A laboratory volcano (1): application to Kilauea

1) Fire fountain:

kinetic energy is transferred to potential energy (ballistic approximation):

$$\text{velocity} = (2\ g\ H)^{1/2}$$

H: fire fountain height
g: acceleration of gravity

H = 400 m → velocity = 100 m/s

Fire fountain during Puu o'O eruption (Kilauea, Hawaii)

Height H → gas velocity
duration
} → gas flux at vent

gas flux at vent = velocity x surface = gas volume / time

→ gas volume = velocity x surface x time

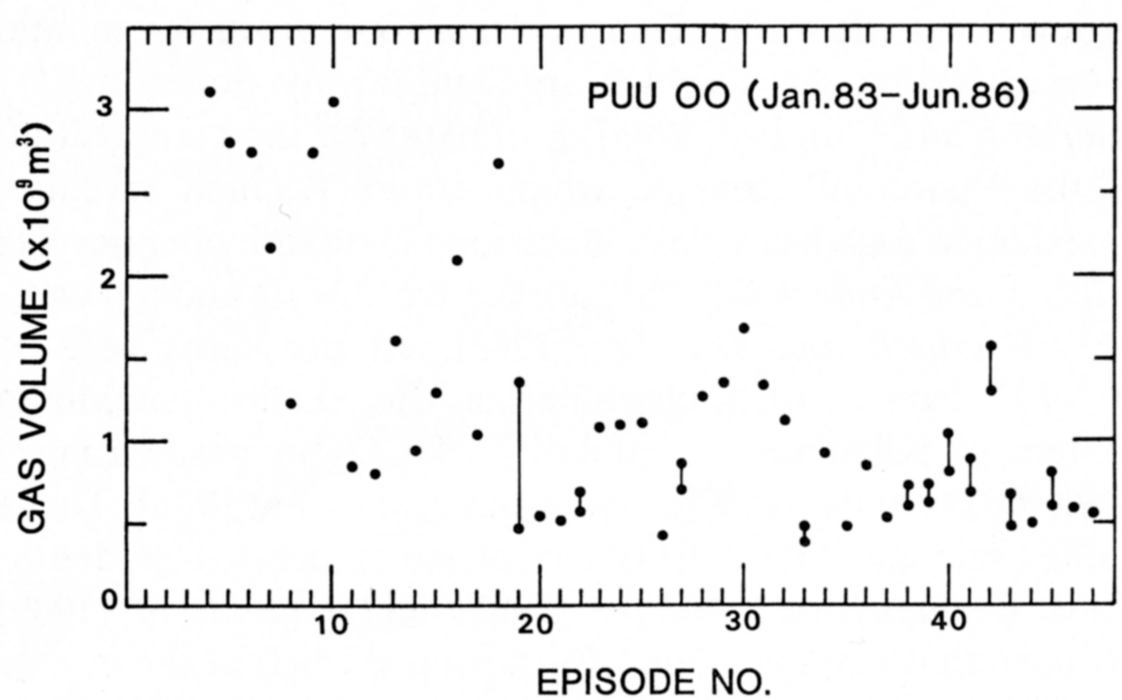
A laboratory volcano (2): application to Kilauea

gas volume at the vent is determined from fire fountain height

perfect gas law: $PV = \text{constant}$

P : pressure;
V: gas volume

$$P_{g\ vent} V_{g\ vent} = P_{g\ reservoir} V_{g\ reservoir}$$



gas volume in magma chamber

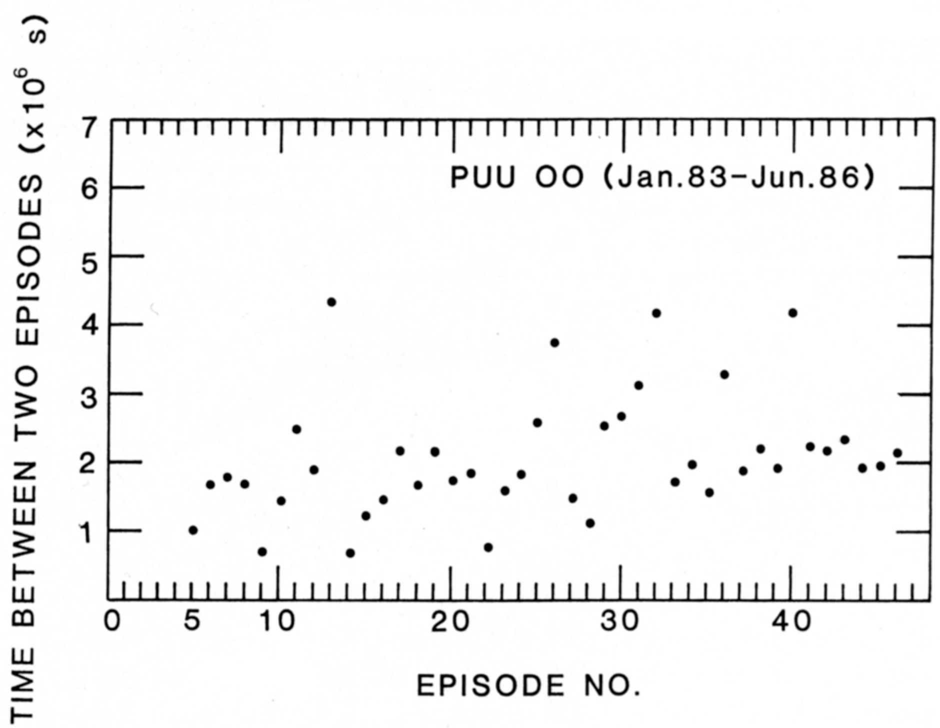
decrease in gas volume over the 3 years and a half

A laboratory volcano (3): application to Kilauea

2) Gas flux in magma chamber Q:

gas volume in magma chamber from fire fountains height

Intermittency between fire fountain: roughly constant



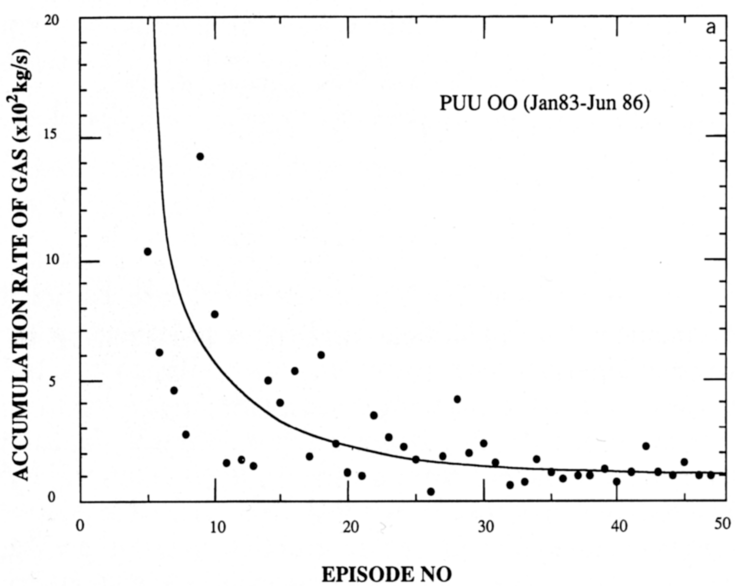
Gas flux in magma chamber is a gas volume at depth over a time during which it has been accumulated

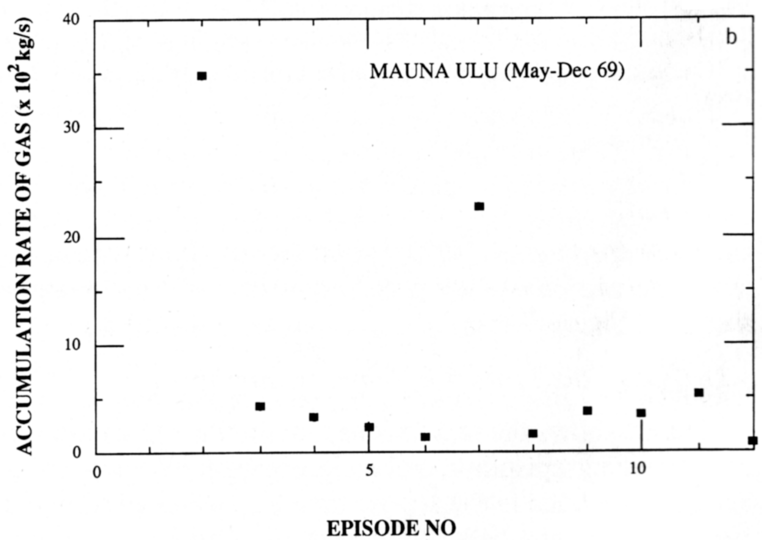
$$Q = \frac{\text{gas volume (2)}}{\text{intermittency (1-2)}}$$

A laboratory volcano (4): application to Kilauea

Gas flux in magma chamber Q:

for Kilauea volcano (Puu O'o and Mauna Ulu eruptions)
calculated for a reservoir at 4 km depth and from fire fountain height





decrease in gas flux in reservoir in time →

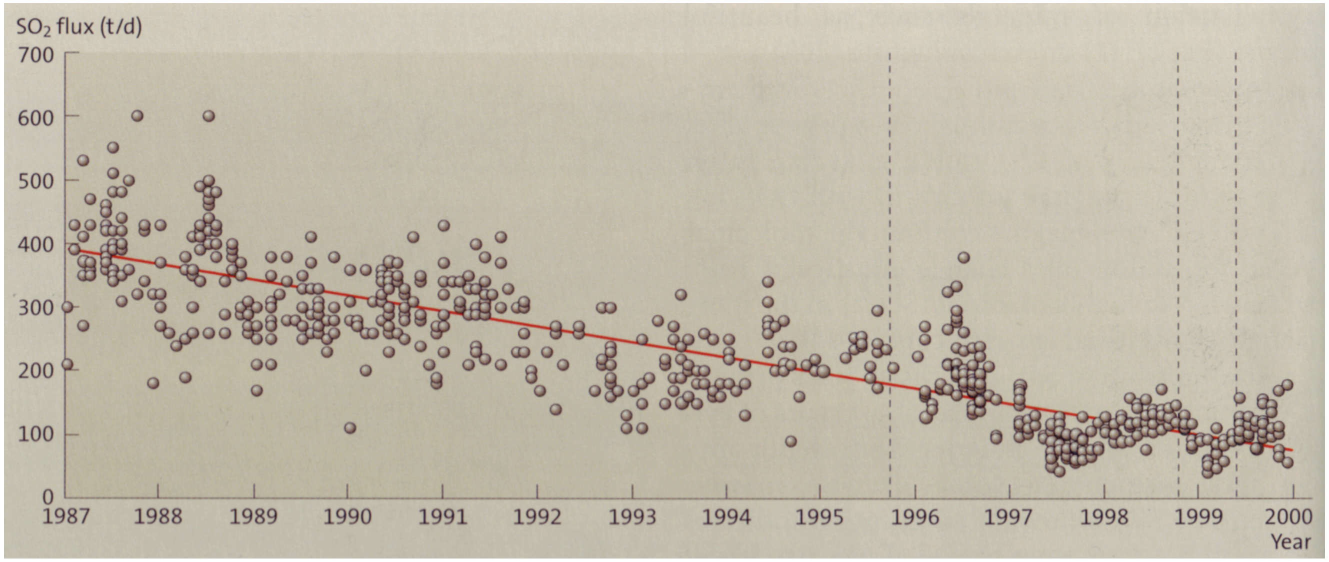
The stopping of fire fountain episodes is associated with the decrease of gas flux in reservoir below the critical gas flux

