From reservoirs to conduits: The role of bubbles in driving basaltic eruptions

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a) Piton Fournaise  b) Etna  c) Etna  d) Lopevi
Description of basaltic eruptions:

- found in various geodynamical settings:
  From hot spot (Kilauea), continental rift (Erta Ale) to volcanic arc (Shishaldin)
  More complex: Etna, Stromboli

- Aerial or submarine with various eruptive regimes, all driven by the gas phase (CO$_2$, H$_2$O)

- Strongest phases; fire fountain or eruptive plumes


- Shishaldin, 1999 (AVO)
Two-phase flow regimes

(Vergniolle + Jaupart, 1986)

At vent: behaviour is dominated by gas; need to be measured
Measurements of gas volume
Measurements of gas volume:
from the gas velocity

\[ \text{Vol}_g = \text{velocity} \times \text{time} \times \text{area} \]

- Ballistics (photo, video…)
Strombolian explosion \(\) (Chouet et al, 1974; Ripepe et al, 1993)
Height of fire fountain \(\) (Wilson, 1980)

- Thermal video camera \(\) (Calvari et al., 2006; Harris+Ripepe, 2007,
Patrick et al., 2007…)

- Radar measurements: Stromboli, Etna,
(Weill et al., 1993; Hort and Seyfried, 1998, Dubosclard et al., 1999…)

- Above the vent: measured after some air entrainment
(entrainment coefficient: 0.12 for plume and 0.28 thermal)
Measurements of gas volume: from chemistry

- Spectroscopy FTIR: ratio of gas species, $\text{H}_2\text{O}/\text{SO}_2$, $\text{CO}_2/\text{SO}_2$ ....

(Oppenheimer et al, 2004; Burton et al., 2007; Edmonds and Gerlach, 2007; Saywer et al, 2008, ....)

- Combined with measurements of $\text{SO}_2$ flux

- $\text{SO}_2$ flux: measured routinely but difficult to interpret
  Erta Ale: $\text{SO}_2$ flux « inactive » crater : 0.6 kg/s
  « active » crater : 0.7 kg/s

Degassing from active lava lake: 0.1 kg/s (15 % of total)
Measurements of gas volume: from acoustic measurements

Only detects gas with overpressure: depend on level of detectability, ie. distance to vent

- Acoustic power: Dimensionless analysis + coefficient: gas velocity
  Robust technique but if radius of source is known
  (Woulff+McGetchin, 1976; Vergniolle et al., 2004; Vergniolle + Caplan-Auerbach, 2006)

- Series of 2 successive integrations of acoustic pressure
  (Johnson et al., 2008,…)

Very sensitive to choice of limits for integration in time and to offset but no need to know the size of the source
Measurements of gas volume: from acoustic measurements

- Inversion of acoustic waveforms:
  (Vergniolle + Brandeis, 1996; Vergniolle + Caplan-Auerbach, 2004)

Based on a model but gives both gas volume and pressure

- Strombolian phase of Shishaldin, April 1999:
  Very good agreement with acoustic power:
  Radius source is confined
  (Vergniolle et al., 2004)
Measurements of gas volume: from acoustic measurements

Prior to the explosion, bubble undergoes longitudinal oscillations:
- Observed in acoustic pressure at Stromboli
  (Vergniolle et al., 1996)
- Observed in laboratory experiments
  (Ripepe et al., 2001; James et al., 2004)
- Could be a seismic source

But depth has to be assumed to estimate the bubble length

In agreement with inversion of acoustic waveforms
Acoustic measurements

- Stromboli: 2 types of acoustic signals due to degassing:
Puffs (weakly overpressurised bubbles but very frequent, 2 s)
Strombolian explosions
  (pressurised bubbles but less frequent, 5-60 min)
(Ripepe et al., 2002; Harris+Ripepe, 2007; Patrick et al, 2007…)
- different types of degassing:
  a) diffuse degassing from flanks of volcano, fumaroles
  b) passive degassing: bubbles freely bursting at the top of the lava column
  c) Puffs: persistent background degassing made of small pressure transients
d) Explosions
- Different techniques may measure different types of gas.
- Overpressurised gas (acoustic) come from depth
Comparaison between techniques for gas volume:

