# How Volcanoes Work



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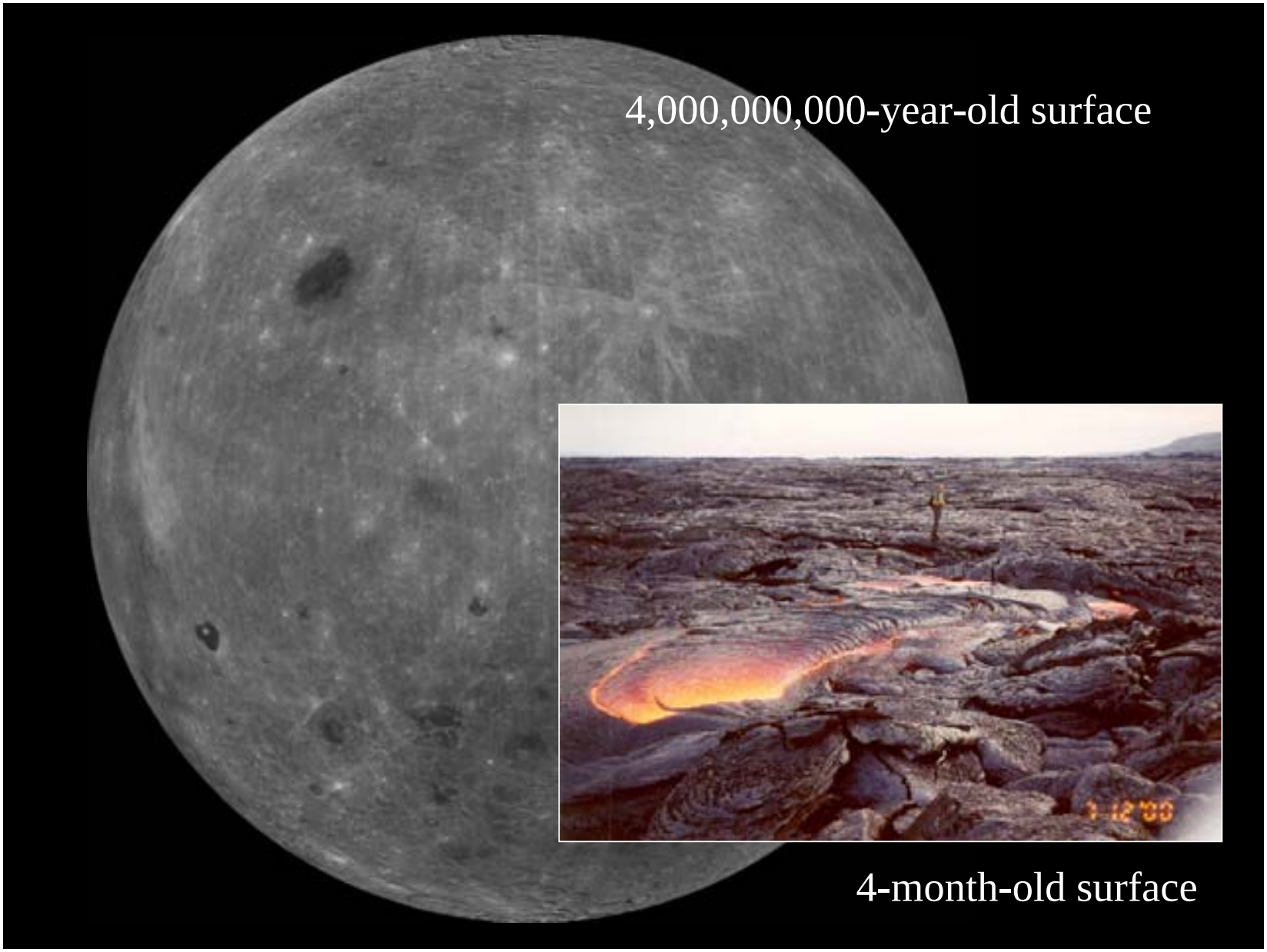
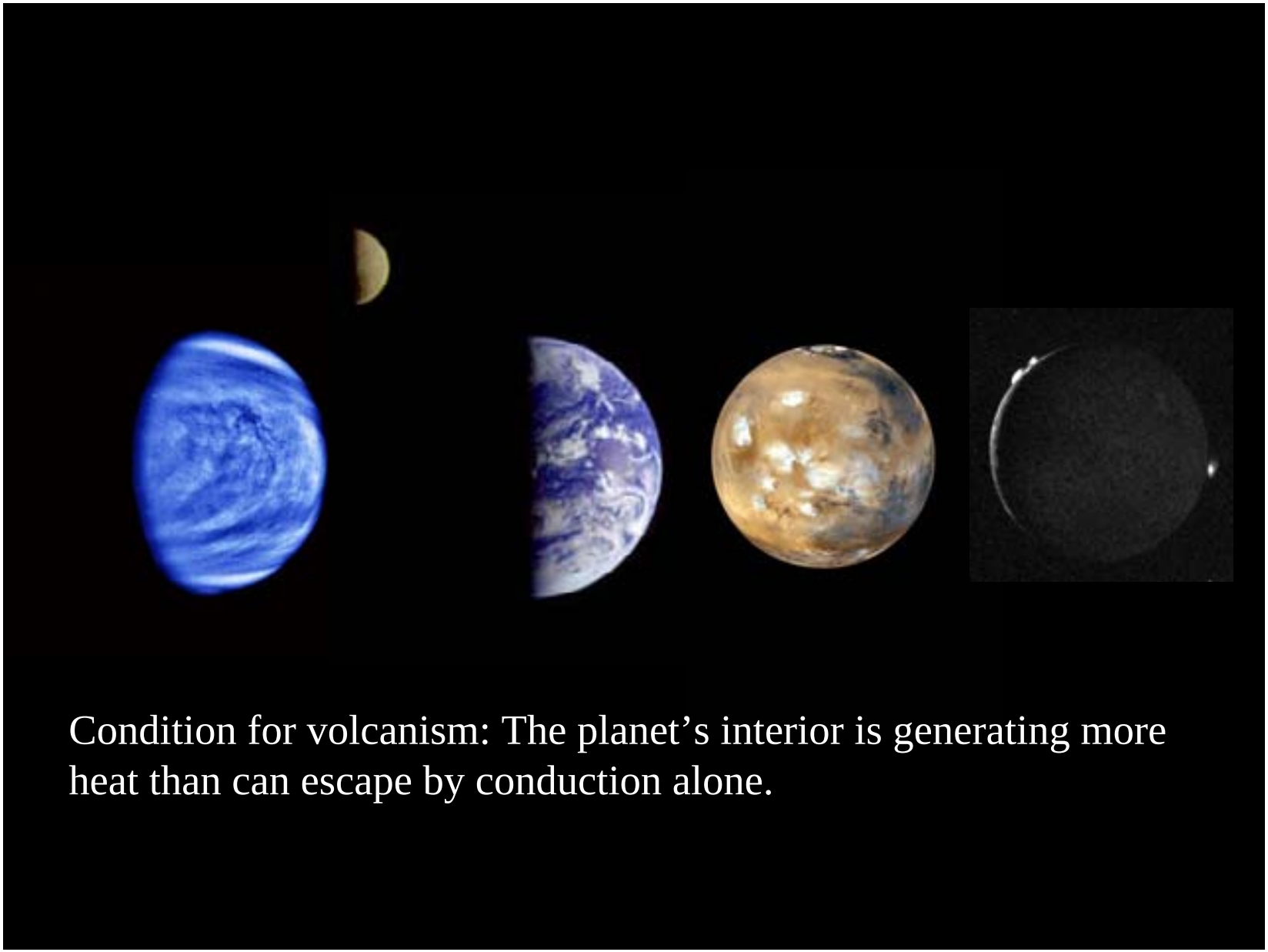
# Why are volcanoes important?

- 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



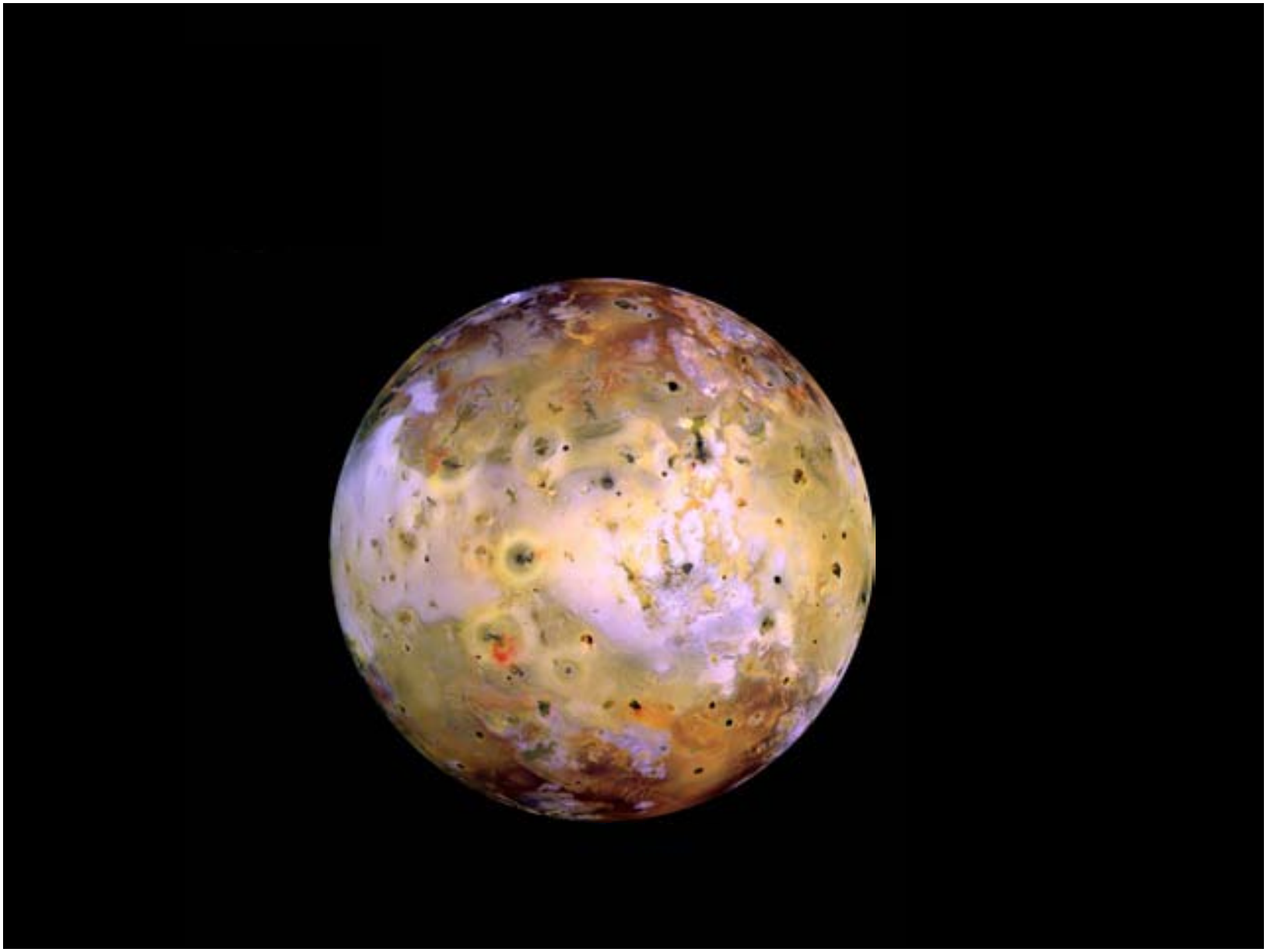
Condition for volcanism: The planet’s interior is generating more heat than can escape by conduction alone.