A laboratory volcano (5): application to Kilauea

The critical gas flux in reservoir, determined from fire fountain height, is approximatively 50 kg/s at Kilauea volcano

SO_2 is a magmatic gas which forms at large depth, which may be indicative of the relative evolution of gas volume and gas flux

SO_2 is easily measured at the vent (mass spectometer: Cospec, FTIR…)

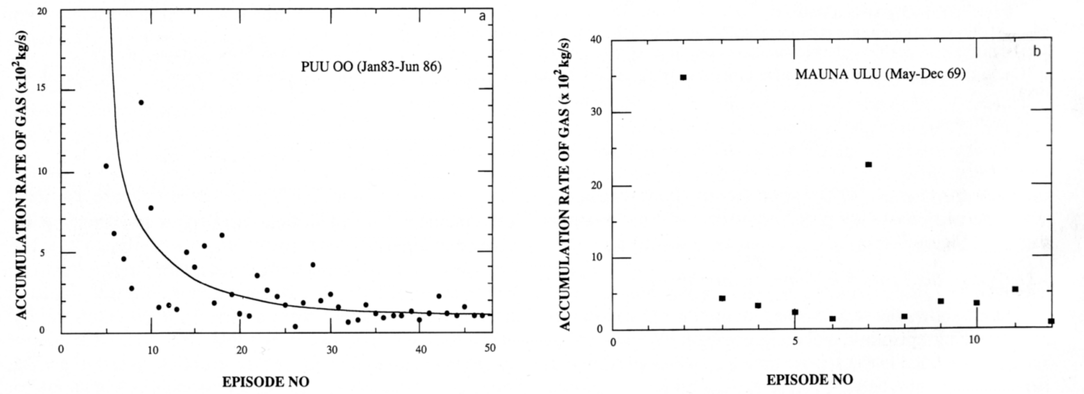


decrease in gas flux during fire fountains is confirmed for the period after the fire fountain episodes (effusive activity)

A laboratory volcano (6): application to Kilauea

Critical gas flux:

estimated from
the fire fountain
height at transition
fire fountain/ effusive



→ Q_c: critical gas flux: 50 kg/s

$$Q_c = B\frac{\sigma^4}{\rho_{liq}^3 \mu_{liq} d^4}$$

B = f(ε, r_c, r_t)

→ d = f(critical gas flux)

Q_c: critical gas flux (m^3/s)
σ: surface tension ($kg.s^{-2}$)
ρ_{liq}: liquid density ($kg.m^{-3}$)
μ_{liq}: liquid viscosity (Pa.s)
d: bubble diameter (m)

ε: gas volume fraction
r_t : reservoir radius (m)
r_c : conduit radius (m)

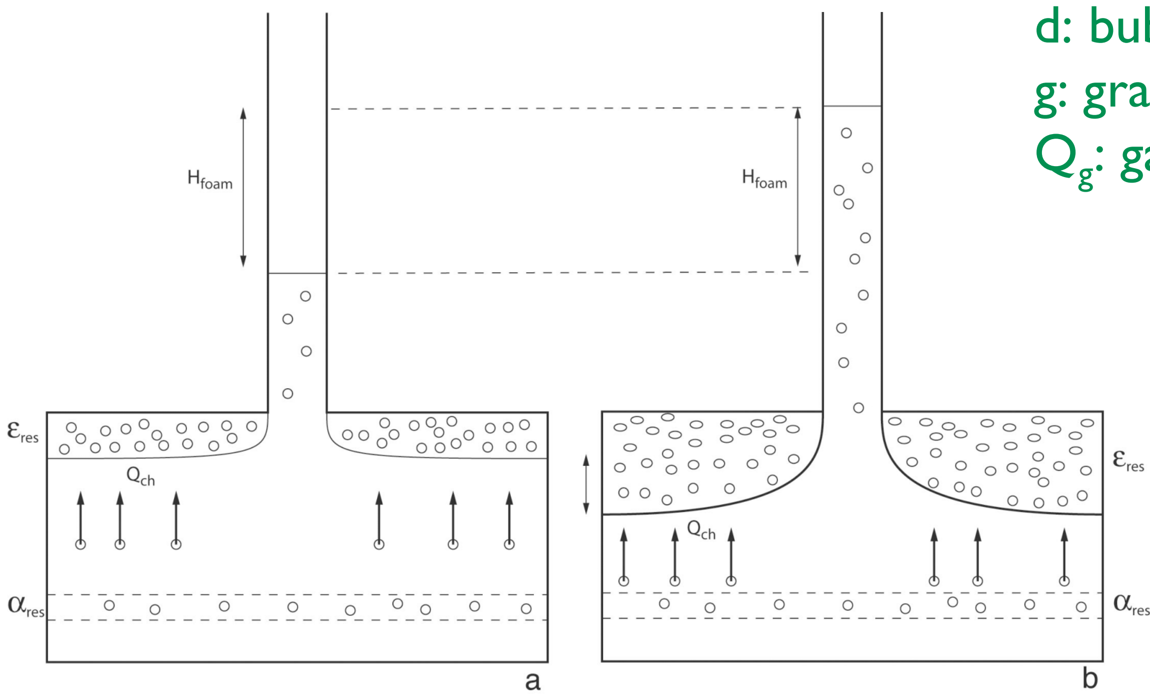
A laboratory volcano (7): application to Kilauea

Gas flux in magma chamber Qg:

from bubble rise velocity v_b : $Q_g = \alpha \ v_b \ S$

$$Q_g = \alpha \frac{(1 - \alpha)\, d^2\, (\rho_{liq} - \rho_{gas})\, g}{18\, \mu} S$$

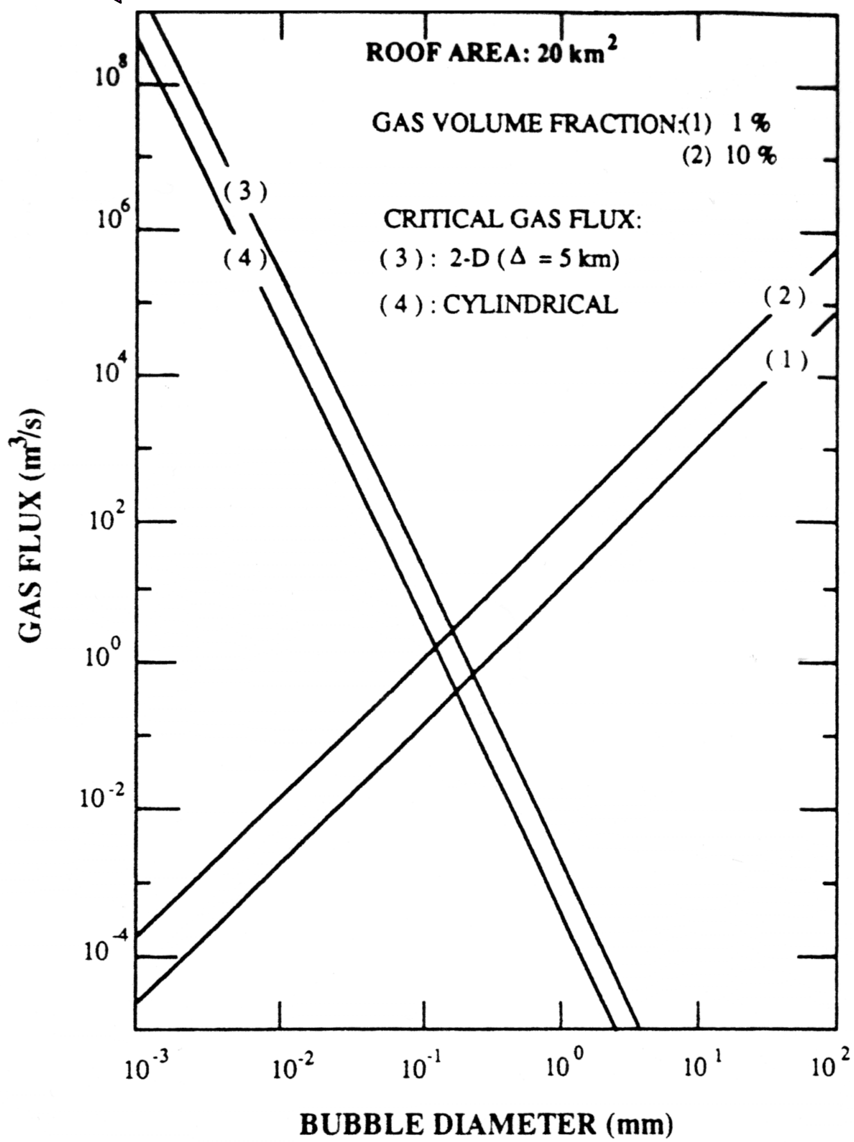
- α: gas volume fraction in reservoir
- S: area of magma chamber (m^2)
- μ: viscosity (Pa.s)
- ρ_{liq}: liquid density ($kg.m^{-3}$)
- d: bubble diameter (m)
- g: gravity
- Q_g: gas flux (m^3/s)



gas flux = f(α, d, area)