Stromboli:
- Synthetic acoustic waveforms:
  Explosions: $10-100 \text{ m}^3$ (Vergniolle+Brandeis, 1996)
  Puffs: $20-35 \text{ m}^3$ (Ripepe+Marchetti, 2002)
- Photoballistics (explosions): $10^3 \text{ m}^3$ (Chouet et al., 1974)
- Radar: $20-80 \text{ m/s}$; 5 s duration; $10\text{m}^2$; $\text{Volg} = 1-4\times 10^3 \text{ m}^3$
  (Weill et al., 1993; Hort et al., 2003)
  - $\text{SO}_2$ flux+FTIR: $1.5-4\times 10^3 \text{ m}^3$ (Burton et al., 2007; Burton+Mori, 2009)

- Relative good agreement between techniques
- Synthetic acoustic waveforms underestimate gas volume:
  different vents, activity, mainly overpressurised/total gas
  + entrainement of air above vents ($\text{H}_2\text{O}$, $\text{CO}_2$ but not $\text{SO}_2$)
Comparaison between techniques for gas volume:

Etna:
- Synthetic acoustic waveforms:
  Explosions: $2000 \text{ m}^3$ (Vergniolle+Ripepe, 2008; Cannata et al., 2009)
  in agreement with videos
  (Dusboclard et al., 1999)
- Radar: max: $160 \text{ m/s}$; 5 s duration; $100\text{m}^2$; Volg < $7\times10^4 \text{ m}^3$
- $\text{SO}_2$ flux+FTIR: several $\times10^4 \text{ m}^3$
- Gas volume (acoustic) $<<$ Volg (radar or FTIR)

Large bubble, Re (inertia/viscous) $= 10^3 - 10^4$
a bubbly wake exists: $\text{Vol}_{\text{wake}} = 4-6 \times \text{Vol}_{\text{slug}}$

Can reconcile part of the discrepancy
but not for Stromboli (Re = 80)

Existence of a thin foam at the top of column?

Implications for gas composition
Comparaison between passive and active degassing

- Stromboli:
  based on FTIR measurements
  Passive degassing corresponds to 92-97 % of the total degassing due to the short duration of explosions (active degassing)
  (Allard et al., 1991, 1994, 2000; Burton et al., 2003; 2007…)

- Ertu Ale:
  Passive degassing = 85 % of total degassing (fumaroles) (Oppenheimer et al., 2004)

Active degassing (explosions), which comes from depth, is a crucial parameter to be measured (acoustic, radar, video…)
Summary: measurements of gas volume

- good constraint on the gas volume

- For strombolian activity, bubbles are large, they fill up the conduit diameter (slug)

How do large bubbles form?

Origin of Strombolian explosions

July 25 2001, photo by T Pfeiffer
Origin of Strombolian explosions

- Laboratory measurements:
  Large gas pocket: regular coalescence/build-up of a foam layer accumulated at the top of the reservoir

  (Jaupart + Vergniolle, 1988;1989)

  Stromboli: FTIR: depth for slug formation: 3 km
  (Burton et al., 2007b)

- could be responsible for seismic+acoustic
  Stromboli: inversion of VLP signals
  (Chouet et al., 2003)

- no seismic evidence of shallow magma chamber
- coalescence of 2 bubbles together does not release enough energy for explaining the VLP signals
But no need for a large area, just a bubble trap simultaneous coalescence of many bubbles could $\Delta P$
Massive foam coalescence

Preliminary laboratory experiments with high-speed camera

- initiation of coalescence
- $n$: Number of coalescing bubbles
  $\Delta t = 4 \times 10^{-3} \text{ s}$