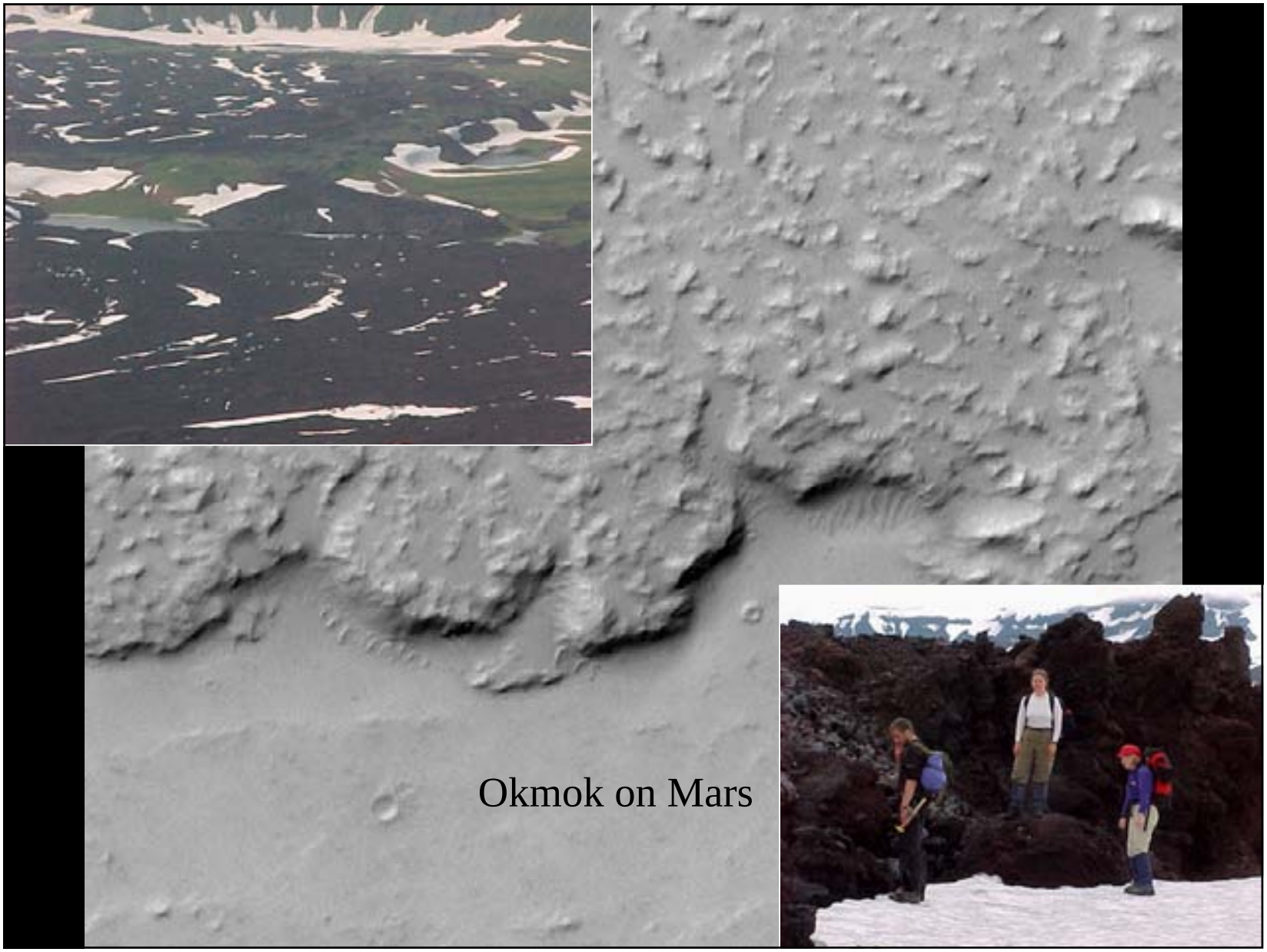
Venus

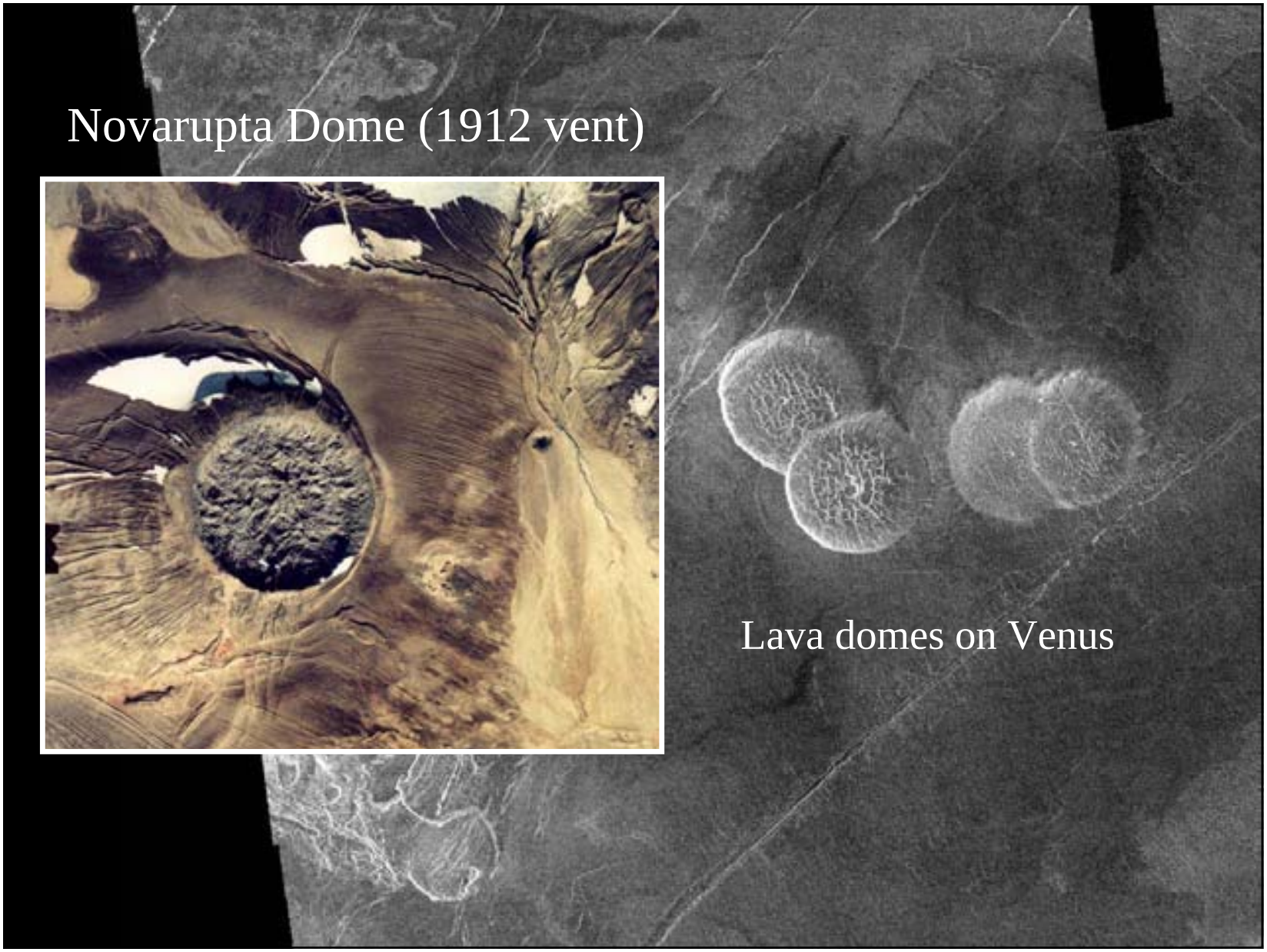
Earth

Mars

Io



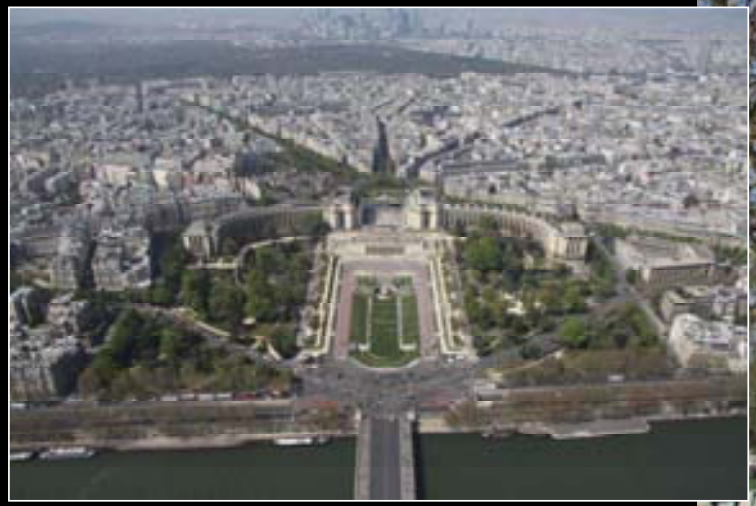

Okmok on Mars

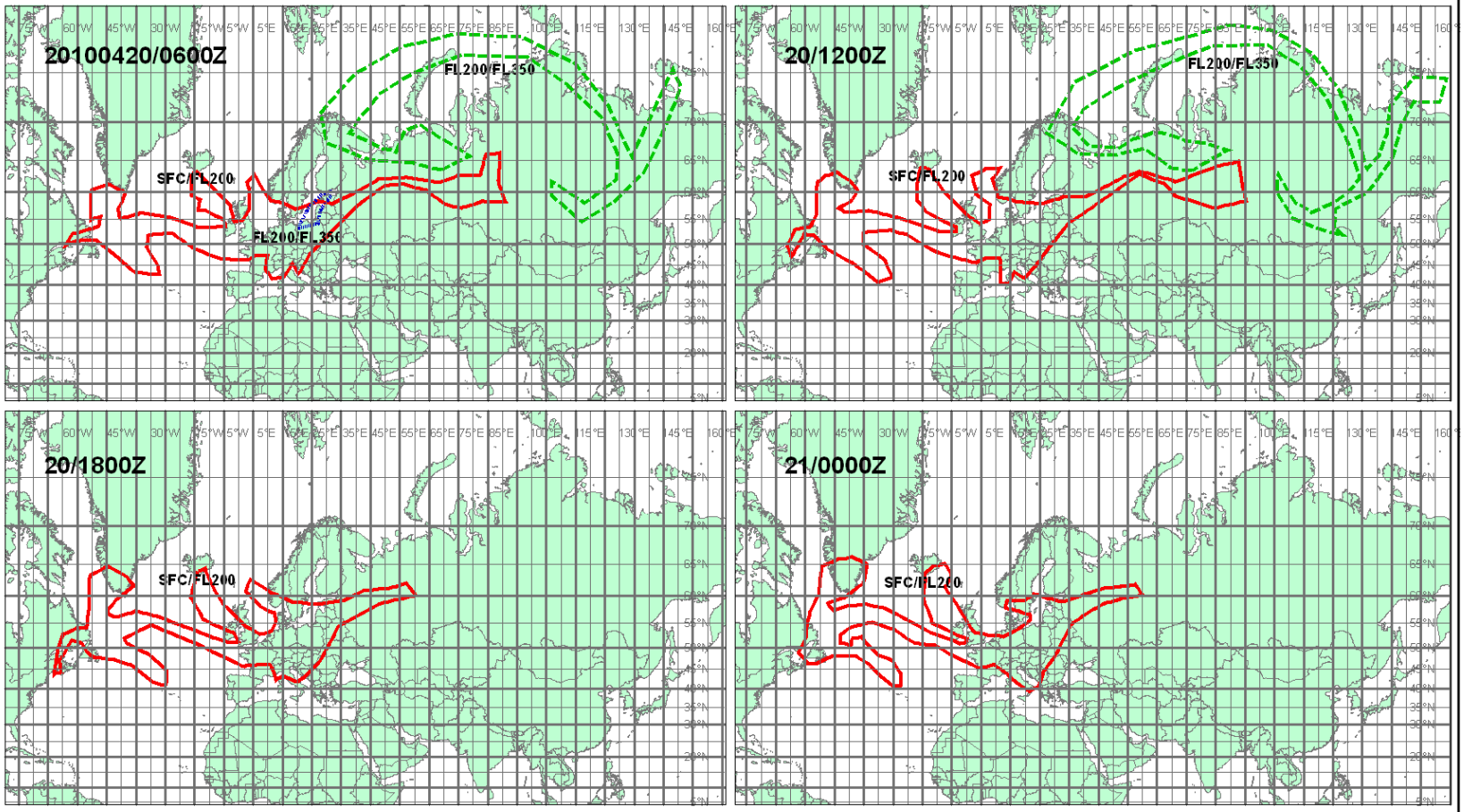

Novarupta Dome (1912 vent)
Lava domes on Venus

# The ash problem

What’s wrong with this picture?

April 18, 2010

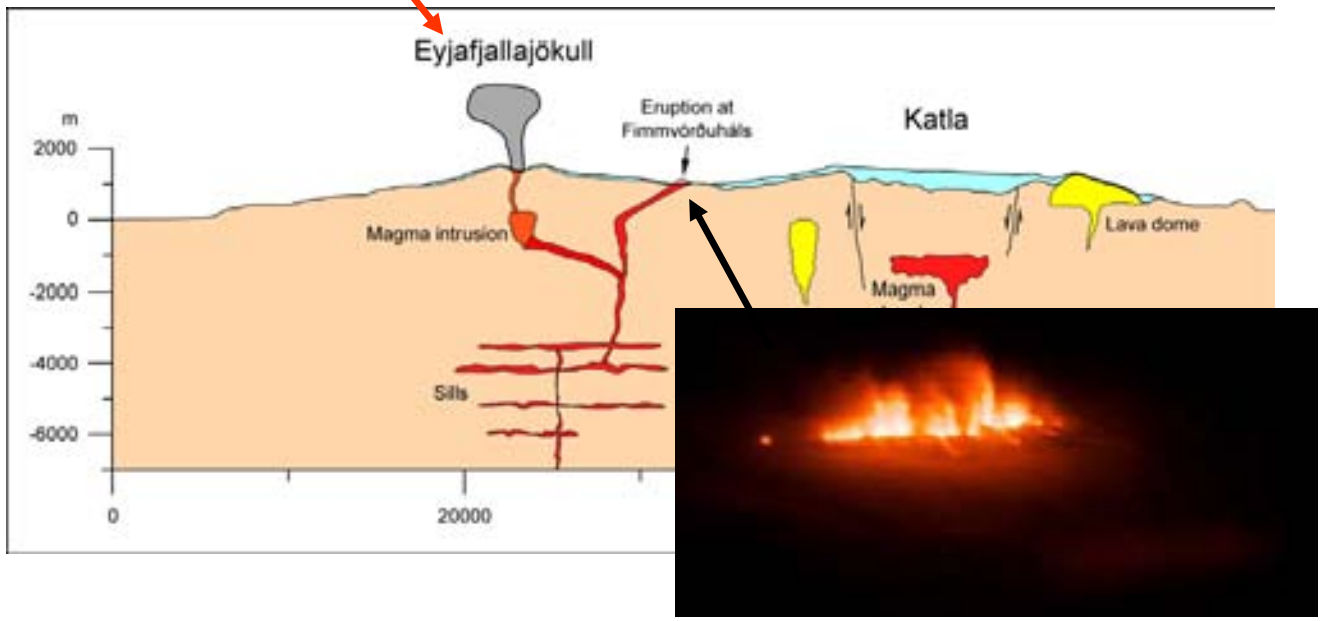





VA ADVISORY
DTG: 20100420/0600Z
VAAC: LONDON
VOLCANO:
EYJAFJALLAJOKULL 1702-02
PSN: N6338 W01937
AREA: ICELAND

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


Eyjafjallajökull
Eruption at
Fimmvörðuháls
Katla
m
2000
0
-2000
-4000
-6000
Magma intrusion
Lava dome
Magma
Sills
0
20000

*747 COCKPIT - ANCHORAGE CENTER CONVERSATION,*

*12/15/89*

# *Pilot: KLM B-747*

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

CUT1.WAV

# *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,”*

BITE2.WAV

# *Pilot: KLM B-747*

*“We have to go*
*left now…*
*it’s smoky in the cockpit*
*at the moment sir.”*

BITE3.WAV

# *Anchorage Center*

*“KLM 867 heavy, roger, left at your discretion.”*

CUT3.WAV

# *Pilot: KLM B-747*

*Climbing to level 390, we're in the black cloud, heading 130."*

BITE4.WAV

# *Pilot: KLM B-747*

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

BITE5.WAV

# *Anchorage Center*

*“KLM 867 heavy... Anchorage.”*

BITE5B.WAV

# *Pilot: KLM B-747*

*"KLM 867 heavy*
*we are now descending*
*now....*
*We are in a fall!!"*

BITE6.WAV

# *Pilot: KLM B-747*

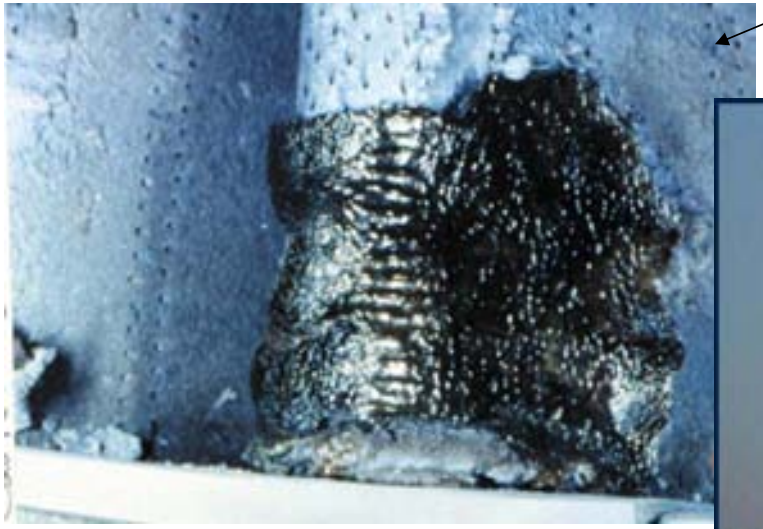
*“KLM 867 we need all the assistance you have sir. Give us radar vectors please.”*

