How Volcanoes Work

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Why are volcanoes important?

• Fundamental planetary process- transfer of rock to the surface and gas to the atmosphere and oceans. Seafloor volcanism has resurfaced 60% of Earth in that past 5% of its history.

• Clue to internal materials and conditions

• Serious hazard

• Resource: geothermal energy, ore deposits
4,000,000,000-year-old surface

4-month-old surface
Condition for volcanism: The planet’s interior is generating more heat than can escape by conduction alone.
Okmok on Mars
Novarupta Dome (1912 vent)

Lava domes on Venus
The ash problem
What’s wrong with this picture?

April 18, 2010
VA ADVISORY
DTG: 20100420/0600Z
VAAC: LONDON
VOLCANO: EYJAFJALLAJÖKULL 1702-02
PSN: N6338 W01937
AREA: ICELAND

SUMMIT ELEV: 1666M
ADVISORY NR: 2010/025
INFO SOURCE: ICELAND MET OFFICE
AVIATION COLOUR CODE: RED
ERUPTION DETAILS: ERUPTION CONTINUING TO AROUND 4000M WITH LAVA VISIBLE IN THE CRATER.

RMK: NO SIG ASH ABOVE FL350, AND FROM 20/1800Z NO SIG ASH ABOVE FL200
NXT ADVISORY: 20100420/1200Z
What's wrong with this picture?
747 COCKPIT - ANCHORAGE CENTER CONVERSATION, 12/15/89
Pilot: KLM B-747

“KLM 867 heavy is reaching {flight} level 250 heading 140.”
Anchorage Center

“Do you have good sight of the ash plume at this time?”
Pilot KLM B-747

“Its just cloudy it could be ashes. Its just a little browner than a normal cloud, ”
Pilot: KLM B-747

“We have to go left now… it’s smoky in the cockpit at the moment sir.”
“KLM 867 heavy, roger, left at your discretion.”
Pilot: KLM B-747

Climbing to level 390, we’re in the black cloud, heading 130.”
Pilot: KLM B-747

“KLM 867 we have Flame out all engines and we are descending now.”
Anchorage Center

“KLM 867 heavy... Anchorage.”
Pilot: KLM B-747

“KLM 867 heavy
we are now descending
now....
We are in a fall!!”
Pilot: KLM B-747

“KLM 867 we need all the assistance you have sir. Give us radar vectors please.”
December 15, 1989: Anchorage, Alaska
KLM 747 landed safely after in-flight failure of all four engines

Melted ash on turbine blade
Pinatubo 1991

- M6.2 (1013 kg; 5-8 km³ DRE)
- Plinian eruptions
- PDCs & phoenix clouds
- Caldera collapse
- Death toll in 100's
ΔT < -0.7 °C (McGee et al, 1997) lowest O₃ values ever measured

NASA
Lahars
Chaiten

Appalachian trail
Outline

• What is magma?
• Phase changes
• Source to surface
• Basic principles
• Eruptions
Magma

Gas bubbles (H2O>CO2>SO2)

Silicate melt

Crystals (e.g., feldspar, pyroxene, hornblende)
Basic principles

• Rate of downward increase in pressure with depth is proportional to rock density: In the upper crust, pressure increases about 1 kilobar (1000 atmospheres) per 4 km.

• Multicomponent melts are more stable than single-component endmembers: Therefore, addition of water to hot rock at high pressure causes melting.

• Pressure favors the denser phase: Therefore, decompression causes boiling.

• Transport of heat by flow always beats conduction over large distances (e.g., > meter scale): Therefore, little heat is lost during magma ascent. Eruptions can be thought of as isothermal decompression of magma.

• Conduction of heat is ~instantaneous on micro-scale: Therefore, thermal equilibrium between gas and melt (or ash) is maintained during eruption; all thermal energy in magma is available to drive expansion.

• Water diffuses orders of magnitude faster than other chemical components: Therefore, chemical equilibrium between gas and melt is maintained; ~all water in magma is available to drive expansion. Bubbles grow on an eruptive time scale but crystals do not. Crystals preserve a record conditions during magma storage.
Boiling ("vesiculation")

Phase change due to decompression (ascent)

Silicate melt

- $\Delta P$

boiling

Silicate melt

+ Vapor (bubbles)
Crystallization

Phase change due to cooling
Melting

Phase change due to addition of water ("freezing point depression")

Crystals + H2O → Silicate melt + Crystals
Typical circum-Pacific volcanic rock (andesite)

On eruption, gas makes bubbles and escapes, melt becomes glass, and previously grown crystals remain the same, preserving a pre-eruption record of magma history.
Seismic cross section: Colors roughly correspond to temperature, white dots are earthquakes. Underthrusting (subduction) of Pacific plate introduces water to mantle under Alaska, causing melting.
Basic processes of volcanism

vesiculation

buoyant rise

melting
During storage: equilibrium
But ascent of magma disturbs equilibrium

\[
\begin{align*}
T & \rightarrow \\
P & \downarrow \\
1 \text{ kbar} & \\
1000^\circ\text{C} &
\end{align*}
\]
Water dissolved in magma (wt.%)
liquid  foam  dusty gas
Explosive eruption

fragmentation

conduit

Each 1 wt% of dissolved water can produce 100x expansion on decompression to one atmosphere!
What do these things have in common?
Boiling in a vertical tube!
\[ P = \rho gh \]