Fast coalescence:
Large peak in overpressure

$\Delta P$ $\Rightarrow$ Number of bubbles
$\Rightarrow$ Foam thickness

A mechanism for overpressure: a source for acoustic+seismic
Origin of Strombolian explosions

- Stromboli: seismic evidence of an inclined shallow dike

Laboratory experiments on inclined tubes: transition from bubbly to slug flows occurs for a gas rate one order of magnitude smaller than for a vertical tube

(Lane et al., 2001; Chouet et al., 2003)

- Homogenous 2 phase flow:
Relatively slow rise of a magma vesiculating on its way up: progressive bubble coalescence

(Parfitt + Wilson, 1995; Parfitt et al., 1995; Parfitt, 2004)

Relatively shallow and no obvious source of overpressure
Origin of Strombolian explosions

- Large gas pocket: results from concentration waves within a bubbly magma if magma velocity << bubble velocity

(Manga, 1996)

- Interpretation used for puffs at Stromboli

(Ripepe et al., 2002)
Origin of Strombolian explosions

For gas volume fraction $> 2\%$:
- bubbles interact:
  formation of rising bubbly zones and downward bubbly zones

- Formation of bubble clusters: can coalesce on their way up

- Could explain the puffs, but probably not the explosions (no obvious source of overpressure)
Stability of large bubbles in conduit

- Large bubbles, such as at Stromboli, are not stable: They should break into bubbles with a smaller diameter as a result of instabilities at the surface.

(Suckale et al., 2010)
Stability of large bubbles in conduit

- Numerical calculations give a criteria on the Reynolds Number (Re= inertia/viscous forces) > 50 for breakup

(Suckale et al., 2010);
comments by James et al., 2011
(lack of comparison with laboratory experiments, Re only criteria)

Large bubbles at Stromboli or Etna should not exist

- But large bubbles are observed at vents:

Breaking and reforming constantly
Effects related to the free surface
(overpressure, skin layer such as foam ?, ....)

But skin layer will be destroyed by explosions
Non-newtonian: ? But analysis is not valid

Etna, July 25 2001, photo by T Pfeiffer
Origin of Strombolian explosions

- Various interpretations exist for their origin: difficult to test,
  we may have more than one type
  and large bubbles may coalesce together

- Estimating the bubble overpressure is important
  This requires inversion of acoustic waveforms, hence knowing the source

  Overpressure within large bubbles (slugs)?

*Stromboli, 1992*
Overpressure within slugs

- Exists as shown by the initial gas velocity and acoustic pressure

- if acoustic pressure is due to the formation of a hole during bursting, it is unrelated to the initial overpressure within the slug (Vidal et al., 2010)

- if the main pulse in acoustic is due to some other mechanisms, such as bubble vibration or growing of instabilities, etc., it should give the \( \Delta P \) of bubble

(Vergniolle and Brandeis, 1996; Vergniolle and Caplan-Auerbach, 2004)

\( \Delta P \) is probably related to depth, magma viscosity…
Overpressure within slugs

- Theoretical investigation (perturbation theory on $L_{\text{slug}}$) based on magma static and geometry (Del Bello et al., 2012)

  → Length and depth for bursting

- Simplified model which ignores the bubble rise during bursting, the rounded shape of the bubble nose,…

- Good order of magnitude for $\Delta P$ from inversions of acoustic waveforms (Vergniolle and Brandeis, 1996)

- Predicts a relationship between $\Delta P$ and Volg: can be tested

- Predicts a good transition between passive degassing and explosive bursting occurs for slugs volume > 24-230 m$^3$
Overpressure within slugs

- Laboratory experiments: dynamic pressure associated with the ascent of individual slugs in vertical/inclined conduits
  
  Could be a seismic source  
  
  (James et al., 2004)

- Laboratory experiments: deformations of a slug at a flare
  
  (James et al., 2006)

Slug is deformed and break for severe change in diameter
Can excite longitudinal mode of bubble until it passed flare