A laboratory volcano (8): application to Kilauea

Q_c: critical gas flux



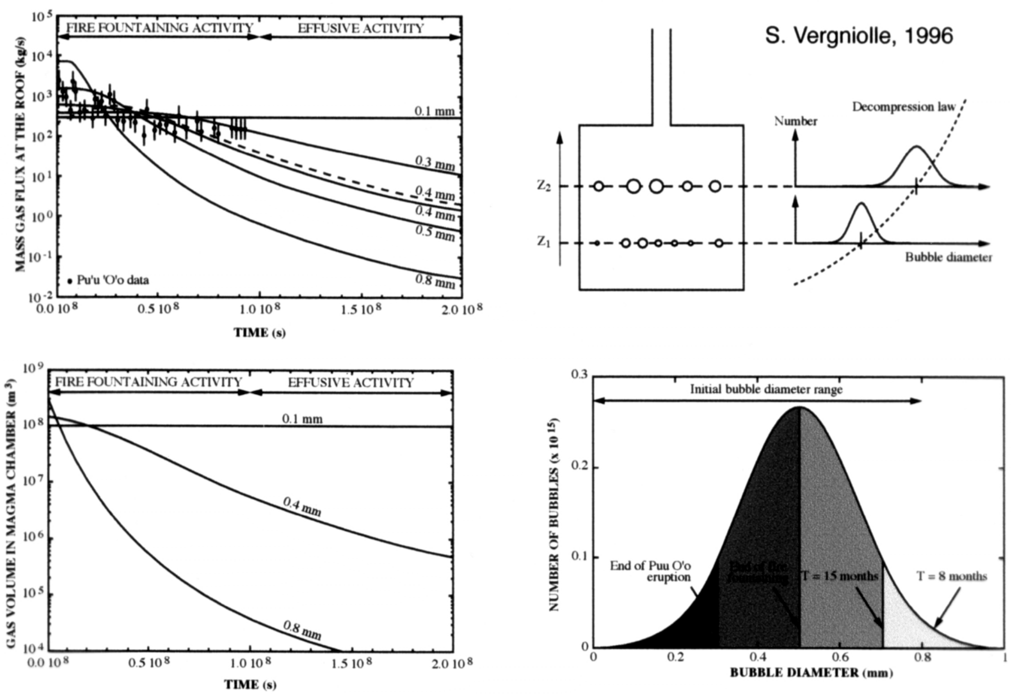
bubble rise

bubble diameter
in magma chamber
0.4 mm

Etna, 600 m
(Sept 26 1989)

A laboratory volcano (9): application to Kilauea

Duration of an eruption : evolution of a polydisperse suspension of bubbles initially widespread everywhere in a closed magma reservoir



Duration of eruption

time for smallest bubbles to reach the top of the magma chamber

Eruption stops when magma chamber has been depleted of most of its bubble content

A laboratory volcano (10): application to Kilauea

General trend: decrease of gas flux in time

1st bubbles are the largest and the latest bubbles the smallest

2 dimensionless times based on observed durations : τ_f^* and τ_e^*

Duration of fire fountain τ_f :

$$\tau_f^* = \tau_f \, \frac{d_0^2 \, (\rho_{liq} - \rho_{gas}) \, g}{18 \, \mu \, h_c}$$

$\tau_f^* = 1.1$: Puu O'o eruption (1987-now)

$\tau_f^* = 1.3$: Mauna Ulu eruption (1969-1971)

Duration of eruption τ_e :

$$\tau_e^* = \tau_e \, \frac{d_0^2 \, (\rho_{liq} - \rho_{gas}) \, g}{18 \, \mu \, h_c}$$

$\tau_e^* = 4.2$: Puu O'o eruption (1987-now)

$\tau_e^* = 4.3$: Mauna Ulu eruption (1969-1971)

Mean bubble diameter: 0.4 mm: Puu O'o and Mauna Ulu eruptions

Degassing layer = 2 km (Puu O'o) and 300 - 500 m (Mauna Ulu)

Duration of Puu O'o eruption is 6 times longer than Mauna Ulu

A laboratory volcano (11): application to Kilauea

Lava pond, Puu O'o eruption
(Kilauea, March 1988)

Makaopuhi lava lake, 1965:
height = 83 m = h_c
viscosity = 50 Pa.s = μ

Temperature measurements + model of thermal convection

→ for the first 5 months of emplacement:
no thermal convection because of bubble rise

τ_e^* = 5 months
τ_e^* = 4.2

} mean bubble diameter d_0 = 1 mm

same order of magnitude as for Puu O'o and Mauna Ulu eruptions

A laboratory volcano (12): application to Etna (Italy)

Recent activity: a series of regular eruptive episodes
(64 episodes in 2000; 15 episodes in 2001; id 1989; 1998)
each episode: a series of Strombolian explosions
a episode lasts a few hours, intermittency: a few days

Etna,
July 2001
(Pfeiffer)

Each explosion corresponds to large bubble bursting (diameter of several meters)

Acoustic measurements → gas volume at vent

A laboratory volcano (13): application to Etna (Italy)

FTIR measurements: gas composition with high CO_2/S and S/Cl

→ violent emptying of a foam layer accumulated at 1.5-2 km depth

Perfect gas law → Gas volume at depth of reservoir

+ intermittency between episodes (3-5 days) → Gas flux at depth of reservoir
Bubble diameter: 0.7 mm

9 May-13 July 2001: trachybasalt
at summit (South East Crater)
17 July-9 August 2001: flank-eruption:
alkali-rich basalt (primitive):
3.4 wt% H_2O; 0.11-0.41 wt% CO_2.

Etna, flank eruption 2001

Origin of flank eruptions is not well-known
but in July 2001 associated with new fresh magma

Basaltic magma reservoirs

1. Physical parameters
2. A laboratory volcano:

3. Gas volume measurements

4. Conclusion

Velocity measurements with a Sodar at Stromboli, juin 1991

Basaltic magma reservoirs

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   b) acoustic records

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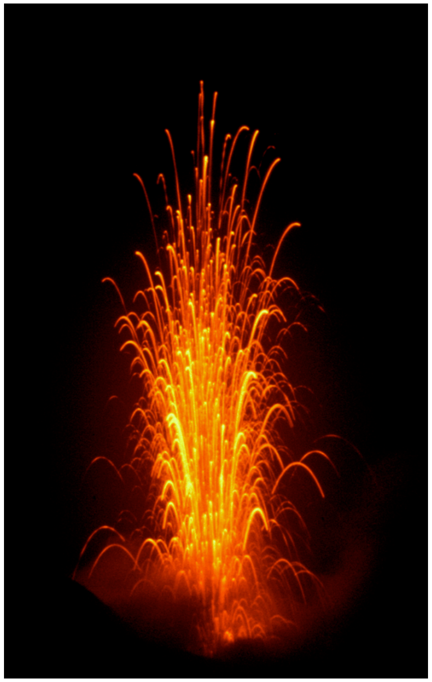
Velocity measurements with a Sodar at Stromboli, juin 1991

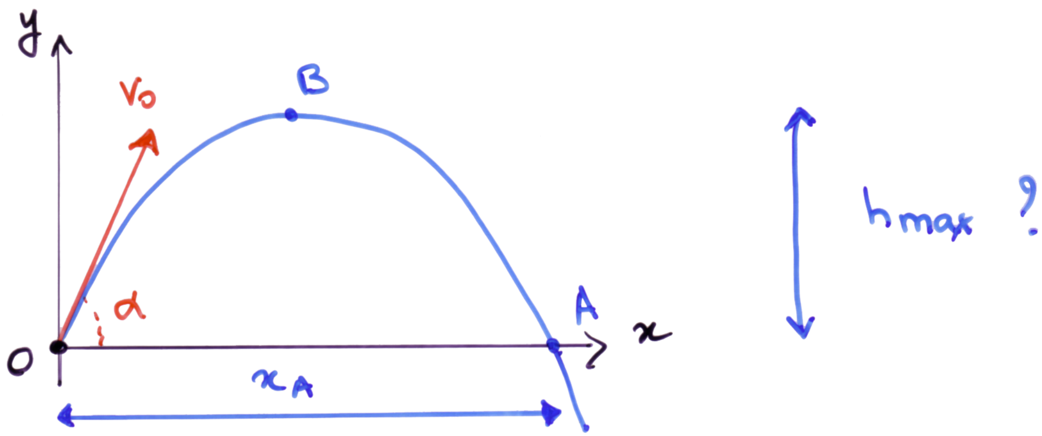
Direct measurements (1): ballistics

Strombolian explosion:
A series of bubbles bursting at the top of the magma column
duration: a few seconds
Intermittency: minutes to hours



Stromboli, 1992

Ballistic of a point:



assumption:
no air resistance

$$h_{max} = \frac{v_0^2 \sin^2(\alpha)}{2g}$$

Direct measurements (2): ballistics

For a vertical gas jet → $v_0 = (2\, g\, h_{max})^{1/2}$

(kinetic energy is transformed into potential energy)

Example: Stromboli

$h_{max} = 100$ m → $v_0 = 50$ m/s

v_0 is not too sensitive to h_{max}, which is difficult to measure

Impact on the ground: x_a

$$x_a = \frac{v_0^2 \sin(2\alpha)}{2\, g}$$

x_a is maximum for $\alpha = 45°$

$\alpha = 60°$; $v_0 = 50$ m/s; $x_a = 220$ m

Maximum distance reached by ballistics ejecta: a few km.

