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, Kamchatka, 1975
plume of 2 km high
Physical parameters (1): Different types of surface activity

**Explosive silicic activity**

- **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)

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

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

St Helens, 18/05/80 2 pm

Unzen, June 1991

Mt Pelée
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

**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
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

- Effusive Activity
- Strombolian explosions
- Fire fountains
- Plinian columns

Increasing gas content
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

+ existence of potential levels for «horizontal» magma accumulation, with a shallow reservoir and deep ones
Kilauea (Hawaii):
Summit shallow reservoir:
seismicity + deformations
volume = 5 \times 10^8 \text{ m}^3
depth = 2 - 4 \text{ km}

Etna (Italy):
below the south east crater:
depth: 2 - 4 \text{ km};
volume = 4 \times 10^7 \text{ m}^3
Etna main degassing reservoir = 5 \times 10^8 \text{ m}^3; depth : 6 \text{ km and deeper}

Stromboli (Italy): 2 reservoirs: sismo + petro
shallow (seismicity): depth: 300 m
deep (petrology only): depth: 7 - 8 \text{ km}
Physical parameters (7): volcanic conduits

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, May 2004
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

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:

- 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
- bubbly liquid viscosity / pure liquid viscosity

**Figure 5**: Melt viscosity as a function of dissolved water content for natural melts spanning the range rhyolite to komatite. 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).

**Gas volume fraction**
Physical parameters (12): viscosity of magma

Magma: very large range of viscosities

Basalts are less viscous $\rightarrow$ Basalts leads to gentle eruptions

Consequences:

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

$\rightarrow$ 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)  

$G = \rho_{\text{mixt}} \cdot w \cdot S = \text{constant}$

$w$: velocity (m/s); $S$: area (m²); $\rho$: magma density (kg/m³)

Volcanological implications:

vent: $\rho_{\text{mixt}3} ; w_3 ; S_3$

base of conduit: $\rho_{\text{mixt}2} ; w_2 ; S_2$

top of magma reservoir: $\rho_{\text{mixt}1} ; w_1 ; S_1$

$\rho_{\text{mixt}3} \cdot w_3 \cdot S_3 = \rho_{\text{mixt}2} \cdot w_2 \cdot S_2 = \rho_{\text{mixt}1} \cdot w_1 \cdot S_1$
Physical parameters (14): conservation of mass

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

$$\rho_{\text{mixt}3} = \rho_{\text{mixt}1} \quad \text{w}_3. = \text{w}_1. \frac{S_1}{S_3}$$

$$S_1 = \pi R_{\text{ch}}^2; \quad R_{\text{ch}} = \text{few km} \quad \quad \quad \quad \quad \quad \quad \text{S}_1 / \text{S}_3 = 10^4$$

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

**Vesiculation:** $$S_2 = S_3 \quad \text{w}_3. = \text{w}_2. \frac{\rho_{\text{mixt}2}}{\rho_{\text{mixt}3}}$$

$$\rho_{\text{mixt}} = (1 - \alpha) \cdot \rho_{\text{liq}} + \alpha \cdot \rho_{\text{gas}} \quad \alpha : \text{gas volume fraction}$$

$$\alpha_3 = 0.99 \quad \text{w}_3. = \text{w}_2. \frac{(1 - \alpha_2)}{(1 - \alpha_3)} = 100 \quad \text{w}_2$$

$$\alpha_2 = 0$$

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)
Basaltic magma reservoirs

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Kilauea

Etna, 600 m, Sept 26 1989
Basaltic magma reservoirs

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

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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)

Pelee’s hair (very elongated magma droplets)  
Reticulite (highly vesiculated magma)

65 % of gas density = 900 kg.m\(^{-3}\)
85 % of gas density = 400 kg.m\(^{-3}\)

1 cm across; 98 % of gas density = 50 kg.m\(^{-3}\)
less 1 mm thickness
Evidence of gas in fire fountains:

Plume above fire fountains
Reticulite
Peak in CO2 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
A laboratory volcano (4): origin of fire fountains

Dynamics of an annular flow

Formation of fragments:

- 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

Lava lake / top of magma column: gas piston activity

bursting of large bubble

gas piston at lava lake, Hawaii:

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
- Bubble exsolution
- Bubble nucleation and growth
- Densely 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

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

- September 26, 1989 at 8:30 height: 600 m
- July 25, 2001
Basaltic magma reservoirs

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2. A laboratory volcano:
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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?
Laboratory experiments for fire fountains (2):

Description of an Hawaiian eruption

Fire fountain: central gas jet with suspended lava clots

Effusive activity: rise of vesicular magma

Large variation of liquid level
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

