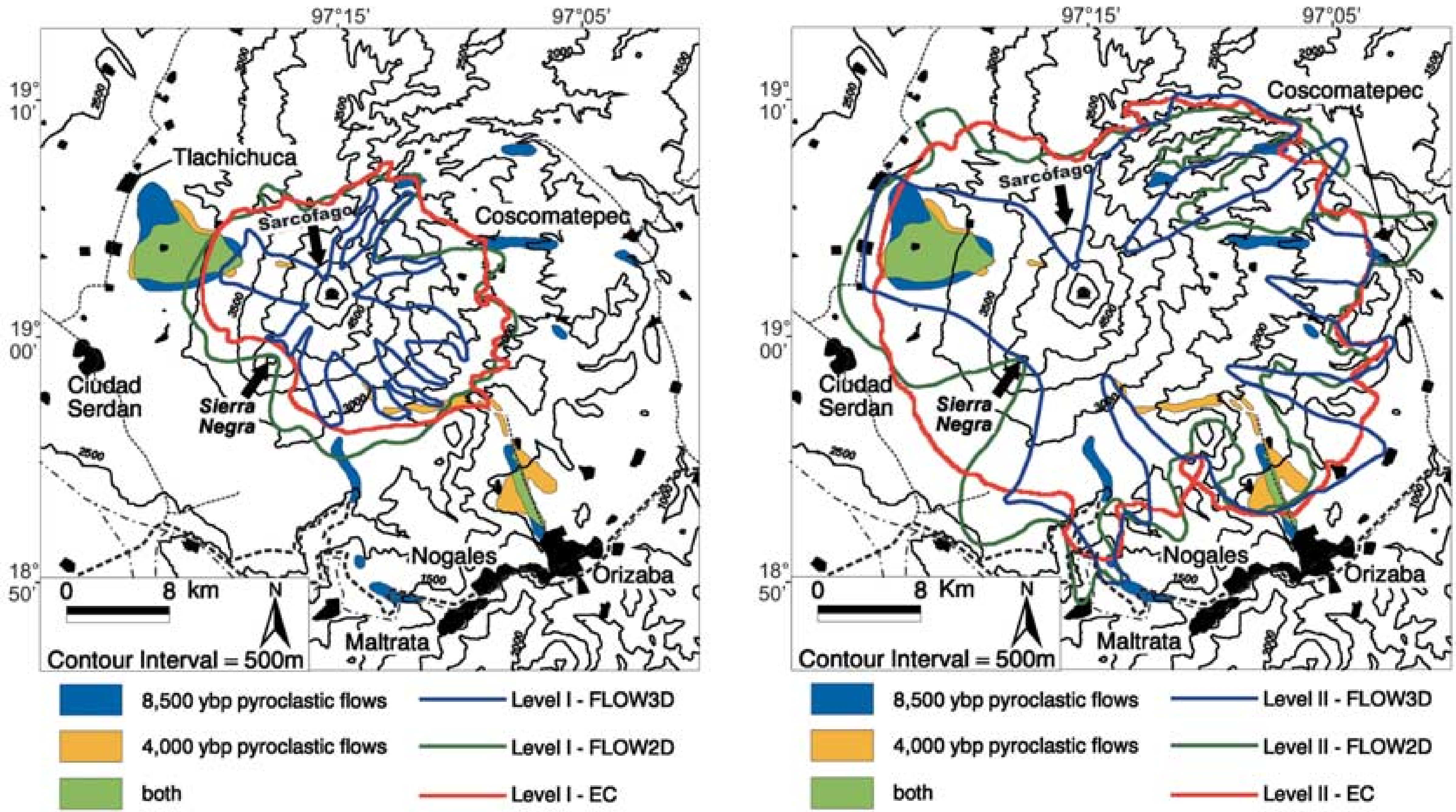
From Hayashi and Self 1992

Energy line



Convective thrust (billowing ash)
Top of gas-thrust zone
Energy lines
Gas thrust
Ash collapse
12° for largest eruptions (pyroclastic flows reach farther)
Cloud
30° for small eruptions
Pyroclastic flow
H
L
Topographic barriers (hills)

H/L and energy line/cone

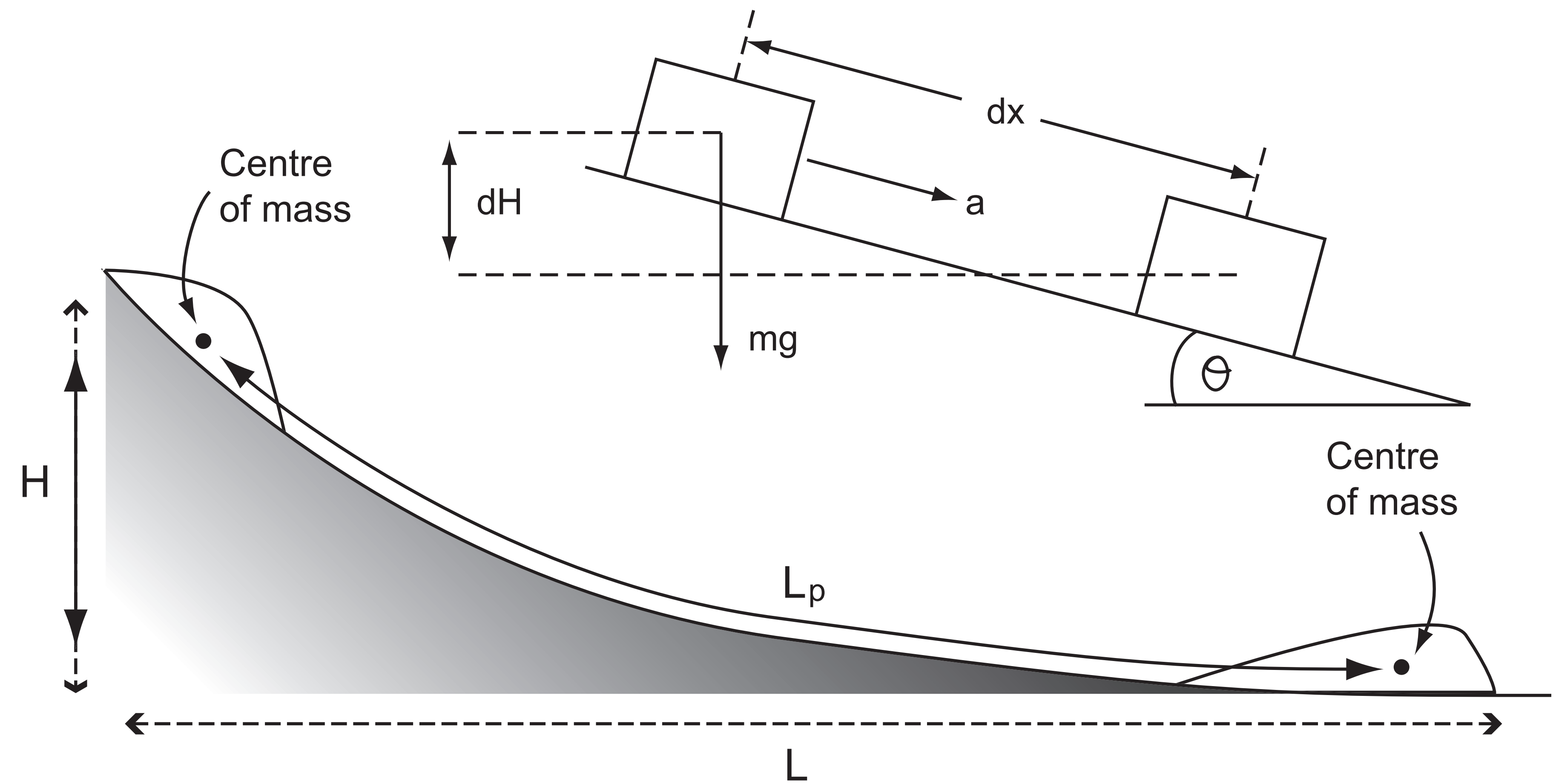


H/L = 0.26

H/L = 0.18

Sheridan et al. (2004). Pyroclastic Flow Hazard at Volcán Citlaltépetl. Natural Hazards

Segmentation of the path



$$mg\,dH = \frac{1}{2}m\,dv^2 + mA\,dx$$

$$\left(\ dH/dx = sin\theta\ \right)$$

$$\frac{1}{2}\frac{dv^2}{dx} = gsin\theta - A$$

Voellmy–Salm–Gubler model

(A simple model for flowing snow avalanches)

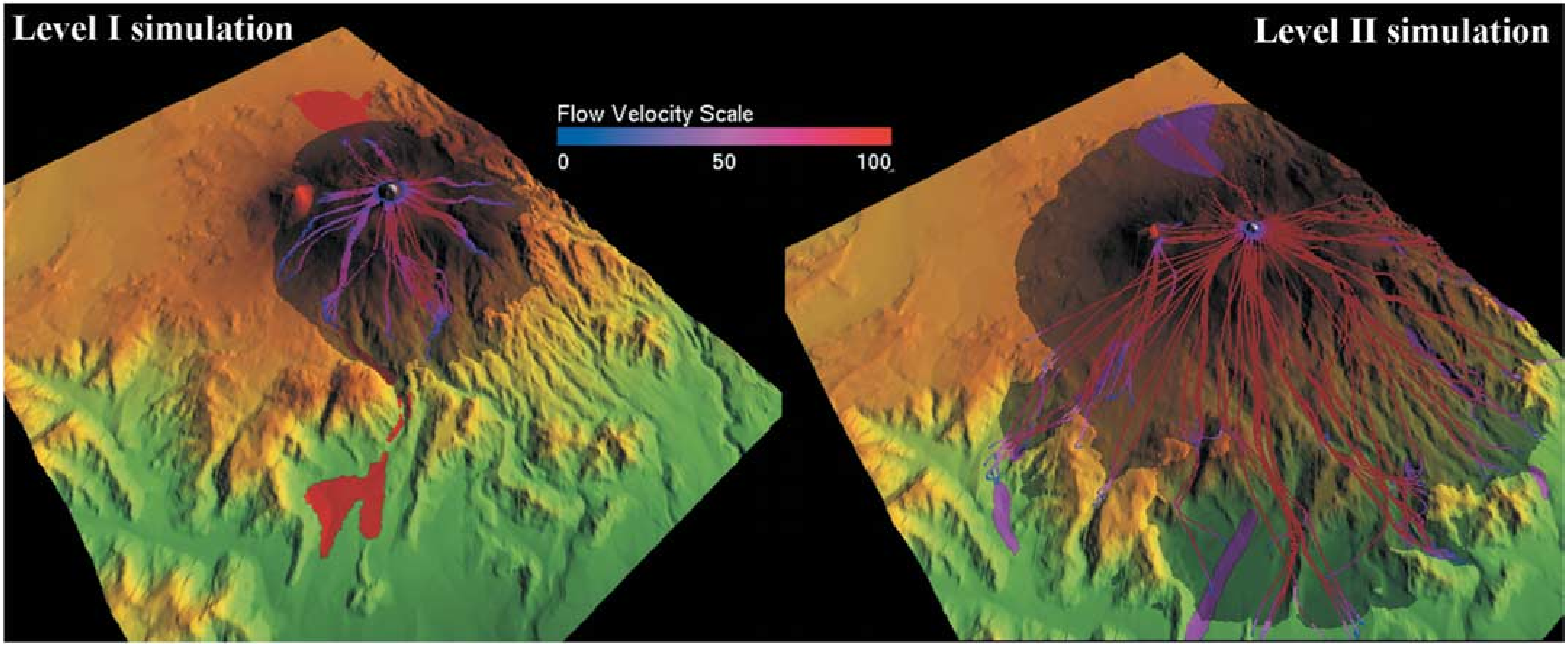
$$\frac{A}{g} = \mu \cos\theta + \frac{v^2}{\xi h}$$

h flow depth

μ Coulomb friction coefficient: 0.3 (small avalanches) - 0.155 (large avalanches)

ξ turbulent friction coefficient [m/s^2]: 400 (confined) - 1000 (wide open slope)