If a small plume is formed, small ejecta can be carried further away

Direct measurements (3): ballistics

Bubble rise in a magma:

$$v_{gas} = \frac{d^2 (\rho_{liq} - \rho_{gas})\, g}{18\, \mu}$$

μ: viscosity (Pa.s);
ρ_{liq} and ρ_{gas} liquid and gas density (kg/m^3);

balance between viscous resistance in magma and bubble buoyancy

Basalt: a bubble of 1 mm in diameter (d) takes 6 months to rise 1 km

particle in gas jet:

$$v_{part}^2 = \frac{2\, \pi\, d\, (\rho_{liq} - \rho_{gas})\, g}{3\, C_d\, \rho_{air}}$$

C_d: drag coefficient (turbulent) = 1.18

balance between friction in air and particle weight

Remark: Stromboli; crystal settling: d = 1 mm; v_{cryst} = 56 m/s

Apparent velocity: $w = v_{gas} - v_{part}$

ballistics → v_{part} = 50 m/s : particle velocity

→ V_{gas} = 100 m/s : gas velocity

Direct measurements (4): ballistics

Particle diameter (cm) — Apparent Particle velocity

$w = v_{gas} - v_{part}$

Stromboli, 1971

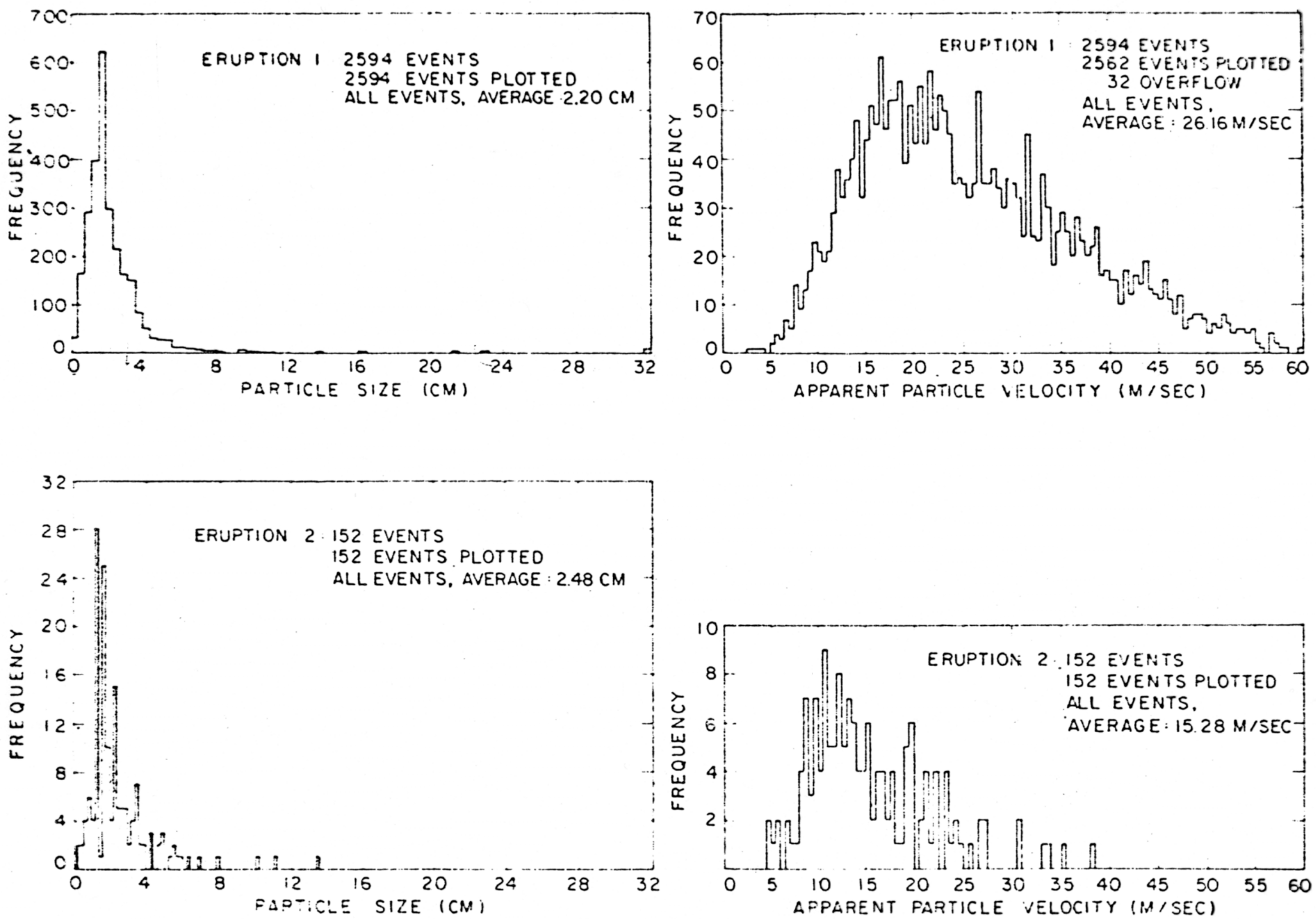
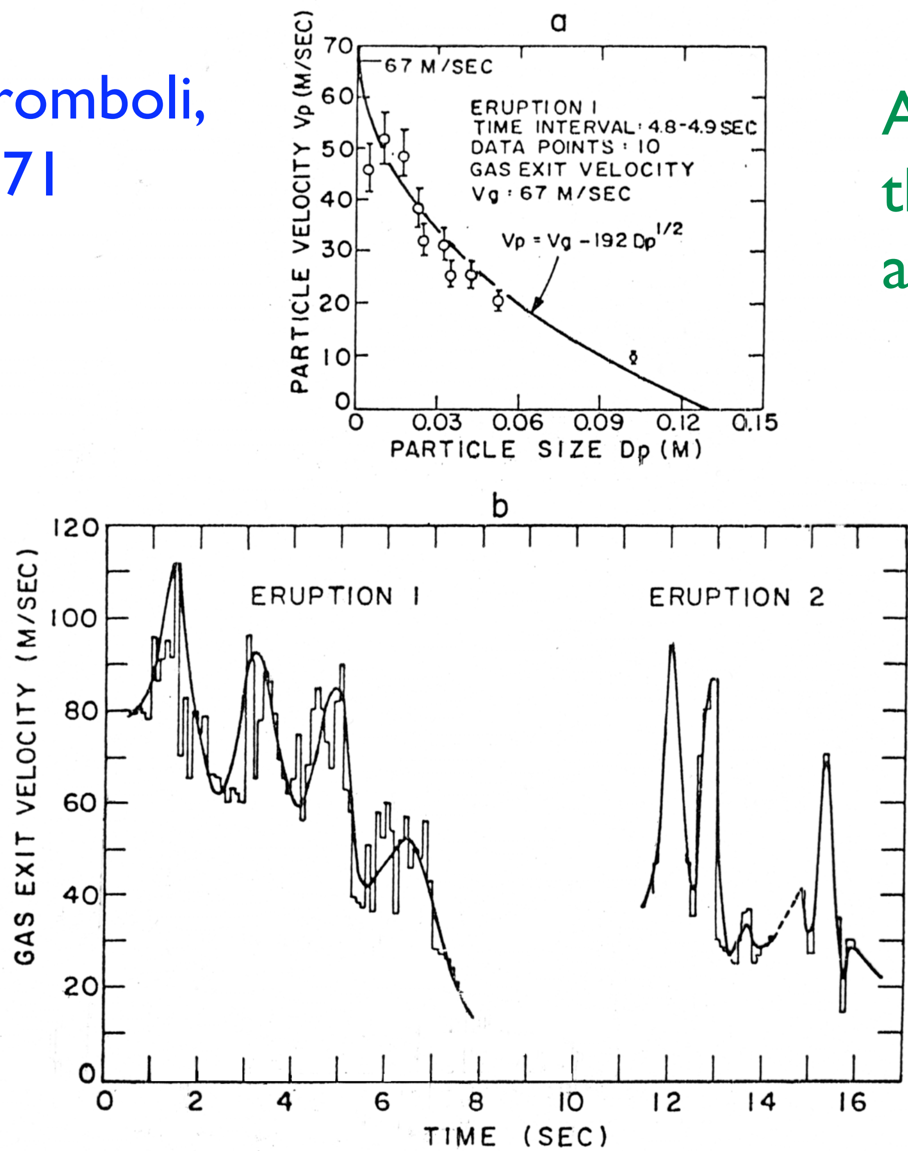


Fig. 9. Frequency distributions of particle sizes and apparent particle velocities for the bulk of the two eruptions studied.

Direct measurements (5): ballistics

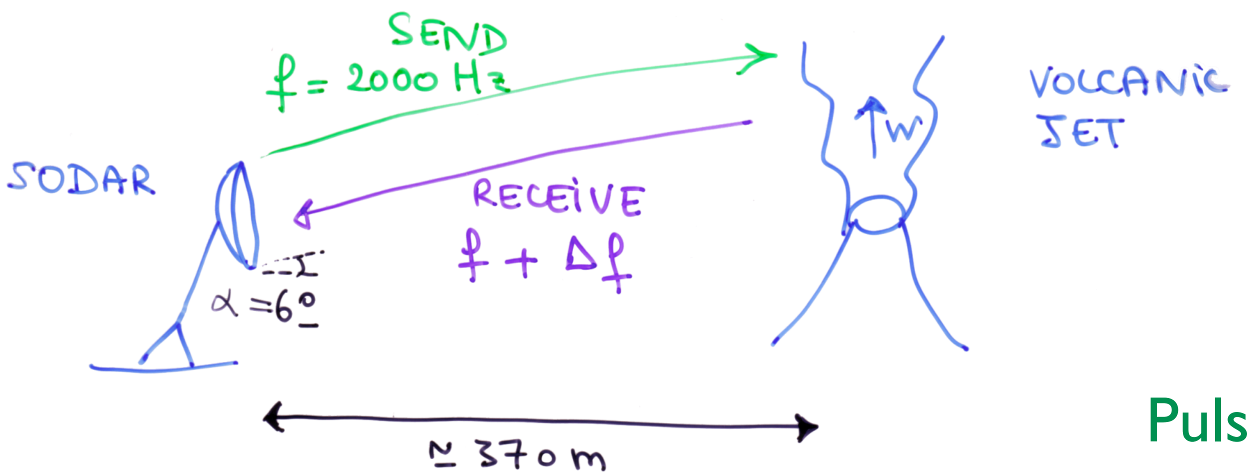
Stromboli, 1971



Apparent particle velocity:
the smallest particle moves
at the same velocity as the gas

Oscillations in gas jet:
attributed to resonances
of the conduit
(300 m length)