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

<table>
<thead>
<tr>
<th>Fluids:</th>
<th>Silicone</th>
<th>Glycerol</th>
</tr>
</thead>
<tbody>
<tr>
<td>viscosity $\mu$ (Pa.s)</td>
<td>$10^{-2} - 1$ (5)</td>
<td>$1.2 - 0.15$</td>
</tr>
<tr>
<td>Surface tension $\sigma$ (kg.s$^{-2}$)</td>
<td>$2 \times 10^{-2}$</td>
<td>$6.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>gas flux (m$^3$/s)</td>
<td>$2 \times 10^{-6} - 3 \times 10^{-5}$</td>
<td>$2 \times 10^{-6} - 3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Bubble diameter (mm)</td>
<td>$1.7 - 5$ (8)</td>
<td>$1.7 - 5$ (8)</td>
</tr>
</tbody>
</table>
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) \[ \rightarrow \] 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
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

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; $\mu$: viscosity; d: bubble diameter

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

Buoyancy > surface tension, $\sigma$  Unstable foam

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

$\varepsilon$: gas volume fraction in foam;
$\rho$: magma density; g: acceleration of gravity

$H_m > H_c$  Foam coalescence

Gas jet = fire fountain
Basaltic magma reservoirs

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A laboratory volcano (1): application to Kilauea

1) Fire fountain:

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

\[ \text{velocity} = (2gH)^{1/2} \]

H: fire fountain height

\[ \text{velocity} = 100 \text{ m/s} \]

\[ H = 400 \text{ m} \]

\[ \text{gas flux at vent} = \text{velocity} \times \text{surface} = \frac{\text{gas volume}}{\text{time}} \]

\[ \text{gas volume} = \text{velocity} \times \text{surface} \times \text{time} \]
A laboratory volcano (2): application to Kilauea

gas volume at the vent is determined from fire fountain height

perfect gas law:

\[ P \cdot V = \text{constant} \]

\[ P_{\text{g vent}} \cdot V_{\text{g vent}} = P_{\text{g reservoir}} \cdot V_{\text{g reservoir}} \]

P: pressure; V: gas volume

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
The critical gas flux in reservoir, determined from fire fountain height, is approximately 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 spectrometer: 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

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

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

$d = f(\text{critical gas flux})$

$\varepsilon$: gas volume fraction
$r_t$: reservoir radius (m)
$r_c$: conduit radius (m)

$\sigma$: surface tension (kg.s$^{-2}$)
$\rho_{\text{liq}}$: liquid density (kg.m$^{-3}$)
$\mu_{\text{liq}}$: liquid viscosity (Pa.s)

$d$: bubble diameter (m)
A laboratory volcano (7): application to Kilauea

Gas flux in magma chamber $Q_g$:

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

$$Q_g = \alpha \ \frac{(1 - \alpha) \ d^2 \ (\rho_{\text{liq}} - \rho_{\text{gas}}) \ g \ S \ 18 \ \mu}{\rho_{\text{liq}} \ \text{liquid density} \ (\text{kg.m}^{-3}) \ \mu: \text{viscosity} \ (\text{Pa.s}) \ \rho_{\text{liq}}: \text{liquid density} \ (\text{kg.m}^{-3}) \ d: \text{bubble diameter} \ (\text{m}) \ g: \text{gravity} \ \alpha: \text{gas volume fraction in reservoir} \ \ S: \text{area of magma chamber} \ (\text{m}^2) \ Q_g: \text{gas flux} \ (\text{m}^3/\text{s}) \$$

gas flux = $f(\alpha, d, \text{area})$
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: $\tau_f^*$ and $\tau_e^*$

Duration of fire fountain $\tau_f$:

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

$\tau_f^* = 1.1$ : Puu O’o eruption (1987-now)
$\tau_f^* = 1.3$ : Mauna Ulu eruption (1969-1971)

Duration of eruption $\tau_e$:

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

$\tau_e^* = 4.2$ : 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 = \( \mu \)

Temperature measurements + model of thermal convection

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

\[ \tau_e^* = 5 \text{ months} \]
\[ \tau_e^* = 4.2 \]
mean bubble diameter \( d_0 = 1 \text{ mm} \)
same order of magnitude as for Puu O’o and Mauna Ulu eruptions
A laboratory volcano (12): application to Etna (Italy)

each episode: a series of Strombolian explosions
a episode lasts a few hours, intermittency: a few days

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\textsubscript{2}/S and S/Cl

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

Perfect gas law $\rightarrow$ Gas volume at depth of reservoir

+ intermittency between episodes (3-5 days) $\rightarrow$ 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\textsubscript{2}O; 0.11-0.41 wt% CO\textsubscript{2}.