FLOW3D

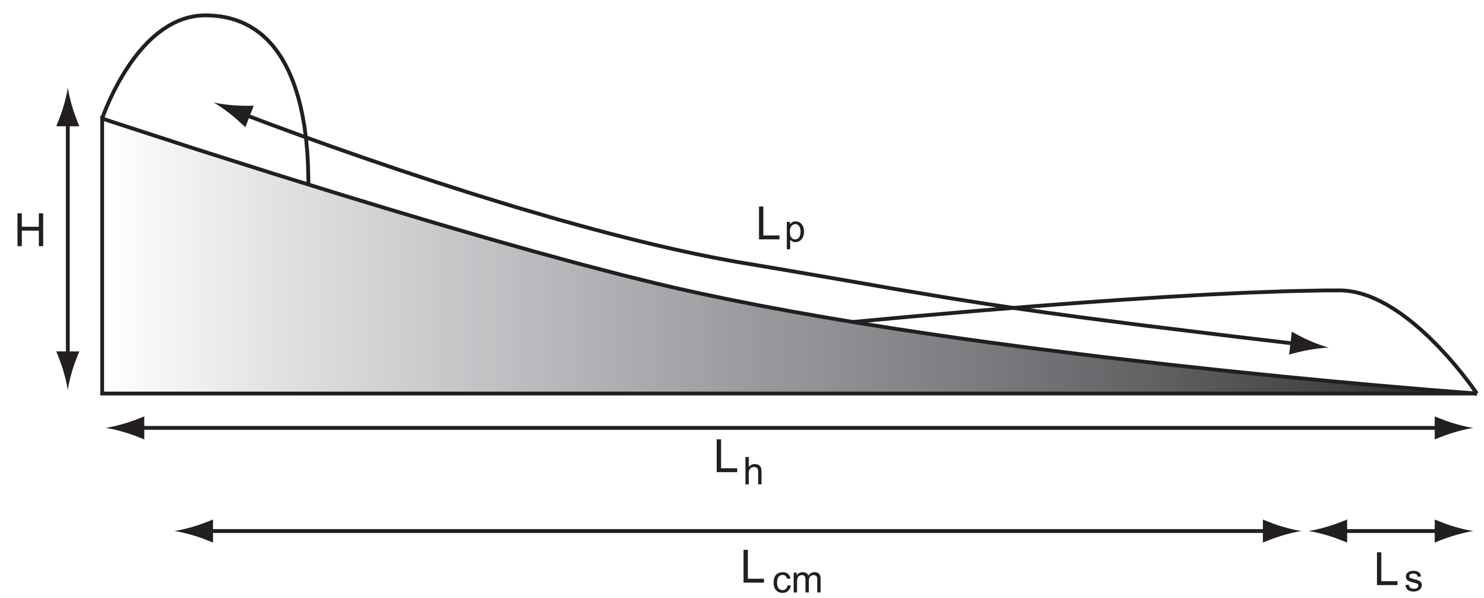


Sheridan et al. (2004). Natural Hazards

$$\tau = a_0 + v^* a_1 + v^{2*} a_2$$

basal friction viscosity turbulence

Flow spreading and deposition



$$L_p \approx (H^2 + L_{cm}^2)^{1/2}$$

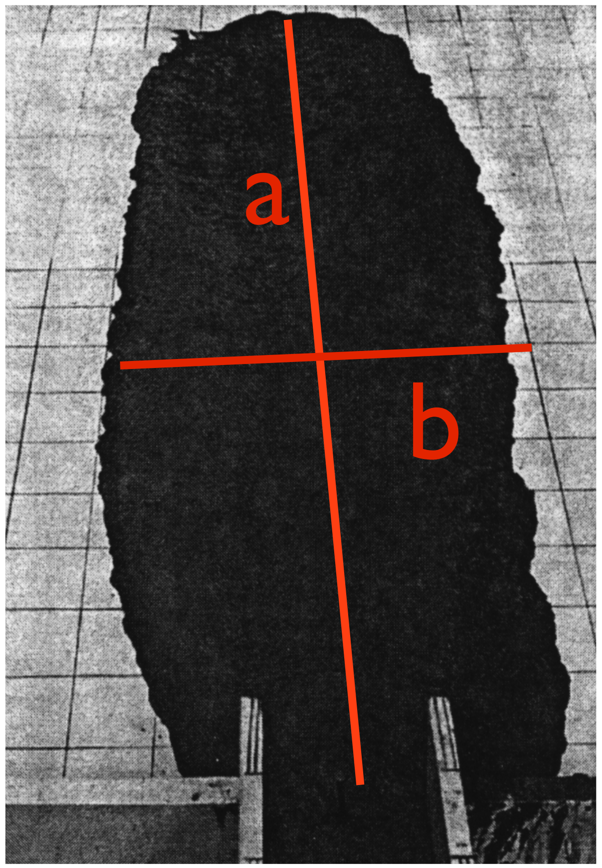
$$H_{cm} = H - \frac{1}{2}\frac{V}{S} = H - \frac{1}{2}\bar{h}$$

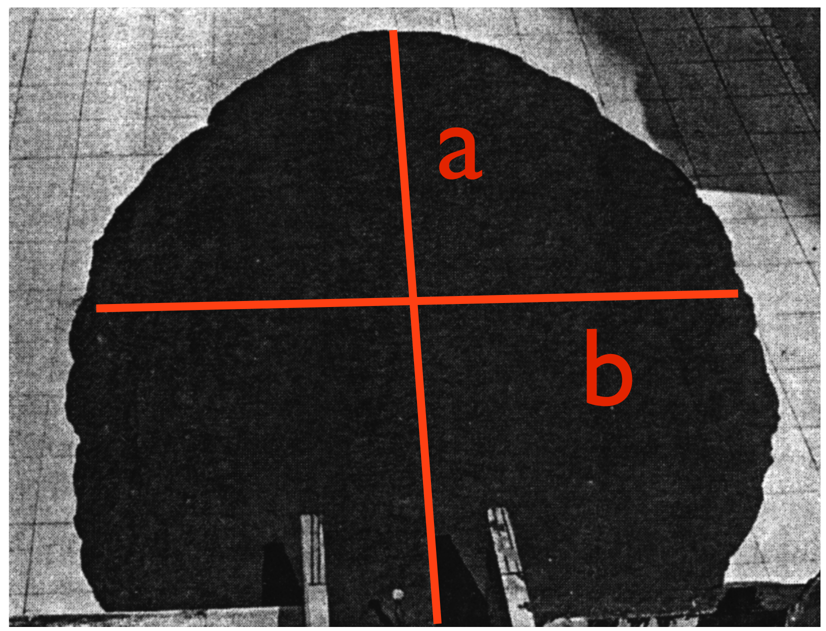
V volume
S planimetric area
$\bar{h}$ average depth

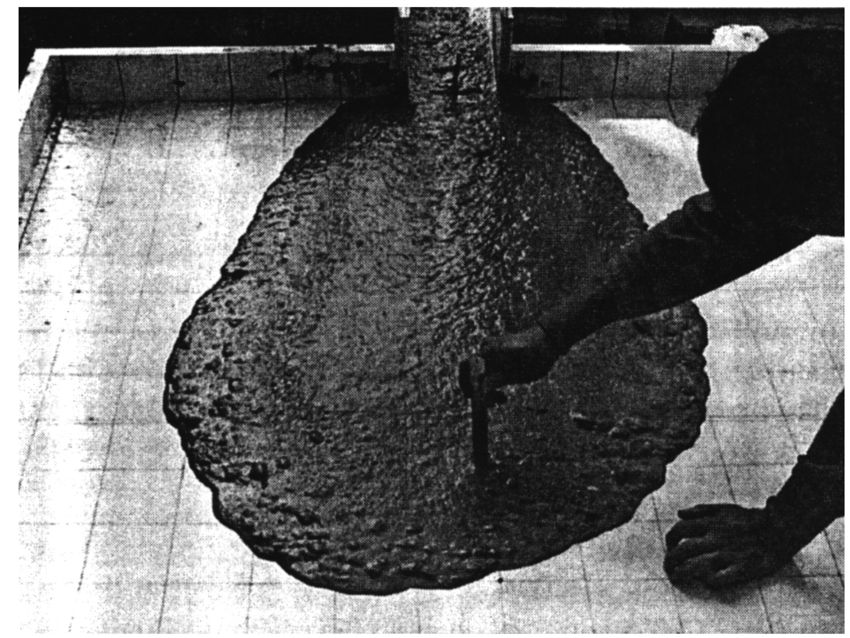
$$L_s = \left(\frac{S}{k_s}\right)^{1/2}$$

k_s is a shape factor: *4c* for a rectangle, πc for an ellipse (c is the ratio between axes)

