Basaltic magma reservoirs

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« Volcano instability » short course
MTU, Michigan, March 22 2007;

Basaltic magma reservoirs

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

Tolbachick, Kamchatcka, 1975

plume of 2 km high

Physical parameters (1): Different types of surface activity

Explosive silicic activity

St Helens, 18/05/80 2 pm

Plinian column: gas jet + fragments
of magma above 10 km high
A few hours
200 - 300 m/s or more (70 to 1000 km/h)

Unzen,
June1991

Pyroclastic flow: dense gravity currents
50 m/s (180 km/h)

Mt Pelée

Lava dome: viscous gravity current
10^{-5} to 10^{-4} m/s (4 cm/h to 40 cm/h)

Physical parameters (2): Different types of surface activity

Basaltic activity

Fire fountain: central gas jet + magma
A few days; height = 400 m;
100 m/s to 200 m/s

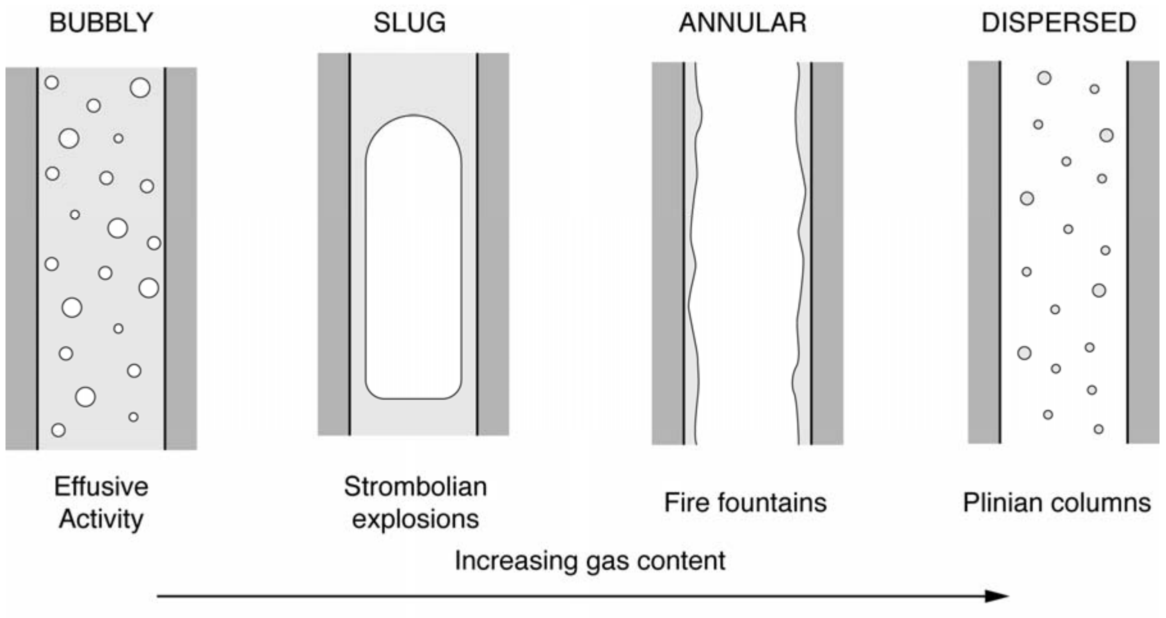
Kilauea

Gas piston activity: Strombolian explosions
Bursting gas bubbles: 50 m/s to 100 m/s

Lava flows:
0.01 m/s to 1 m/s

Piton de la Fournaise 1977

Physical parameters (3): classification with gas content



Gas volume fractions for transition of regimes are unknown and depend strongly on magma viscosity; but roughly transition to slug: 10 - 60 %

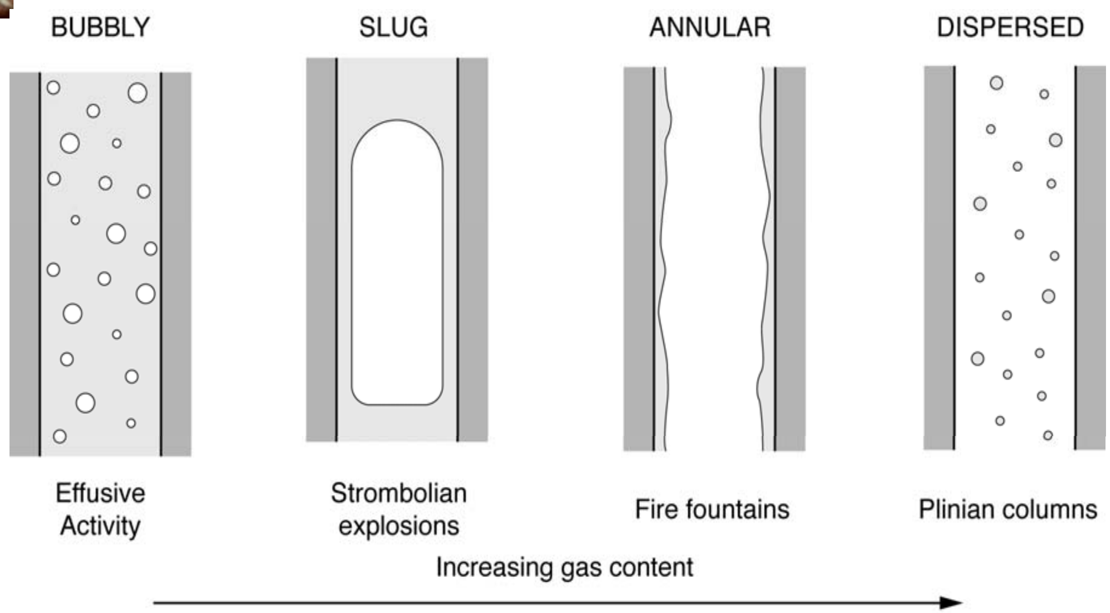
Annular : 70 % + : downward liquid flow
70 % ++ : upward liquid flow

Dispersed: 70 % ++ : entirely upwards

Hawaiian fire fountain: drainage during fountaining → Annular flow

Plinian column: dispersed flow

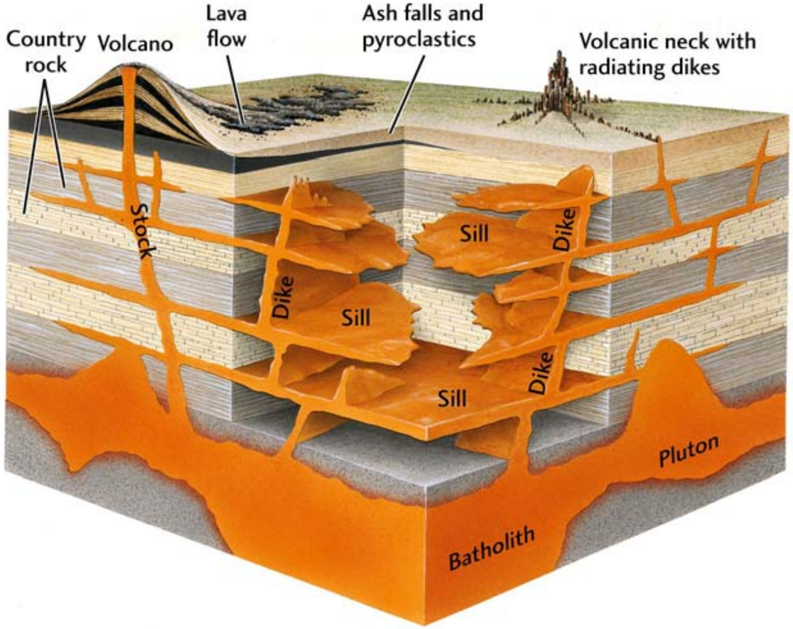
Physical parameters (4): Mechanisms of eruptions



Physical parameters (5): Geometry of magma reservoirs

Controversy between petrologists and seismologists

Old magma chamber exists:
Petrological observations:
Skaergaard (Greenland), Stillwater (US), Bushweld (South Africa)
Horizontal extent: 10 to 100 km
Vertical extent: few km to 10 km

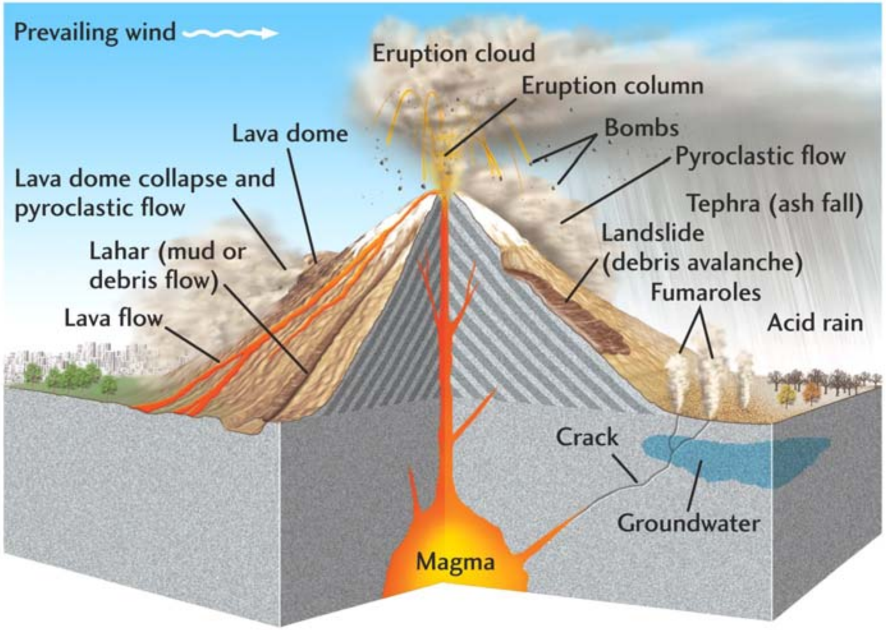


Aseismic zones mark zones rich in liquid but no large reservoir is seismically observed → A plexus of dikes ?

+ existence of potential levels for « horizontal » magma accumulation, with a shallow reservoir and deep ones

Physical parameters (6): Geometry of magma reservoirs

Kilauea (Hawaii):
Summit shallow reservoir:
seismicity + deformations
volume = 5 10^8 m^3
depth = 2 - 4 km



Etna (Italy) :
below the south east crater:
depth: 2 - 4 km;
volume = 4 10^7 m^3

Etna main degassing reservoir = 5 10^8 m^3 ; depth : 6 km and deeper

Stromboli (Italy): 2 reservoirs: sismo + petro
shallow (seismicity): depth: 300 m
deep (petrology only): depth: 7 - 8 km

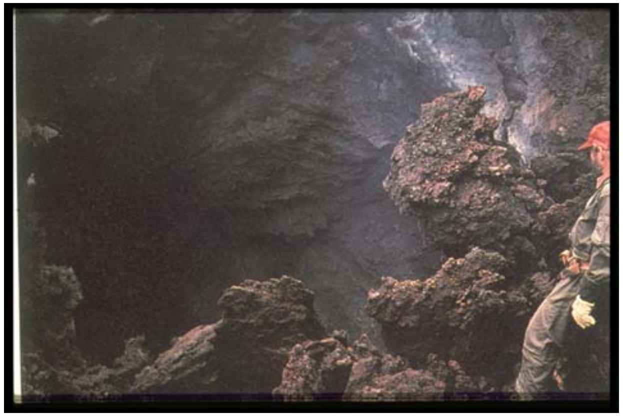
Physical parameters (7): volcanic conduits

Kilauea, Puu O’o, May 2004

Volcanic conduit: cylindrical

Cylindrical: Kilauea, radius: 7 m
Etna, radius: 5 m
Stromboli radius: 1 m

Drilling + deformations (dome):
same size at 100 m depth than surface

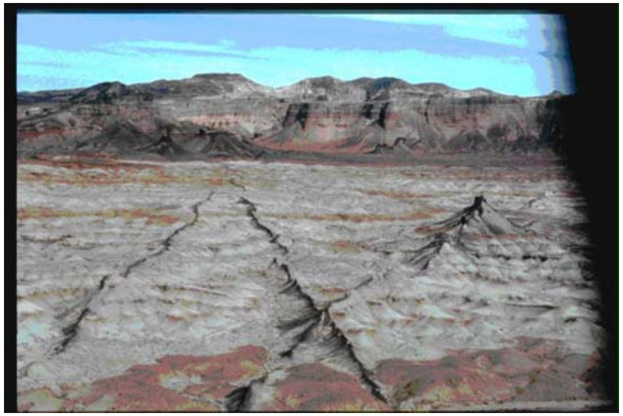


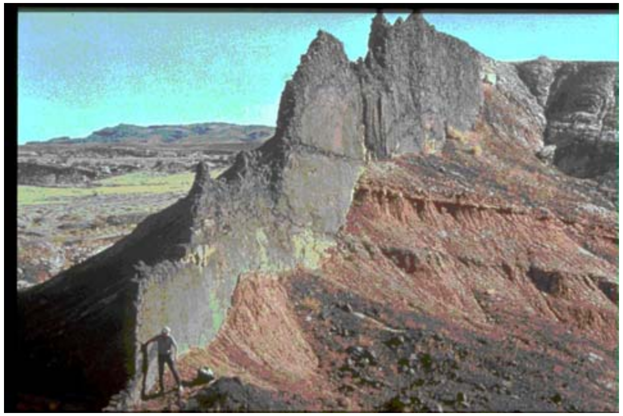
Kilauea, Puu O’o eruption

Stromboli, 1970

Physical parameters (8): dikes and old conduits

Colorado plateau





Dike (Massif Central, France)

Old conduit (Massif Central, France)

Shiprocks, towering 515m above flat sediments is a volcanic pipe, exposed by erosion

Physical parameters (9): fluid inclusions

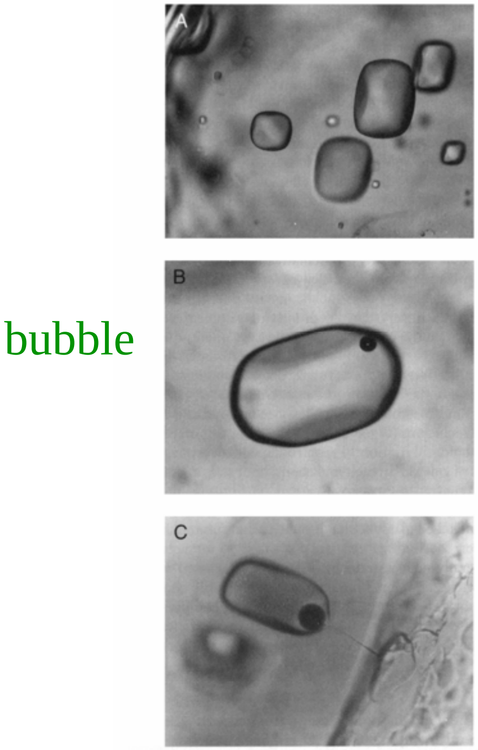


FIGURE 8 Glass (melt) inclusions in crystals from volcanic rocks. (A) A fragment of an ~3-mm quartz phenocryst from the rhyolitic Bishop Tuff containing inclusions of glass up to about 100 μm in diameter. (B) Close-up of a melt inclusion containing a small vapor bubble. The inclusion is about 80 μm long and is partly faceted. Bubbles that are small relative to the inclusion size form during cooling after the inclusion is trapped because the melt in the inclusion contracts more on cooling than does the surrounding quartz host crystal. (C) An hourglass inclusion in a late Bishop quartz. The neck of the hourglass is about 3 μm in diameter and it connects the inclusion to a small depression or dimple on the exterior surface of the quartz phenocryst. The main body of the hourglass is partly faceted, partially finely devitrified, and it contains a ~5 vol% bubble near the neck. The

Fragments of initial magma are brought up at the surface by getting trapped into crystals. They can be a fluid or bubbles.