BITE7.WAV

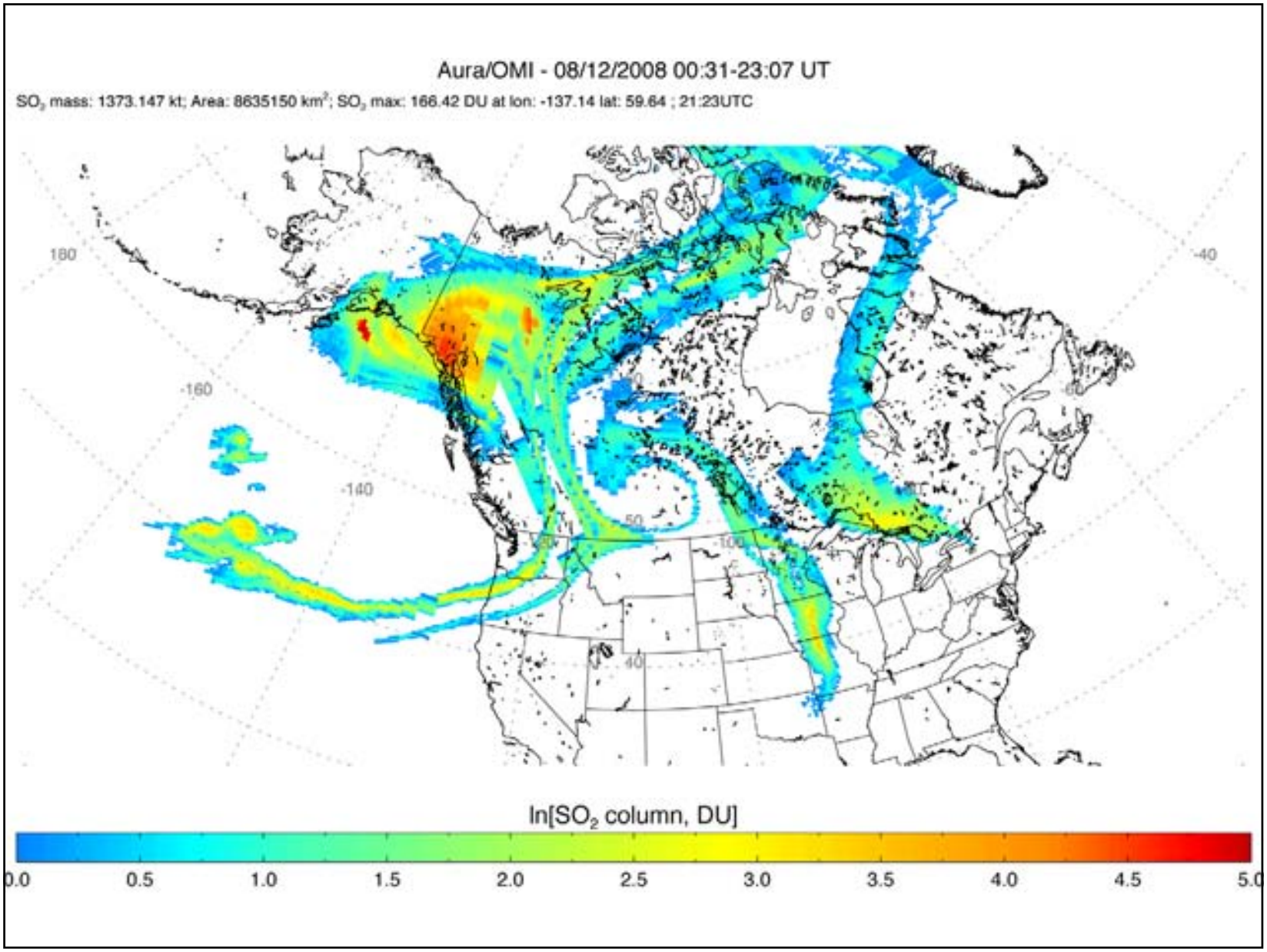
December 15, 1989:
Anchorage, Alaska

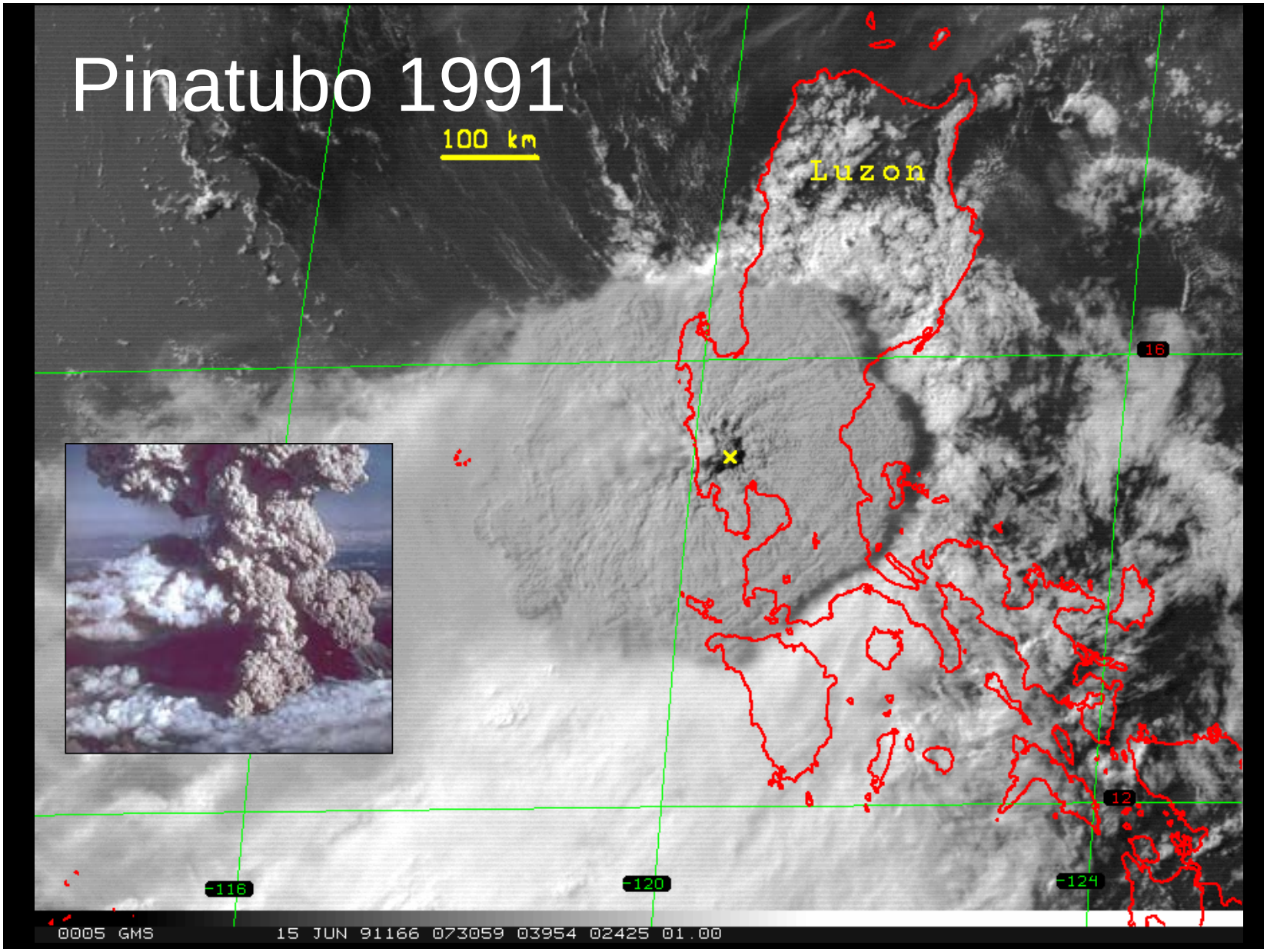
KLM 747 landed safely after in-flight failure of all four engines

Melted ash on turbine blade

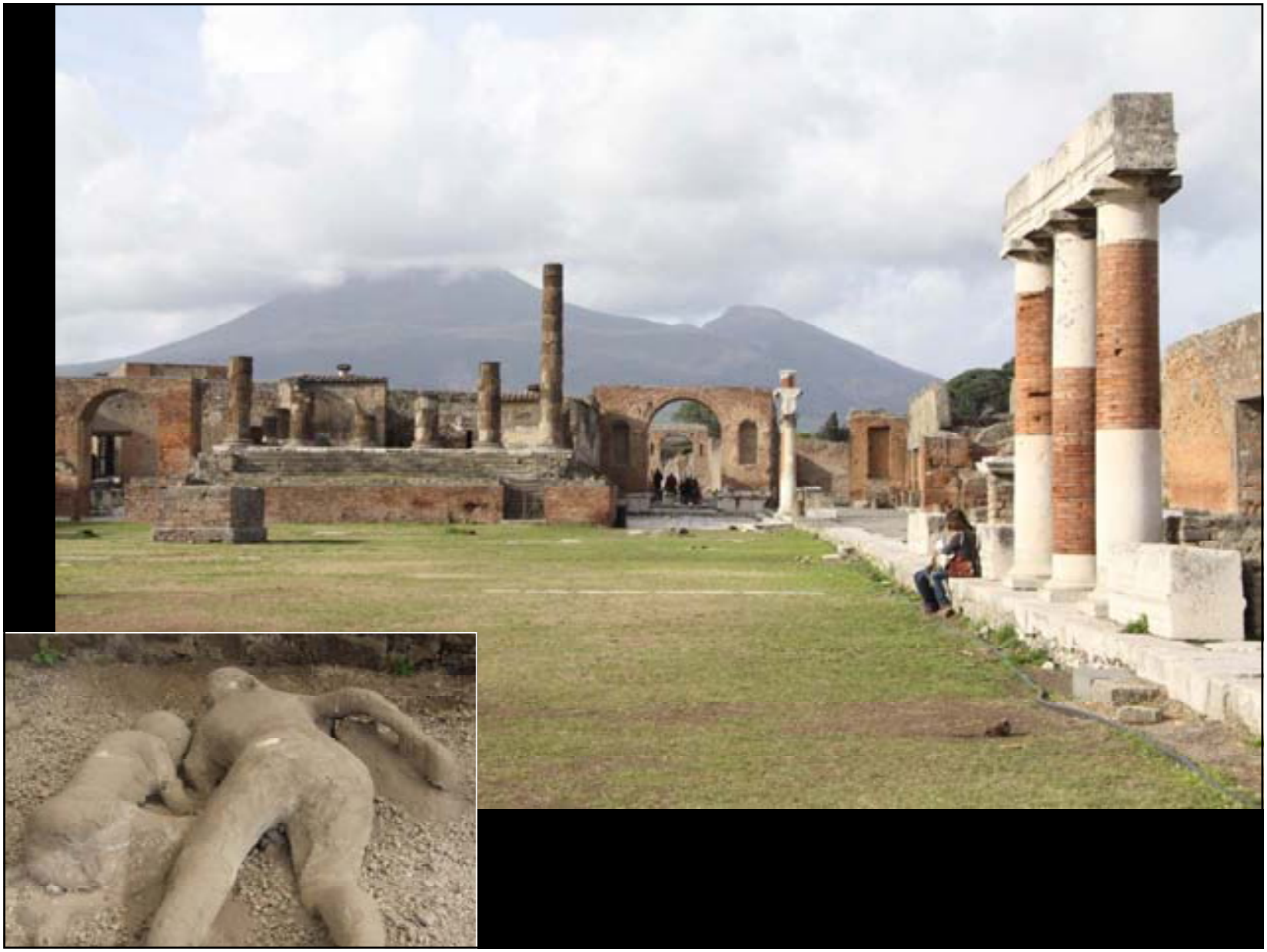



Redoubt, Alaska 2009
Chaiten, Chile 2008
Savonoski, 1912


Aura/OMI - 08/12/2008 00:31-23:07 UT
SO2 mass: 1373.147 kt; Area: 8635150 km2; SO2 max: 166.42 DU at lon: -137.14 lat: 59.64 ; 21:23UTC
180
-160
-140
-40
ln[SO2 column, DU]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