Flow spreading and deposition

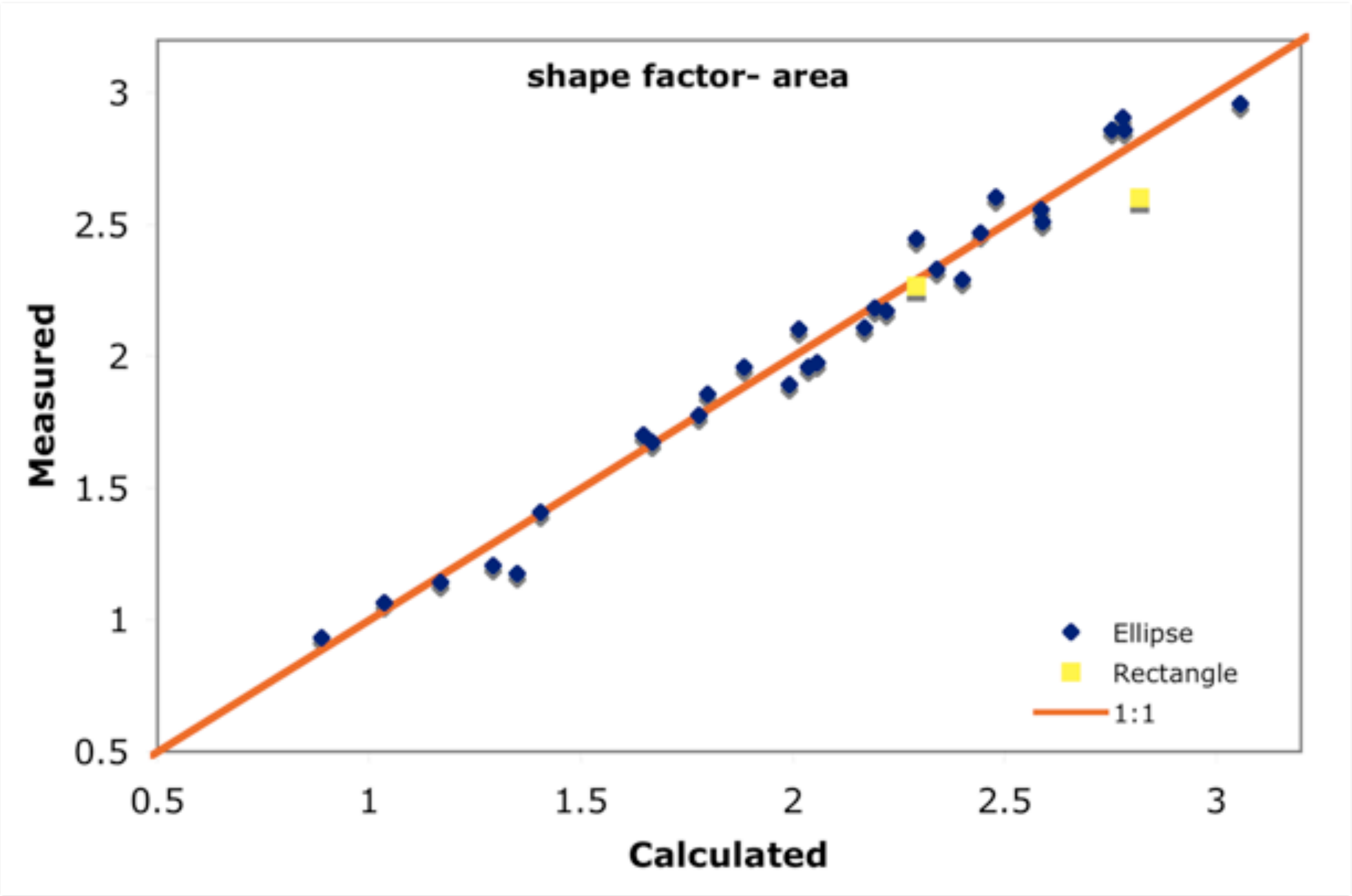


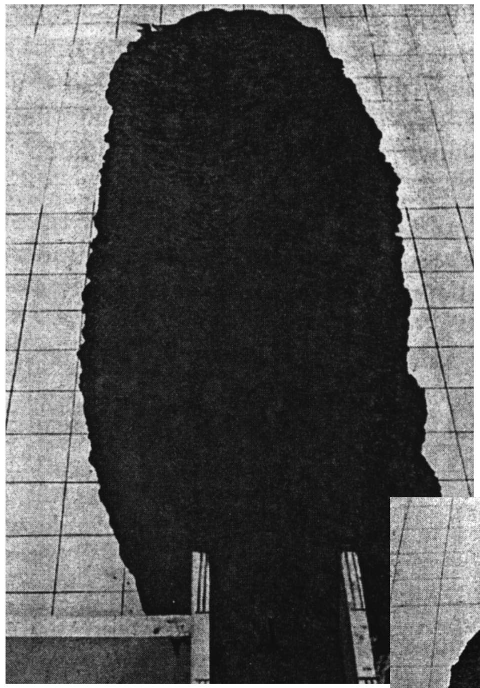


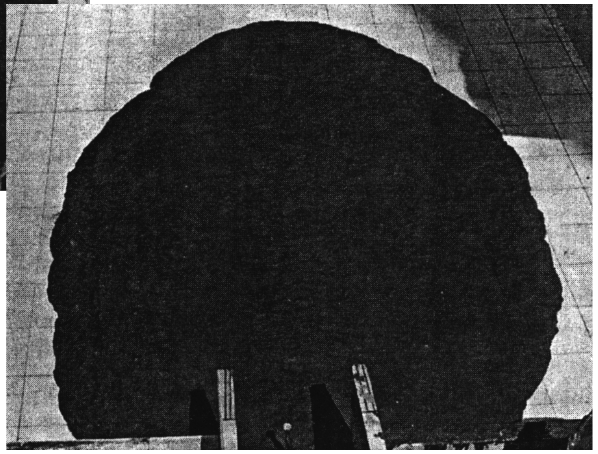


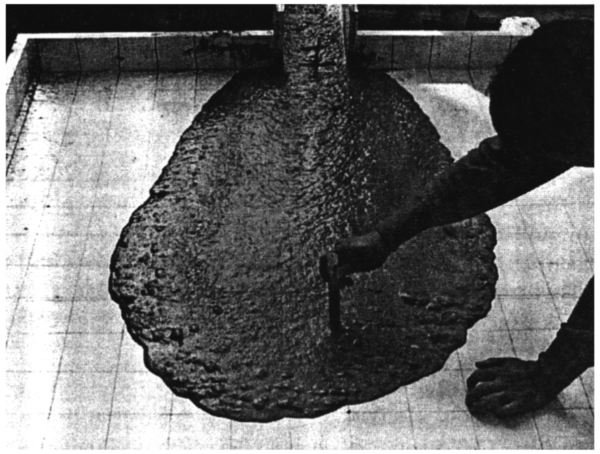
X. Liu. Size of debris flow deposition: model experiment approach. Environmental Geology, 98(2):70-77, 1995.

Flow spreading and deposition









X. Liu. Size of debris flow deposition: model experiment approach. Environmental Geology, 98(2):70-77, 1995.

Flow spreading and deposition

$$L_s = \left(\frac{S}{k_s}\right)^{1/2}$$

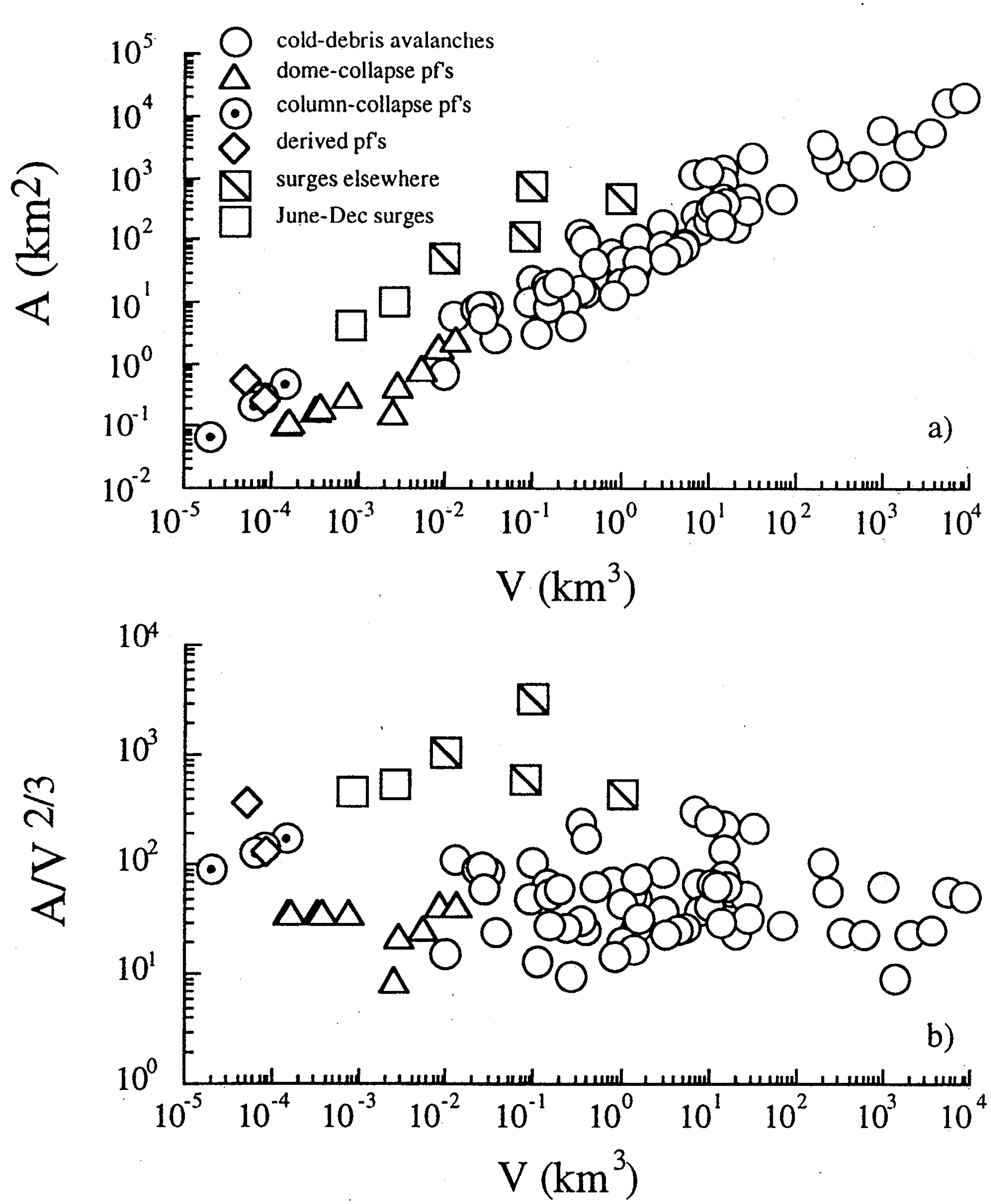
k_s is a shape factor: $4c$ for a rectangle, πc for an ellipse (c is the ratio between axes)