Chemical analyses + at equilibrium

→ magma composition at depth
composition and amount of volatiles

→ Pressure of formation =
depth of magma chamber

Physical parameters (10): viscosity of magma

Resistance to flow = internal friction

Example:

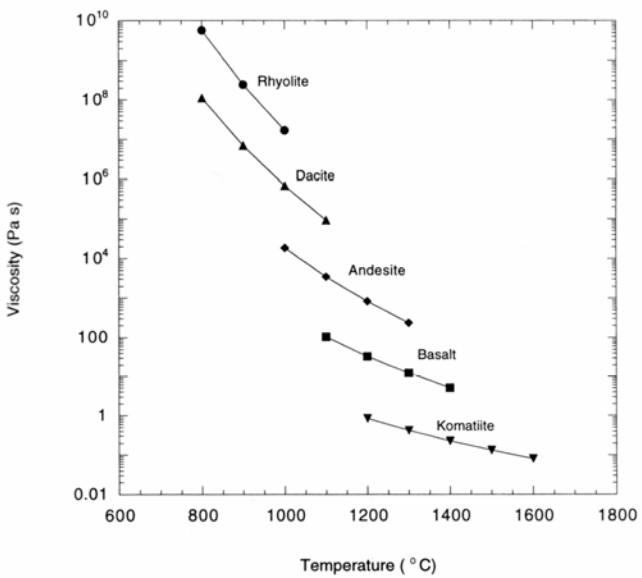


FIGURE 4 Viscosity as a function of temperature at 1 bar (10^{-4} GPa) for natural melts spanning the compositional range rhyolite to komatiite. All compositions are volatile free. The temperature range is illustrative of typical eruption temperatures for each composition.

air: 10^{-5} Pa.s
water: 10^{-3} Pa.s
basalts: 10^1 to 10^2 Pa.s (Kilauea)
basalts: 10^2 to 10^3 Pa.s (Stromboli)
Silicic: 10^4 to 10^6 Pa.s (explosive)

very large range of values

function of composition, and temperature

Physical parameters (11): viscosity of magma

function of dissolved water

function of the amount of crystals and bubbles

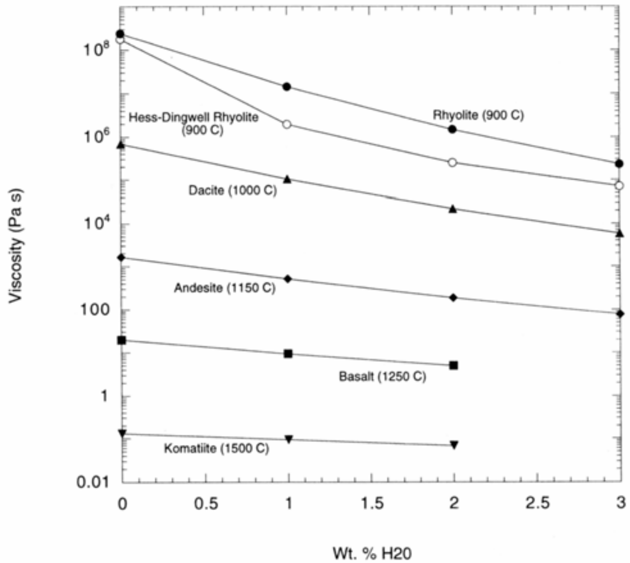
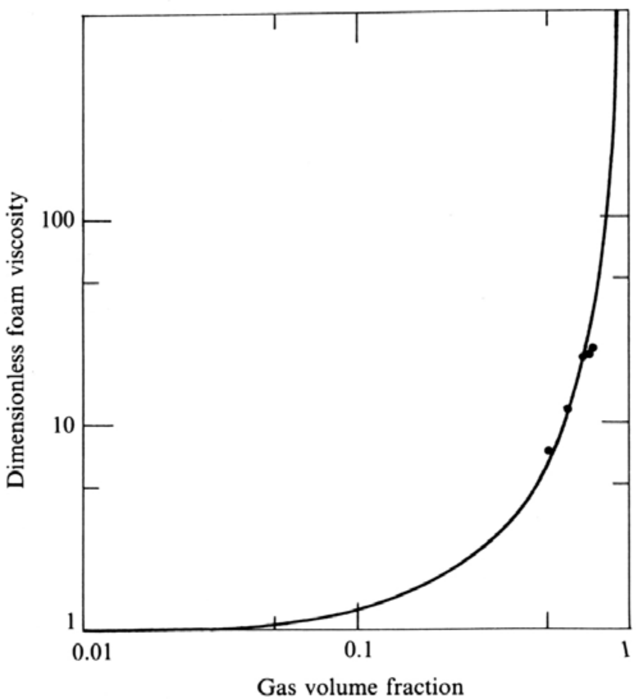


FIGURE 5 Melt viscosity as a function of dissolved water content for natural melts spanning the range rhyolite to komatiite. Temperatures for each composition are characteristic eruption temperatures. Viscosities are calculated for pressure equal to 1 bar (10^{-4} GPa). For the rhyolite composition, two different models are shown. Note the very dramatic effect of dissolved water on the viscosity of natural melts. Viscosity models are from Shaw (1972) and Hess and Dingwell (1996).

bubbly liquid viscosity / pure liquid viscosity



Gas volume fraction

Physical parameters (12): viscosity of magma

Magma: very large range of viscosities

Basalts are less viscous → Basalts leads to gentle eruptions

Consequences:

Effusive activity: basalts 10^{-2} to 1 m/s -- lava domes: 10^{-5} to 10^{-4} m/s

→ viscosity is important

Explosive activity: velocity is independant of lava chemistry

Plinian column: 200 - 300 m/s

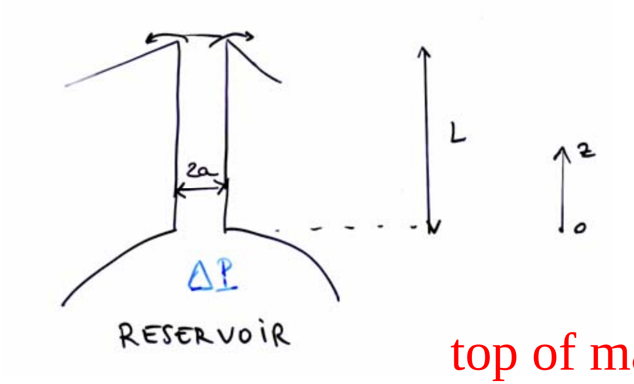
Physical parameters (13): conservation of mass

mass flux: G (kg/s)

$$G = \rho_{mixt} . w. S = constant$$

w: velocity (m/s); S: area (m^2); ρ: magma density (kg/m^3)

Volcanological implications:



vent: ρ_{mixt3} ; w_3; S_3

base of conduit: ρ_{mixt2} ; w_2; S_2

top of magma reservoir: ρ_{mixt1} ; w_1; S_1

$$\rho_{mixt3} . w_3. S_3 = \rho_{mixt2} . w_2. S_2 = \rho_{mixt1} . w_1. S_1$$

Physical parameters (14): conservation of mass

Geometrical constriction exists between reservoir and conduit.
If mixture of constant density

$\rho_{mixt3} = \rho_{mixt1}$; $w_3. = w_1. S_1 / S_3$

$S_1 = \pi R_{ch}^2$; R_{ch} = few km

$S_3 = \pi R_{cond}^2$; R_{cond} = few 10 m

→ $S_1 / S_3 = 10^4$

Vesiculation: $S_2 = S_3$; $w_3. = w_2. \rho_{mixt2} / \rho_{mixt3}$

$\rho_{mixt} = (1 - \alpha). \rho_{liq} + \alpha. \rho_{gas}$ α : gas volume fraction

$\alpha_3 = 0.99$ $w_3. = w_2. (1 - \alpha_2) / (1 - \alpha_3) = 100\ w_2$

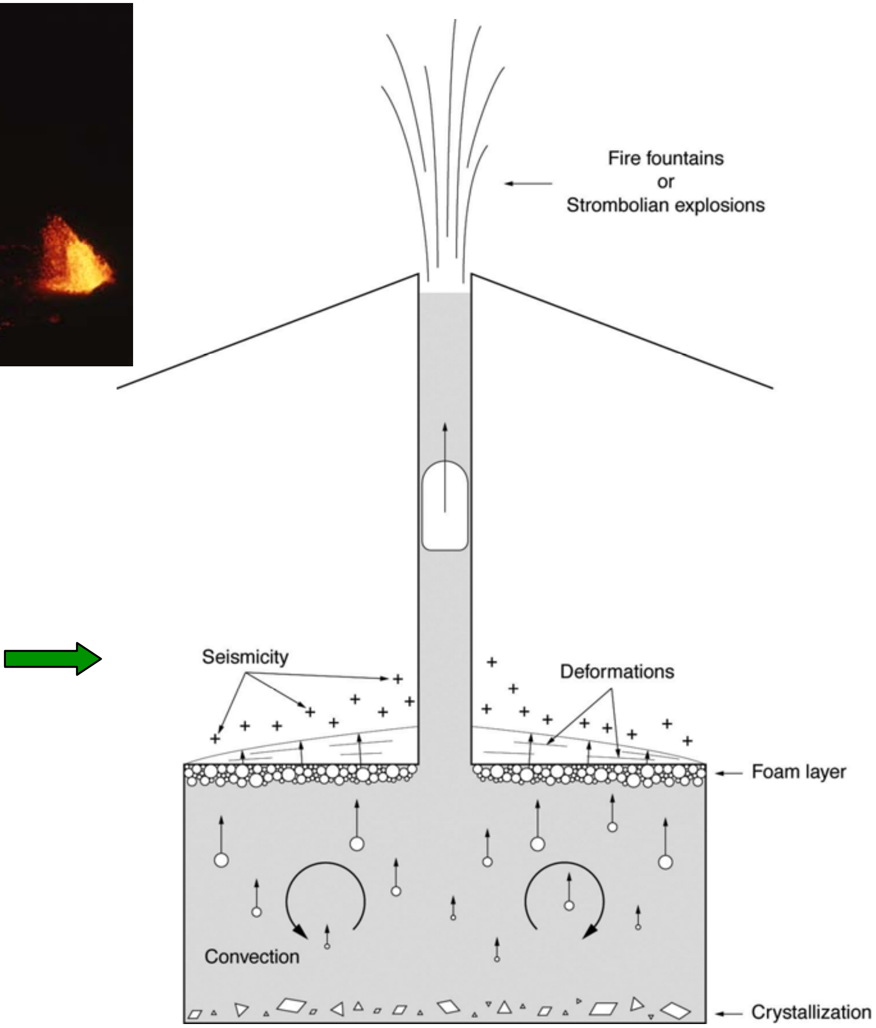
$\alpha_2 = 0$

→ large velocity at the vent, either due to bubble or contraction at the conduit

Physical parameters (15): sketch of a basaltic volcano

Fire fountains
(Kilauea)

Prior to eruption



Lava flows

Physical parameters (16): sketch of an explosive volcano

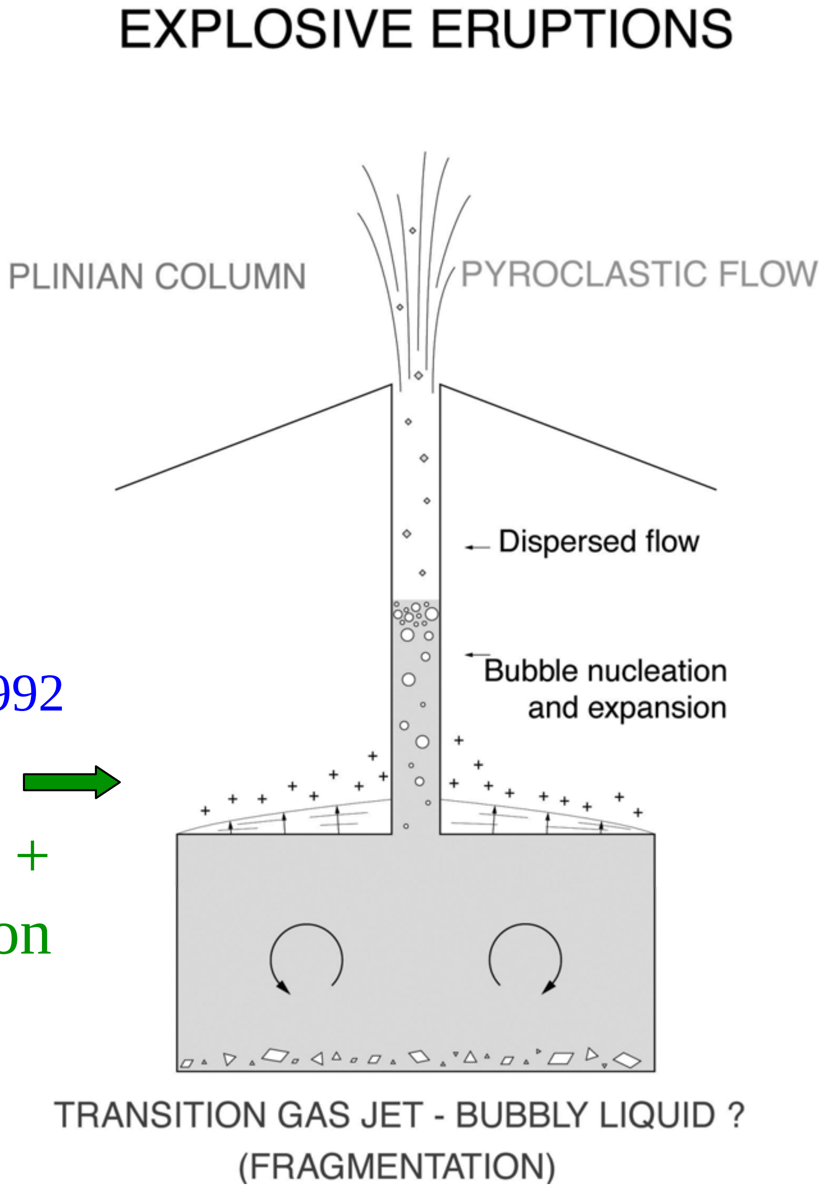
Plinian column:

Mt Spurr, Alaska, 1992

Prior to eruption:

seismicity +

deformation



Pyroclastic flow
(Soufrière Hills;
Montserrat;
West Indies)

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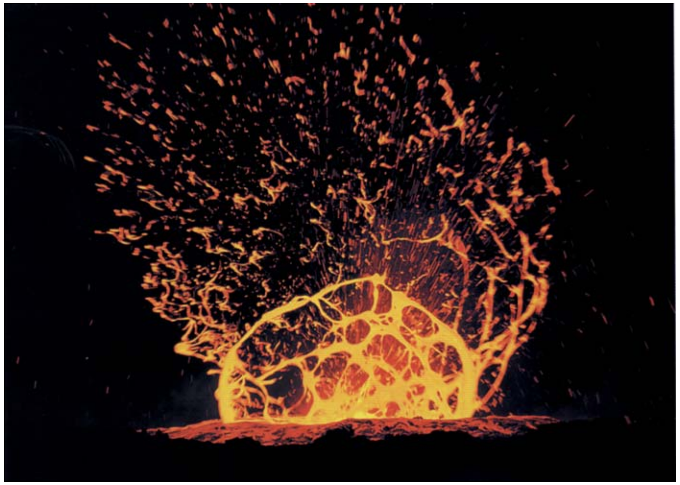

Kilauea

Etna, 600 m,
Sept 26 1989

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    a) Observations of surface activity

    a) Laboratory experiments

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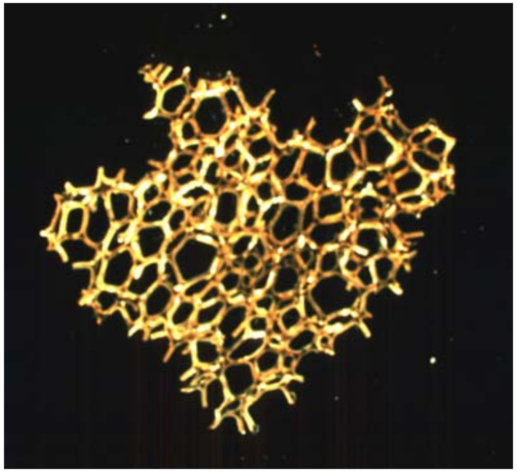


Reticulite (Kilauea)

A laboratory volcano (1): origin of fire fountains

Fire fountain: central gas jet + magma
A few days; height = 400 m;
100 m/s to 200 m/s

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

Hawaiian eruptions start by a curtain of fire (1 day) and then turn to a series of fire fountains

Curtain of fire at Krafla (Iceland)

A laboratory volcano (2): origin of fire fountains

Deposits formed during fire fountains:

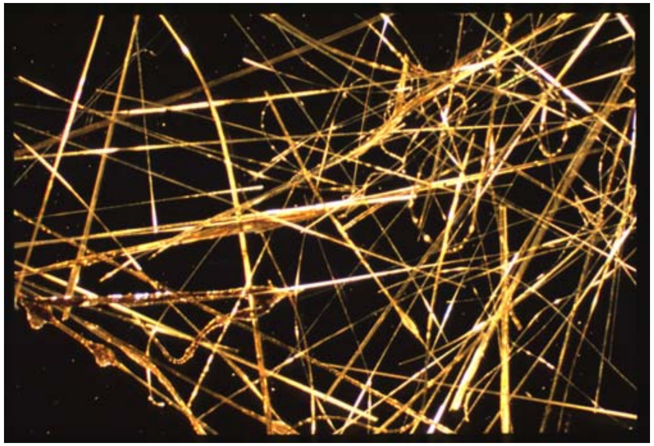
Tears (elongated magma droplets)

Scoria and spatter (vesiculated magma)

65 % of gas
density = 900 kg.m^{-3}

85 % of gas
density = 400 kg.m^{-3}

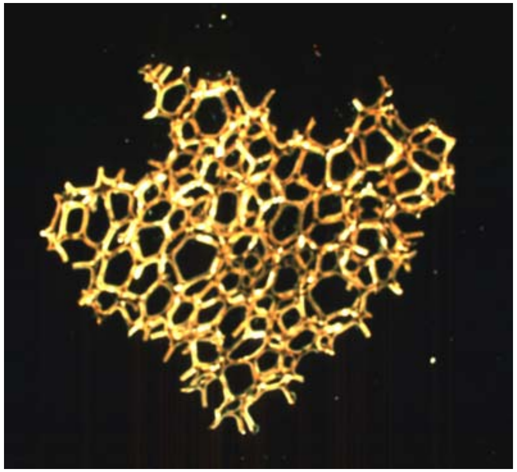
Pelee's hair (very elongated magma droplets)



less 1 mm
thickness

Reticulite (highly vesiculated magma)

1 cm across;
98 % of gas
density = 50 kg.m^{-3}



A laboratory volcano (3): origin of fire fountains

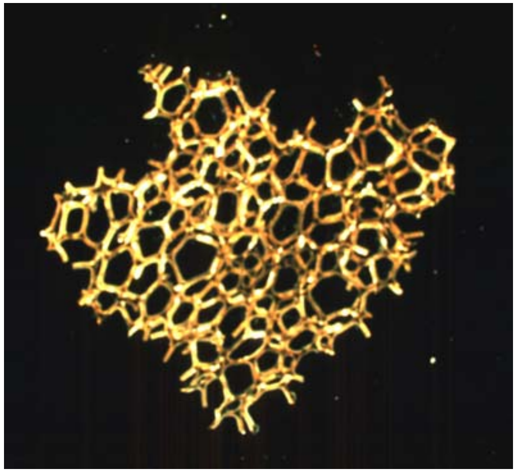
Evidence of gas in fire fountains:

Plume above curtain of fire at Krafla (Iceland)

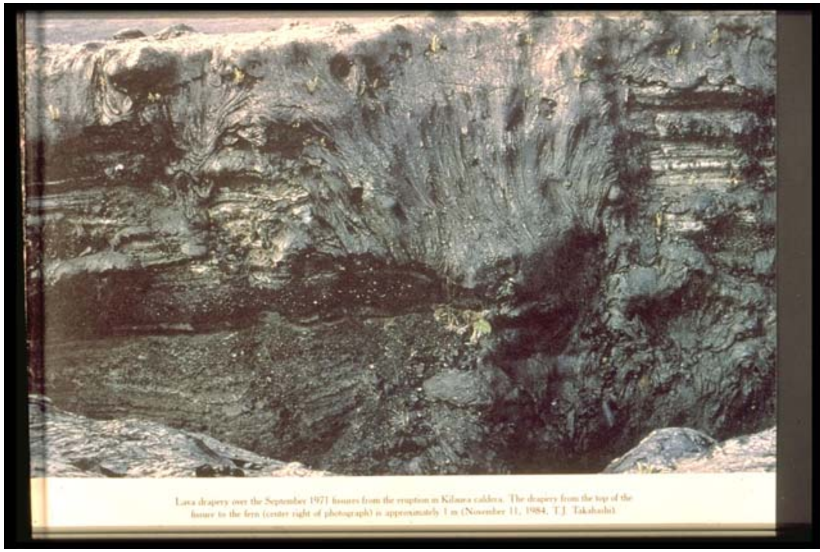
Plume above fire fountains
Reticulite
Peak in CO_2 during fire fountains
Upwards motion of fire fountains simultaneously of drainage in conduit

→ characteristic of an annular flow

Sudden stopping of fire fountains: in less than a few minutes



Reticulite (high fire fountains)

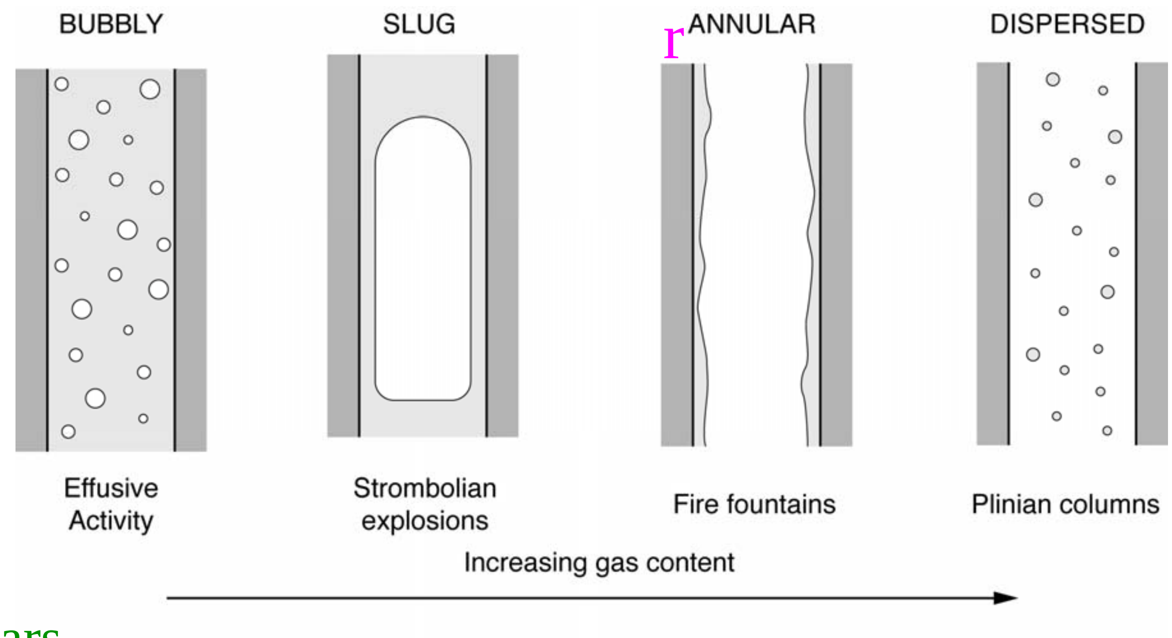


drainback of lava (Kilauea)

A laboratory volcano (4): origin of fire fountains

dynamics of an annular flow → formation of fragments:

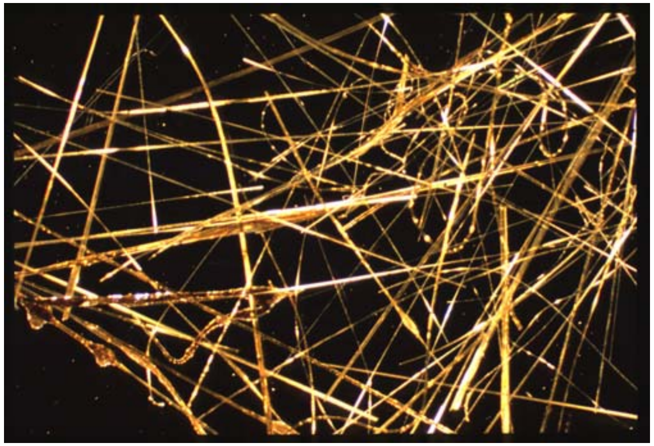
annular



elongation of magma droplets in a fast upwards gas flow → tears, Pelee's hair

Tears

Pelee's hair



A laboratory volcano (5): origin of fire fountains

Bubble bursting on
Kilauea lava lake (Hawaii)

Lava lake / top of magma column:
gas piston activity

↔ bursting of large bubble

gas piston at lava lake, Hawaii:

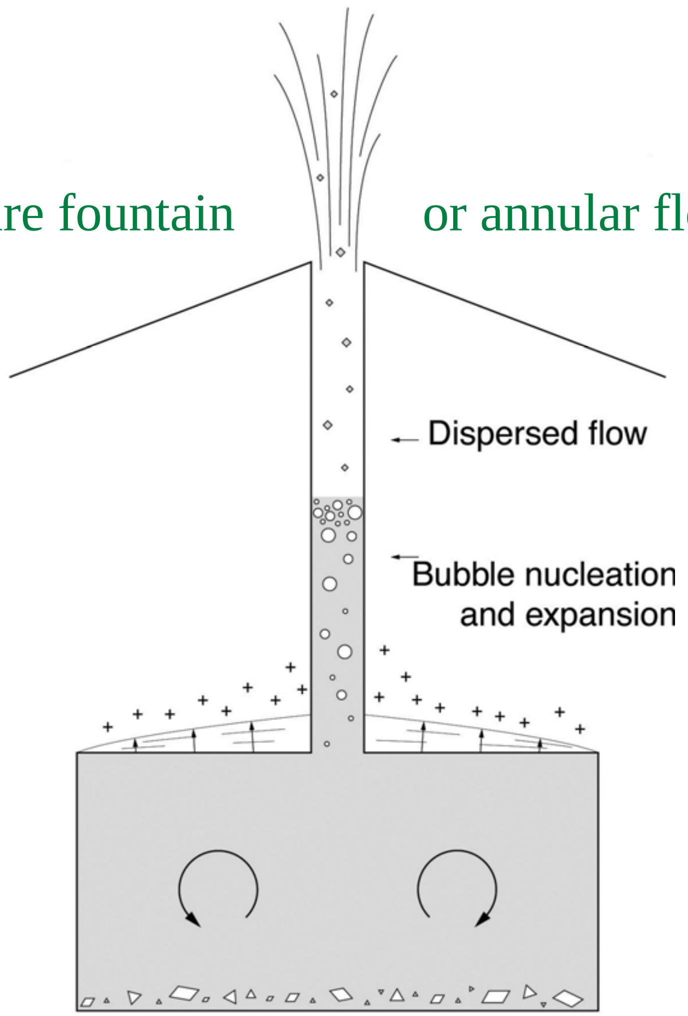
A few minutes later

Existence of scoria and spatter (rich in gas)

A laboratory volcano (6): origin of fire fountains

1) in the conduit:

Fire fountain or annular flow



Etna, 600 m,
Sept 26 1989

Bubble exsolution →

Bubble nucleation and growth

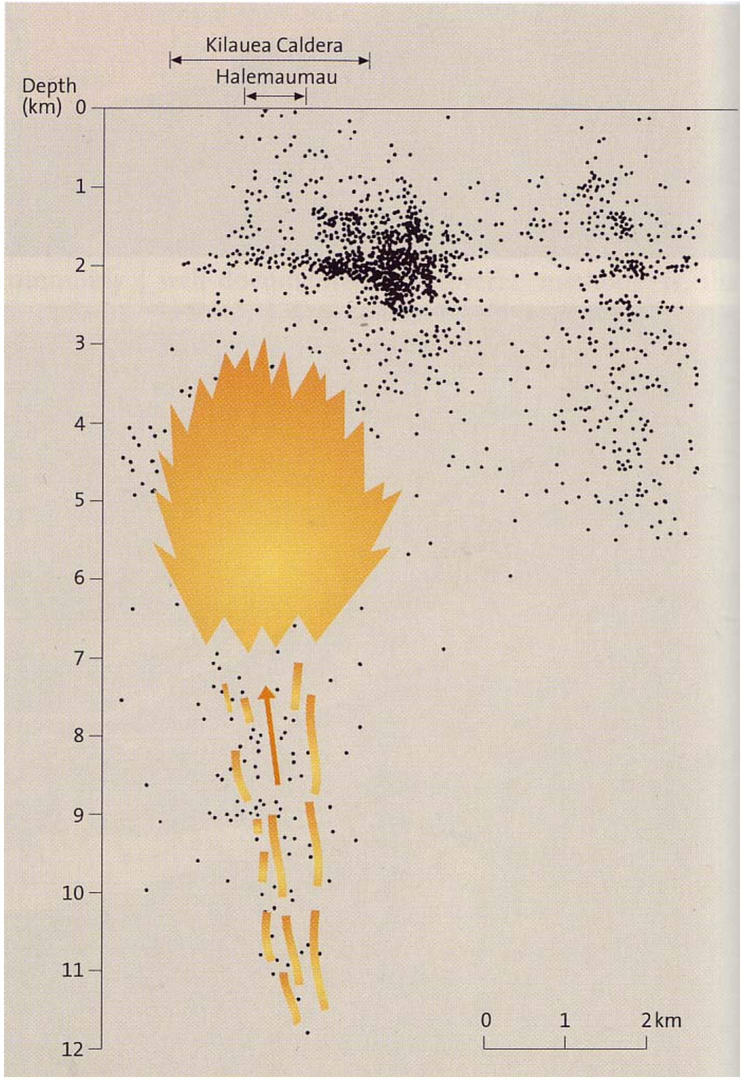
→ densily packed mixture: suspension of bubbles

Problem: coalescence is very difficult in viscous fluids

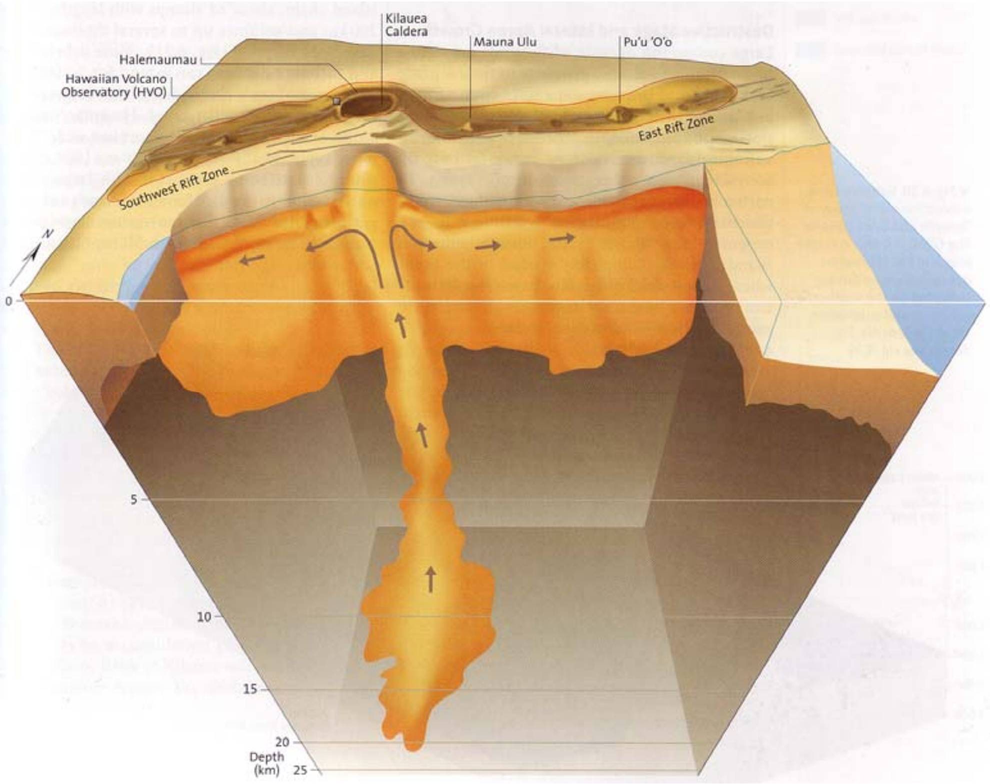
Alternate model: fire fountains are formed at depth

A laboratory volcano (7): origin of fire fountains

Kilauea magma chamber: zone free of earthquake:



Summit area + rift area



A laboratory volcano (8): origin of fire fountains

Etna: some eruptions show intermittency between eruptive episodes and quiet periods (1989,1998, 2000, 2001…)

Eruptive episode: a series of Strombolian explosions leading to fire fountains

July 25 2001

September 26, 1989 at 8:30 height: 600 m

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Fire fountain
in conduit

Laboratory experiments for fire fountains (1):

1) Basalt is saturated in CO_2 at the depth of the magma chamber, 0.7 wt %

Fluid inclusions → gas content and depth of formation

2) Hawaii: cyclic activity between two steady-states (fire fountains and effusive activity)

→ process in the magma chamber

3) Hypothesis to be tested:
Origin of various eruption regimes ?

→ dynamics of a degassing reservoir ?

glass inclusions

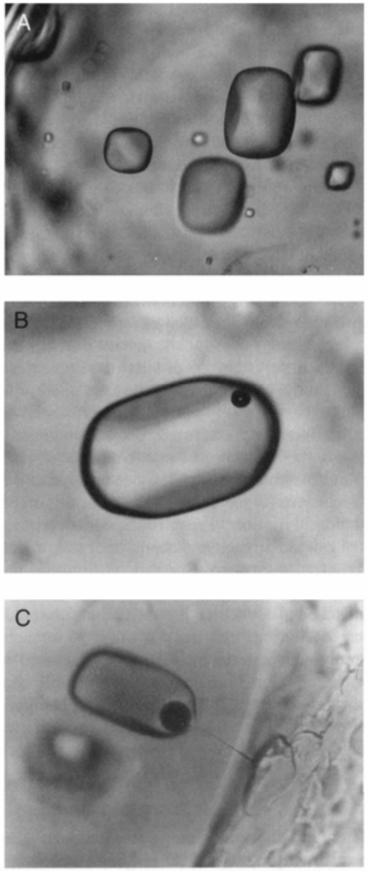


FIGURE 8 Glass (melt) inclusions in crystals from volcanic rocks. (A) A fragment of an ~3-mm quartz phenocryst from the rhyolitic Bishop Tuff containing inclusions of glass up to about 100 μm in diameter. (B) Close-up of a melt inclusion containing a small vapor bubble. The inclusion is about 80 μm long and is partly faceted. Bubbles that are small relative to the inclusion size form during cooling after the inclusion is trapped because the melt in the inclusion contracts more on cooling than does the surrounding quartz host crystal. (C) An hourglass inclusion in a late Bishop quartz. The neck of the hourglass is about 3 μm in diameter and it connects the inclusion to a small depression or dimple on the exterior surface of the quartz phenocryst. The main body of the hourglass is partly faceted, partially finely devitrified, and it contains a ~5 vol% bubble near the neck. The

Laboratory experiments for fire fountains (2):

Puu O'o eruption (Kilauea)

Description of an hawaiian eruption

Fire fountain: central gas jet with suspended lava clots

Effusive activity: rise of vesicular magma

Lava flow (Surtsey, 1963)

Large variation of liquid level

Puu O'o eruption (Kilauea)