Direct measurements (6): radar: Acoustic sounder



Doppler shift

⬇

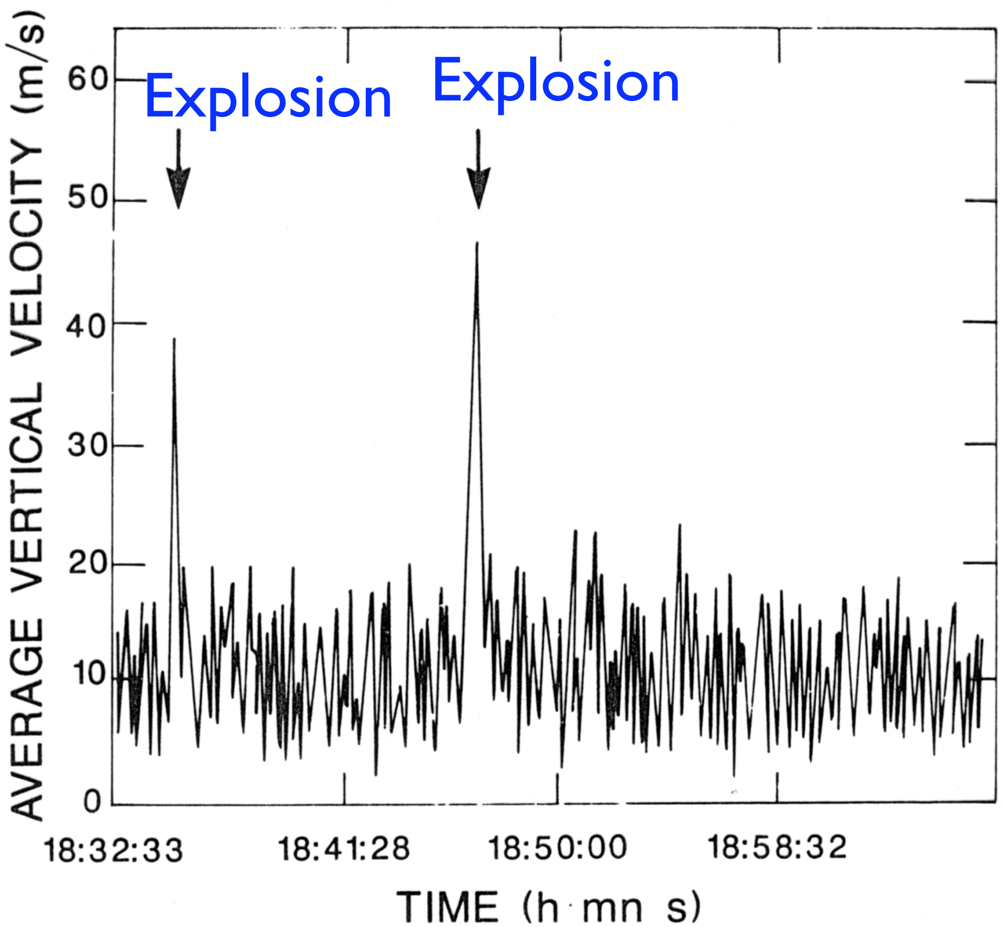
velocity

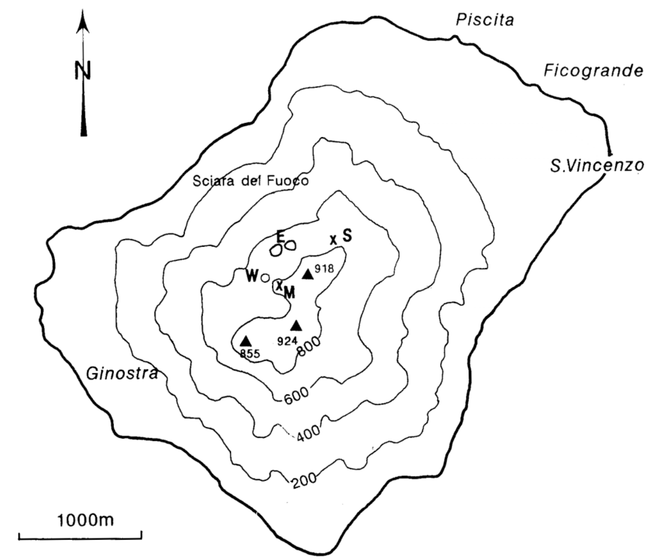
Pulse: each 4 s; τ_{on} = 50 ms

$\Delta f / f = - 2\, w \sin(\alpha) / c$

c: sound speed
air: 340 m/s
hot gas : 700 m/s

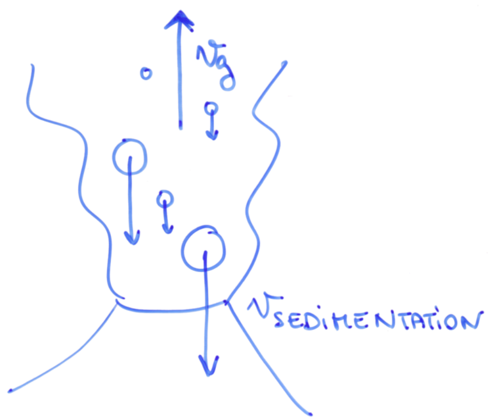
Direct measurements (7): Acoustic sounder





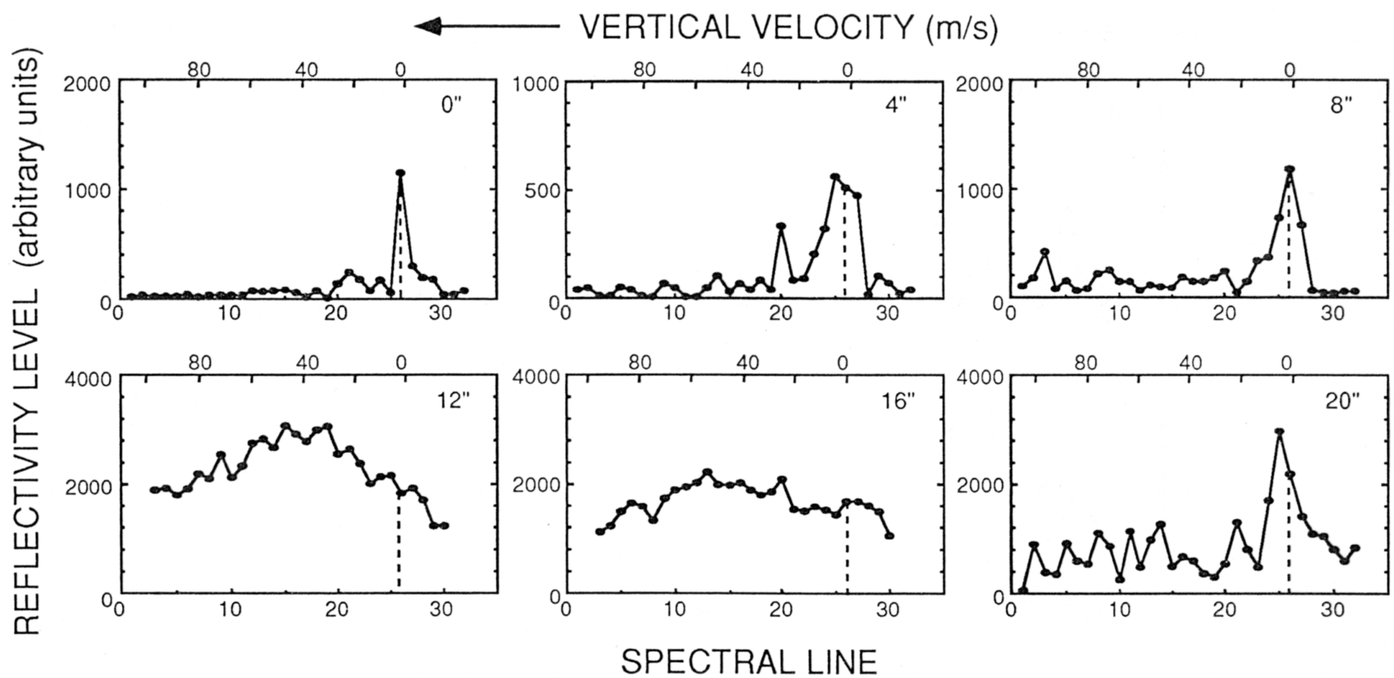
Summit vents
at Stromboli

Direct measurements (8): Acoustic sounder



$w = v_g - v_{part}$

A range of particles velocity because of a range of particle diameter



Basaltic magma reservoirs

1. Physical parameters
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Acoustic measurements at Yasur, Vanuatu, 1993

Direct measurements (9): Acoustic records

Microphone,
Yasur, 1994

Yasur, 1994

Sound is produced by a volcano has a strong intensity

Sound : variation of pressure, which propagate in a compressible fluid
correspond to density variations in an elastic media
radiation of sound in air from volcano vent

Sound waves are longitudinal waves (P):
elements of fluid move parrallel to the direction of propagation
move back and forth: zones of compression and dilatation

Acoustic: related to oscillatory motion
identical to seismology except propagation in air

Direct measurements (9): Acoustic records

Microbarograph
at Yasur
(oct 2002)

Yasur,
(oct 1993)

Sound is produced by a volcano → Informations on volcanic activity

recording sound waves is a way to monitor volcanic activity

What is the source of the sound?

source = gas

Frequency = size of the source

Amplitude = overpressure → ejecta velocity

Phase = initial condition

Evolution in time of the eruption characteristics

Direct measurements (10): Acoustic records

First developped on Strombolian explosions:
permanent activity and not dangerous (close to the vent)

A series of bubbles bursting at the top of the magma column
duration: a few seconds
Intermittency: minutes to hours

Etna,
July 2001
(Pfeiffer)

Ejecta velocity = 50 m/s

Gas velocity = 100 m/s

Ejecta size = 2 cm (Stromboli)

= 20 cm (Etna)

Buble diameter = several meters (Heimaey, Etna, Erebus, Kilauea…)

Direct measurements (11): Acoustic records

Etna, July 2001

Gas exists in conduit for basaltic eruption:

strombolian explosions: a few meters long

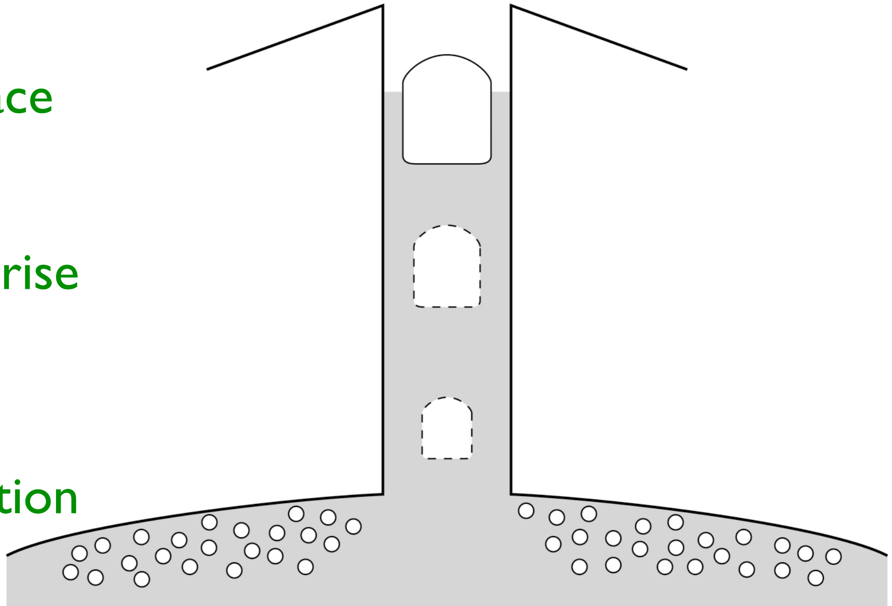
fire fountains: several tens of meters long