- Pressure
- Density
- Gravity
- Height of liquid column
Experimental volcano

(Walmart, $9)
\[ P_{\text{magma}} = \rho_{\text{water}} gh \]

\[ P_{\text{conduit}} = \rho_{\text{water+steam}} gh \]

\[ m = \rho_{\text{water+steam}} \]

\[ m = \rho_{\text{water}} \]
Conduit

Magma chamber

Eruption!
Pulsatory; not steady-state
What’s the difference between coffee makers vs. volcanoes and geysers?

• Boiling in coffee makers is caused by heating; boiling in volcanoes and geysers is caused by decompression.

• Volcanoes and geysers (and gas-rich oil wells) are therefore self-pumping.
At P and T of boiling

- $\Delta P$

boiling

liquid

water

gas

steam
Boiling water geyser

Conduit

\[ P_V = P_L \]
WATER MAGMA CONDUIT

$P_V > P_L$

Iceland
WATER MAGMA Conduit

PV > PL

Conduit

100

L

V
Water table

H₂O column at boiling

Steam-saturated aquifer

Heat
Water table

H2O column at boiling

steam-saturated aquifer

heat
Water table

H₂O column at boiling

steam-saturated aquifer

heat
This is cold water!
Carbonated water geyser.
At P and T of “Boiling” (vapor saturation)

CO2-rich water

- ΔP

boiling

CO2-poor water

CO2
Water table

CO2-sat
H2O column

CO2-saturated aquifer

CO2
Water table

CO2-sat

H2O column

CO2-saturated aquifer

CO2
Lake Nyos, Cameroon: CO2-staurated crater lake
solid + liquid \rightarrow \text{CH4-rich ice} \rightarrow \text{Gas hydrate} \rightarrow \text{boiling} \rightarrow \text{vapor} \rightarrow \text{CH4}
Gas-rich oil geyser (artificial)
Cement plug fails
Cement plug fails

BOP fails
• So what does this have to do with volcanoes?
At P and T of “Boiling” (vapor saturation)

- ΔP

boiling

water-rich magma

liquid

water-poor magma

liquid

steam

doing
Lava

$X_{H_2O}$

$L + V$

$L$

$L$

$P_V = P_L$

$P_V > P_L$
Dikes (magma flowing in planar cracks) are how magma travels in Earth’s crust.
Dikes in caldera wall, Katmai
$P_V = P_L$

$P_V > P_L$
MAGMA

Conduit

Reservoir

10^4 kg/s
10^8 kg/s

Plinian

High pressure gradient!

Under-pressured!
Sustained explosive eruptions

Spurr, Alaska  1992
Kliuchevskoi Volcano, Kamchatka, in eruption (Space Shuttle photo). Subduction-zone volcanism can be highly explosive, presumably due to the introduction of water into the magma source zone.
Kamchatka
Volume of a Yellowstone eruption

Redoubt eruption

Katmai eruption
Katmai Caldera, Alaska, formed in 1912: Eruptions of $\geq 10 \text{ km}^3$ of magma usually result in collapse of the magma chamber’s roof, forming a caldera.
Alaska's Super Volcano

John Eichelberger
Professor of Volcanology
University of Alaska Fairbanks

8pm Sunday, June 11, Brooks Auditorium
Russians!

(mostly)
Katmai National Park is not just about bears!
**BUT**, magma does not always fragment at the vent, but sometimes erupts intact as lava.
Unzen Volcano, Kyushu, Japan, 1991-1995
Effect of composition and temperature on viscosity of lava.

Hot Fluid

- Hawaii: 0.5-m-thick basalt

Cool Viscous

- Kamchatka: 5-m-thick andesite
- California: 50-m-thick rhyolite

Wt.% SiO2

50 60 70 80
spines and pressure ridges

Lava flow or exogenous dome

Endogenous dome

rubble

high flux

low flux
Contrasting behaviors

Tephra

300 m/s

P

0

10^8 kg/s

Lava

0.01 m/s

P

0

10^4 kg/s
Explosive eruption: tephra

Effusive eruption: lava

Flow of gas from bubble to bubble

Fast ascent

Wet magma

Fragmentation

Slow ascent

Wet magma

Dry lava

(Conduit width exaggerated)
VHP observatories combine an array of real-time data streams to interpret the behavior of volcanoes, turning observations quickly into information that society needs:

- **AVO operations room**
- **AVO field installation**
- **Satellite surveillance for hotspots and ash**
- **Volcano deformation from radar satellites**
- **Volcano deformation from GPS**
- **Eruption onset from seismic network**
- **Magma chamber location from seismic tomography**

**Volcano Hazards**

**NEXT WEEK**