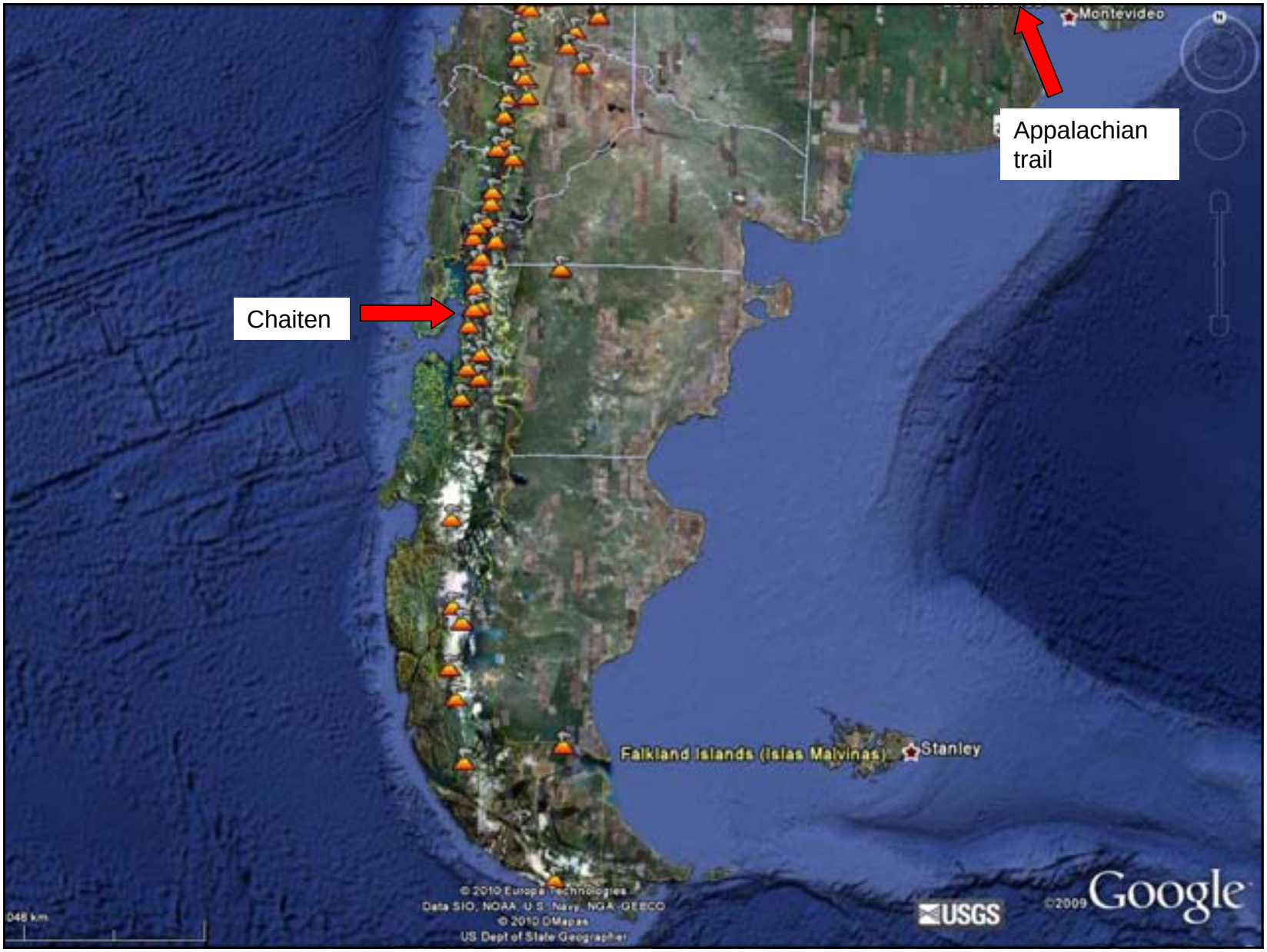

Pinatubo 1991
100 km
Luzon
16
12
-116
-120
-124
0005 GMS
15 JUN 91166 073059 03954 02425 01.00

NASA



# Lahars

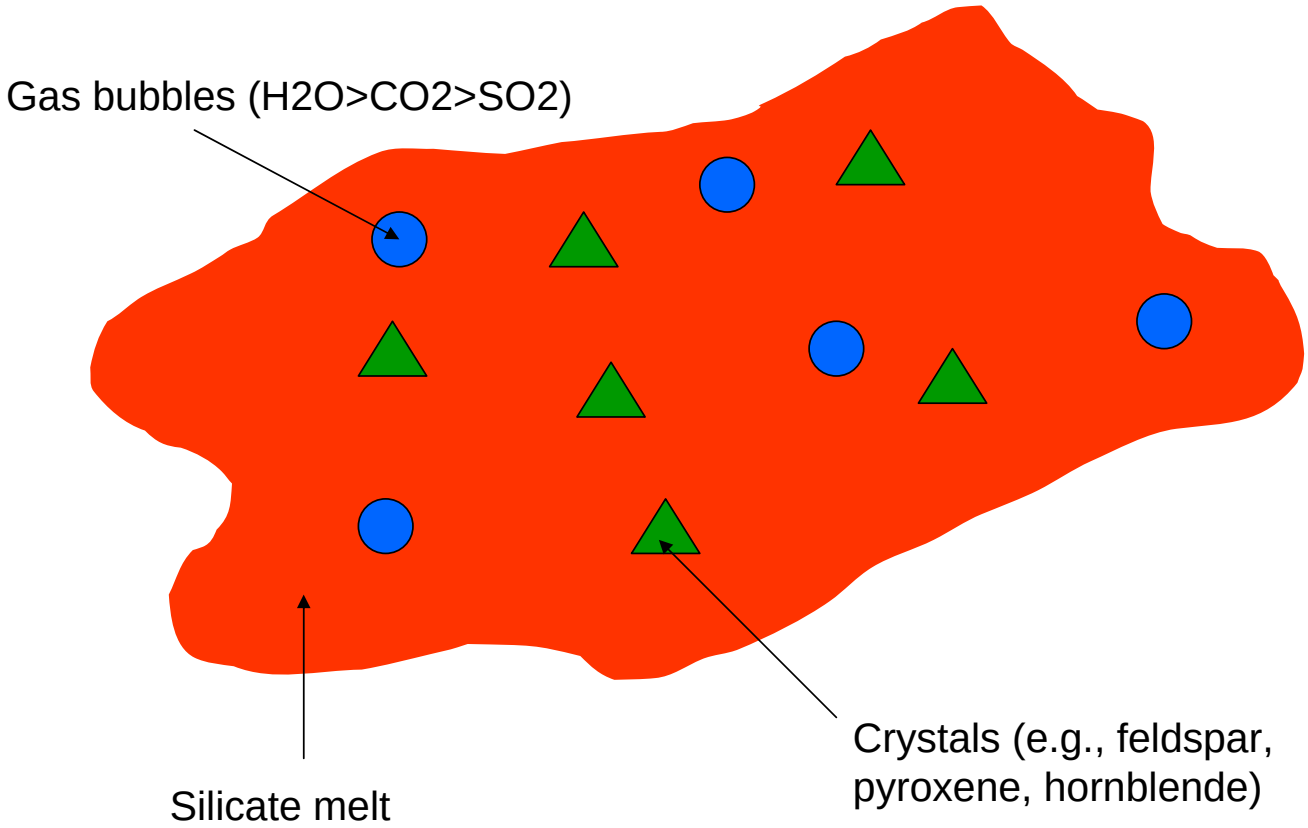

Redoubt, Alaska 2009
Chaiten, Chile 2008
Savonoski, 1912


Montevideo
Appalachian trail
Chaiten
Falkland Islands (Islas Malvinas)
Stanley
USGS
©2009 Google

# Outline

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

# Magma

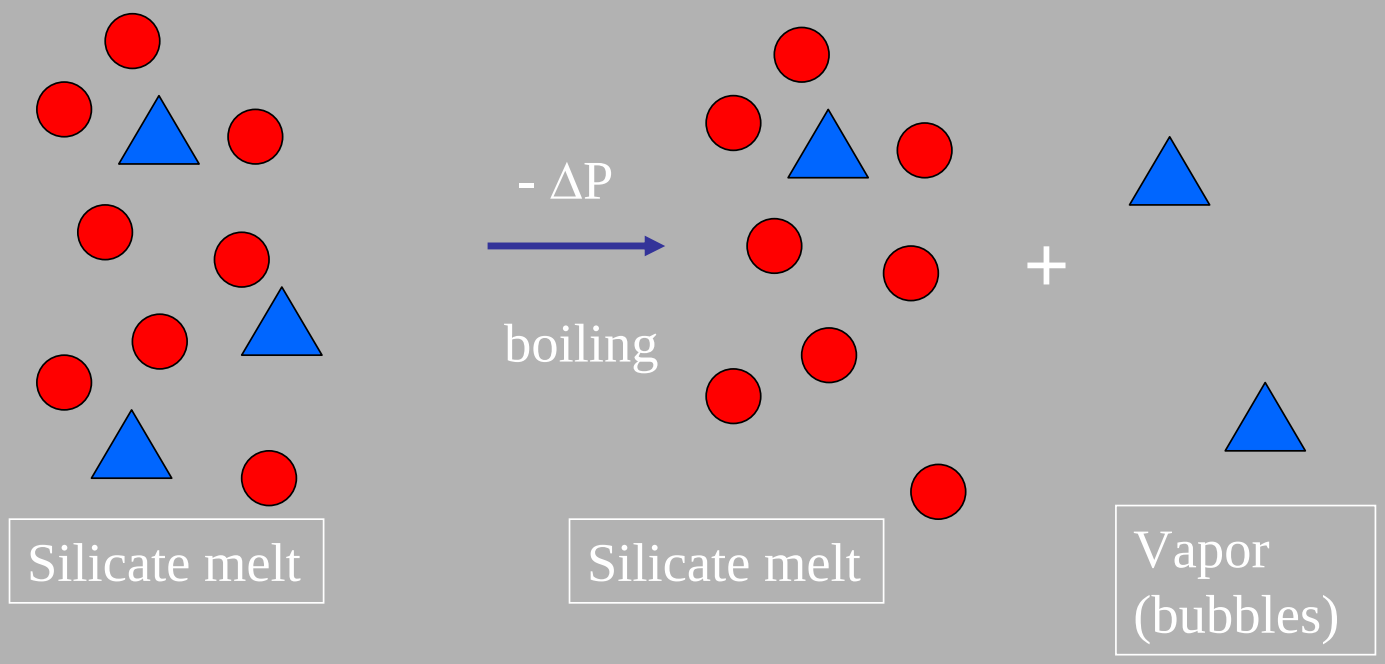

Gas bubbles (H2O>CO2>SO2)
Silicate melt
Crystals (e.g., feldspar, pyroxene, hornblende)

# 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.

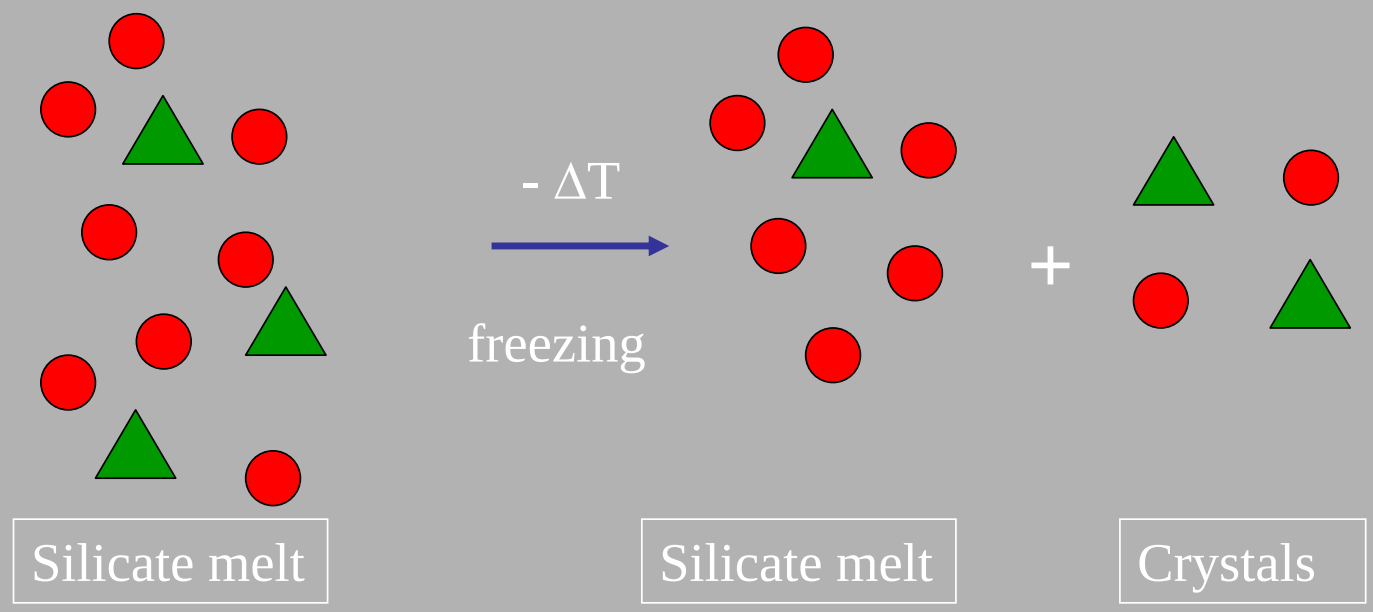
## Boiling ("vesiculation")

Phase change due to decompression (ascent)