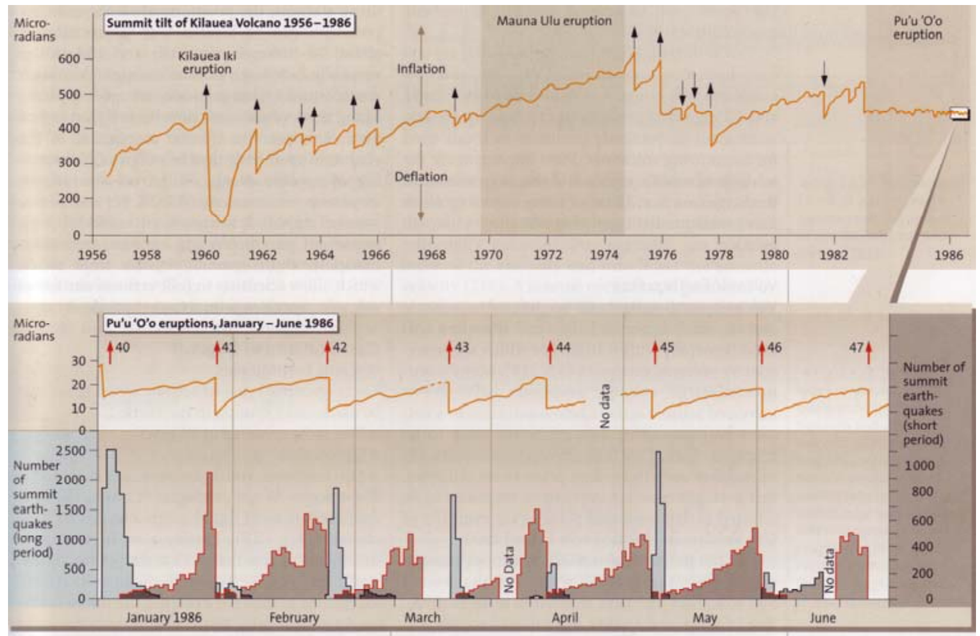
Laboratory experiments for fire fountains (3):

Description of an hawaiian eruption

In the first few months of the eruption: cyclic behaviour between fire fountains and a quieter activity (effusive activity)

Kilauea Iki:

before a fire fountain, increase in deformations and in low frequency earthquakes



▲ Fig. 13.18. Swelling and subsidence of the summit of Kilauea volcano between 1956 and 1986 with major eruptive periods (Kilauea Iki, Mauna Ulu and Pu'u 'O'o). For the Pu'u 'O'o eruption (January-June 1986) the frequency of short- and long-period earthquakes are also shown (386)

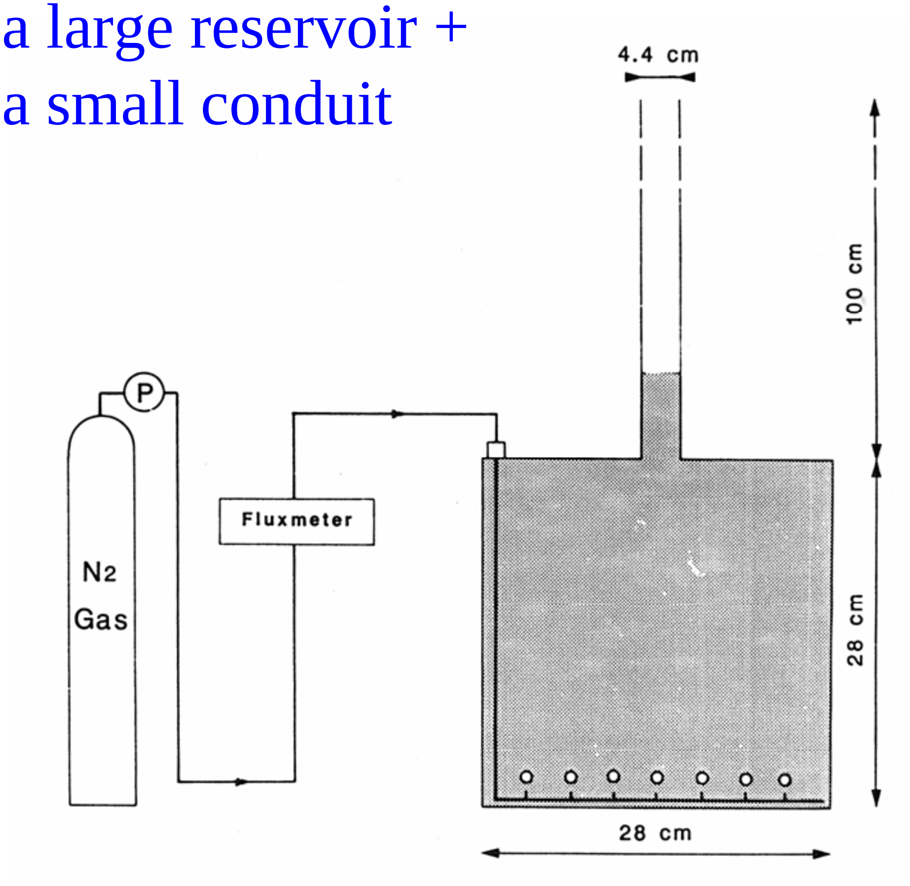
After the first phase (3 years and a half), no fire fountain activity

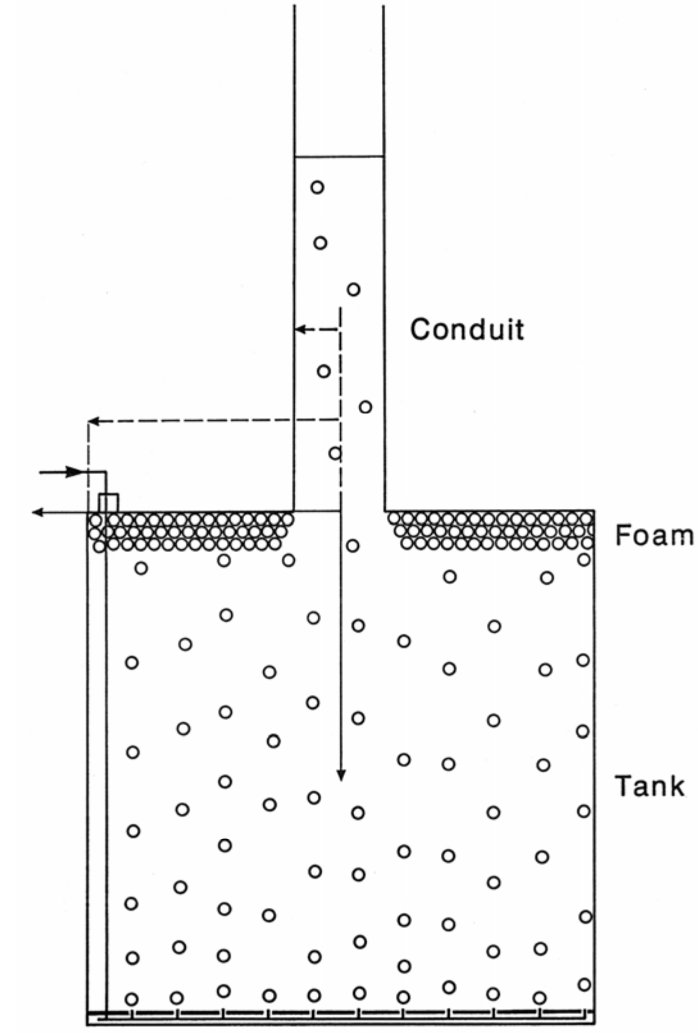
→ cyclic behaviour between steady states is generated in magma chamber

Laboratory experiments (4):

Building up a laboratory volcano:

a large reservoir +
a small conduit

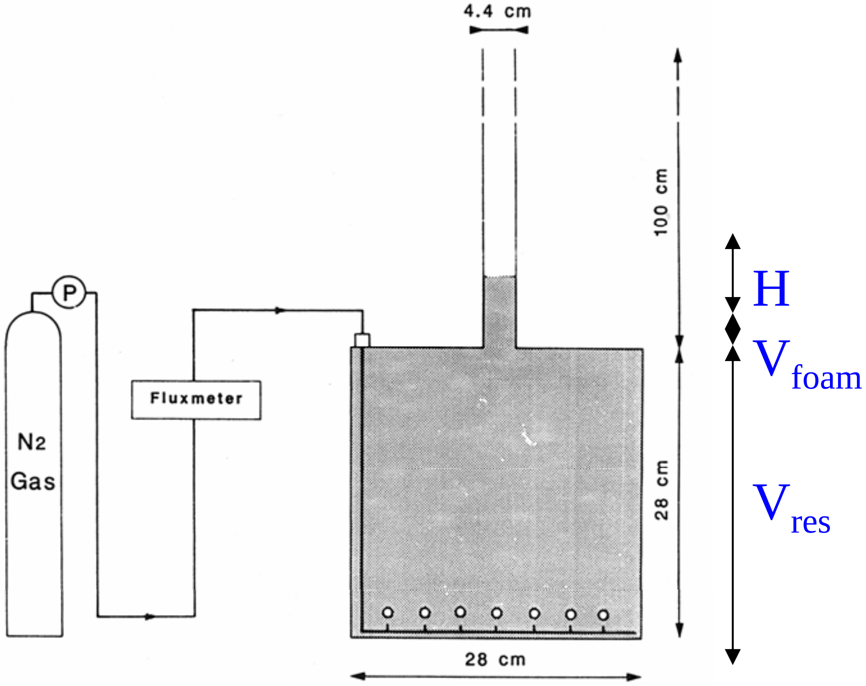




Bubbles are generated at the base of the reservoir, filled with viscous liquids

Laboratory experiments (5):

Fluids used for laboratory volcano: viscous oils



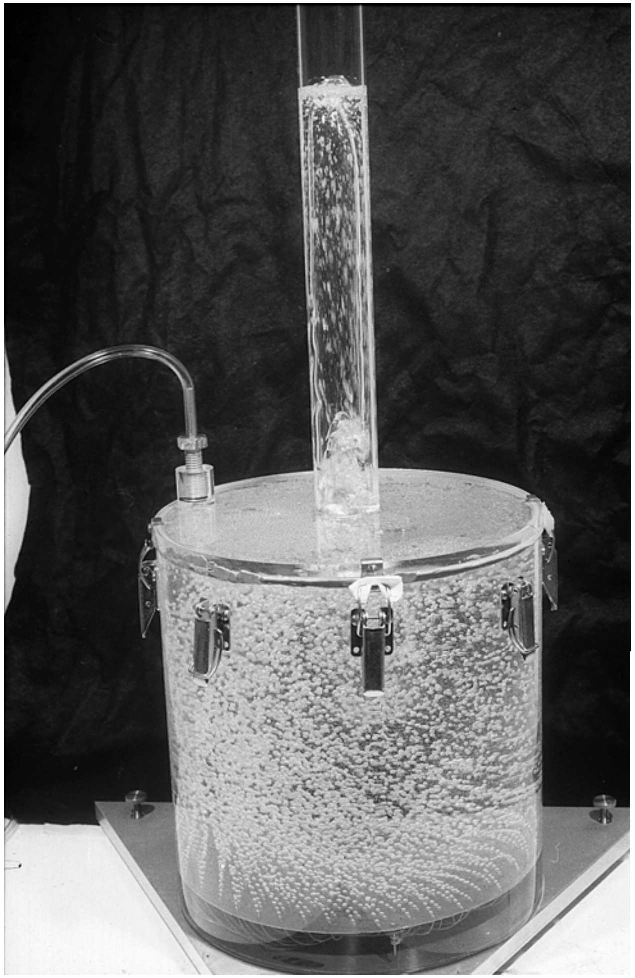
Oils:	Silicone	Glycerol
viscosity μ (Pa.s)	10^{-2} - 1 (5)	1.2 - 0.15
Surface tension σ ($kg.s^{-2}$)	2 10^{-2}	6.4 10^{-2}
gas flux (m^3/s)	2 10^{-6} - 3 10^{-5}	2 10^{-6} - 3 10^{-5}
Bubble diameter (mm)	1.7 - 5 (8)	1.7 - 5 (8)

Laboratory experiments (6):

Basaltic eruption: hawaiian eruption

relatively fluid silicone oil (0.1 Pa.s)

Effusive activity

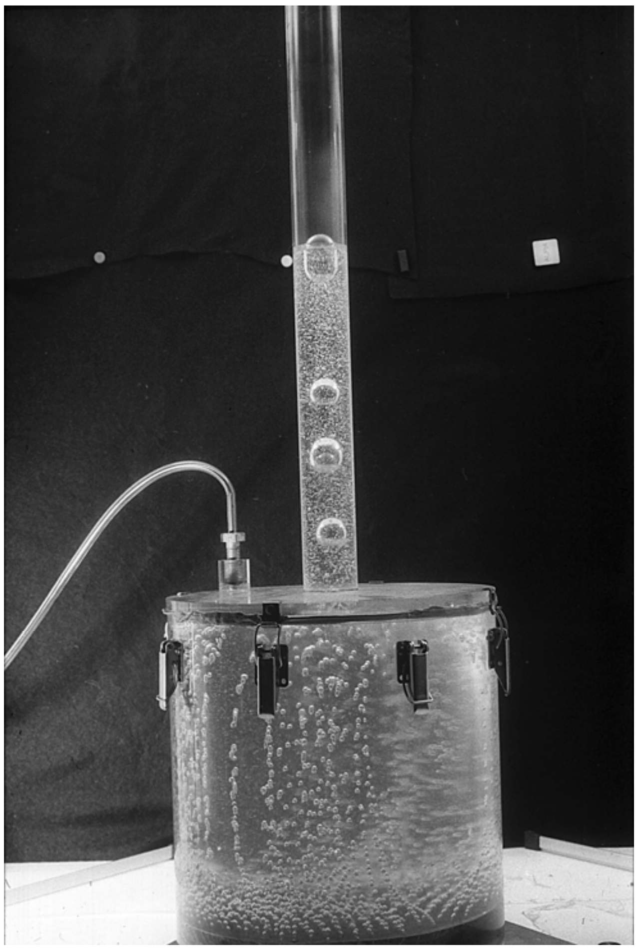


Fire fountain in conduit

Laboratory experiments (7):

Basaltic eruption: strombolian activity

relatively viscous silicone oil (1 Pa.s) → smaller gas pocket, but more often



↔

Bubble bursting at Etna, July 2001

→ Series of strombolian explosions in conduit

Laboratory experiments (8):

Description of an experiment:

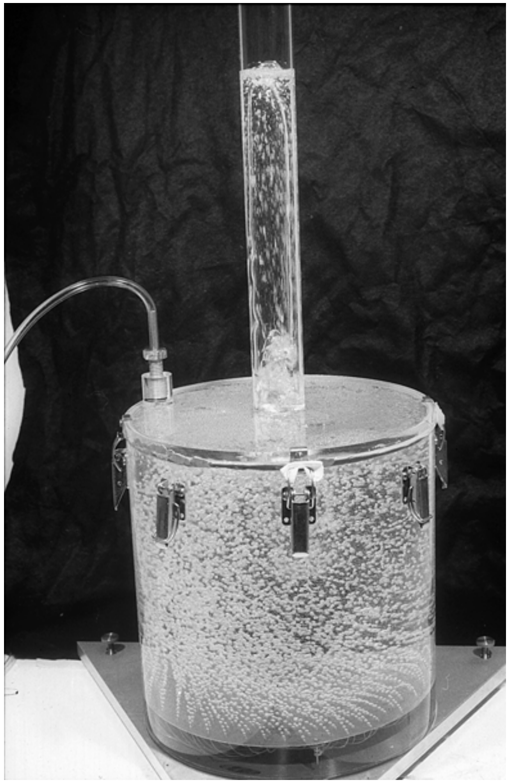
Existence of a foam at the top of the reservoir

Two stages for the foam:

formation of gas jet in conduit

↑

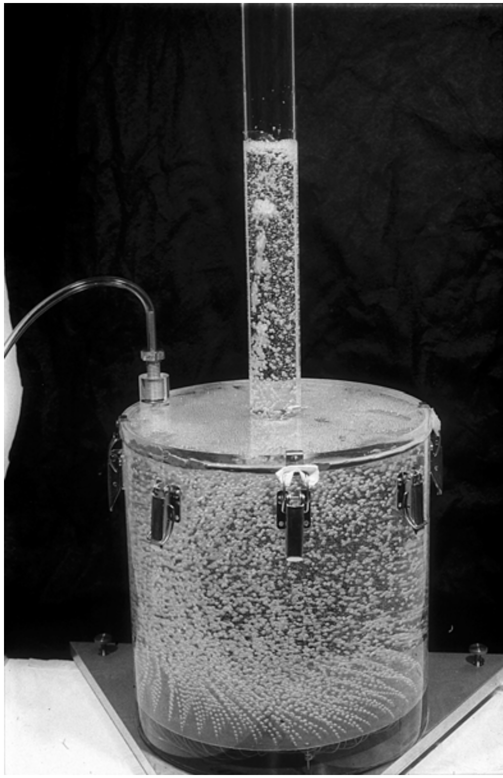
entire collapse



slow rise of liquid

↑

re-building the foam



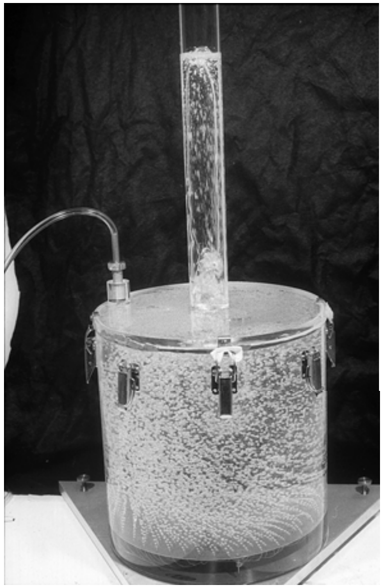
↔

regular alternance

Laboratory experiments (9):

Volcanological applications:

formation of gas jet in conduit



slow rise of liquid

Fire fountains (Puu O’o eruption)

Lava flow (Kilauea)

Laboratory experiments (10):

Description of an experiment:

Existence of a foam at the top of the tank

Two stages for the foam:

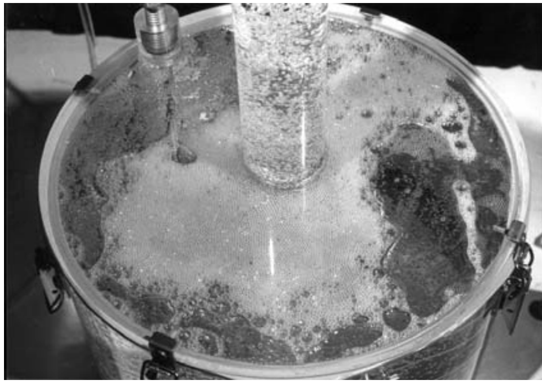
Entire collapse → formation of gas jet in conduit

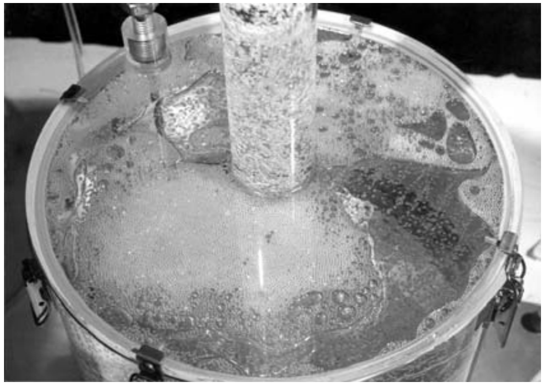
Rebuilt of foam → slow rise of the liquid

Regular alternance

1

2





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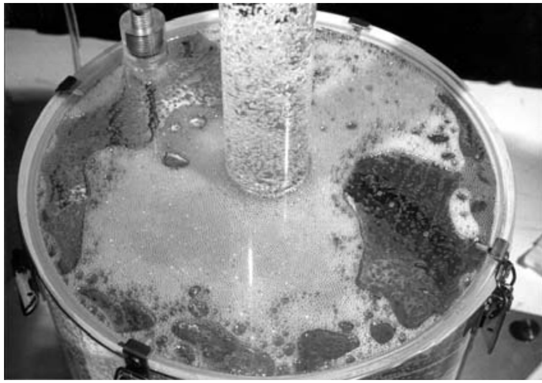


4

Laboratory experiments (11):

The experiments reproduce:

1) Each eruptive regime

Fire fountain = collapse of the magmatic foam at the top of reservoir

Effusive activity = rebuilt of the foam

Puu O'o (Kilauea, May 2004)

2) Cyclicity between the two regimes

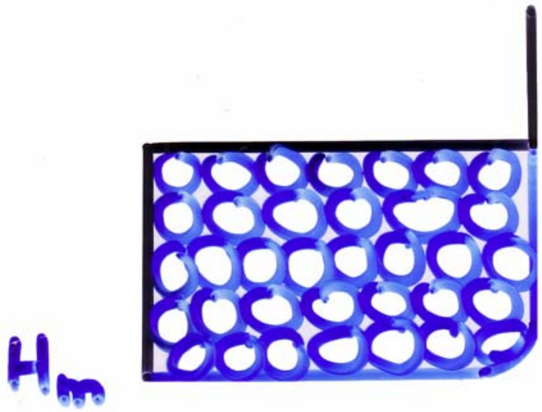
3) Some details of the eruption:

- large variations of magma level
- at the end of fire fountain: conduit is emptied
- drainback of magma
- gas piston activity

→ Eruptive activity is dominated by the dynamics of the foam at the top of the reservoir

Laboratory experiments (12):

Foam shape at steady-state:



1) Maximum height: H_m

$$H_m = f(Q, \mu)$$

Q: gas flux; μ : viscosity; d: bubble diameter

2) Critical height above which the foam starts to coalesce: H_c

Buoyancy > surface tension, σ → Unstable foam

$$H_c = \frac{4\sigma}{\rho g d \varepsilon}$$

$H_m > H_c$ → Foam coalescence

↓

Gas jet = fire fountain

ε : gas volume fraction in foam;
ρ : magma density; g: acceleration of gravity

Basaltic magma reservoirs

Etna, 600 m
(Sept 26 1989)

1. Physical parameters

2. A laboratory volcano:
    a) Observations of surface activity
    b) Laboratory experiments

    c) Applications to Kilauea

2. Gas volume measurements
4. Conclusion

A laboratory volcano (1): application to Kilauea

1) Fire fountain:

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

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

H: fire fountain height
g: acceleration of gravity

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

H = 400 m → velocity = 100 m/s

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

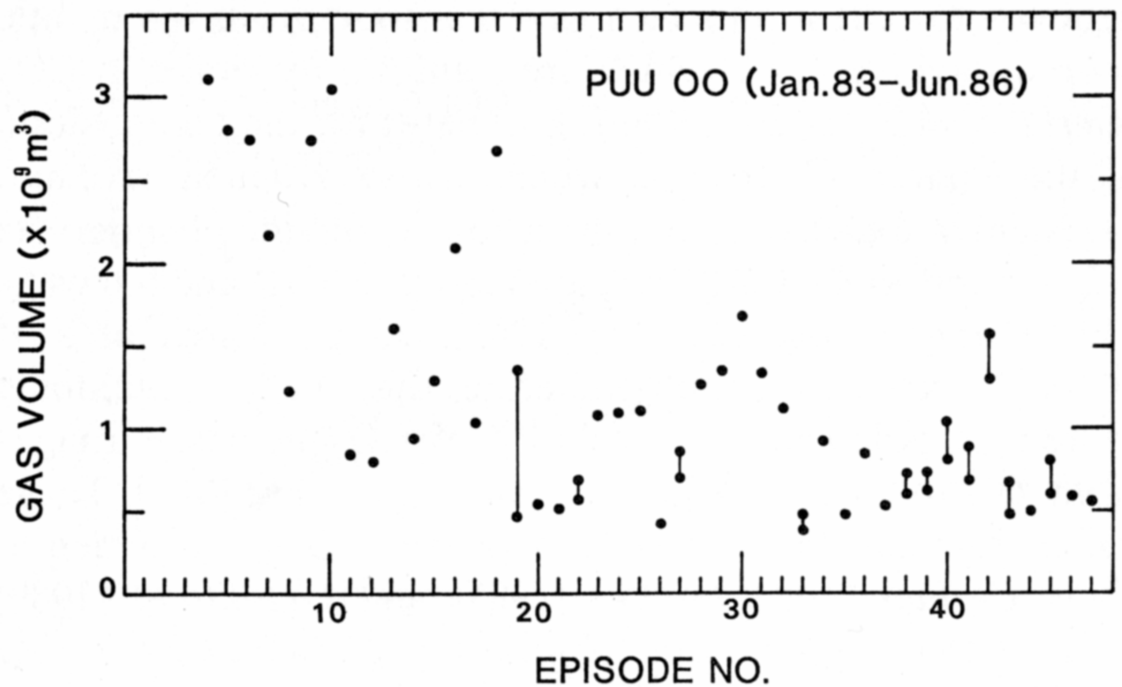
A laboratory volcano (2): application to Kilauea

gas volume at the vent is determined from fire fountain height

perfect gas law: $P\,V = \text{constant}$

P : pressure;
V: gas volume

$$\Rightarrow \quad P_{g\ vent}\, V_{g\ vent} = P_{g\ reservoir}\, V_{g\ reservoir}$$



↓ gas volume in magma chamber

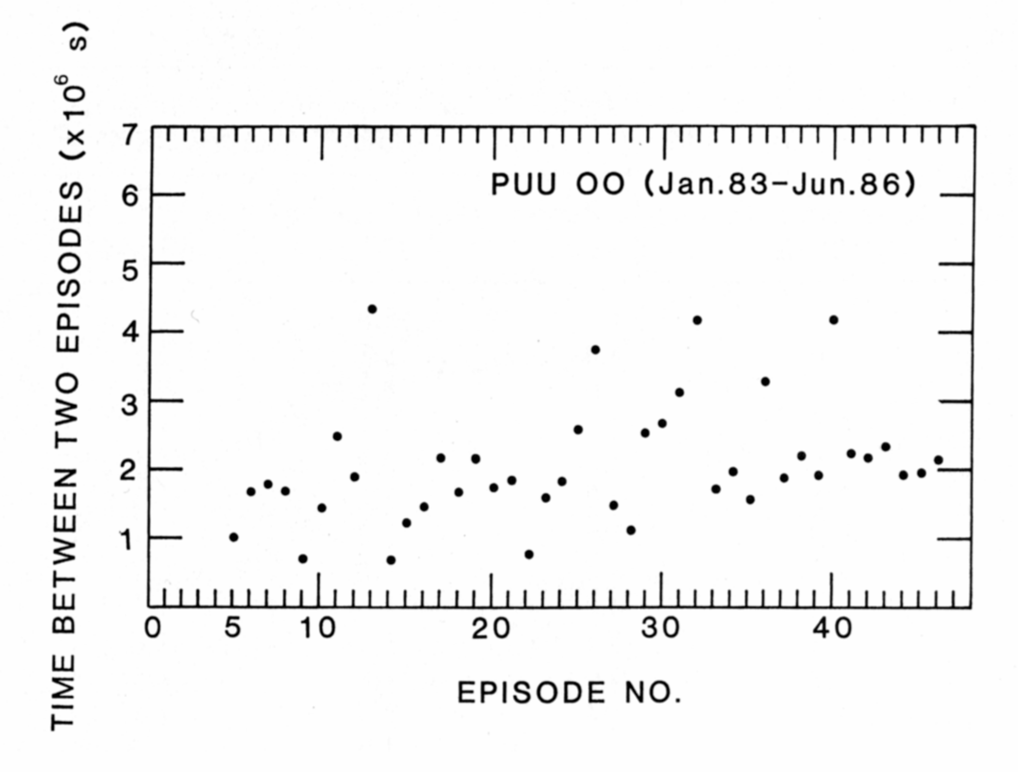
decrease in gas volume over the 3 years and a half

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



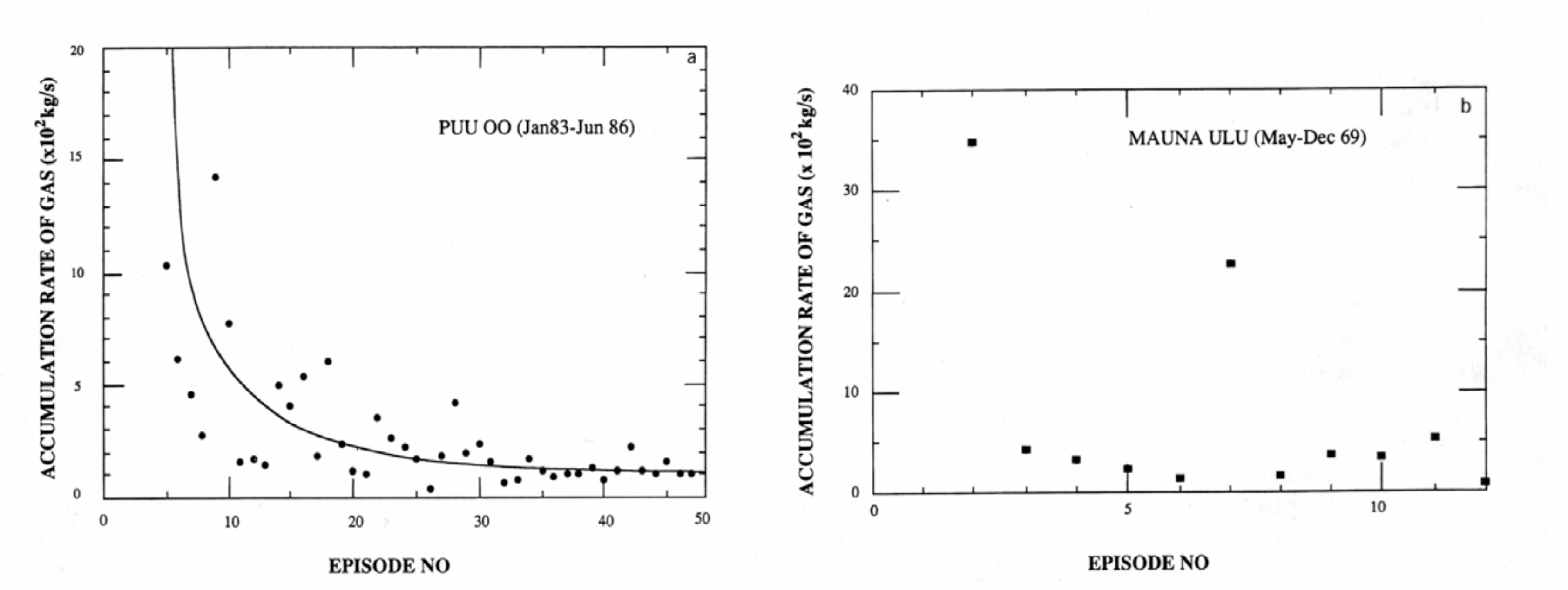
Gas flux in magma chamber is a gas volume at depth over a time during which it has been accumulated

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

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

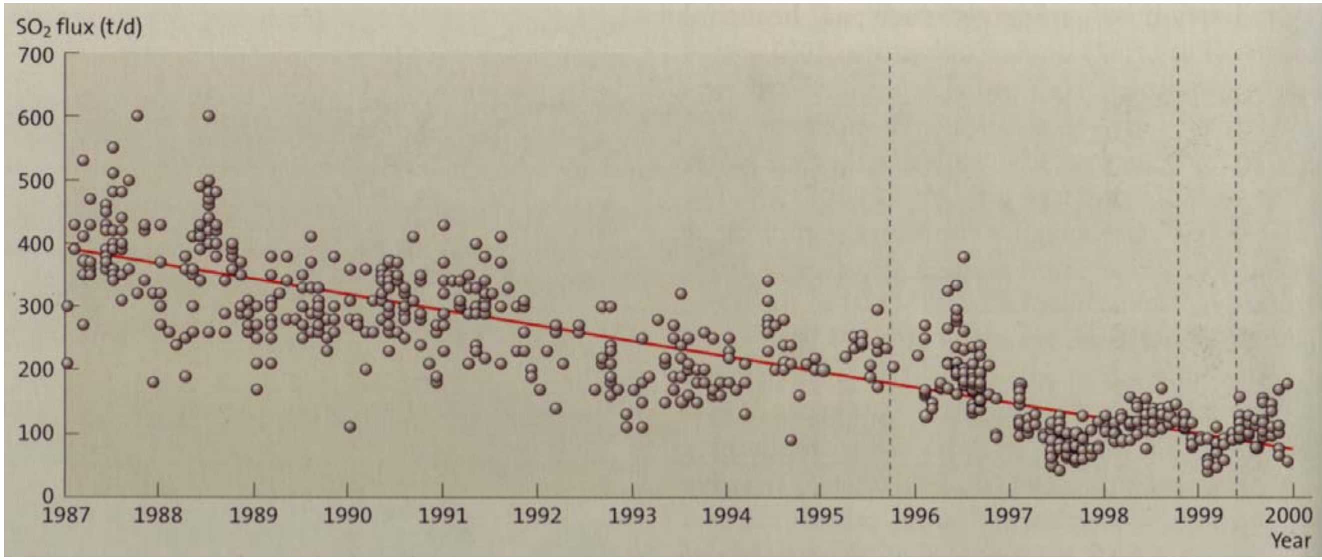
The stopping of fire fountain episodes is associated with the decrease of gas flux in reservoir below the critical gas flux

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…)

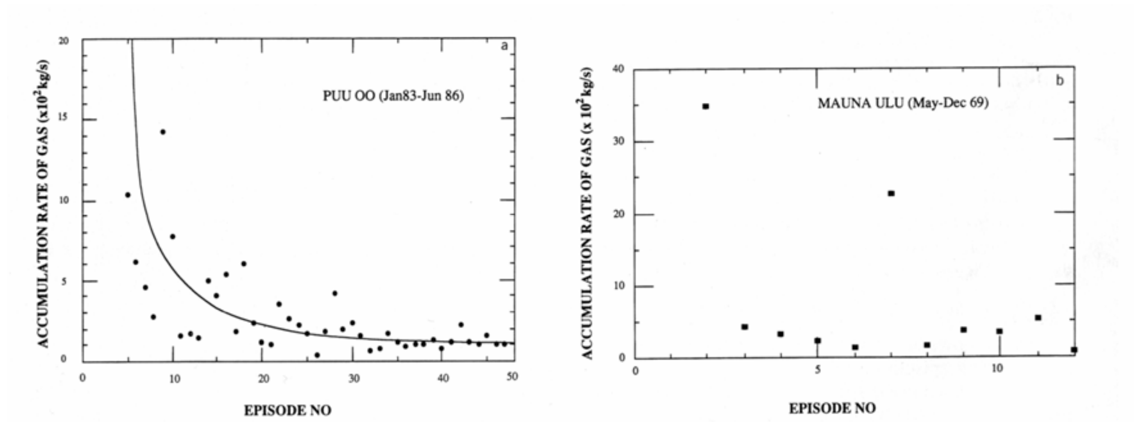


decrease in gas flux during fire fountains is confirmed
for the period after the fire fountain episodes (effusive activity)

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

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

$B = f(\varepsilon, r_c, r_t)$

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)