Bubble bursting

Bubble at interface

Bubble rise

Bubble formation



sound waves

bubble size and pressure

bubble pressure at depth

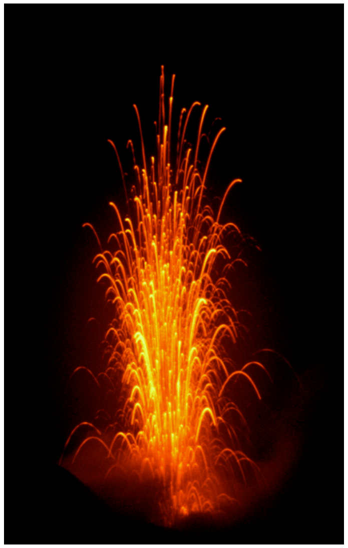
Eruption dynamics

Direct measurements (12): Acoustic records

Strombolian explosions or fire fountains:
origin of large bubbles at depth (carry informations from depth)
understanding large bubbles, is understanding eruptive behaviour

Fire fountain
Puu o'O eruption
(Kilauea, Hawaii)

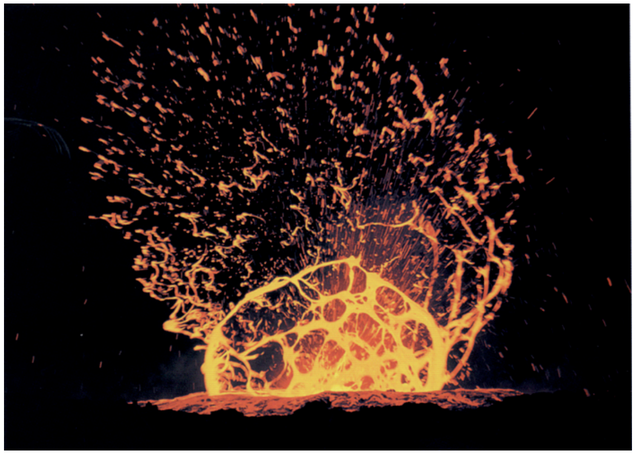
Stromboli,
1992



Acoustic measurements:
remote measurements of « magmatic » bubbles at the vent

Observations at the surface
+ flow model in conduit → quantitative information at depth

Direct measurements (13): Acoustic records



Bubble bursting at the surface of lava lake (Kilauea, Hawaii)

Sound is produced by bubble breaking at the surface of lava column / lava lake

→ bubble must have a residual overpressure

Bubble breaking = balloon bursting ?

balloon bursting → frequency = sound speed / radius

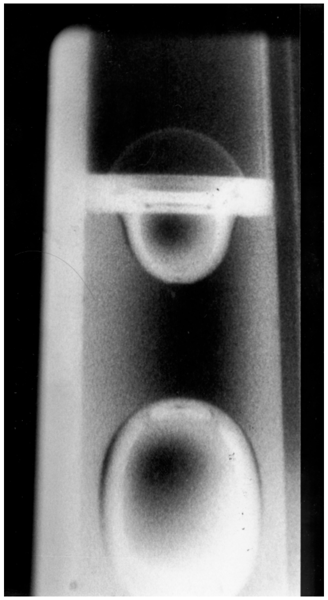
sound speed = 340 m/s
+ radius = 2 m → frequency = 150 Hz

Frequency measured on volcanoes: 1 - 10 Hz

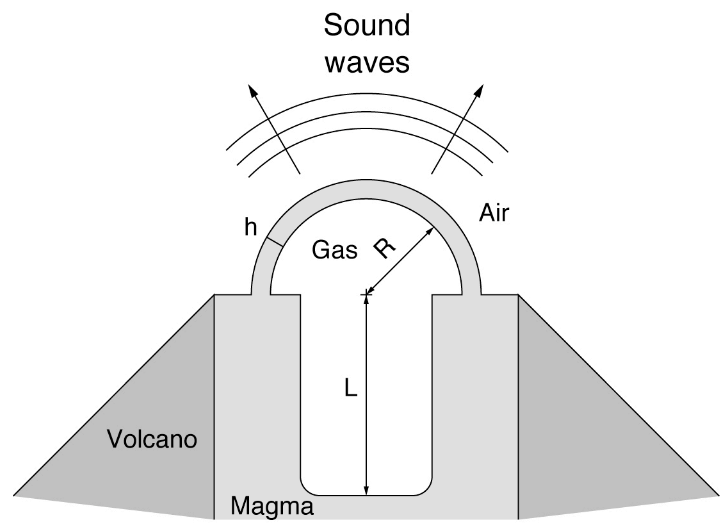
→ more than 1 order of magnitude discrepancy
the mechanism is not bubble bursting such as for a balloon

Direct measurements (14): Acoustic records

Bubble vibration model:
bubble arrives at the surface of lava column with an overpressure ΔP



Laboratory experiments
(silicone oil 12.5 Pa.s,
tube diameter = 0.14 m)



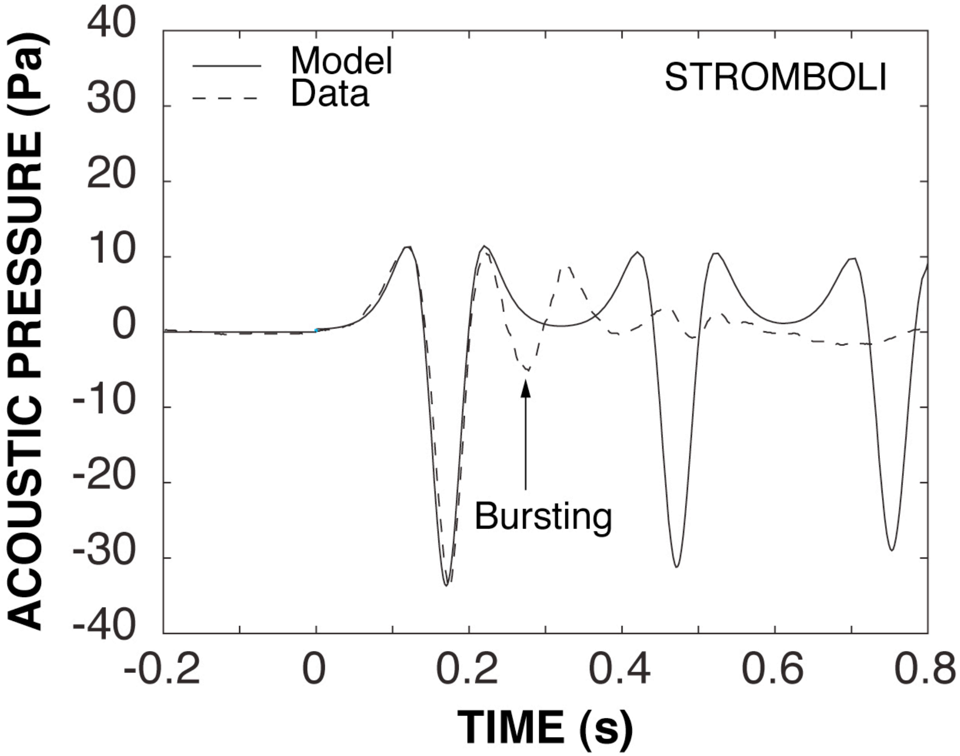
Sketch of bubble
vibration model

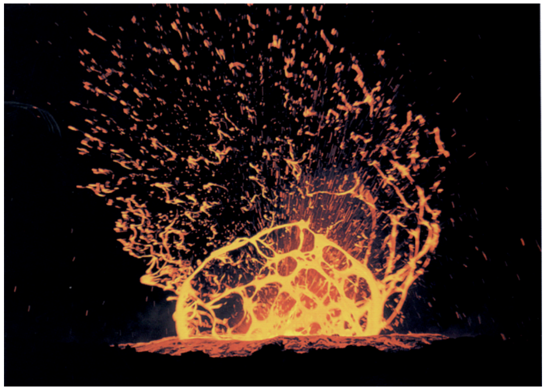
Bubble grows and pass equilibrium position with non-zero velocity: bubble overshoot, so the bubble become larger than equilibrium has a pression less than equilibrium. Gas compressibility acts to restore the equilibrium pressure, so bubble shrinks.

→ bubble oscillations

Direct measurements (15): Acoustic records

Bubble vibration model: comparison between theory and measurements: best fit method





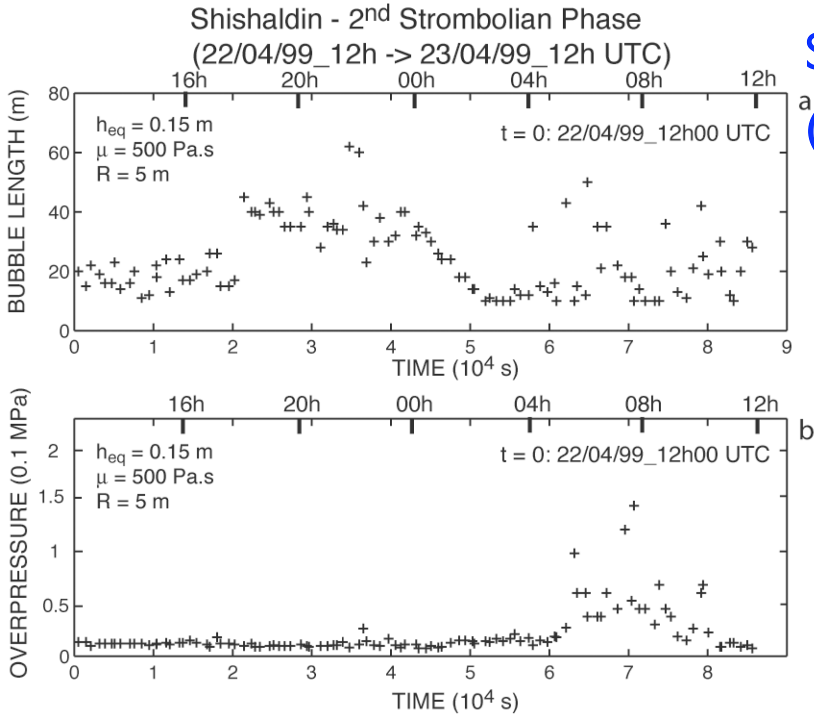
Bubble bursting at the surface of lava lake (Kilauea)