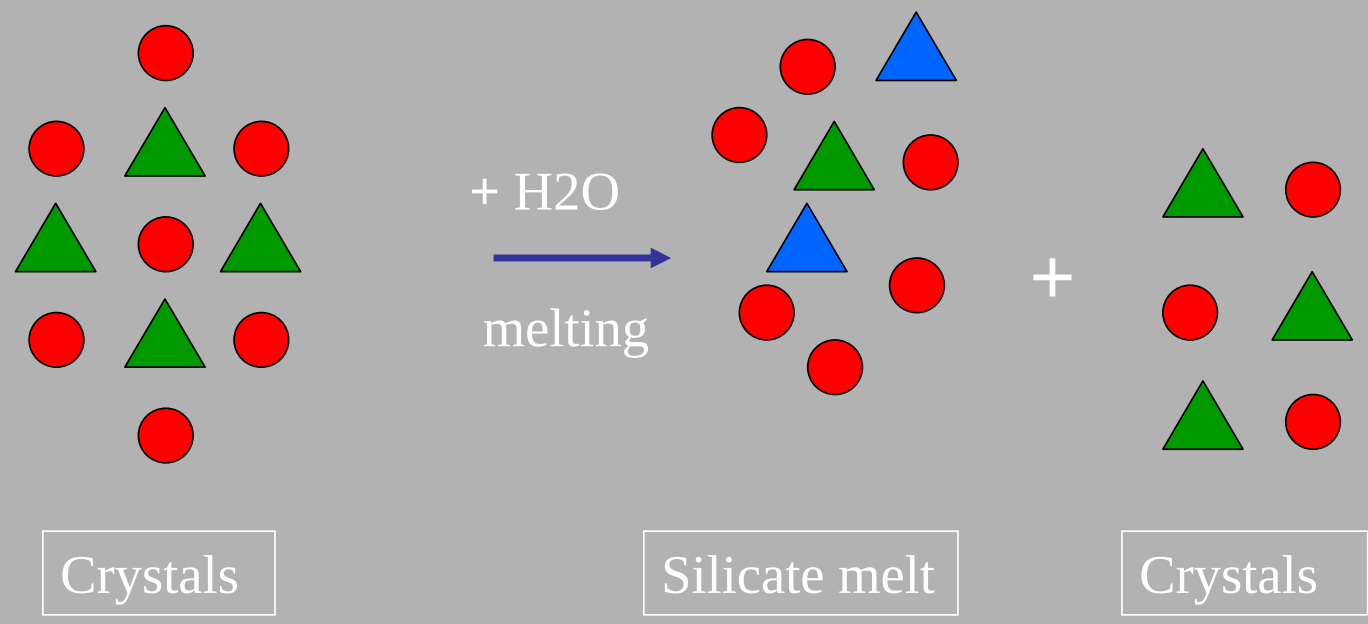
## Crystallization

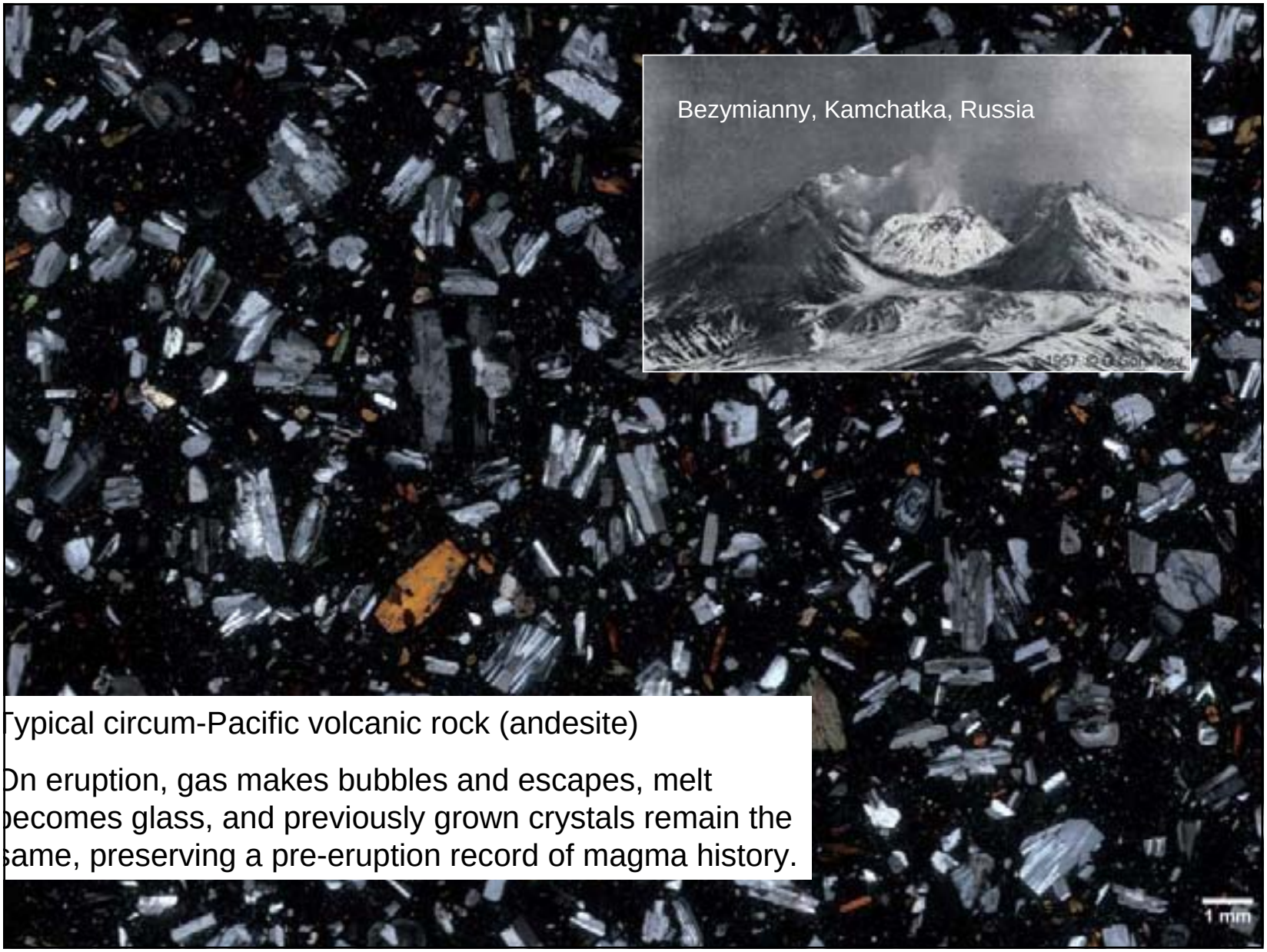
Phase change due to cooling



## Melting

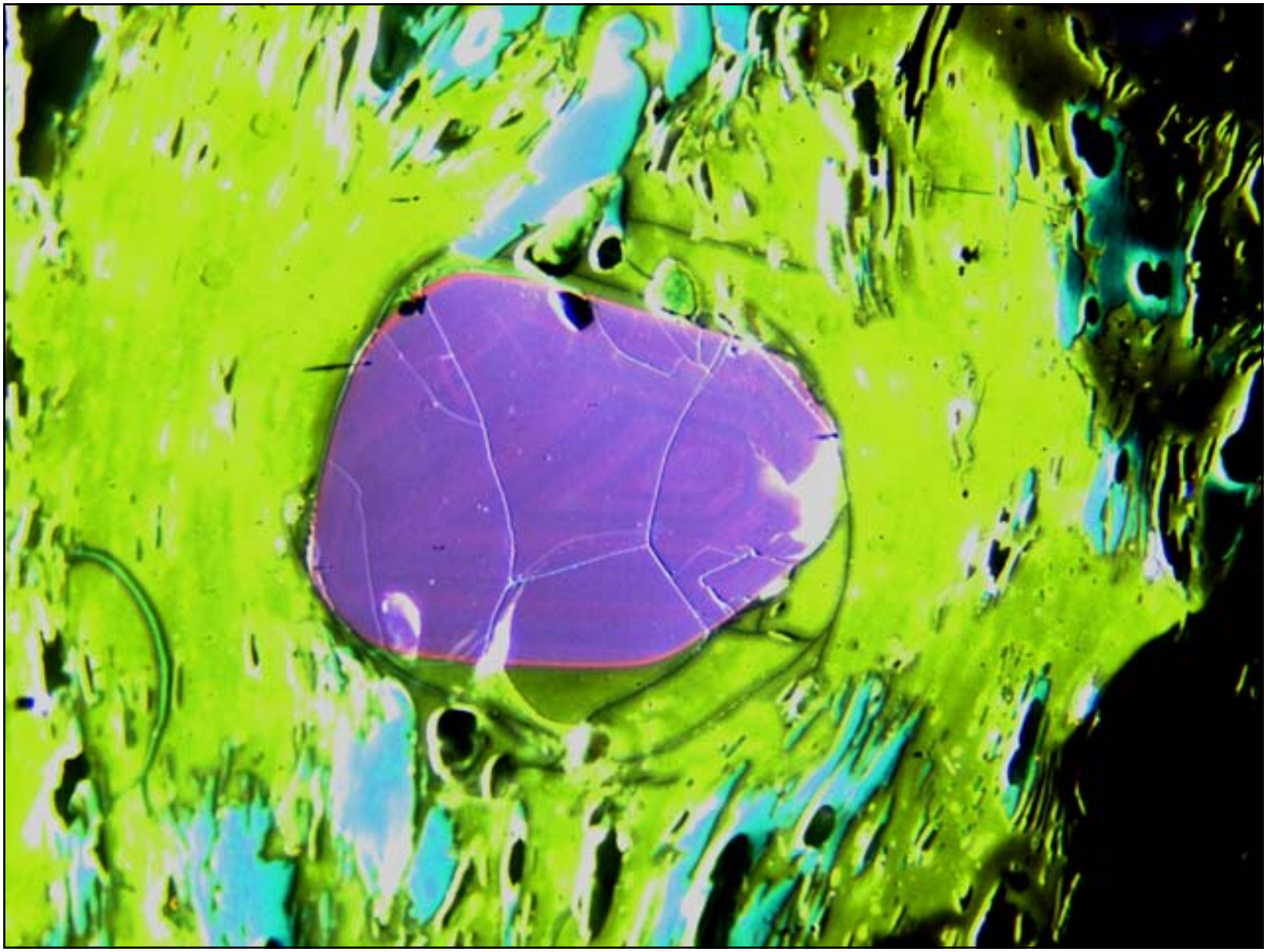
Phase change due to addition of water
(“freezing point depression”)