$$L_s = \left(\frac{V}{k_v}\right)^{1/3}$$

k_v is a shape factor related to the volume of the flow

$$S = \frac{k_s}{k_v^{2/3}} V^{2/3}$$

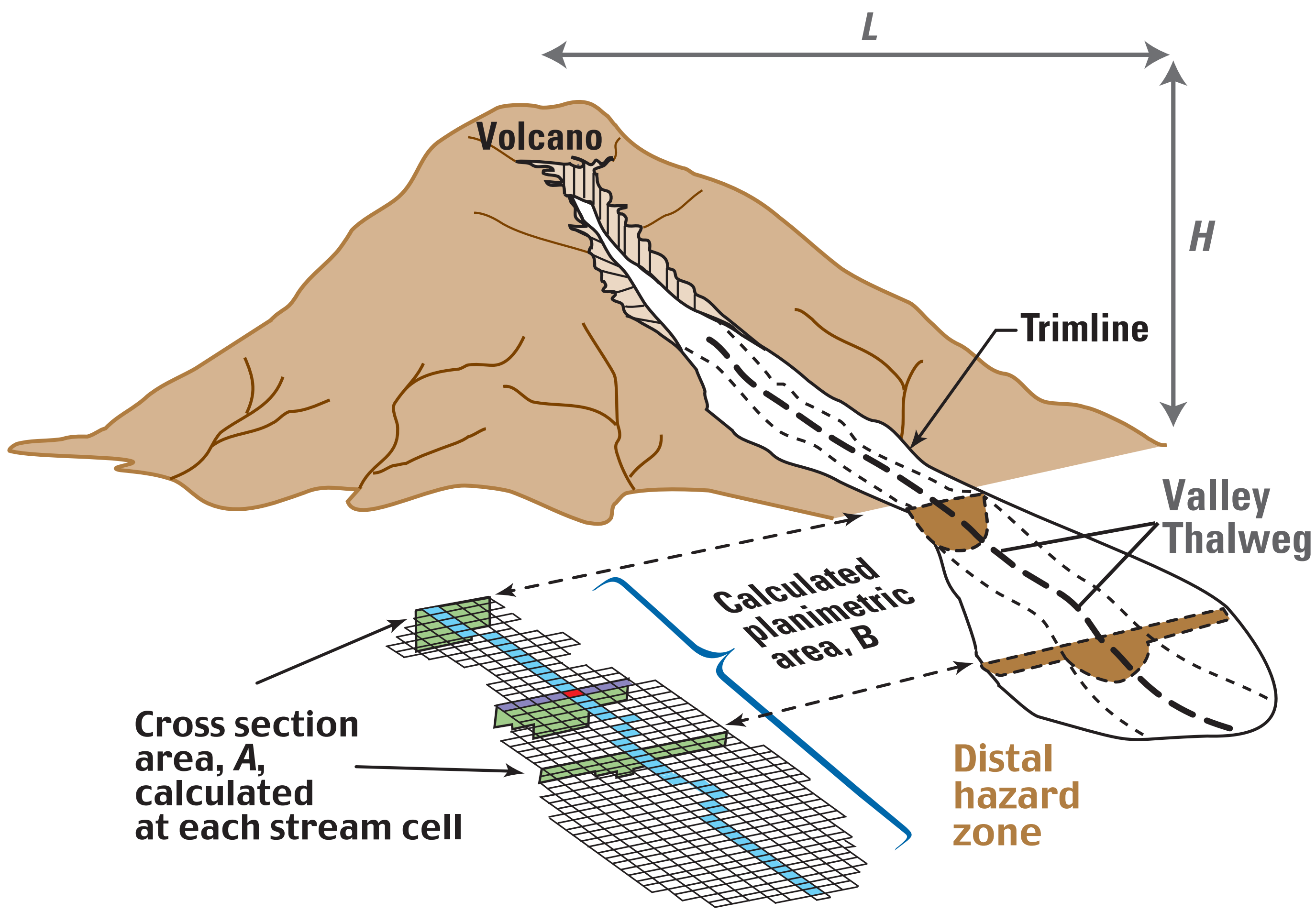
Flow spreading and deposition



Calder et al. (1999). GRL

LAHARZ

Iverson et al. (1998). GSA Bulletin



$$\boxed{A = c_1 V^{2/3}}$$

$$Q^*_{max} = \frac{Q_{max}}{A_{max}\sqrt{gR}},$$ dimensionless peak discharge

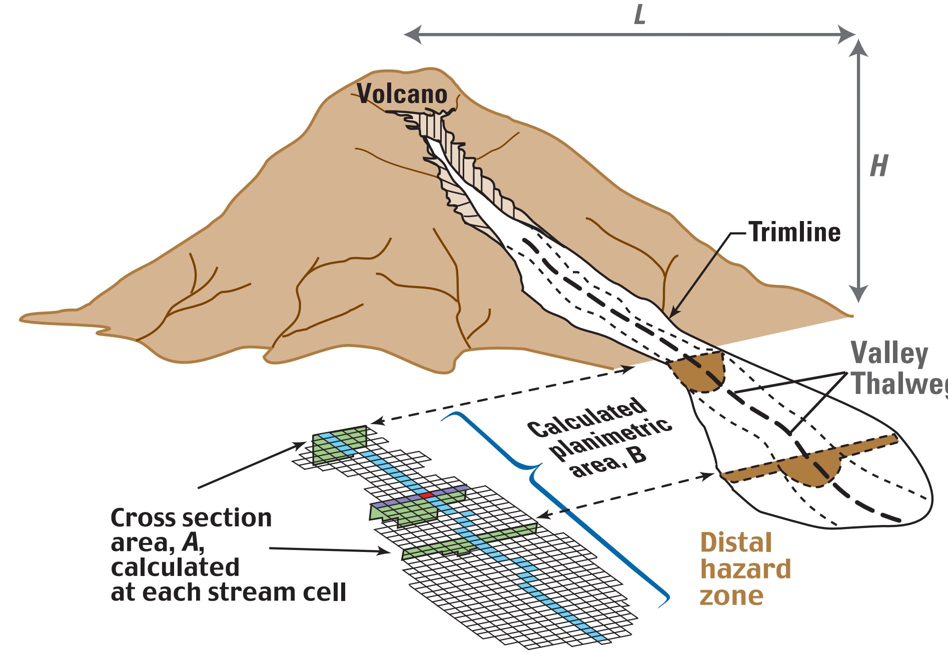
$$T^* = \frac{T}{\sqrt{A_{max}}/\sqrt{gR}}.$$ dimensionless lahar duration at cross section

$$c_1 = (KQ^*_{max}T^*)^{-2/3}$$

K dimensionless parameter related to lahar hydrograph

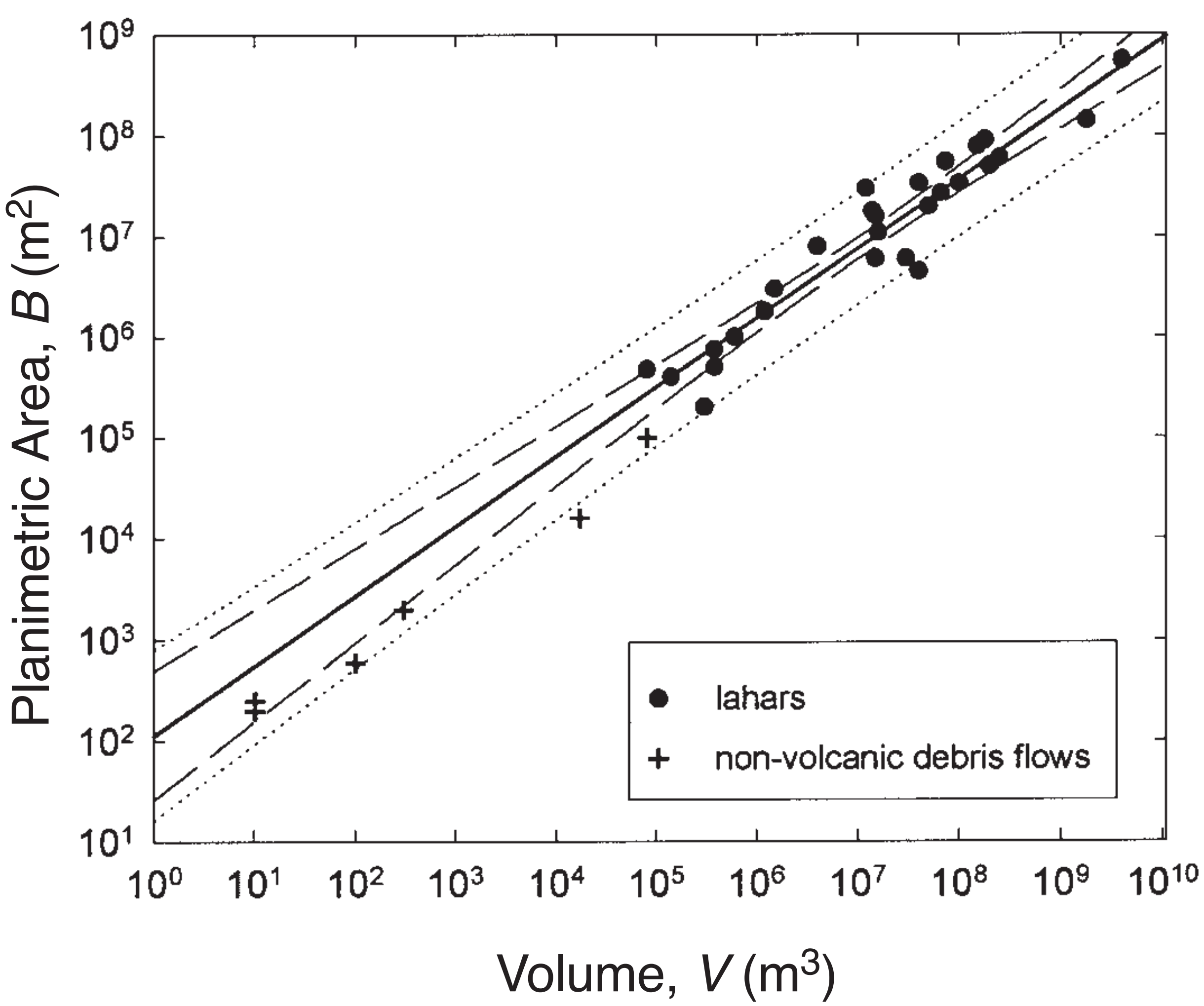
$$\boxed{B = c_2 V^{2/3}} \qquad c_2 = \varepsilon^{-2/3} \qquad \varepsilon = \bar{h}/\sqrt{B} << 1$$