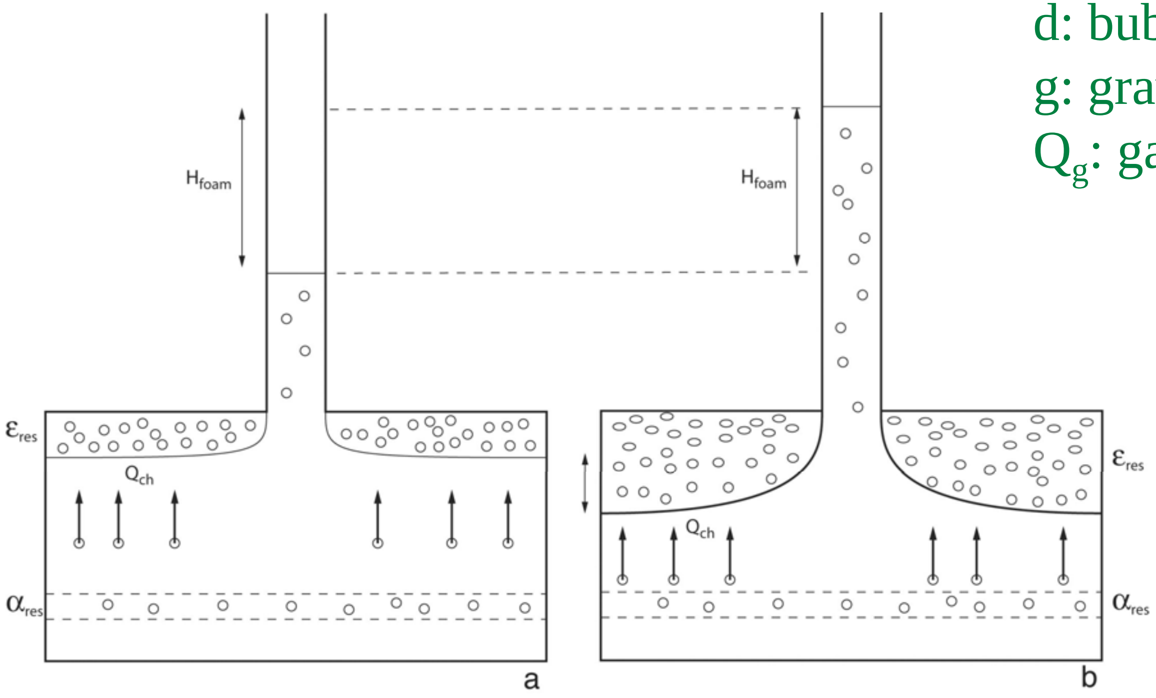
A laboratory volcano (7): application to Kilauea

Gas flux in magma chamber Qg:

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

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

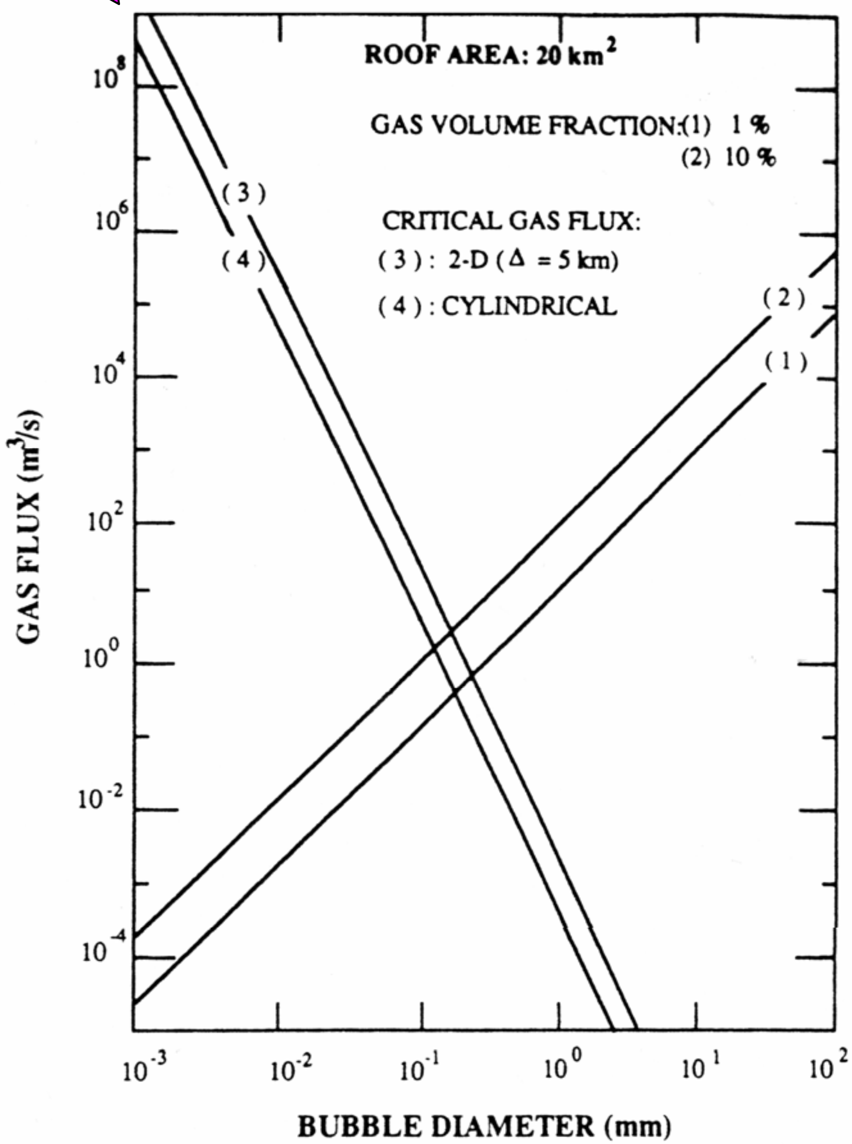
α: gas volume fraction in reservoir
S: area of magma chamber (m^2)
μ: viscosity (Pa.s)
ρ_{liq}: liquid density ($kg.m^{-3}$)
d: bubble diameter (m)
g: gravity
Q_g: gas flux (m^3/s)



gas flux = f(α, d, area)

A laboratory volcano (8): application to Kilauea

Q_c: critical gas flux



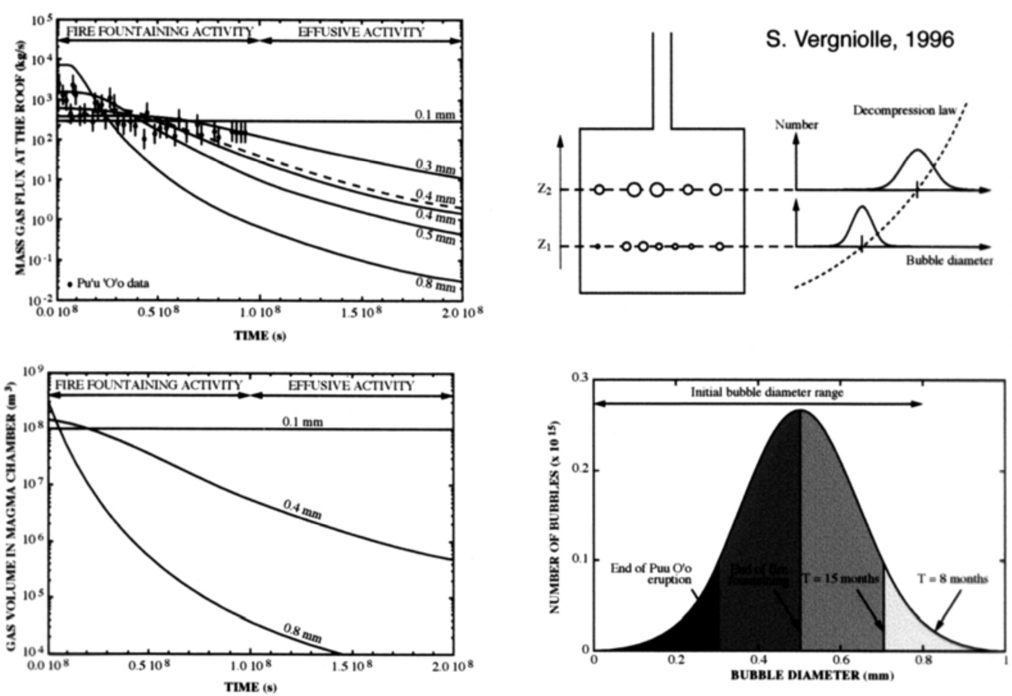
Etna, 600 m
(Sept 26 1989)

bubble rise

bubble diameter
in magma chamber
0.4 mm

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

1. Physical parameters
2. A laboratory volcano:

3. Gas volume measurements

a) ballistics and radar

b) acoustic records

4. Conclusion

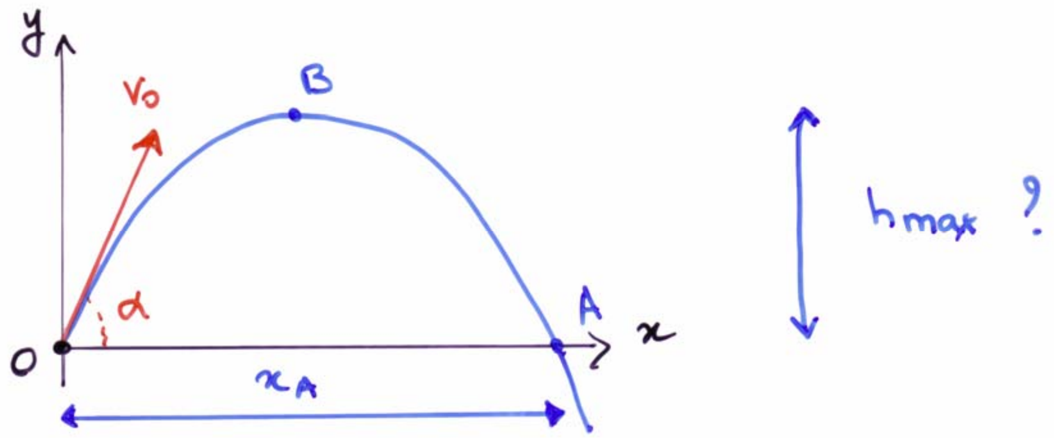
Velocity measurements with a Sodar at Stromboli, juin 1991

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

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

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

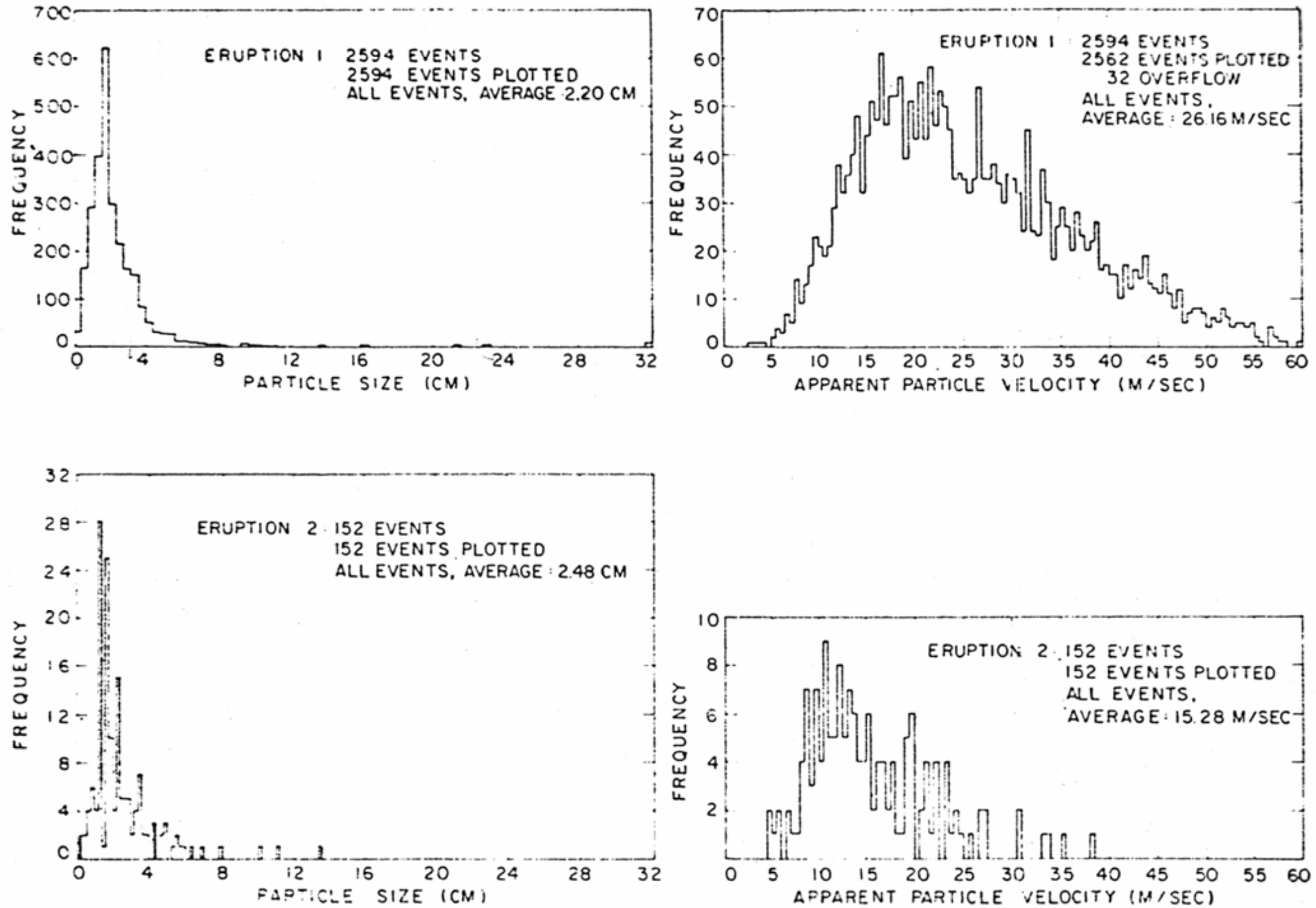


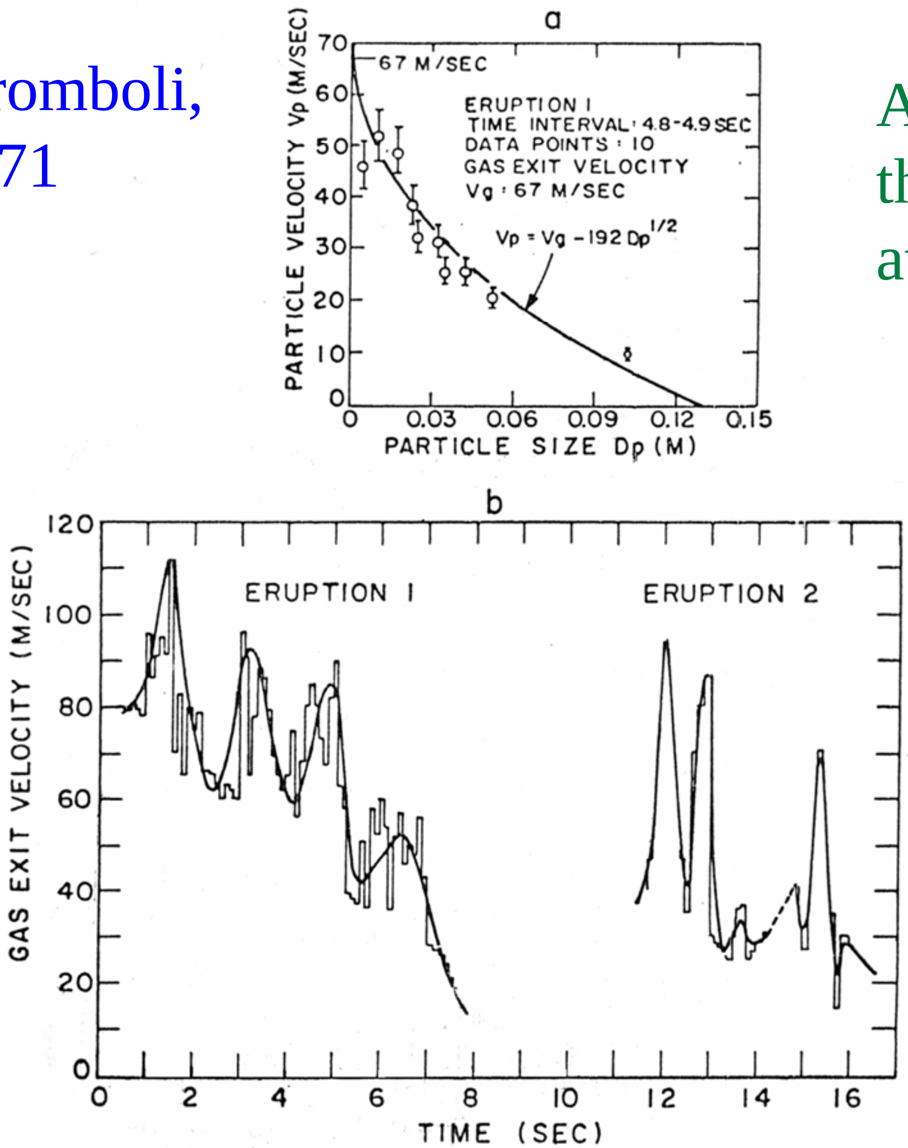
Fig. 9. Frequency distributions of particle sizes and apparent particle velocities for the bulk of the two eruptions studied.