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

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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
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

Ballistic of a point:

assumption: no air resistance

\[ h_{\text{max}} = \frac{v_0^2 \sin^2(\alpha)}{2g} \]
Direct measurements (2): ballistics

For a vertical gas jet \( v_0 = (2 \ g \ h_{\text{max}})^{1/2} \)
(kinetic energy is transformed into potential energy)

Example: Stromboli
\( h_{\text{max}} = 100 \ \text{m} \) \( \rightarrow \) \( v_0 = 50 \ \text{m/s} \)

\( v_0 \) is not too sensitive to \( h_{\text{max}} \), 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 \( \alpha = 45 ^\circ \)
\( \alpha = 60 ^\circ; \ v_0 = 50 \ \text{m/s}; \ x_a = 220 \ \text{m} \)

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:
\[ v_{\text{gas}} = \frac{d^2 (\rho_{\text{liq}} - \rho_{\text{gas}})}{g} \times 18 \mu \]

\( \mu \): viscosity (Pa.s);
\( \rho_{\text{liq}} \) and \( \rho_{\text{gas}} \) liquid and gas density (kg/m³);

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:
\[ v_{\text{part}}^2 = \frac{2 \pi d (\rho_{\text{liq}} - \rho_{\text{gas}}) g}{3 \ C_d \ \rho_{\text{air}}} \]

\( C_d \): drag coefficient (turbulent) = 1.18

balance between friction in air and particle weight

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

Apparent velocity: \( w = v_{\text{gas}} - v_{\text{part}} \)

Ballistics

\( v_{\text{part}} = 50 \) m/s : particle velocity

\( V_{\text{gas}} = 100 \) m/s : gas velocity
Direct measurements (4): ballistics

Particle diameter (cm) \hspace{1cm} \text{Apparent Particle velocity}

\[ w = v_{\text{gas}} - v_{\text{part}} \]

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; $\tau_{on} = 50$ ms

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

$c$: 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

\[ w = v_g - v_{\text{part}} \]

A range of particles velocity because of a range of particle diameter
Basaltic magma reservoirs

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   b) acoustic records
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Acoustic measurements at Yasur, Vanuatu, 1993
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 parallel 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

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?

- Frequency = size of the source
- Amplitude = overpressure
- Phase = initial condition

source = gas

ejecta velocity

Evolution in time of the eruption characteristics
Direct measurements (10): Acoustic records

First developed 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)
Bublee diameter = several meters (Heimaey, Etna, Erebus, Kilauea…)

Direct measurements (11): Acoustic records

Gas exists in conduit for basaltic eruption:
- strombolian explosions: a few meters long
- fire fountains: several tens of meters long

- Bubble formation
- Bubble at interface
- Bubble rise
- Bubble bursting

- sound waves
- bubble size and pressure
- bubble pressure at depth

Eruption dynamics

Etna, July 2001
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

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

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 $\Delta P$

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

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

Bubble bursting at the surface of lava lake (Kilauea)
Direct measurements (16): Acoustic records

**Shishaldin (Alaska):**

Bubble length, pressure, gas volume and gas flux

**Length > 2 radius**

Peak in overpressure

**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

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, Alaska, USA
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

Direct measurements (19): Acoustic records

Model of bubble vibration: \[ L = 35 \text{ m}; \Delta P = 0.39 \text{ MPa} \]
Direct measurements (20): Acoustic records

Different types for source of sound:

- **monopole source**
- **dipole source**
- **quadrupole**

Acoustic power $\Pi_m$ is proportional to $(U: \text{gas velocity})^n$

$$\Pi_m = K_m \frac{4\pi R_b^2 \rho_{\text{air}} U^4}{c}$$

$K_m = 1$ (sphere)

(1/16 flat circular)

$$\Pi_d = K_d \frac{\rho_{\text{air}} A_d U^6}{c^3}$$

$K_d = 1/3$

(or 0.013)

$$\Pi_q = K_q \frac{\rho_{\text{air}} \pi R_c^2 U^8}{c^5}$$

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

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

variation of mass flux

+ variation of external force (walls of conduit)

+ variation of stress (turbulence)
Direct measurements (21): Acoustic records

Subplinian phase:

Complex waveform

use of acoustic power $\Pi_d$:
proportional to gas velocity

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

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

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= $1.5 \times 10^7$ 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$_2$O + 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

Lava flow into sea (Kilauea, March 1988)

Fire fountains (Puu O’o eruption)

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**

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

Bubble bursting at Etna, July 2001

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, …