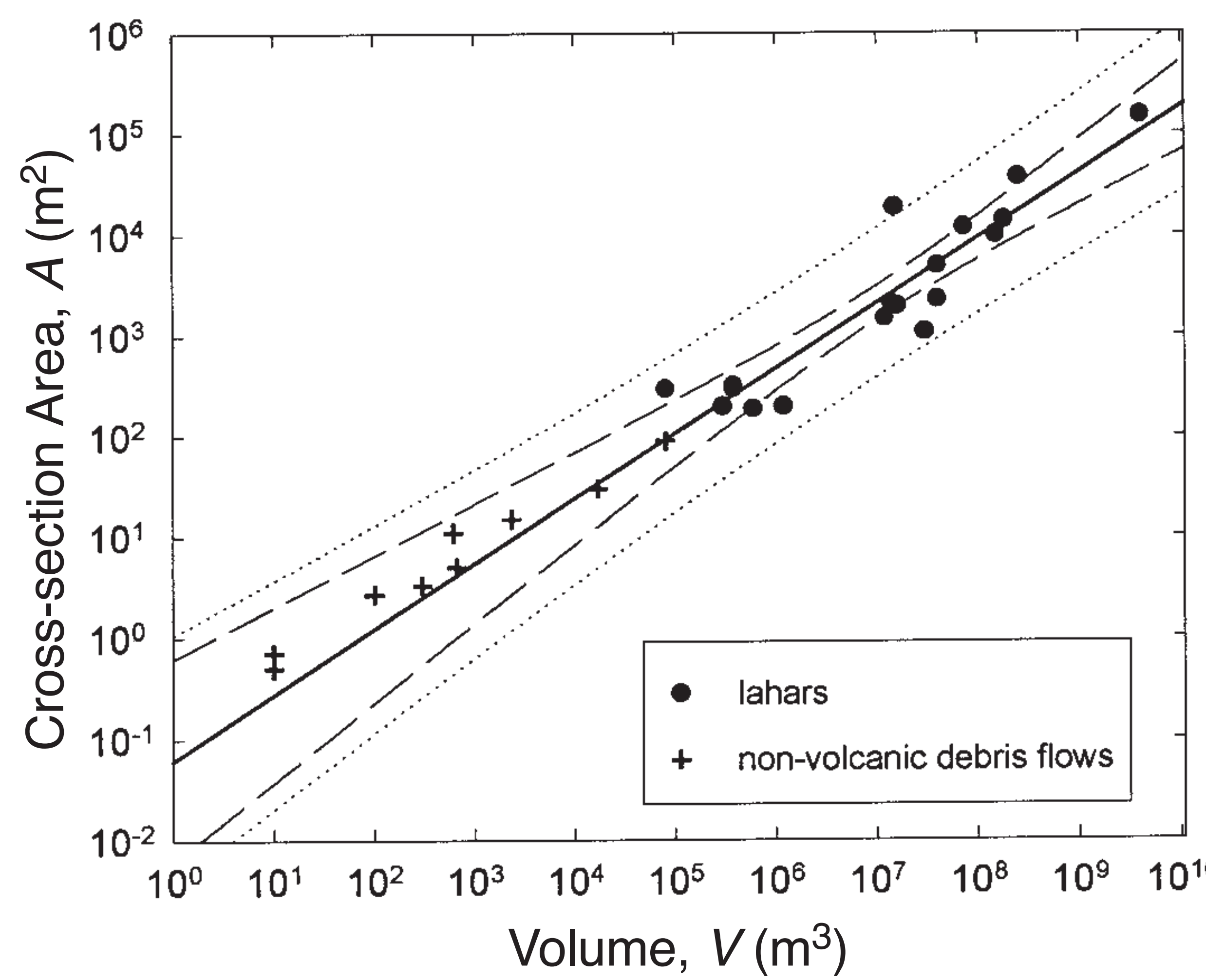
LAHARZ



$$A = 0.05V^{2/3}$$

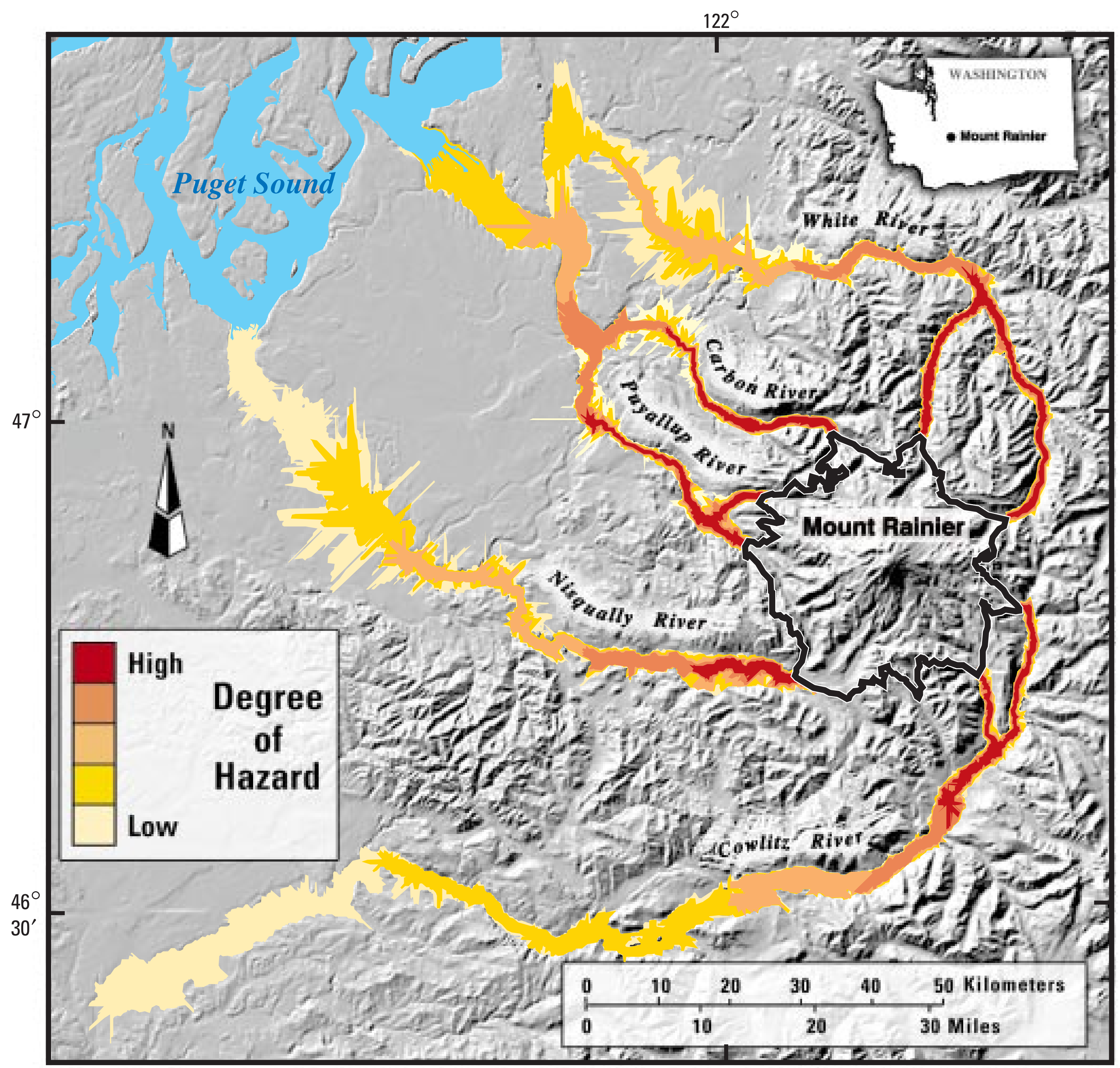
$$B = 200V^{2/3}$$





Iverson et al. (1998). GSA Bulletin

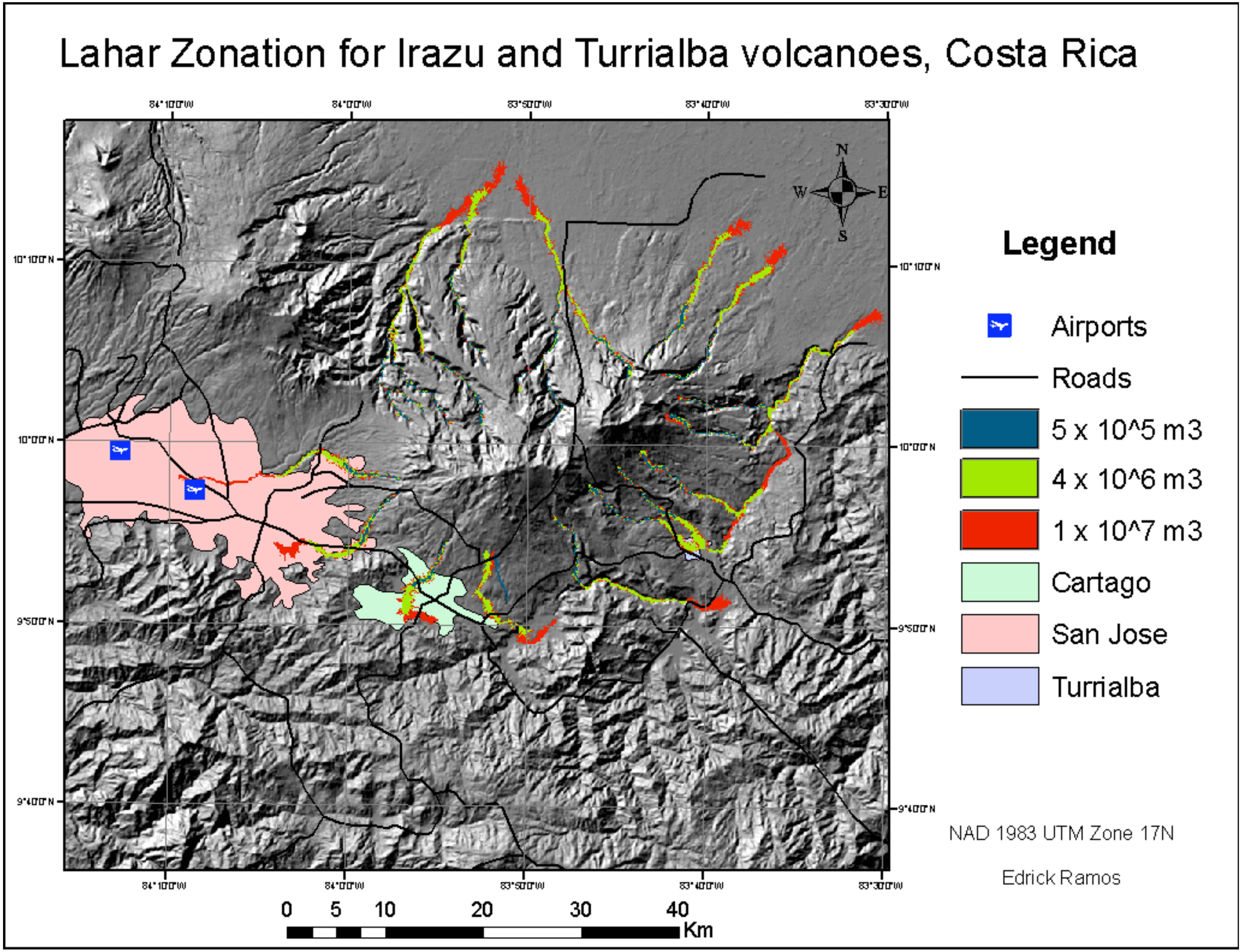
LAHARZ



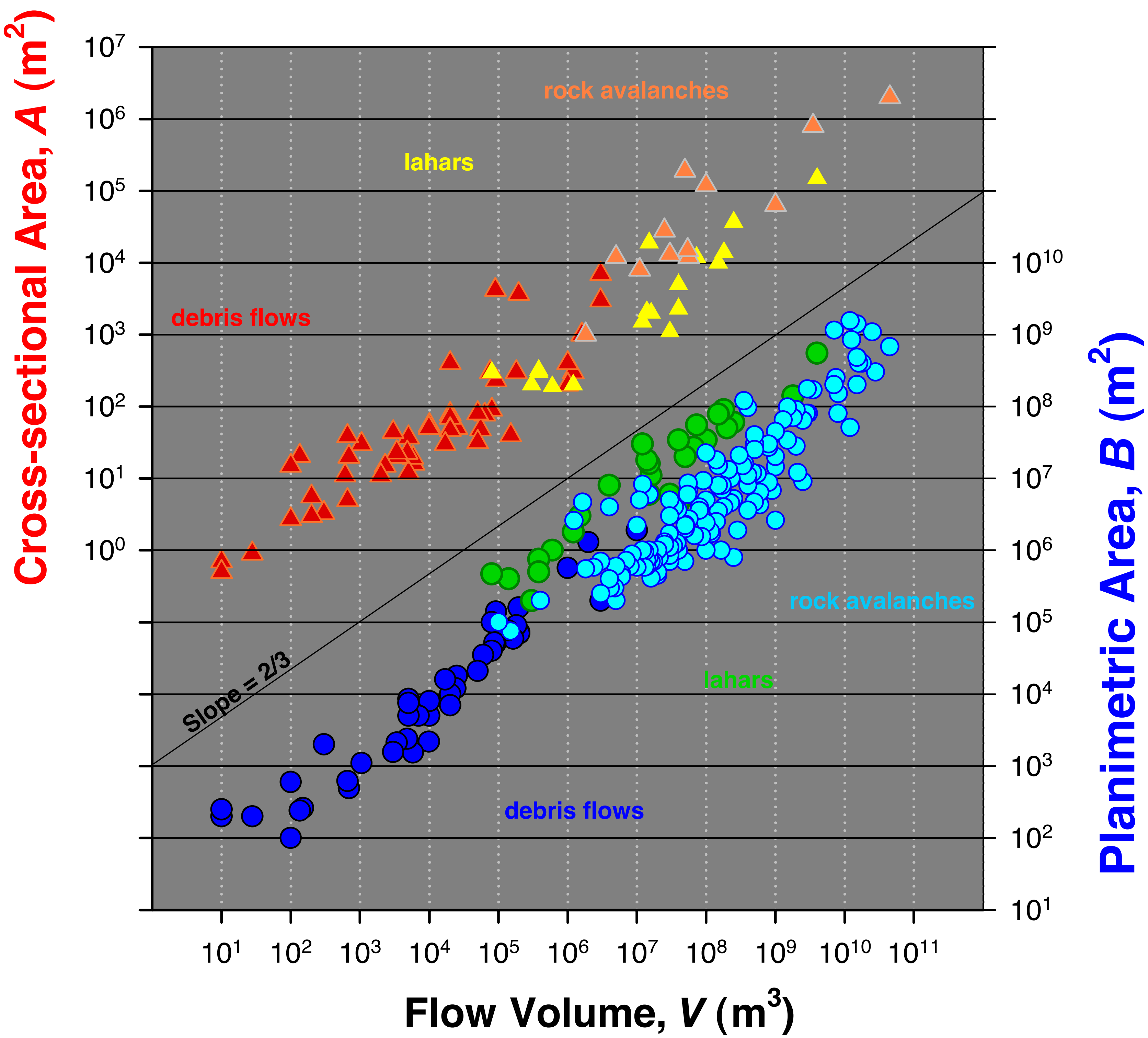
Iverson et al. (1998). GSA Bulletin

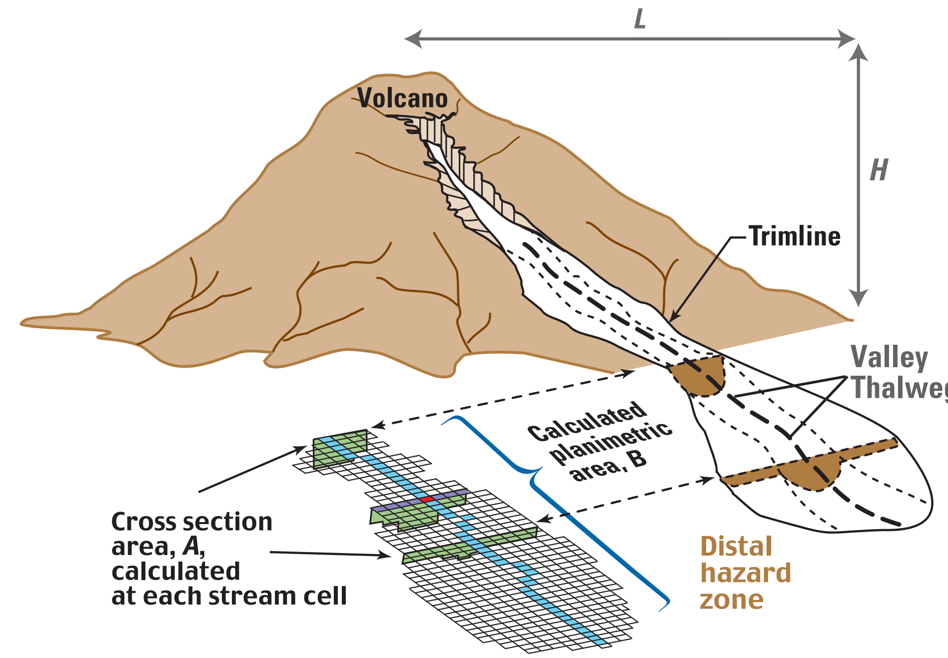
Lahar-inundation hazard map constructed by applying LAHARZ to the Mount Rainier region in western Washington. Topography is depicted by shaded relief. The proximal hazard zone enclosed by the dark line surrounding Mount Rainier is subject to diverse hazards, including lahars.