Point of closure acts as an impulsive trigger mechanism

Predicts 1-10 MPa in agreement with VLP and acoustic data

- Massive foam coalescence at depth could be a source of $\Delta P$
Overpressure within slugs

- Not very well constraint unless inversion of acoustic waveforms

- Important parameter to estimate because it provides additionnal constraints on the degassing, especially if we have two populations, as at Stromboli

Gas volume, ΔP can be estimated

How can permanent activity be maintained?
Characteristics of a slug flow (strombolian)

- Initial gas flow

Laboratory experiments:
vertical tube 6.5 m long

(Pioli et al., 2012)

- Transition to annular flow is expected for gas volume flow rate of $10^3$-$10^4$ m$^3$/s

- Gas flow promotes effective convection of the liquid, favoring magma homogeneity and stable condition

- Bimodal bubble population, the small being recirculated with liquid and contribute to less than 20-50% of gas outflow

- Gas flow circulation may counteract the cooling gradients and may explain why the conduit stays open and magma hot
Characteristics of open vent volcanoes

- They emit much more gas than magma
  (Francis et al., 1993; Allard, 1997…)

- Existence of a convective loop between volatile-rich magma rising up and degassed magma going down
  (Kazahaya et al., 1994; Stevenson + Blake, 1998)

- Growth of volcanic edifice by emplacing the degassed magma at depth but open systems, like Erebus, do not show deformations

- Recycling of degassed magma at depth
Characteristics of open vent volcanoes

- Model for magma circulation between ascending degassing magma and degassed descending magma

(Burton et al., 2007a)

- Stromboli:
  Conduit diameter = 2.5-2.9 m
  for a magma flow rate of 575 kg/s to maintain the quiescent SO$_2$ flux of 200 t/day

Very reasonable value for conduit diameter
- Injecting fresh magma in the central core and degassing volatile at equilibrium with exsolution law leads to the formation of a foam (60%) between 3.6 and 1.8 km depth

  (Burton et al., 2007a)

- Transition from closed systems (below the percolation zone) to open systems

- Final gas emission is superposition of gases from below and above the percolation transition
Characteristics of open vent volcanoes

- a few unresolved issues: (Burton et al., 2007a)
- Assumption: no differential motion for bubbles, i.e. large magma velocity

When $\alpha > 2\%$ at depth, bubble interaction, formation of bubble clusters, coalescence, no foam

$\alpha \leq 2\%$

Formation of a bubble cluster

1.8 - 3.6 km

$\alpha \geq 2\%$

Formation of a very close series of large bubbles

Could be puffs but puffs are very shallow

Vesiculation due to exsolution may be postponed until shallow (buoyancy is provided by thermal effects)
Characteristics of open vent volcanoes

(Burton et al., 2007a)

- For a newtonian rheology, difficult to build a foam

- Even if a foam is formed, it acts as a trap for bubbles below

- needs cycles of foam collapse/growth to let gas escape thin foam (a long collapsing foam = eruptive plume)

For a non-newtonian rheology, percolation channels can be maintained between open and closed system

Depth: 1.8-3.6 km: accumulation of many cristals ?

How is that possible?
Characteristics of open vent volcanoes

- If large bubbles (explosion) are produced below the bi-directional flow (foam coalescence, ...), disruption of the flow pattern; Bi-directional flow will only have the time between explosions (15 min) to restart

Depth for slug formation = 3 km  (Burton et al., 2007b)

- If explosions every min originate at depth (Yasur), no bi-directional flow is possible.
If explosions are shallow: 1) degassing by bubble clustering /coalescence and delayed vesiculation; 2) non-newtonian effects (many crystals at depth?)

- Partial degassing of fresh magma for each rise
Vesiculation is complicated (nucleation, bubble growth by diffusion and decompression)
Origin of permanent activity

- Requires a permanent gas flow to prevent cooling

- Massive foam coalescence limited by viscous effect
  (Strombolian explosions)
  (Jaupart + Vergniolle, 1988; 1989)

- Flow of a stable foam
  (weak strombolian activity at lava lake)
  (Stix, 2007; Bouche + Vergniolle, subm.)