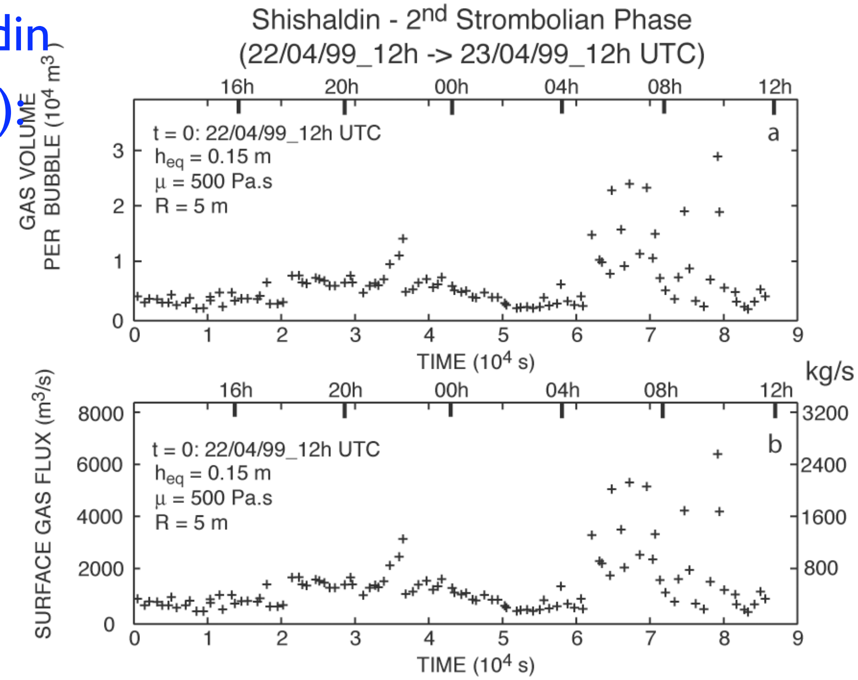
Model for source of sound: bubble radius, length, overpressure
and their evolution in time

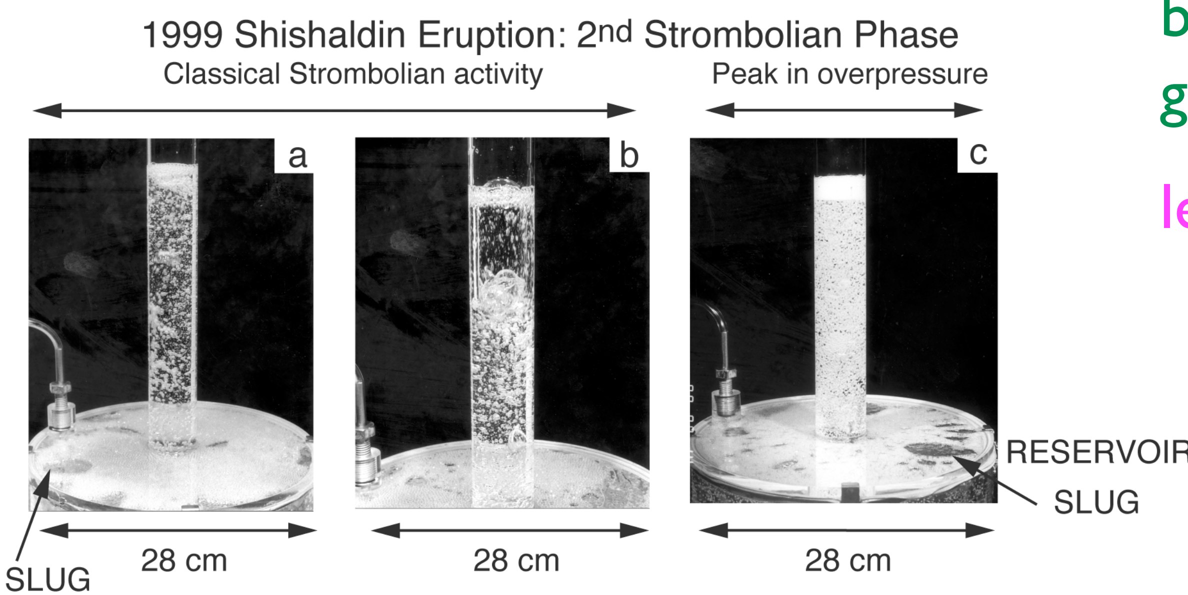
Model is very robust for gas volume estimates because it is based on frequency content

Direct measurements (16): Acoustic records

Shishaldin (Alaska):







bubble length, pressure, gas volume and gas flux

length > 2 radius

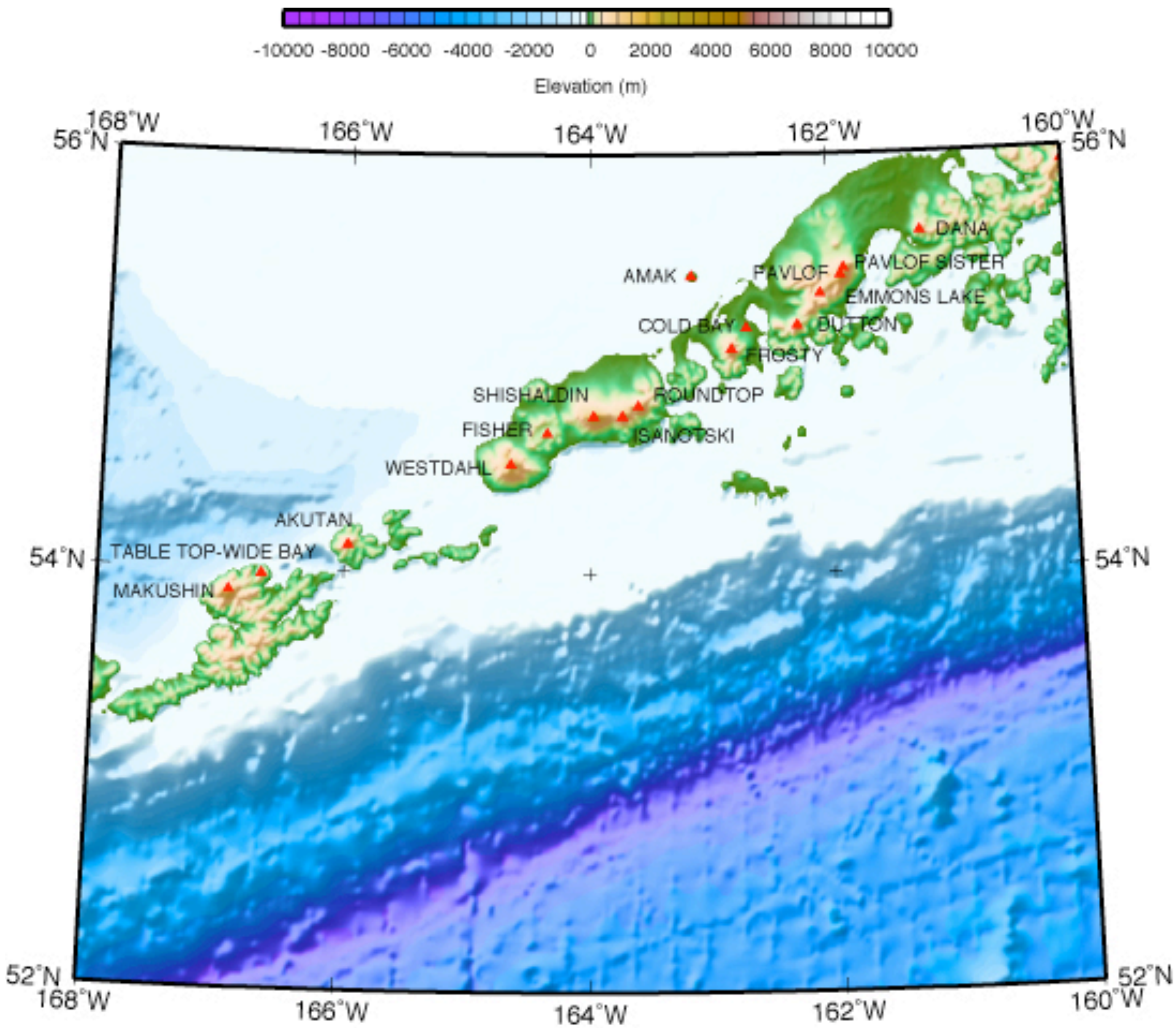
→ slug flow

Peak in pressure: rise of large bubbles in a very bubbly magma

Direct measurements (17): Acoustic records

The 1999 Shishaldin eruption

Alaska subduction zone

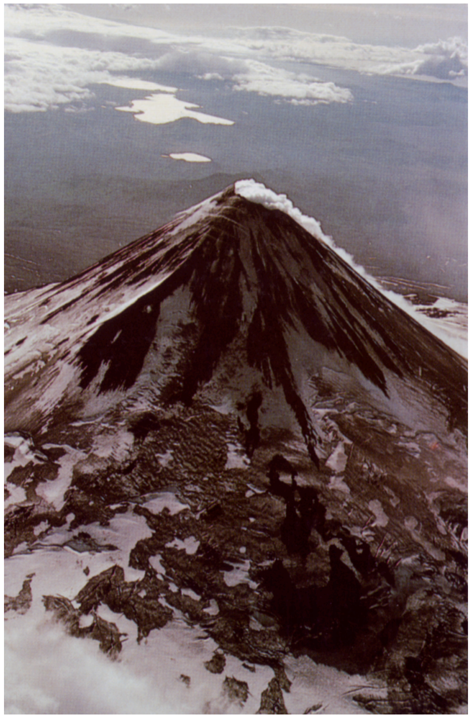


Shishaldin

trench

Direct measurements (18): Acoustic records

Shishaldin, Alaska, USA



Formation of a basaltic plume
height > 16 km

30 % of volcanoes in subduction zone are basaltic (basaltic andesite)

Basaltic plume is very rare

Eruption finishes with Strombolian activity (a series of large bubbles breaking)