LAHARZ


Lahar Zonation for Irazu and Turrialba volcanoes, Costa Rica
Legend
Airports
Roads
5 x 10^5 m3
4 x 10^6 m3
1 x 10^7 m3
Cartago
San Jose
Turrialba
NAD 1983 UTM Zone 17N
Edrick Ramos
0
5
10
20
30
40
Km

LAHARZ

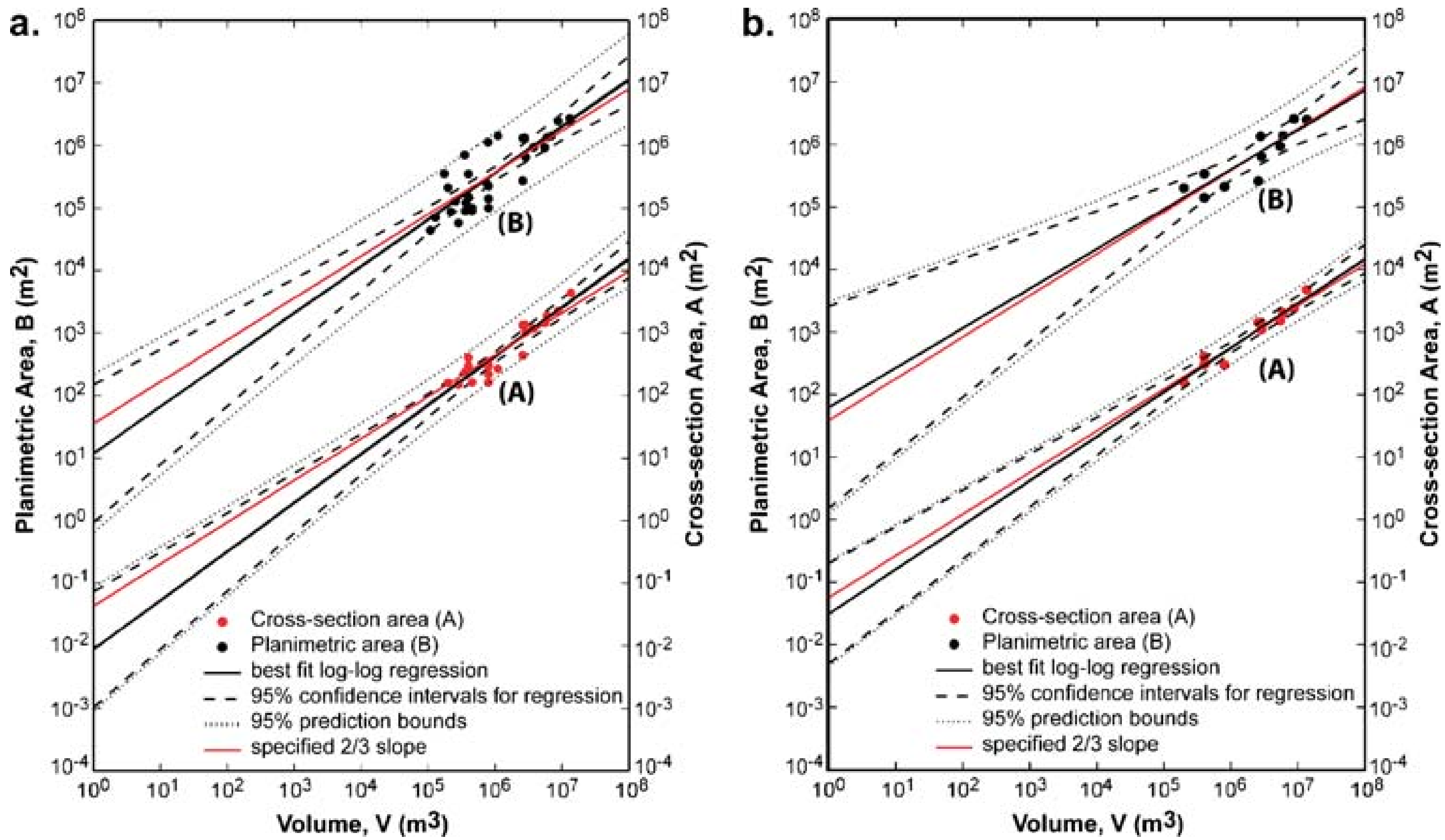




Griswold & Iverson. USGS Scientific Investigations Report 2007-5276

LAHARZ for block-and-ash PFs

Fig. 1 Scatter plots of inundated valley cross-section area *A* and planimetric area *B* as a function of PF volume *V*, using the data of Table 1. The best fit log–log regression lines and 95% confidence intervals for regression, and prediction, are also shown. *Red lines* show the trend for specified 2/3 slope. **a** Data from Table 1. **b** Montserrat data only

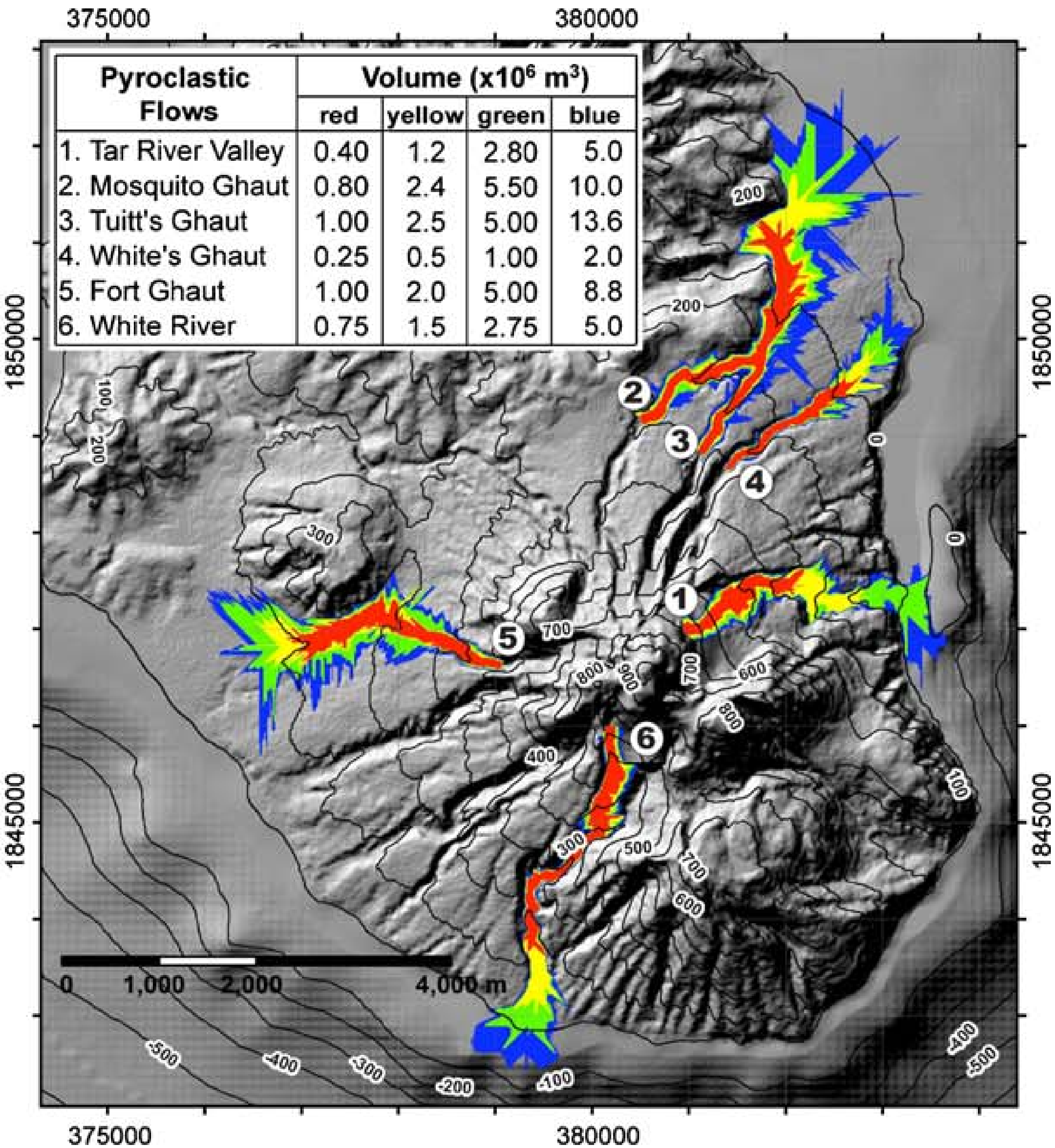


For all data: $A=0.05\ V^{2/3}$, $B=35\ V^{2/3}$

For Montserrat data: $A=0.1\ V^{2/3}$, $B=40\ V^{2/3}$

Widiwijayanti et al. (2008). Bull. Volc.

LAHARZ for block-and-ash PFs



Pyroclastic Flows	Volume ($x10^6$ m^3)			
	red	yellow	green	blue
1. Tar River Valley	0.40	1.2	2.80	5.0
2. Mosquito Ghaut	0.80	2.4	5.50	10.0
3. Tuitt's Ghaut	1.00	2.5	5.00	13.6
4. White's Ghaut	0.25	0.5	1.00	2.0
5. Fort Ghaut	1.00	2.0	5.00	8.8
6. White River	0.75	1.5	2.75	5.0

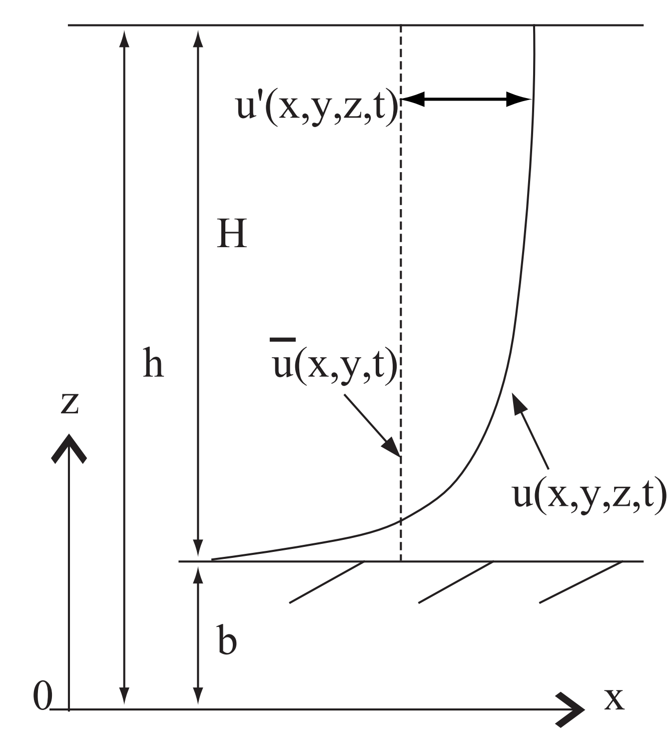
Widiwijayanti et al. (2008). Bull. Volc.

Shallow water models

- Valid when the horizontal length scale is much greater than the vertical length scale.

- Derived from depth-integrating the Navier-Stokes equations.

- Vertical velocity gradient is very small and it is discarded (only one vertical level); vertical pressure gradients are nearly hydrostatic.