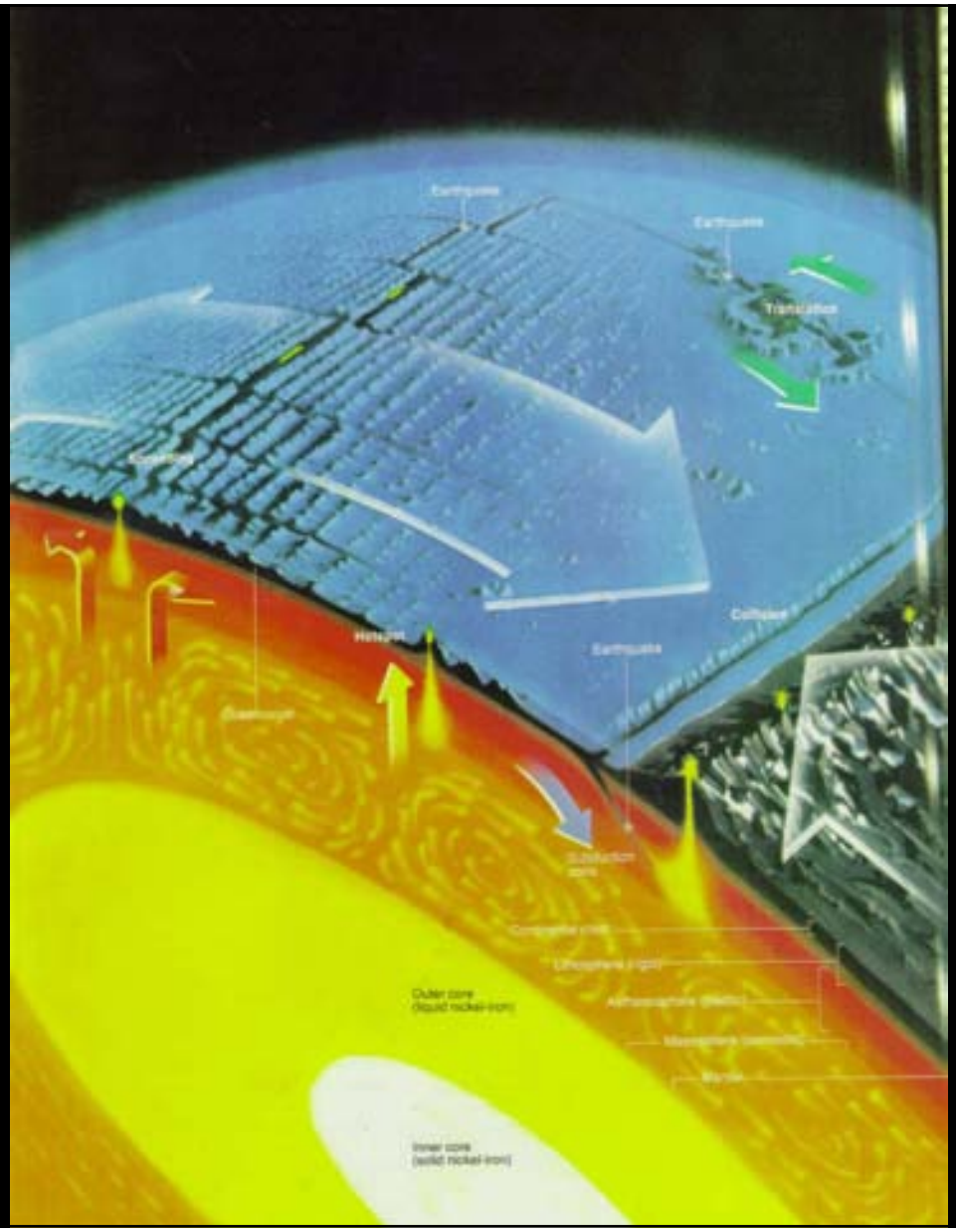


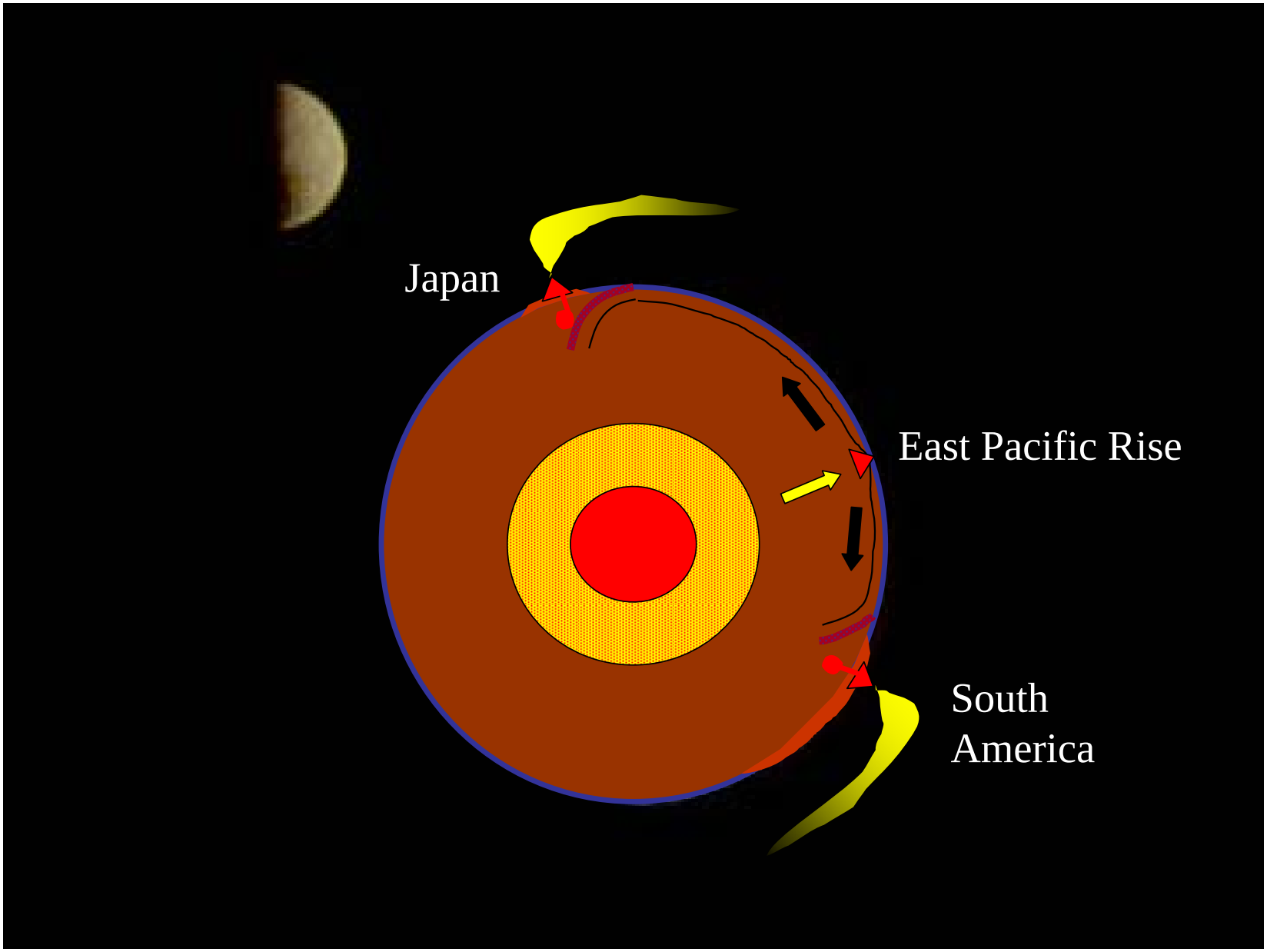


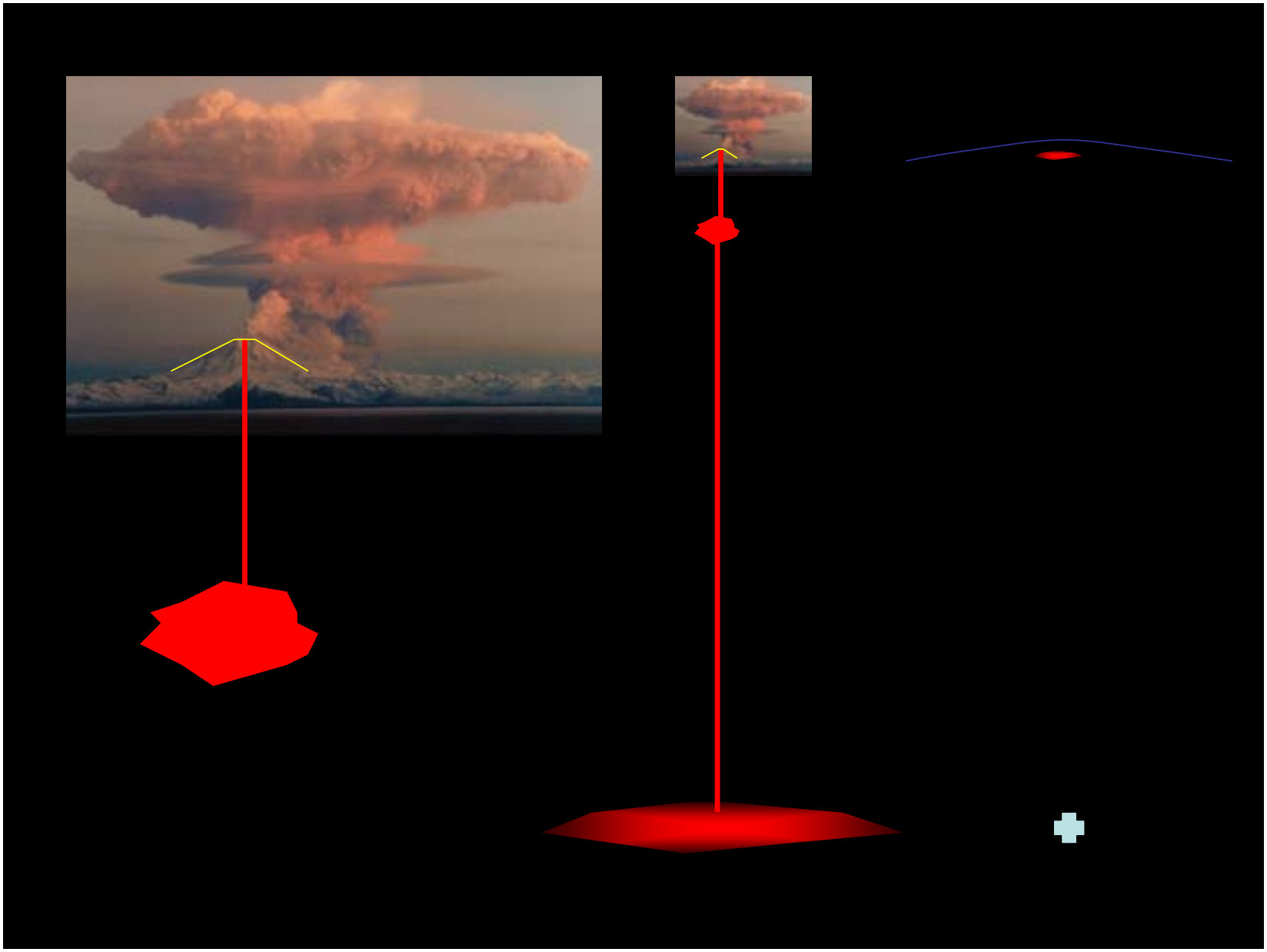

Typical circum-Pacific volcanic rock (andesite)

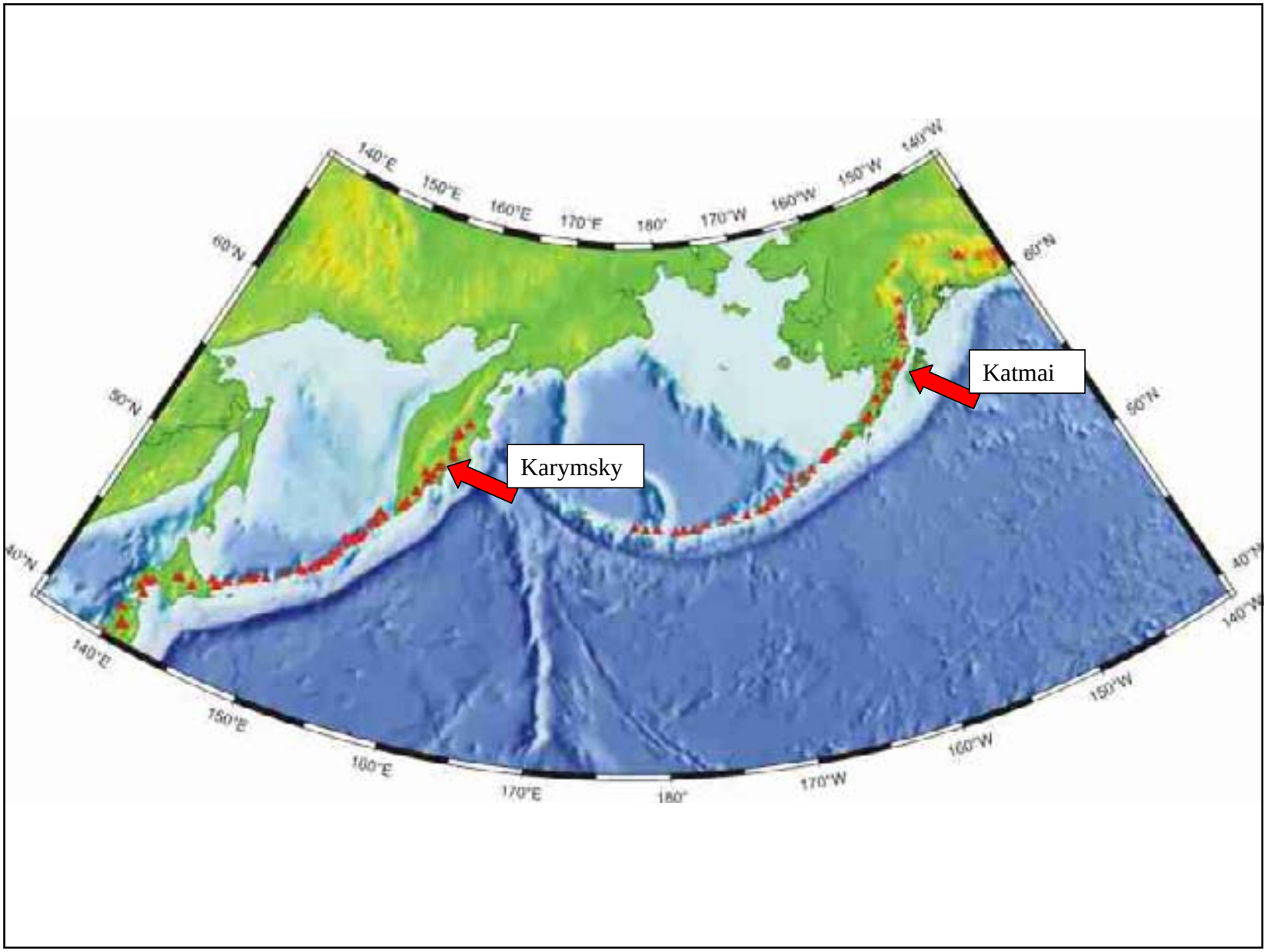
On eruption, gas makes bubbles and escapes, melt becomes glass, and previously grown crystals remain the same, preserving a pre-eruption record of magma history.



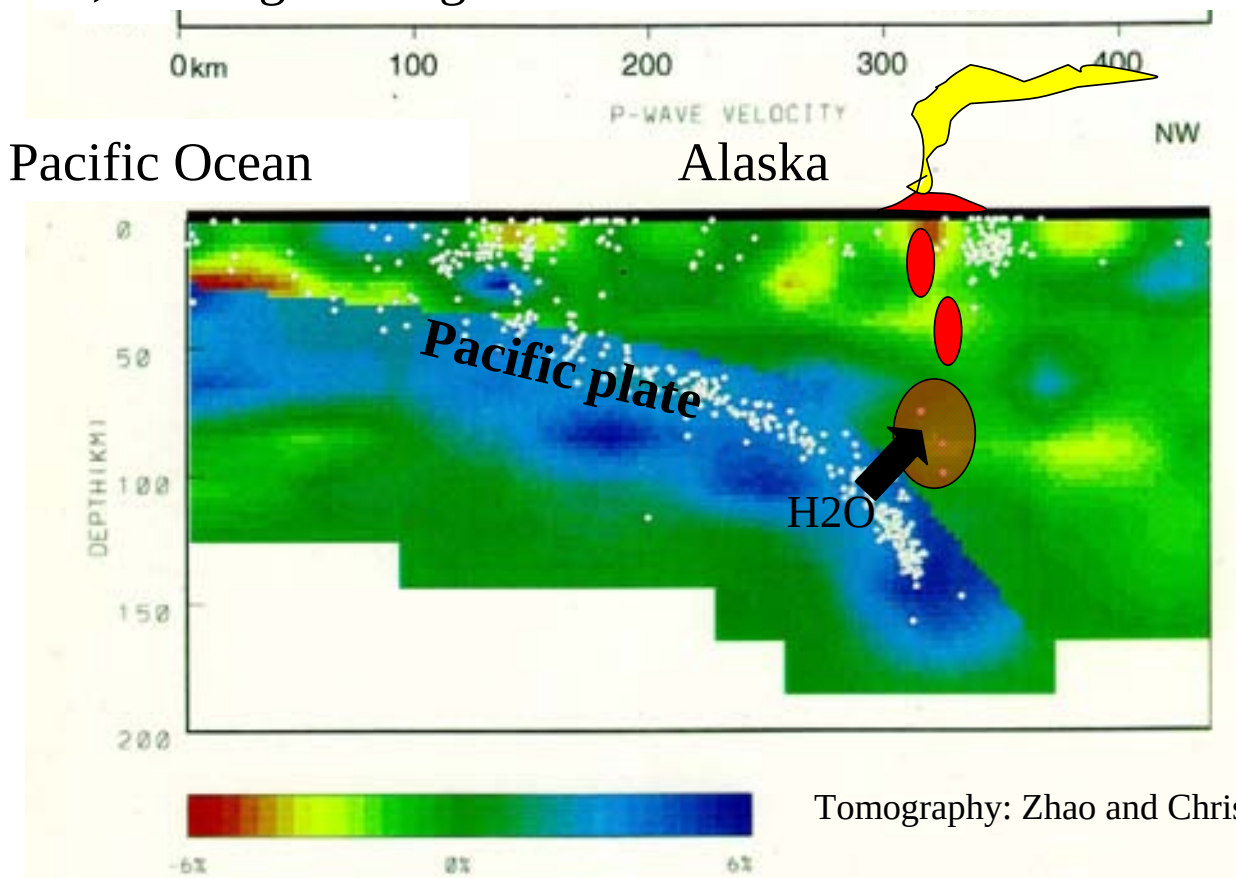

Earthquake
Earthquake
Translation
Collision
Earthquake
Outer core
(liquid nickel-iron)
Inner core
(solid nickel-iron)


