Heat and mass transport in magma II: Processes

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GEOS692
20 October 2006

(Don’t try this at home.)
Lava lake
Villarica Volcano, Chile
Load removed is localized, so does not effect pressure in chamber

But pressure at outlet is reduced by shortening of conduit

Magma accumulation and mixing

Basalt fractionation and crustal melting?
Outline

• Magma mixing (new wine into old).
• Dikes to pipes (the pipes are calling).
• Ascent of magma: buoyancy (melt floats); consequences.
• How does gas escape (foaming at the mouth)?
• Two stable modes of flow (volcanoes as magma geysers).
• Answer to the secret of volcanic life.
Pop quiz: What is the secret of volcanic life (diversity of composition and gas content of magmas)? ______________

a) Bubbles rise and crystals sink in giant magma chambers.
b) Micro-scale ($10^{-5}$ to $10^{-3}$ m) diffusion coupled to meso-scale ($10^{-2}$ to $10^0$ m) porous flow coupled to macro-scale ($10^1$ to $10^4$ m) fracture flow.
c) 42
d) None of the above.
Don’t try this at home either.
Magma mixing

- Critical parameters: $\Delta T$ and $\Delta \mu$ (but note that $\mu = f(T)$)

- Low $\Delta T$: melts (and gases) mix; crystal population commingled; crystals equilibrate with new melt composition depending on Di (fastest for oxides; slowest for plagioclase).
Magma mixing

• Critical parameters: $\Delta T$ and $\Delta \mu$ (but note that $\mu = f(T)$)

• Low $\Delta T$: melts (and gases) mix; crystal population commingled; crystals equilibrate with new melt composition depending on $Di$ (fastest for oxides; slowest for plagioclase).

• High $\Delta T$: clotting behavior.
Mutnovsky Volcano
Pseudobinary rock + water system

S = solid
L = liquid
V = vapor

T

1200

rock  X_{H2O}  water

4 wt%
Pseudobinary rock + water system

- S = solid
- L = liquid
- V = vapor

Temperature (T) and various states:
- S + V
- L + S
- L + V
- S + L + V

Composition (X_{H2O}): 4 wt%
Melt zone
Koyaguchi and Keneko, 2000
DIKES!
Magma cannot penetrate cold hard rock as a finger, it must propagate as a magma-filled crack (dike).

A common story: New magma rising as a dike and activating an old pod.
A continuum from fissure to central vent eruptions

Fissure eruption

Vent chain

Central vent
Why the transition?

- Rapid water loss from magma impedes further rise of the dike blade.

- Rapid escape of water as steam reams fractures that connect to the surface, opening pipes.
Deb cartoon of dikes into magma chambers

Dike into conduit

cross section

along-strike view

$\rho_{\text{magma}} < \rho_{\text{rock}}$

I. Rise of leading edge impeded by degassing

II. Hydrothermal roasting: Gases and heated groundwater channeled through pre-existing fractures

III. Eruption: Enlarged pathway admits viscous magma

Time
The transition from dike to pipe flow occurs at very shallow levels.
Dike and magma chamber

• 2 magma eruptions
Karymsky, Kamchatka

2.3 m
Karymsky, 1996
BUOYANCY and its consequences

- Vesiculation
- Buoyant rise
- Melting
Volume change on melting

water

rock

-10 %

+10 %
Water -lake

Rock –lava lake

solid

liquid

liquid

solid
2.7 g/cm³

2.8 g/cm³

5 km

25 km

$P = \rho gh$

25MPa overpressure

“Textbook” concept: Tall volcano requires deep source.
2.7 g/cm³

2.2 g/cm³: vesicular lava + voids between clasts
“Air lift” in a water well
Consequences

• Vesiculation (boiling)
At 500 m depth: 1 Liter of magma will dissolve 20 g of H2O

At the surface: 1 Liter of magma with 2 g of H2O + 400 L of steam

Pressure = 1 atmosphere

Pressure = 100 atmospheres

At 500 m depth: 1 Liter of magma will dissolve 20 g of H2O
liquid → foam → dusty gas
Magma with 4 wt% H2O