Shallow water models- TITAN2D

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(hu)+\frac{\partial}{\partial y}(hv)=0 \qquad (3)$$

$$\frac{\partial}{\partial t}(hu)+\frac{\partial}{\partial x}(hu^2)+\frac{\partial}{\partial y}(huv)=gh\sin\alpha_x\ -\frac{1}{2}k_{actpass}\frac{\partial}{\partial x}(gh^2\cos\alpha)+\tau_x \qquad (4)$$

$$k_{actpass}=2\frac{1\pm\left[1-cos^2\varphi_{int}(1+tan^2\varphi_{bed})\right]^{1/2}}{cos^2\varphi_{int}}-1$$

$$\frac{\partial}{\partial t}(hv)+\frac{\partial}{\partial x}(hvu)+\frac{\partial}{\partial y}(hv^2)=gh\sin\alpha_y\ -\frac{1}{2}k_{actpass}\frac{\partial}{\partial y}(gh^2\cos\alpha)+\tau_y \qquad (5)$$

$$\tau=-ph\left(g\cos\alpha+\frac{\mathbf{u}^2}{r}\right)tan\varphi_{bed}\frac{u}{\|\mathbf{u}\|}$$

• **TITAN 2D simulation code** → **geophysical mass-flow model** developed at the University of Buffalo, USA (Pitman et al., 2003; Patra et al., 2005)

▶ **depth-averaged granular-flow model** on 3D terrain (Iverson and Denlinger, 2001)

▶ **conservation equations** for mass (3) and momentum (4 and 5) → **Coulomb-type friction** term at the basal interface

▶ incorporation of **topographical data** + **grid structure** (DEM) → **visualization platform** for displaying the flows

Shallow water models- VolcFlow

• **VolcFlow,** developed at the **Laboratoire Magmas et Volcans**, Clermont-Ferrand, by **Karim Kelfoun,** allows the simulation of **dense isothermal volcanic flows**

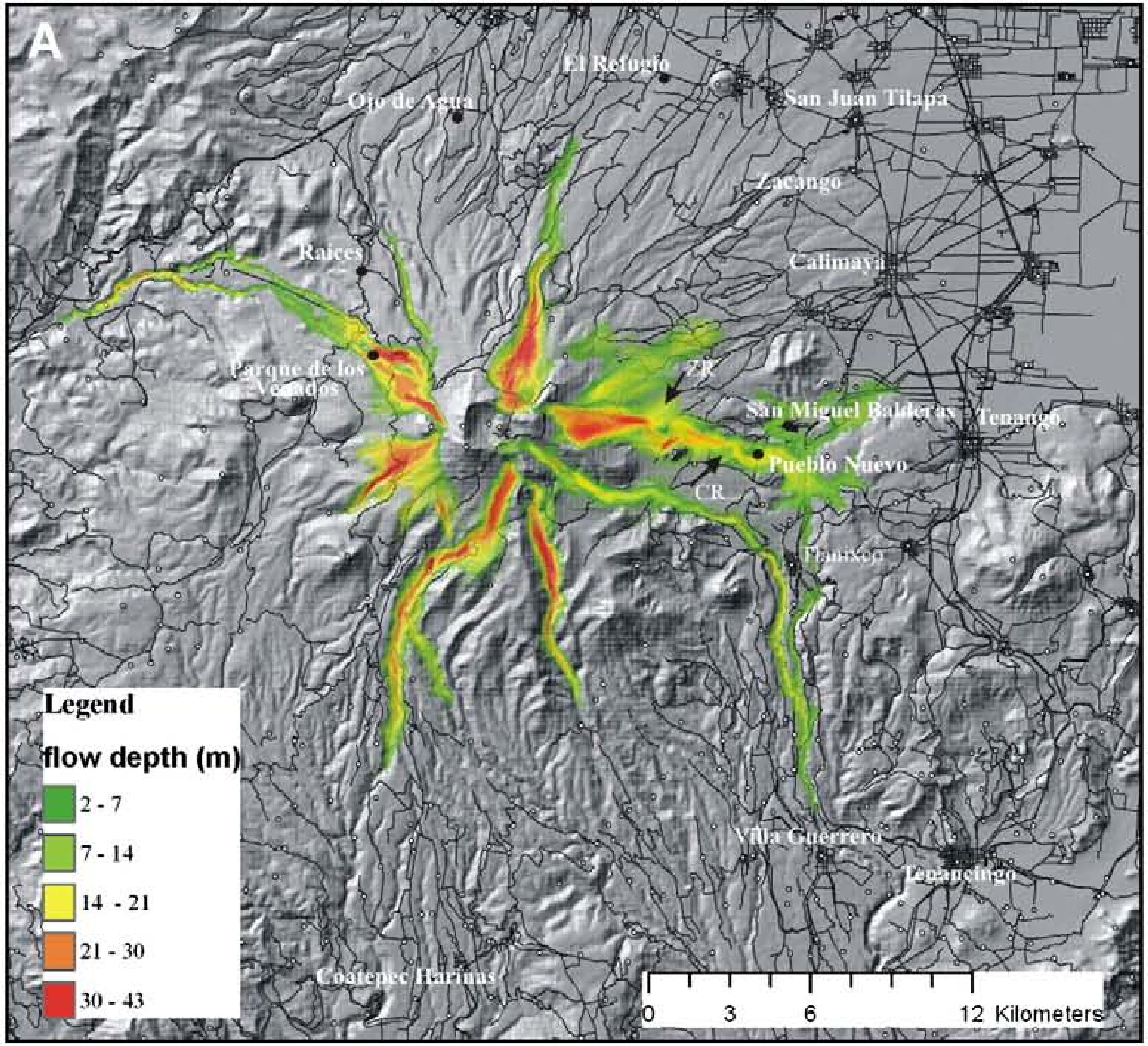
▶ **VolcFlow** is written in **<u>Matlab</u>** and runs on **Windows**

▶ **VolcFlow** can take into account **frictional (with one or two friction angles), viscous, Bingham, Voellmy, etc... as well as more complex, user-defined flow behaviors**

The default equation defining **the stress** in **VolcFlow** is :

$$T = \rho h \tan(\mathrm{delta\_basal}) \times \left(u^2 \mathrm{curb} + g\cos\alpha\right) + \mathrm{cohesion} + \frac{du}{dh}\mathrm{viscosity} + \rho u^2 \mathrm{coef\_u2}$$

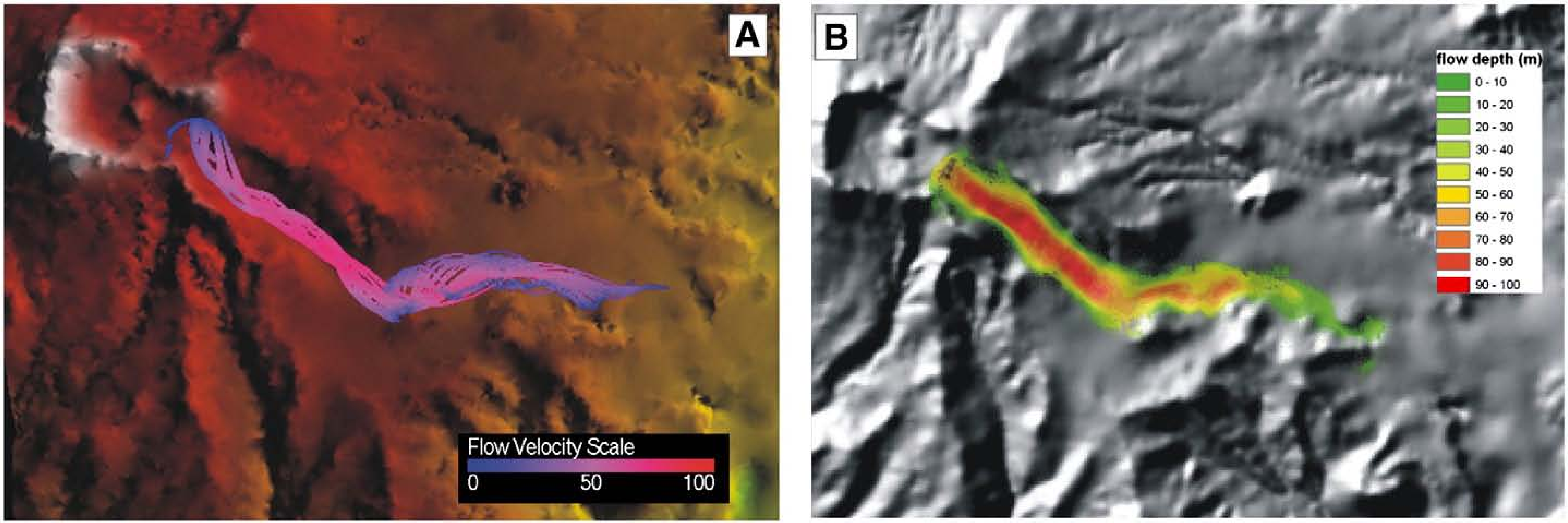
Shallow water models



Pyroclastic flow simulations with TITAN2D showing flow thickness on main ravines.

Capra et al. (2008). Volcanic hazard zonation of the Nevado de Toluca volcano, México. JVGR

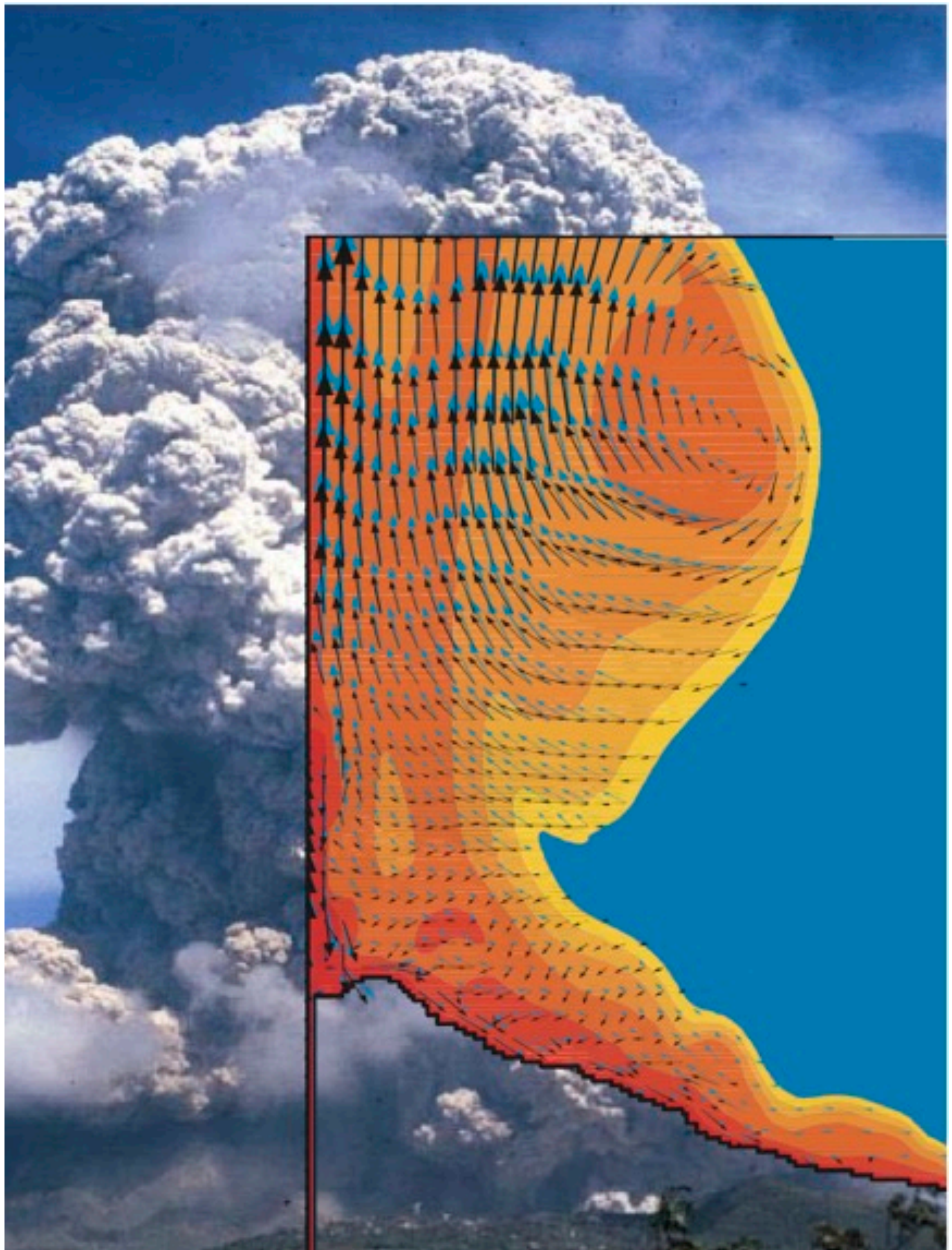
Shallow water models



Capra et al. (2008). Volcanic hazard zonation of the Nevado de Toluca volcano, México. JVGR