- Long inclined conduits
  (Lane et al., 2001; James et al., 2004)
- Gas volume, $\Delta P$

- Formation of large bubbles

- Origin of permanent activity and related problems

« Classical » eruption (beginning and end)

Origin of fire fountains

Kilauea

Etna, 1989, (Bertagnini et al, 1990)
Origin of fire fountains

- Homogenous 2 phase flow:
  Relatively fast rise of a magma vesiculating on its way up:
  progressive bubble coalescence (slow = strombolian)

Fire fountain = dispersed flow

(Parfitt + Wilson, 1995; Parfitt et al., 1995; Parfitt + Wilson, 1999; Parfitt, 2004)
Origin of fire fountains

- Laboratory measurements:
  Large gas pocket: regular coalescence/build-up of a foam layer accumulated at the top of the reservoir

(Jaupart + Vergniolle, 1988;1989)

Etna: FTIR
fire fountain results from foam coalescence at 2 km depth
(Allard et al., 2005)

Agreement with geophysical meas.

Etna, 1989, (Bertagnini et al, 1990)
Origin of fire fountains

- Acoustic
  + height
- Duration of eruption
  (Vergniolle + Gaudemer, 2012)
- reservoir area (acoustic) = 0.18 km²
- model for the foam behaviour

Etna:

  Bubble diameter,
gas volume fraction,
  height of degassing reservoir

Smooth evolution of degassing parameters

A single magmatic reinjection produces a series of eruptions
Decadal evolution of eruptive activity

- A single large magmatic reinjection, is in agreement with decadal cycles, which end by major flank eruptions (1991) (Allard et al., 2006)
- Sr and U isotopes: smooth evolution and a residence time scales of 14-80 years (Albarede, 1993; Condomines et al., 1995)
- Volume of degassing reservoir: 0.5 km$^3$ (Le Cloarec + Pennisi, 2001)
  Equivalent to the volume of a major flank eruption
- Major flank eruptions triggered by a deep magmatic reinjection (Vergniolle + Gaudemer, 2012)
  Reinjection velocity = 4-9 m$^3$/s
Decadal evolution of eruptive activity

- Gas volume available in 0.5 km$^3$ of fresh magma based on fluid inclusions (3.4 wt% $\text{H}_2\text{O}$, 0.41 wt% $\text{CO}_2$, 0.3 wt% $\text{S}$)

  (Métrich et al., 2004)

  Sufficient to explain the $\text{SO}_2$ expelled during 1 decadal cycle

  (Vergniolle + Gaudemer, 2012)

- Thinning of degassing reservoir
  
  Reservoir must be stratified: degassed/undegassed layer

- Key question:
  How can a single batch of magma have phases of bubble formation leading to eruptions and quiescence?
Decadal evolution of eruptive activity

- Piton de la Fournaise has a similar behaviour with a rate for magmatic reinjection of 4-60 m$^3$/s
  
  (Vergniolle + Gaudemer, 2012)

- Ertap Ale has major eruptions (1968-1975), rate for magmatic reinjection of 0.08 m$^3$/s, $\text{vol}_{\text{res}} = 0.02 \text{ km}^3$

Level of lava lake fluctuates;
High level: bubble formation at depth (eruption)
Low level: inter-eruptive period
Conclusion

- Gas volume and overpressure are known at least for Strombolian explosions (not for fire fountain)

- A few ideas about the behaviour in conduit

- Mechanisms in magma reservoir are still poorly known: Bubble formation/quiescence

- Magmatic reinjection can produce series of eruptions

- Open vent systems: window on the reservoir; Observable: level of the lava lake (Jaggar, 1920, 1924..)
  Long time series
  Need to quantify the lack of cooling in open vent systems