400 m/s

1 m/s

conduit
Bezymianny  9 May 2006
Spurr, 1992

View from the side

Loss of buoyancy

Lateral spreading of cloud top

Convective thrust

Entrainment of air

G. McGimsey
Pinatubo, 1991, from above

Philippines

Pinatubo from the side
$\Delta T \leq -0.7 \, ^{\circ}\text{C}$ (McGee et al, 1997)
Consequences

• Vesiculation (boiling)

• But sometimes the gas escapes: how?
Obsidian Dome emerged from a pipe extending from the top of a long dike.
Traditional concepts of degassing

1. Bubble rise
   \[ v = \frac{2\pi r^2 \Delta \rho}{9\eta} \]
   \[ a_1 \text{cm} \quad 29/\text{cm}^3 \]
   \[ 1 \text{m in } 10^{4} \text{a} \]

2. Diffusion
   \[ l = (D\tau)^{1/2} \]
   \[ c_{10^{-8}} \text{cm}^3/\text{s} \]
   \[ 1 \text{m in } 10^{9} \text{a} \]
Pseudobinary rock + water system

Magma at 900°C
conduit

Wet magma in

Dry lava out

Decoupled gas flow

Gas-permeable magmatic foam

conduit

Wet magma in
2 stable modes of flow

- Volcanoes as magma geysers
WATER

- Spring
- Geyser

MAGMA

- Lava: $10^4$ kg/s
- Plinian: $10^7$ kg/s

Conduit

Reservoir

Underpressured borehole!
\[ P_V = P_L \]
\[ P_V > P_L \]
Bezymianny

Mount St Helens

$\Delta t -0.2 \ a -0.1 \ a$

The magma column reached essentially to the surface prior to the cataclysmic eruption.
Bezymianny

Mount St Helens

Δt +1 a

+ 25 a
Sector-collapse produces largest and longest lasting pressure drop in magma system.

Blast
Dominantly explosive
Dominantly effusive

Recharge?

\[ \frac{dV}{dt} \]

\[ t_0 = 1956, 1964, 1980 \]
Edifice fails, conduit is shortened by $\leq 1000$ m.

Failure can be associated with growth of a cryptodome within the edifice.
Magma already in edifice explodes as directed blast.

- Blast
- Dominantly explosive
- Dominantly effusive

Recharge?

t₀ = 1956, 1964, 1980
Edifice collapse

\[ P_V = P_L \]
Edifice collapse

\[ P_V \gg P_L \]

Magma

Lava

\[ X_{\text{H}_2\text{O}} \]
Edifice collapse

\[ P_V = P_L \]

MAGMA
Edifice collapse

\[ P_V \gg P_L \]

MAGMA

Lava

\[ X_{H_2O} \]
Fragmentation surface propagates downward into conduit until it is balanced by upward flow of new magma from chamber or inflow of new water aquifer.

Pressure drop in conduit due to “fragmentation” of upper column.
The meaning of life

• Explaining the diversity in explosivity and chemistry of magmas.
Melt composition and melt viscosity during fractional crystallization
The meaning of life

* How to separate gas and crystals from viscous melt?
Meet Mr. Porous Flow!
Aplite dikes in granodiorite pluton
Mafic system – separation of crystals from melt

Silicic system – separation of melt from crystals

\[ P_m > \sigma_3 \]
1 dike/10 m; $10^{-3}$ m/s porous flow; 20 vol.% melt:
0.2 km$^3$ rhyolite from 1.0 km$^3$ granodiorite pluton in 2 hours
Dante's Inferno

- Vestibul
- River Acheron
- I. Limbo
- II. Lustful
- III. Gluttonous
- IV. Avaricious and Prodigal
- V. Wrathful and Sullen
- River Styx
- City of Dis
- VI. Heretics
- River Phlegethon
- VII. Violent
- Geryon
- Malebolge
- VIII
- IX. Traitors

Map of Dante's Inferno
Suggested reading

• Eichelberger, J.C., P Izbekov, and B Browne, Bulk chemical trends at arc volcanoes are not liquid lines of descent, *Lithos*, 87, 135-154, 2006.