Simulation of the Arroyo Grande debris avalanche with (A) FLOW3D and (B) TITAN2D model

Multiphase flow modeling

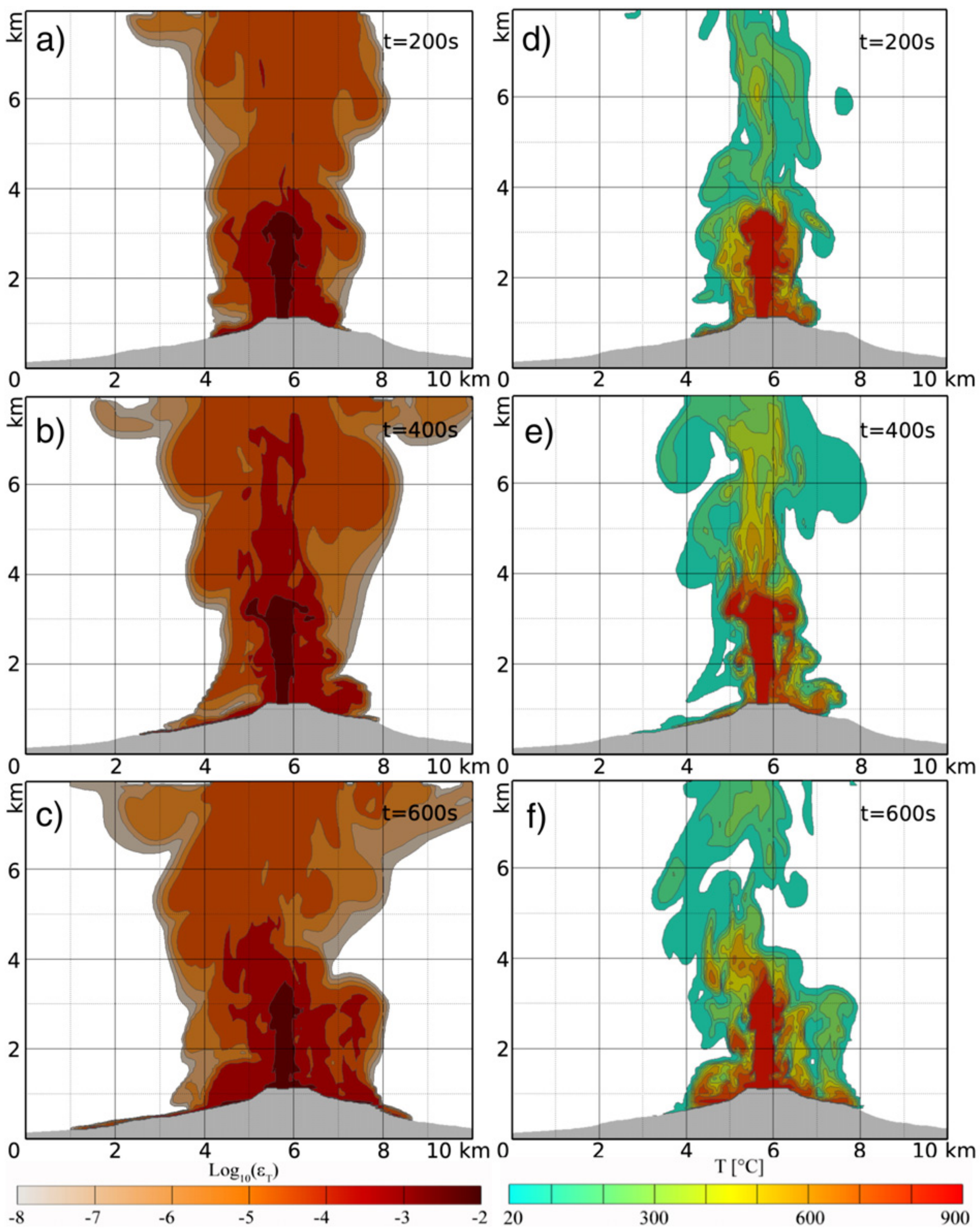


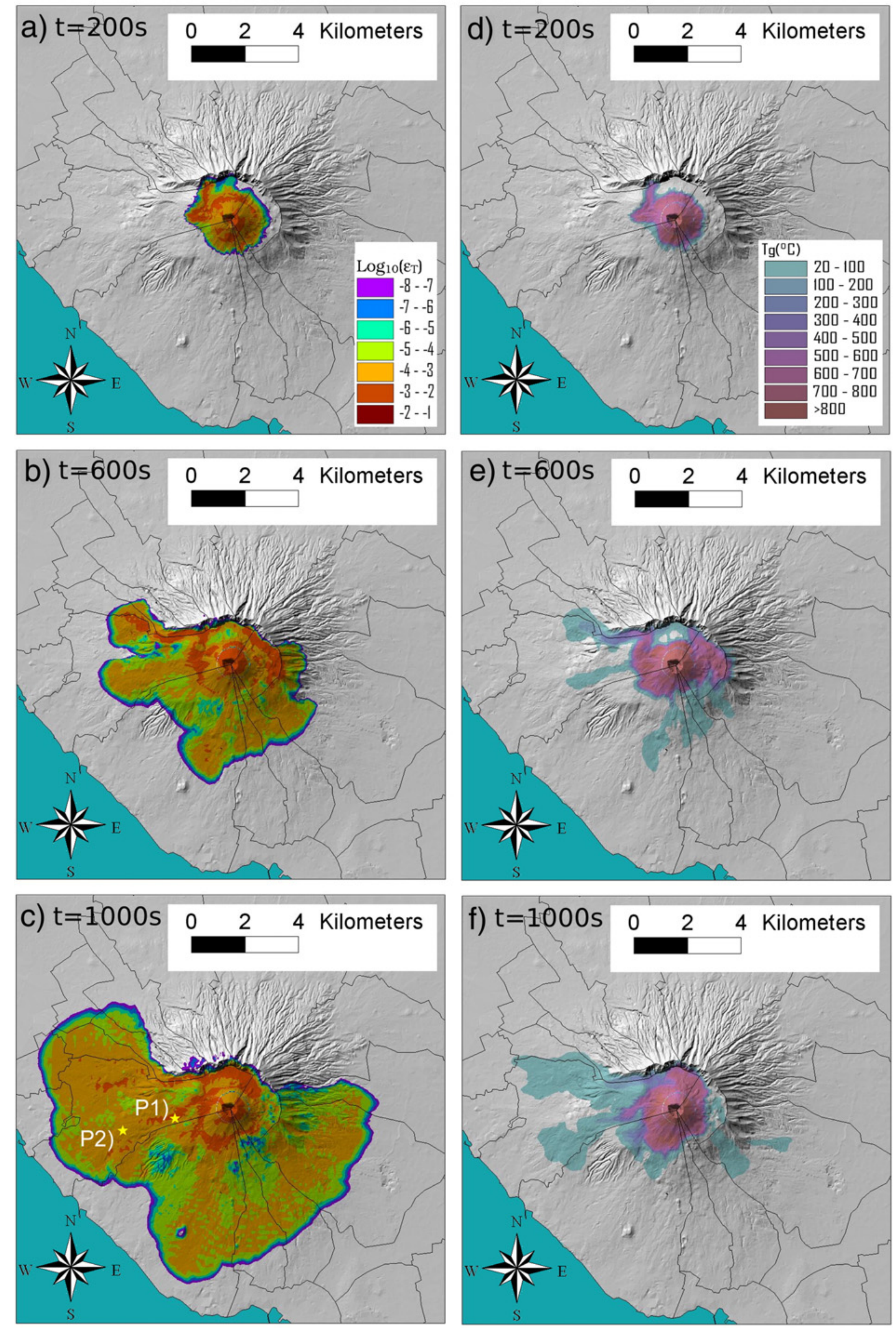
Clarke et al. (2002). Nature

- PDAC2D, axisymmetric, transient

- Solves for one gas phase coupled to a few solid components (different grain size)

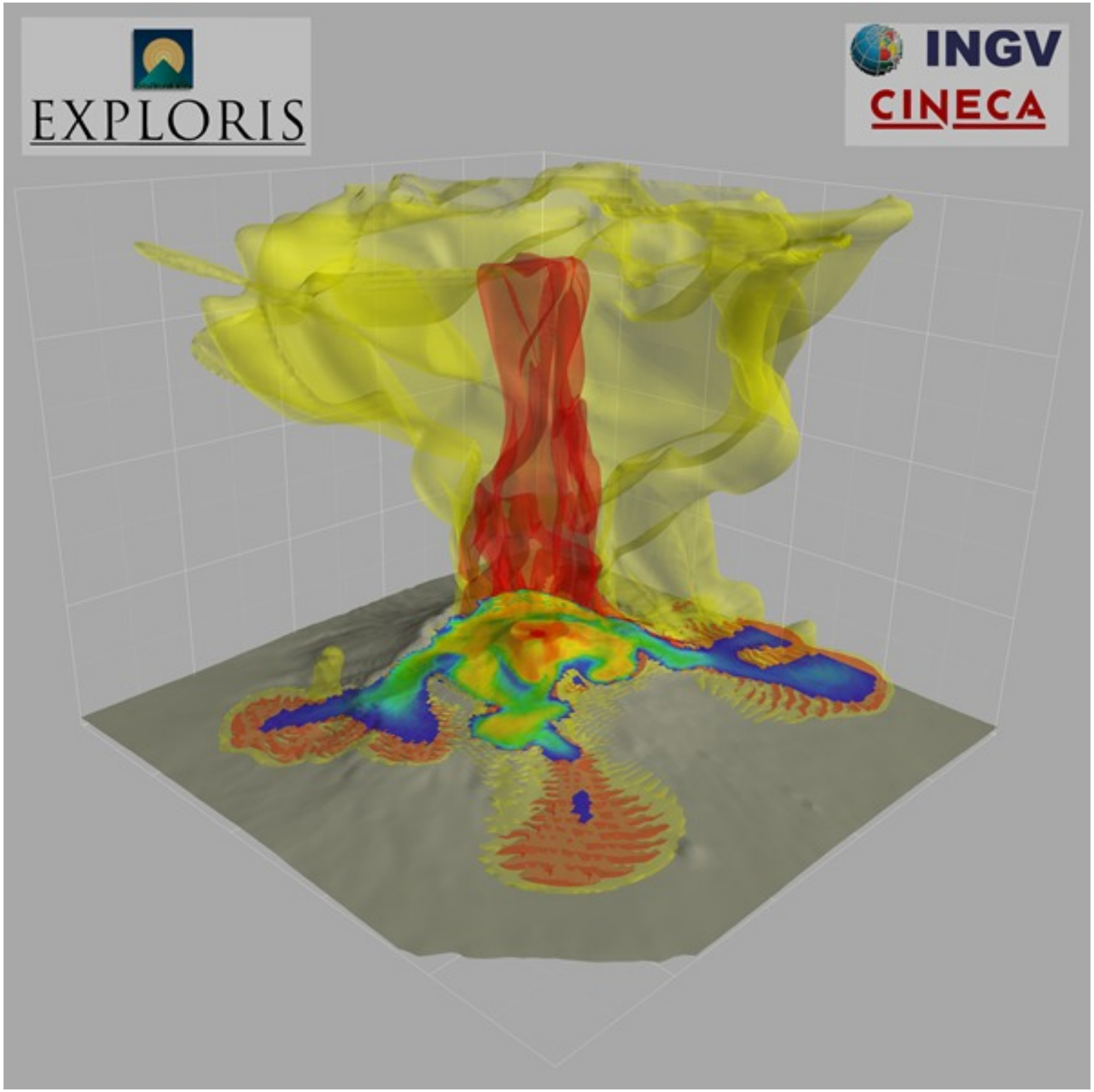
3D multiphase flow modeling





Esposti Ongaro et al. (2008). JVGR

3D multiphase flow modeling



Spatial distribution of pyroclastic particles in the atmosphere 1000s after the start of a sub-Plinian eruption (mass flow = 5.0e07 Kg/s) of Vesuvius. (Image: Menconi et. al. 2005).

End