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

Stromboli, 1971

Direct measurements (5): ballistics

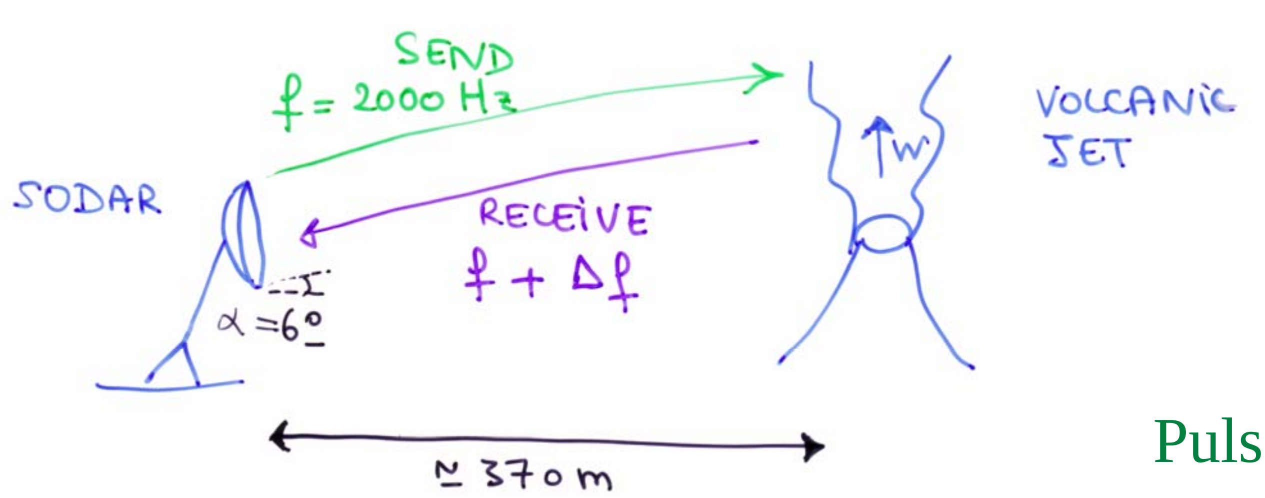
Stromboli, 1971



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

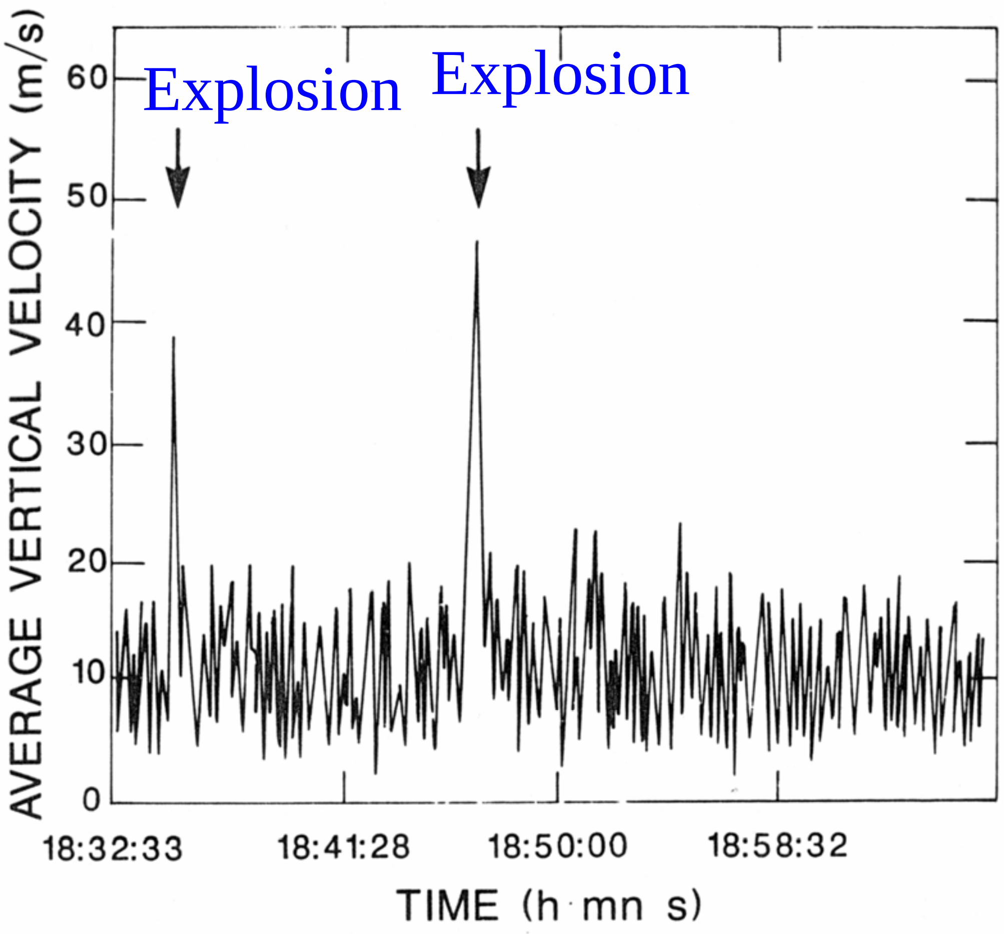
$\Delta f / f = - 2\, w \sin(\alpha) / c$

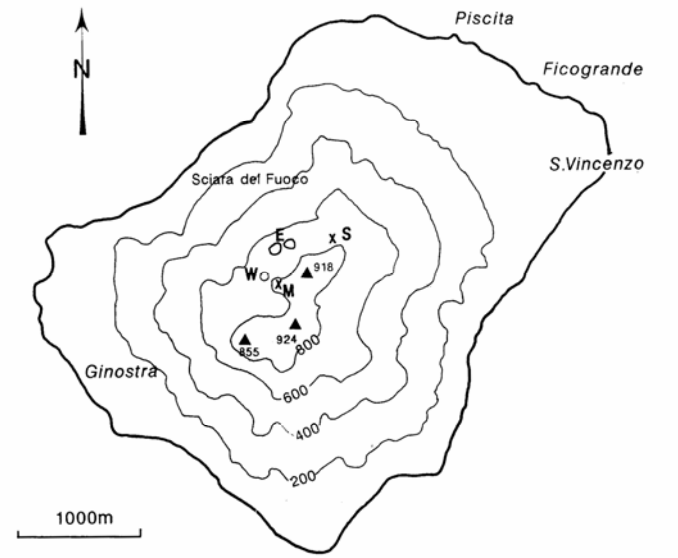
c: sound speed

air: 340 m/s

hot gas : 700 m/s

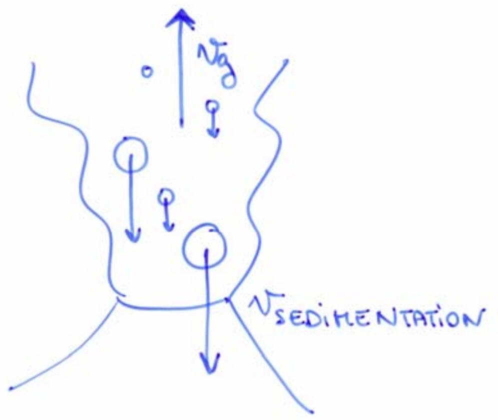
Direct measurements (7): Acoustic sounder





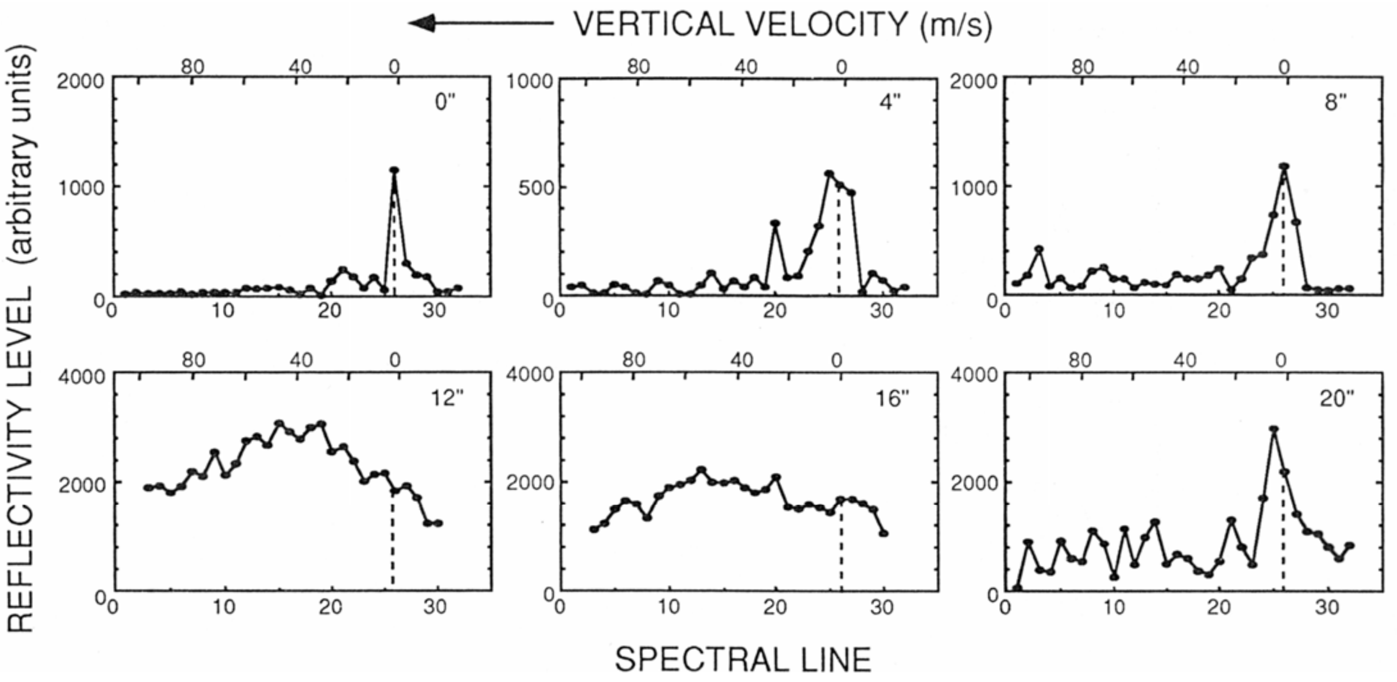
Summit vents
at Stromboli

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
2. A laboratory volcano:

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   a) ballistics and radar

   b) acoustic records

4. Conclusion

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

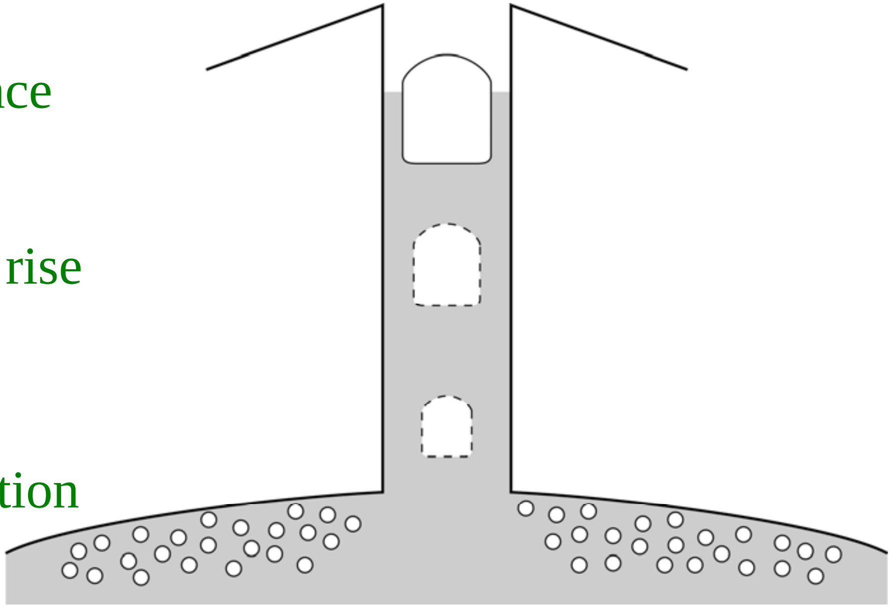
fire fountains: several tens of meters long

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

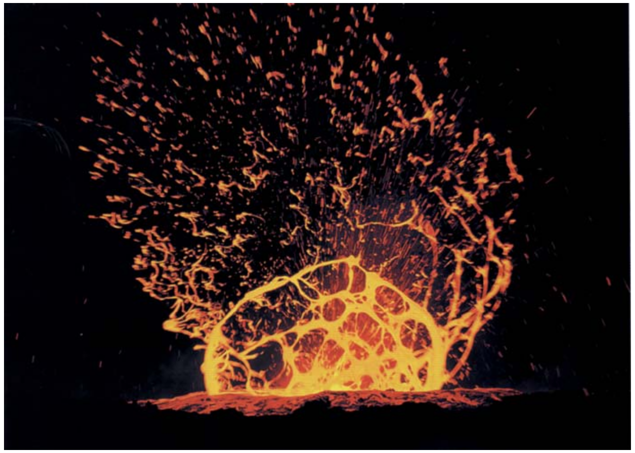
Fire fountain
Puu o'O eruption
(Kilauea, Hawaii)

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

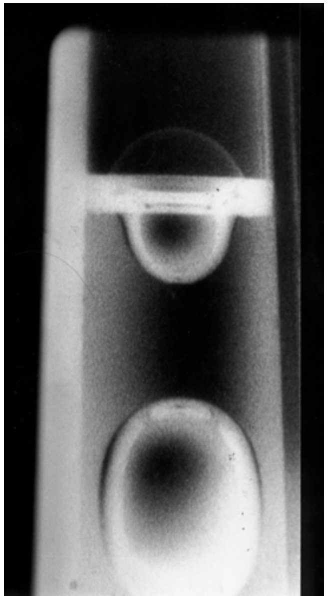
sound speed = 340 m/s
+ radius = 2 m → frequency = 150 Hz

Frequency measured on volcanoes: 1 - 10 Hz

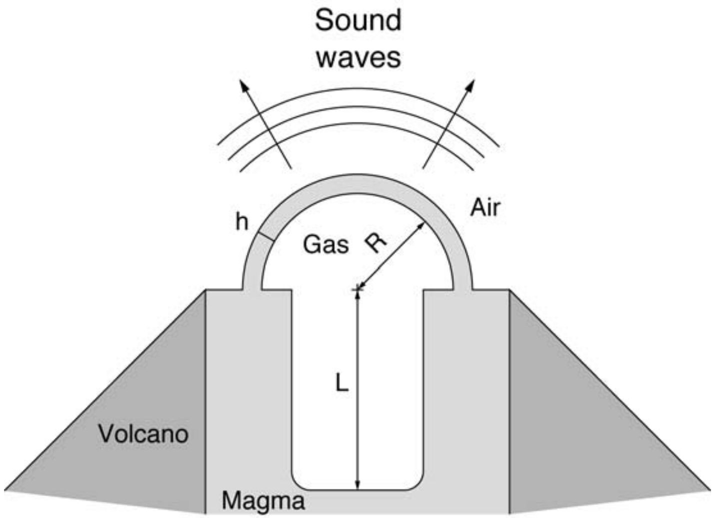
→ more than 1 order of magnitude discrepancy
the mechanism is not bubble bursting such as for a balloon

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)



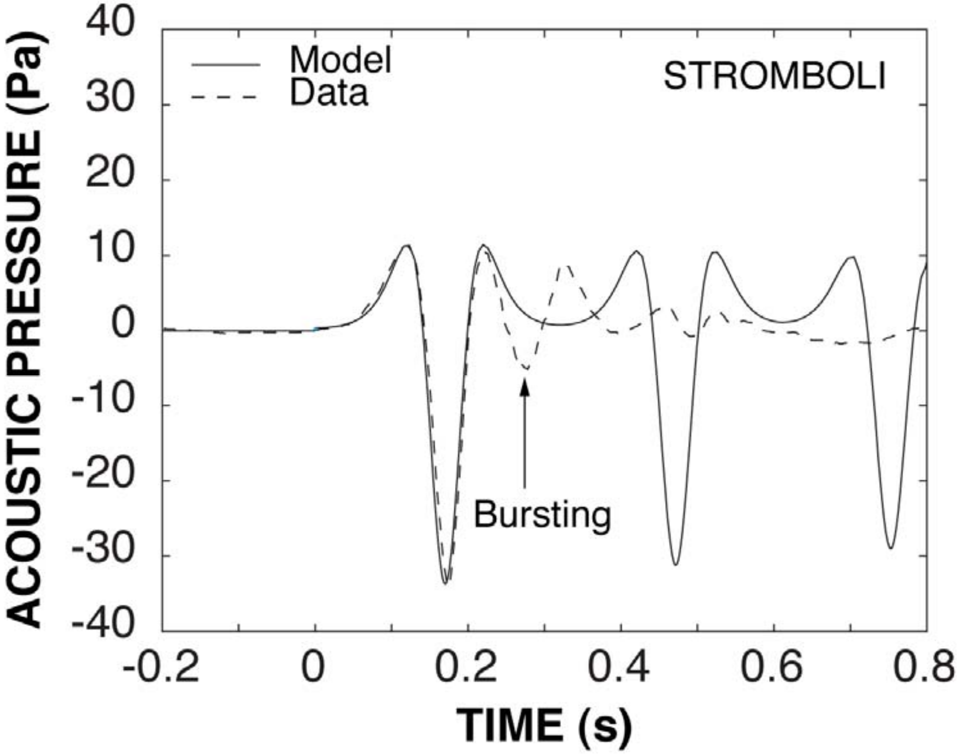
Sketch of bubble
vibration model

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

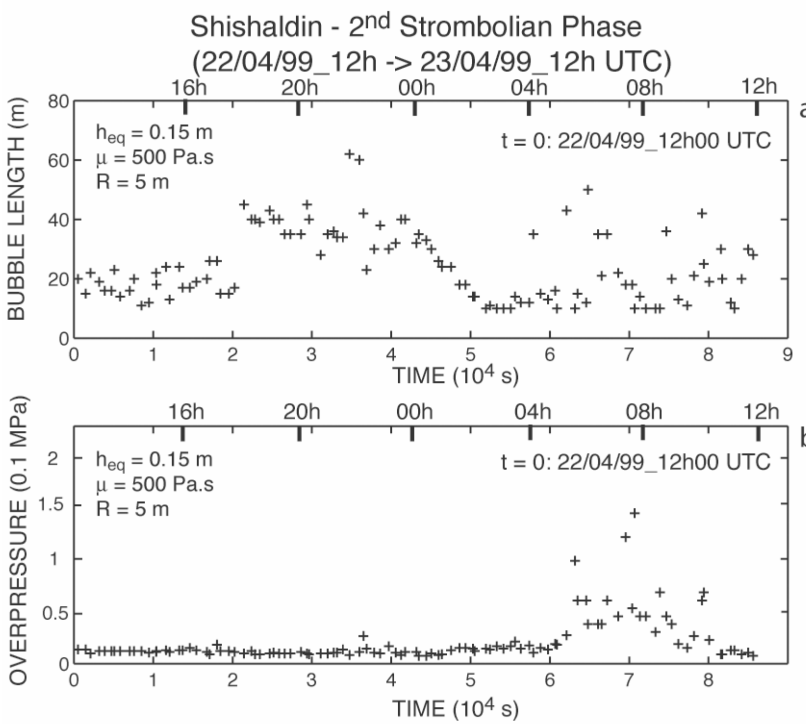


Bubble bursting at the
surface of lava lake (Kilauea)