Plume = very analogous to explosive eruptions

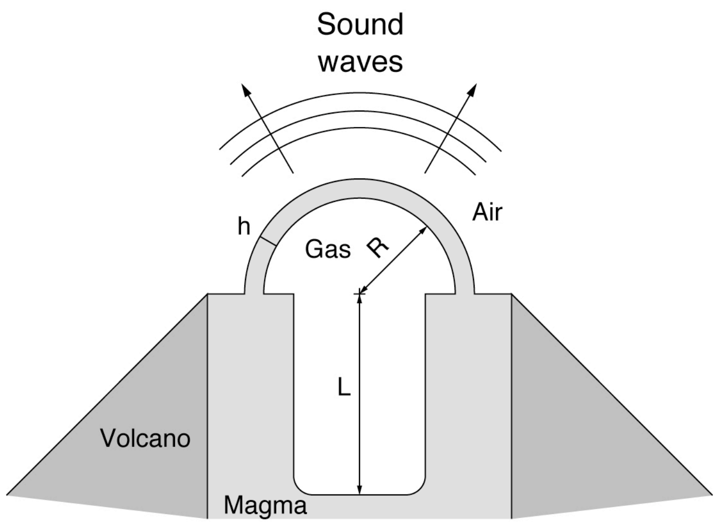
Acoustic measurements
origin of basaltic Subplinian activity
transition Subplinian- Strombolian

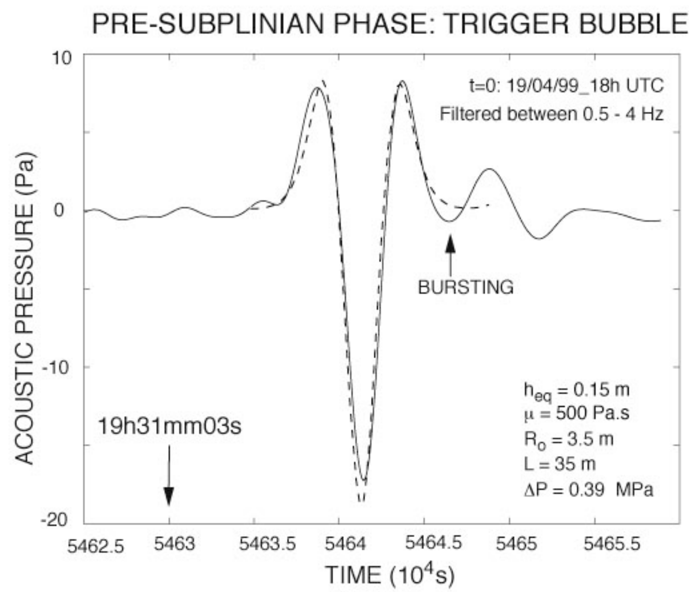
Shishaldin 23/04/99

Direct measurements (19): Acoustic records

Transition to the Subplinian phase:

Very different acoustic pressure than during plume: identical to a single strombolian explosion = bursting of a large overpressurised bubble formed at the depth of the reservoir

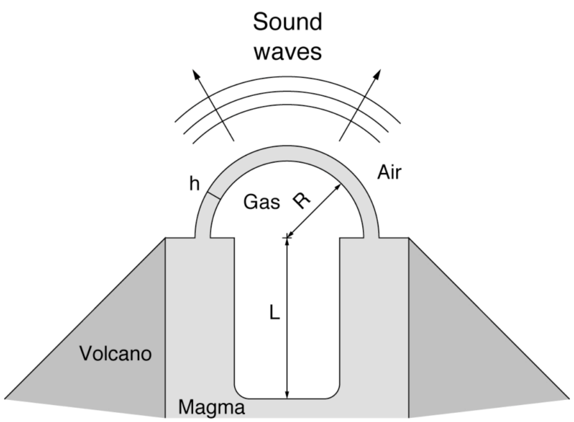
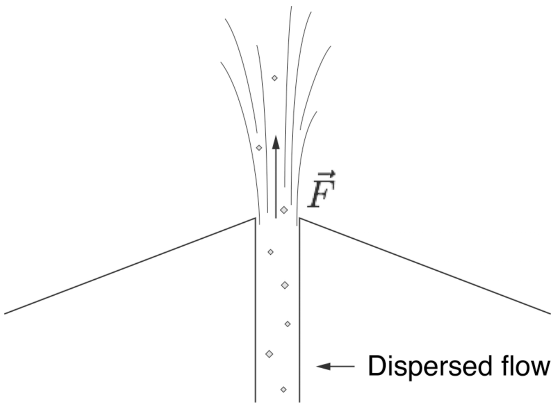
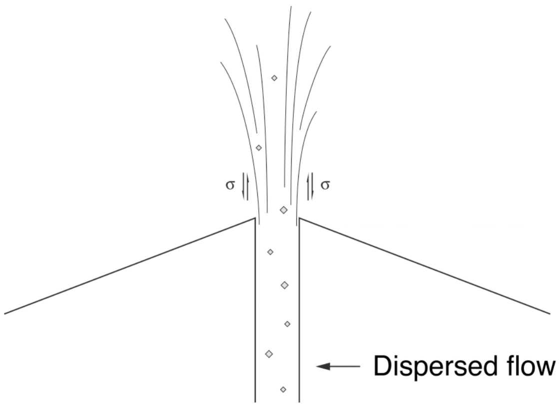




Model of bubble vibration: → L = 35 m; ΔP = 0.39 MPa

Direct measurements (20): Acoustic records

Different types for source of sound:

monopole source	dipole source	quadrupole
		
variation of mass flux	+ variation of external force (walls of conduit)	+ variation of stress (turbulence)

Acoustic power Π_m is proportional to (U: gas velocity)^n

$$\Pi_\mathrm{m} = K_\mathrm{m}\frac{4\pi R_\mathrm{b}^2\rho_\mathrm{air}U^4}{c}$$

K_m = 1 (sphere)
(1/16 flat circular)

$$\Pi_\mathrm{d} = \frac{K_d\,\rho_\mathrm{air}\,A_d\,U^6}{c^3}$$

K_d = 1/3
(or 0.013)

$$\Pi_\mathrm{q} = \frac{K_q\rho_\mathrm{air}\pi R_c^2U^8}{c^5}$$

$K_q = 3\ 10^{-5} - 10^{-4}$

K_m : empirical constant; R_b and R_c: bubble and conduit radius; c: sound speed

Direct measurements (21): Acoustic records

Subplinian phase:

Complex waveform →

use of acoustic power Π_d :
proportional to gas velocity

$$\Pi = \frac{\pi r^2}{\rho_{\rm air} c T} \int_0^T |p_{\rm ac} - p_{\rm air}|^2 dt$$

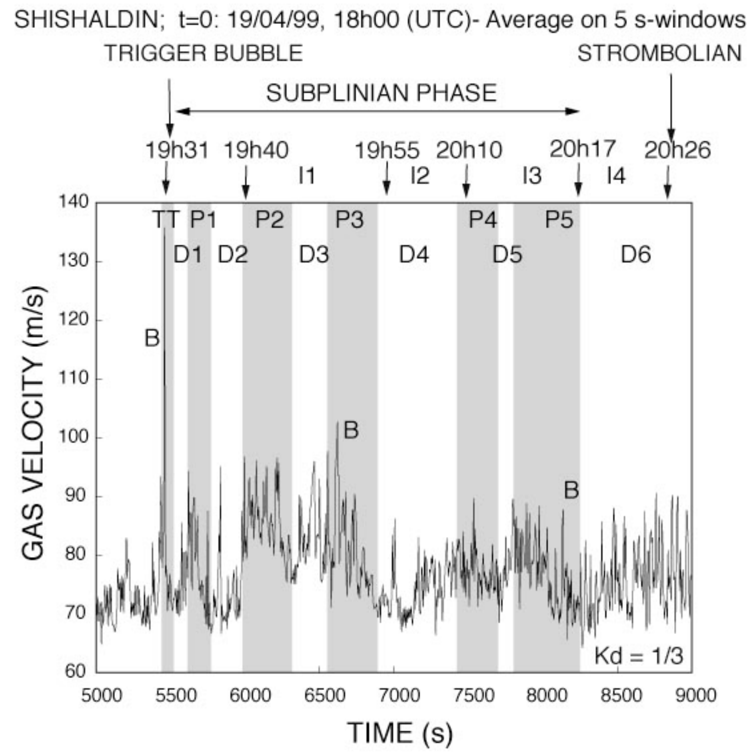
$$\Pi_{\rm d} = \frac{K_d\, \rho_{\rm air}\, A_d\, U^6}{c^3}$$

$K_d = 1/3$

6 periods

gas flux = velocity x area

Shishaldin
23/04/99



In very good agreement with the gas flux deduced from the height in the atmosphere

gas flux = gas volume/time → gas volume= 1.5 10^7 m^3

Direct measurements (22): Acoustic records

Other basaltic volcanoes have magmatic plume eruptions:

Cerro Negro
(Nicaragua)

1992, similar to 1968 eruption
(6 wt% H_2O + 1 wt% CO_2);

Lopevi
(Vanuatu)

10 km high plume
(2001, 2003, next?)

Similar mechanisms than Shishaldin?

Basaltic magma reservoirs

1. Physical parameters
2. A laboratory volcano:
3. Gas volume measurements

4. Conclusion

Velocity measurements
with a Sodar at
Stromboli, juin 1991

Conclusion (1):

Hawaiian eruption: cyclicity between fire fountains and effusive activity

Fire fountains (Puu O'o eruption)

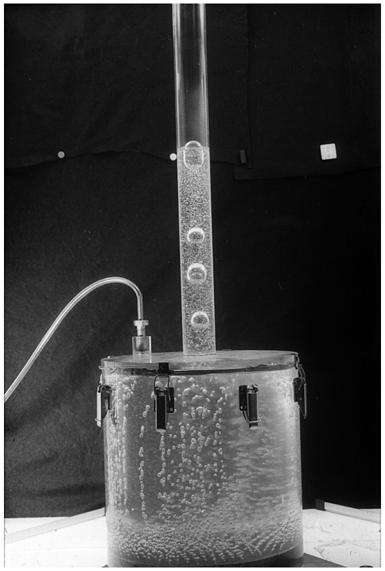
Lava flow into sea (Kilauea, March 1988)

Cyclicity is related to the degassing reservoir: formation of a foam at the top of the reservoir → bubble diameter in reservoir = 0.4 mm

Eruption stops when magma chamber does not contain much bubbles

Conclusion (2):

Strombolian eruption: a series of explosions



Bubble bursting at Etna, July 2001

Alternance between gas pockets and no activity: is similar to Hawaii but corresponds to a larger magma viscosity

Etna: cyclic fire fountains + gas composition gives unambiguous evidence for being driven by gas accumulation at depth

Eruption dynamics is driven by gas

→ Need for measurements of gas volume such as radar and acoustic measurements, …