Japan
East Pacific Rise
South
America

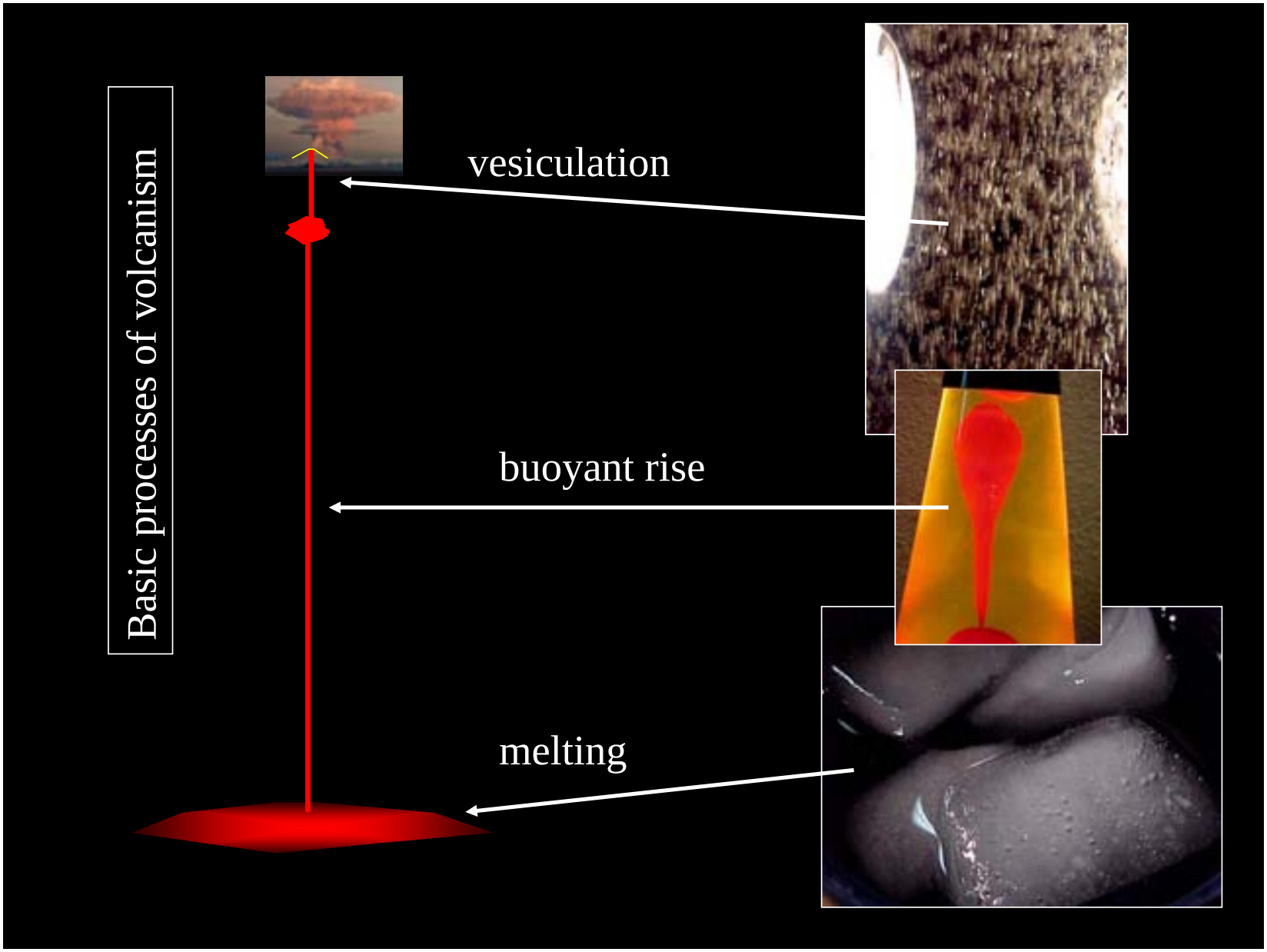



Katmai
Karymsky
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
60°N
50°N
40°N

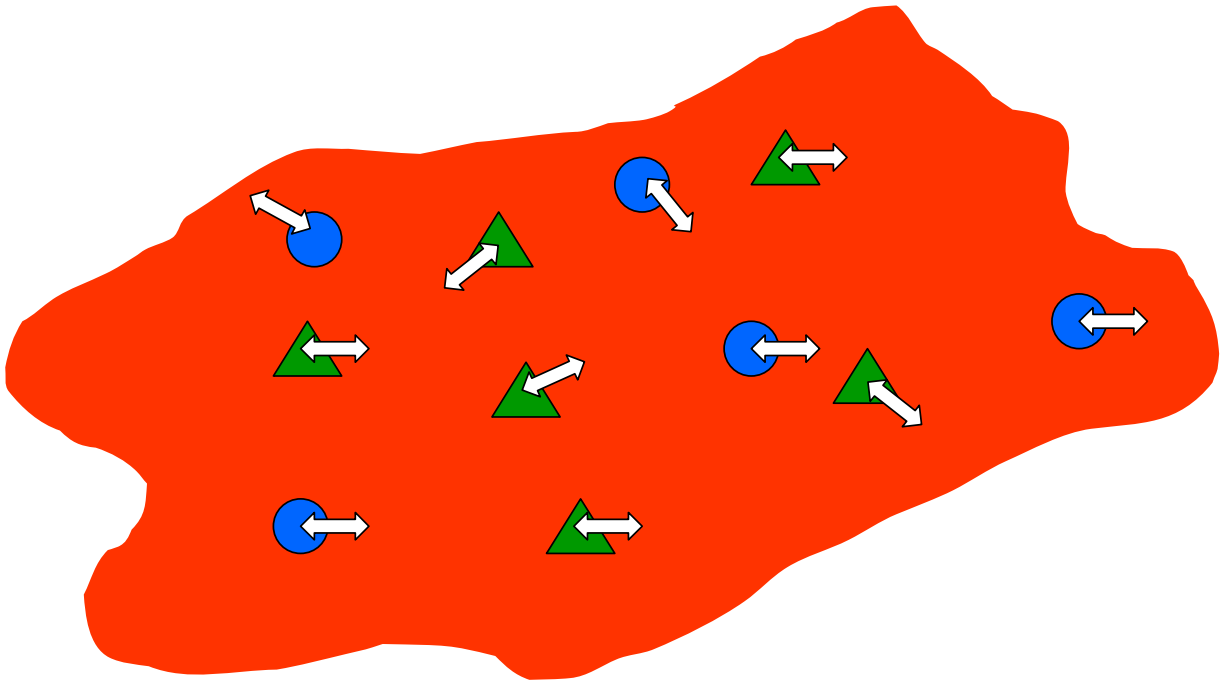
Seismic cross section: Colors roughly correspond to temperature, white dots are earthquakes. Underthrusting (subduction) of Pacific plate introduces water to mantle under Alaska, causing melting.