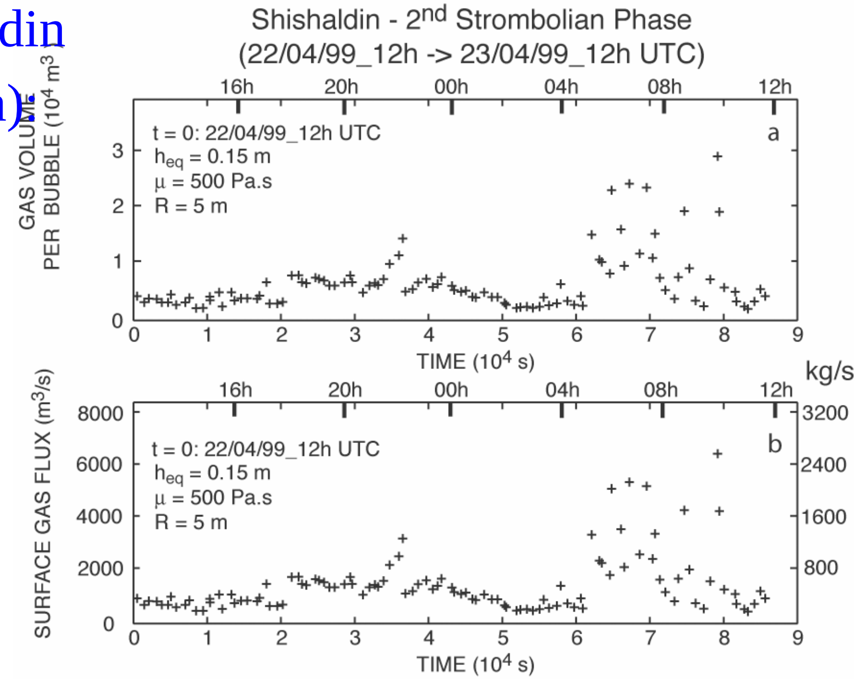
Model for source of sound:
bubble radius, length,
overpressure
and their evolution in time

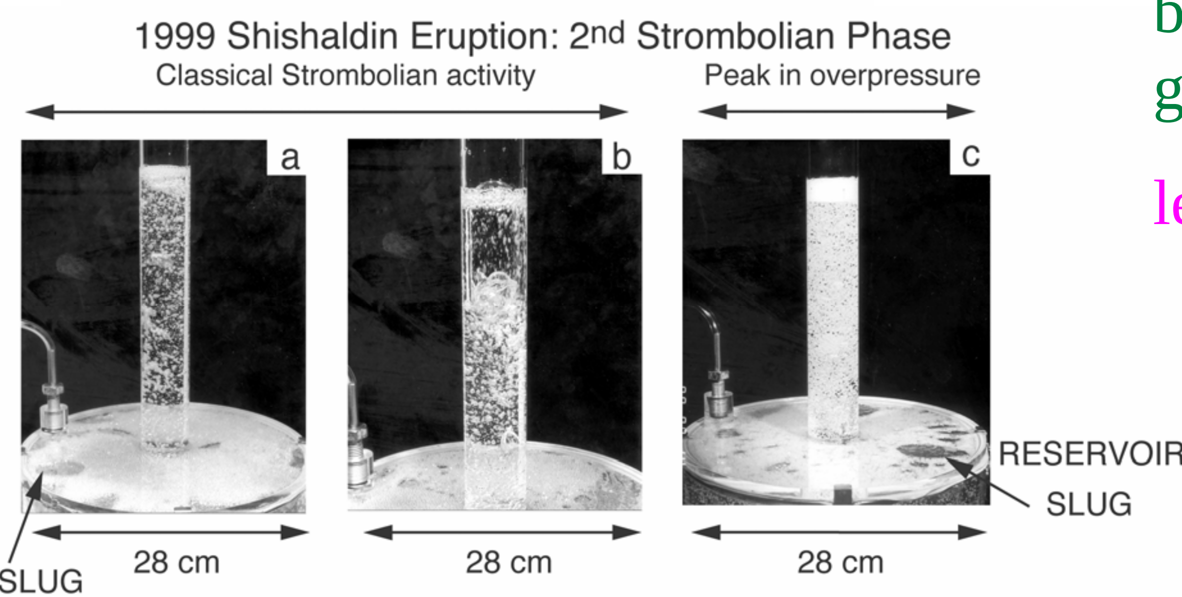
Model is very robust for gas volume estimates
because it is based on frequency content

Direct measurements (16): Acoustic records



Shishaldin (Alaska):





bubble length, pressure, gas volume and gas flux

length > 2 radius

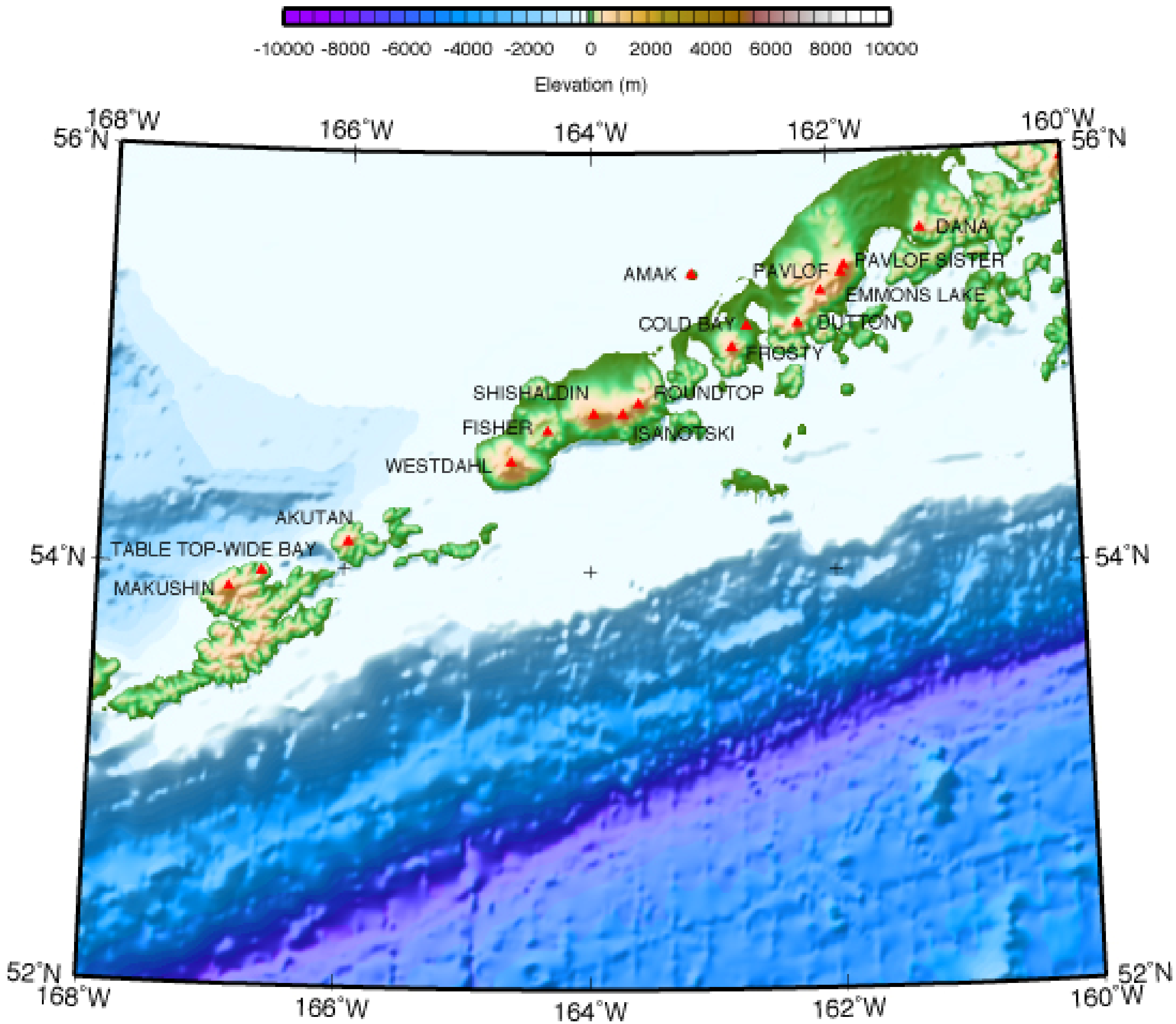
→ slug flow

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

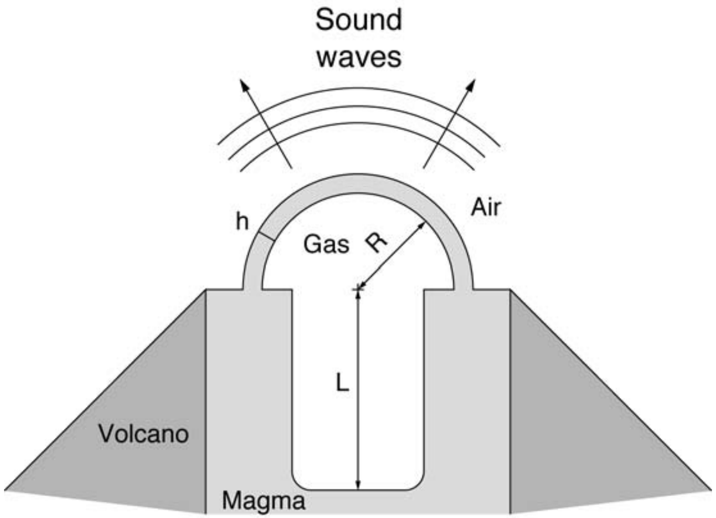
Acoustic measurements
origin of basaltic Subplinian activity
transition Subplinian- Strombolian

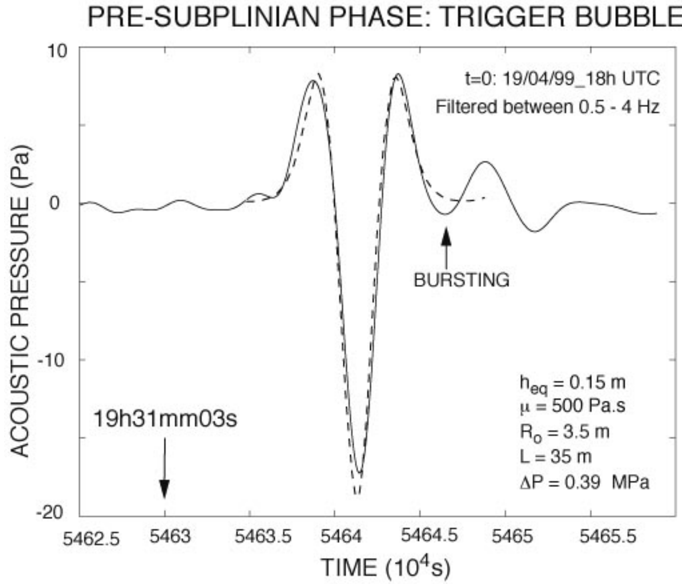
Shishaldin 23/04/99

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



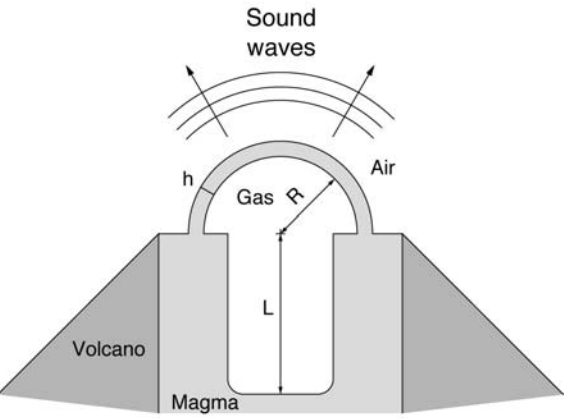


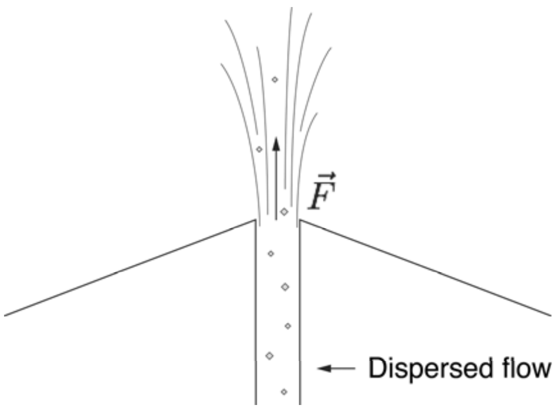
Model of bubble vibration: → L = 35 m; ΔP = 0.39 MPa

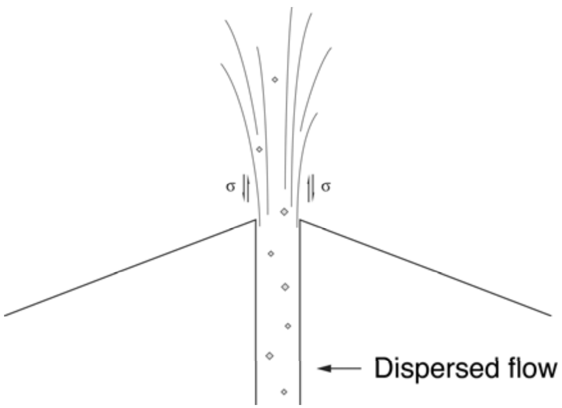
Direct measurements (20): Acoustic records

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)

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

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

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

Direct measurements (21): Acoustic records

Subplinian phase:

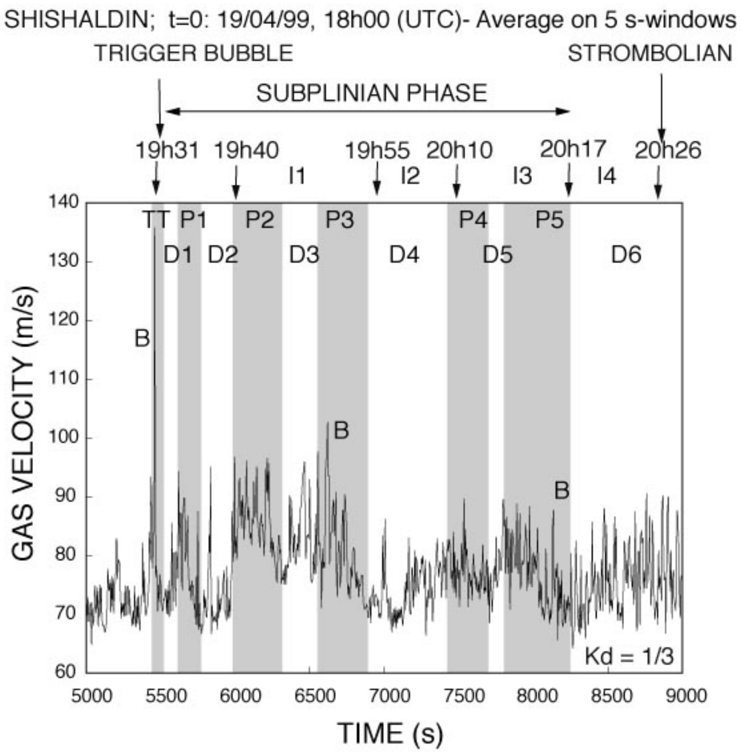
Complex waveform →

Shishaldin
23/04/99

use of acoustic power Π_d :
proportional to gas velocity

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

$$\Pi_d = \frac{K_d \, \rho_{air} \, A_d \, U^6}{c^3} \qquad K_d = 1/3$$



6 periods

gas flux = velocity x area

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)

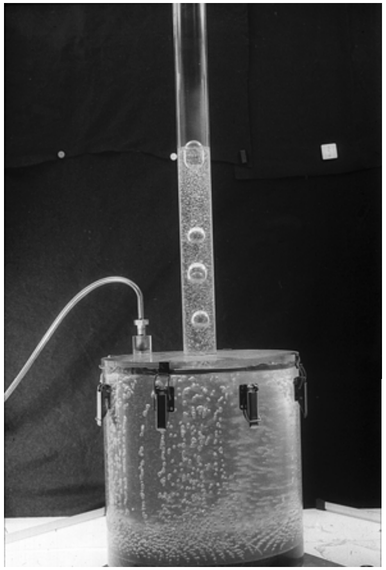
Lava flow into sea (Kilauea, March 1988)

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, …