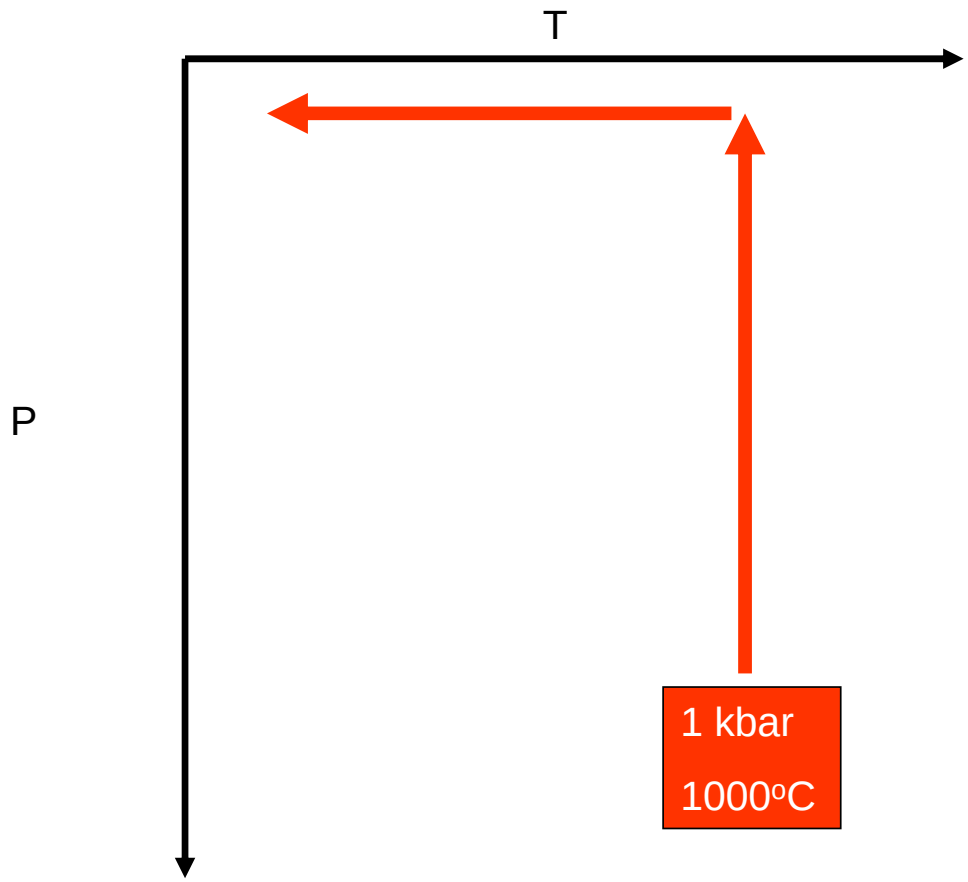

Tomography: Zhao and Christensen

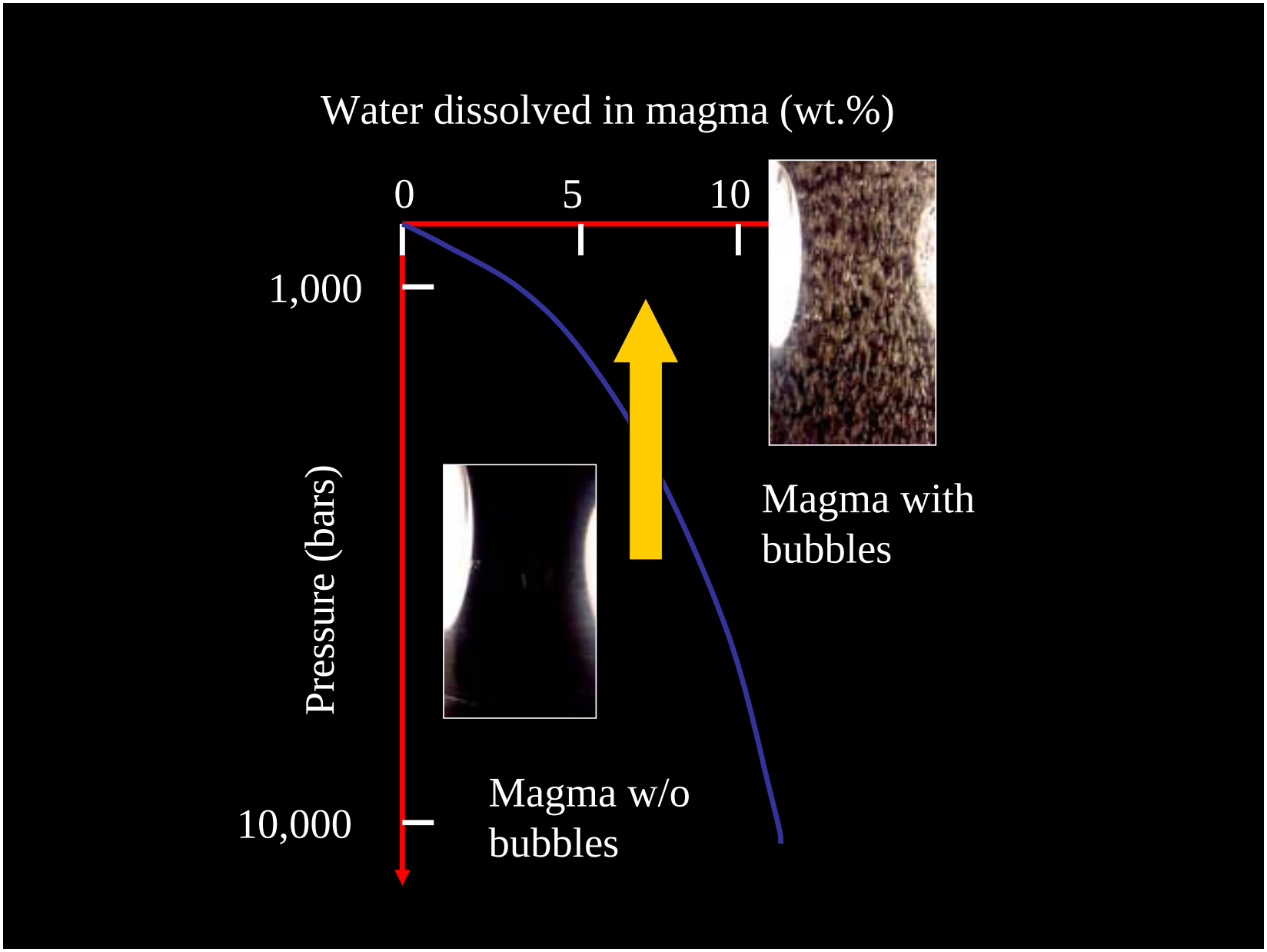

Basic processes of volcanism
vesiculation
buoyant rise
melting

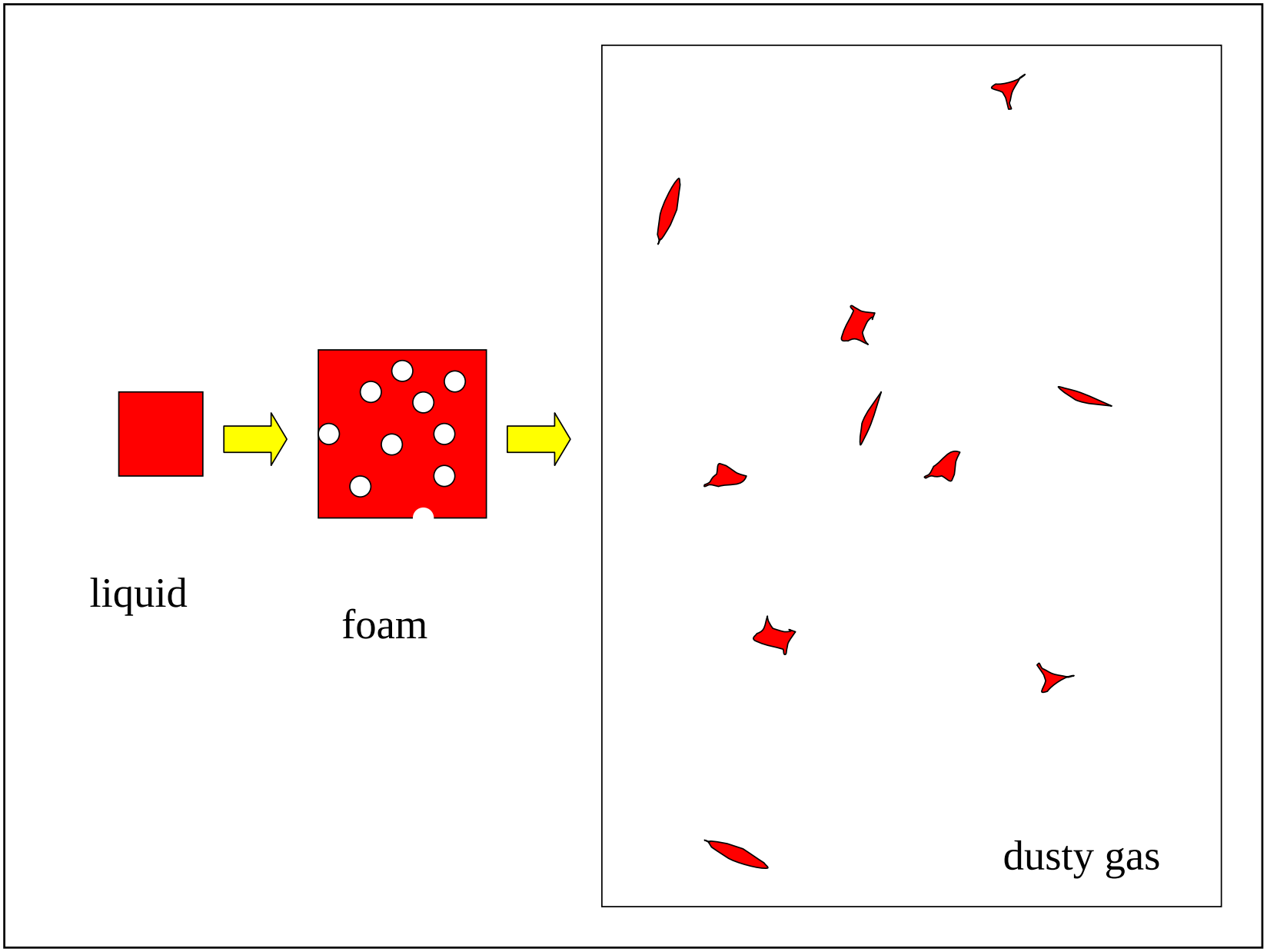
# During storage: equilibrium

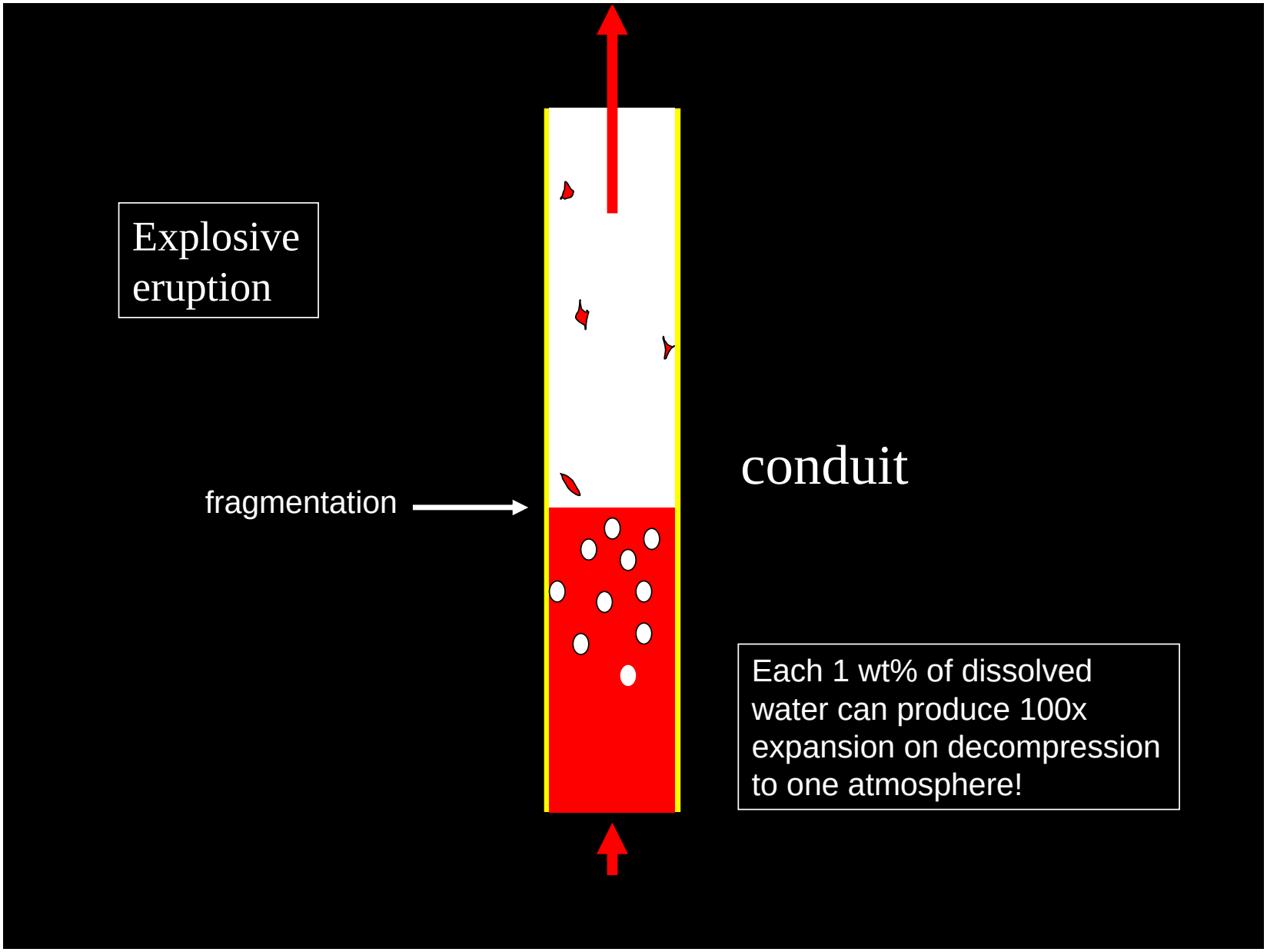


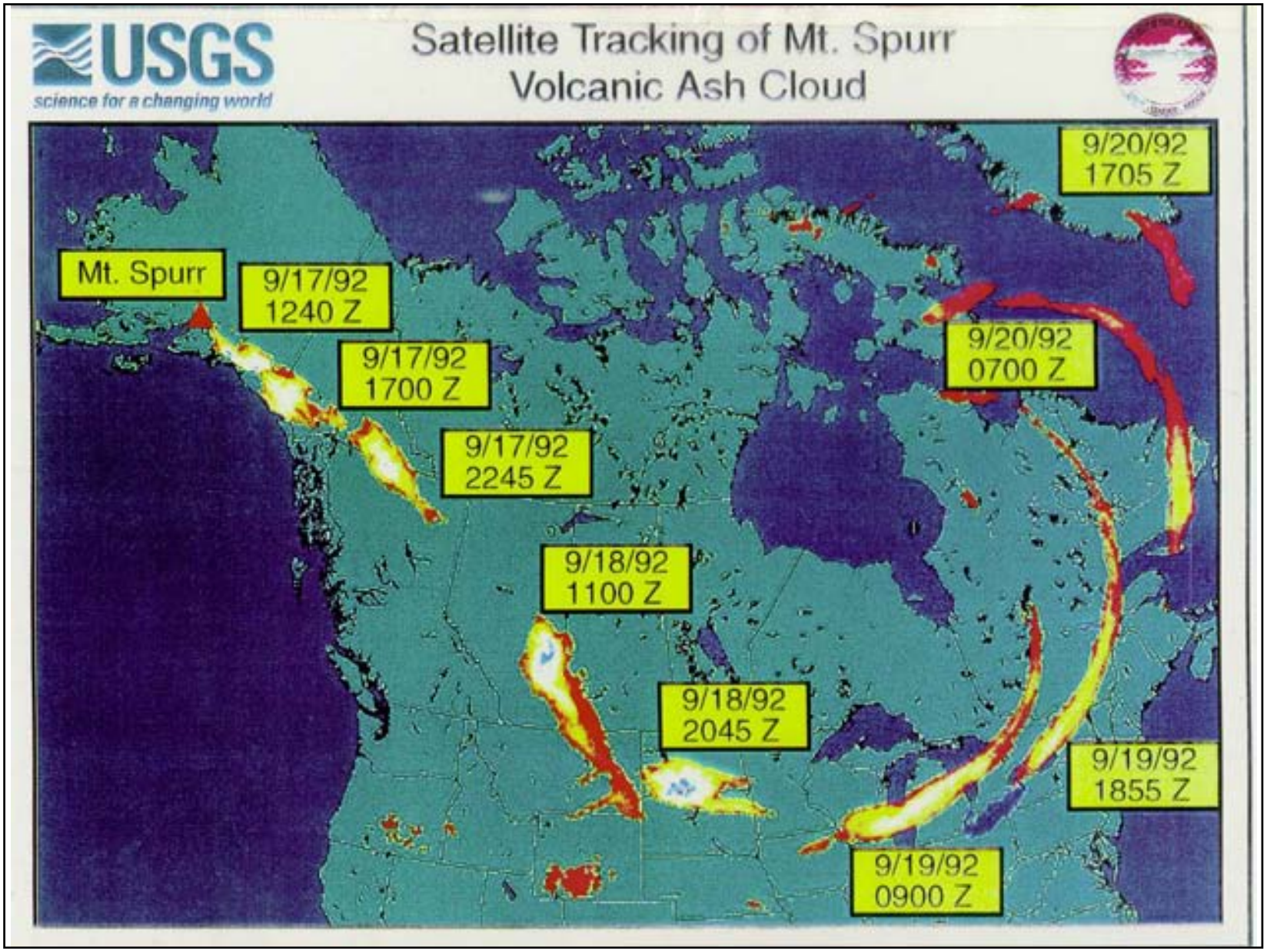
# But ascent of magma disturbs equilibrium




Water dissolved in magma (wt.%)
0
5
10
1,000
10,000
Pressure (bars)
Magma with bubbles
Magma w/o bubbles


liquid
foam
dusty gas


Explosive eruption
fragmentation
conduit
Each 1 wt% of dissolved water can produce 100x expansion on decompression to one atmosphere!


USGS
science for a changing world
Satellite Tracking of Mt. Spurr
Volcanic Ash Cloud
Mt. Spurr
9/17/92
1240 Z
9/17/92
1700 Z
9/17/92
2245 Z
9/18/92
1100 Z
9/18/92
2045 Z
9/19/92
0900 Z
9/19/92
1855 Z
9/20/92
0700 Z
9/20/92
1705 Z

# What do these things have in common?




# Boiling in a vertical tube!




pressure

$$P = \rho g h$$

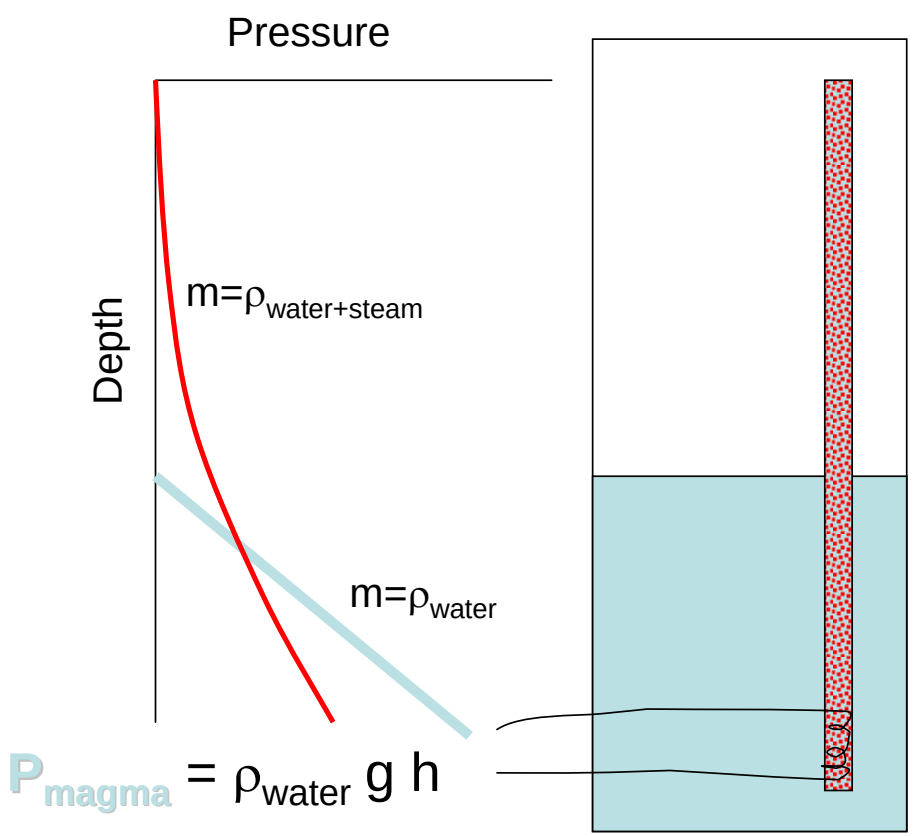
density

gravity

height of liquid column

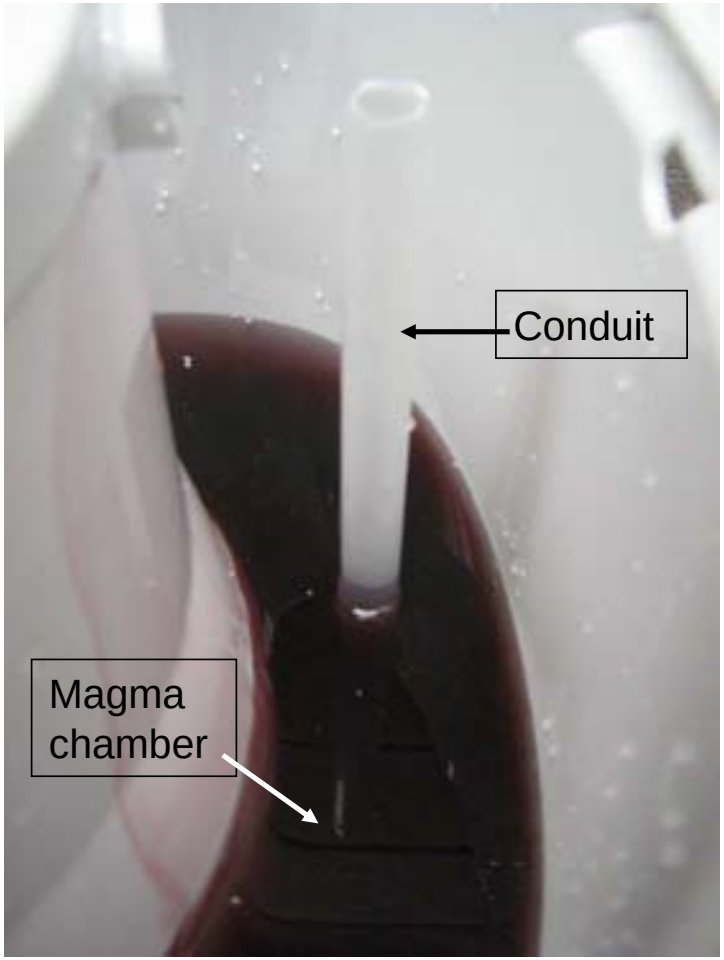
Experimental volcano

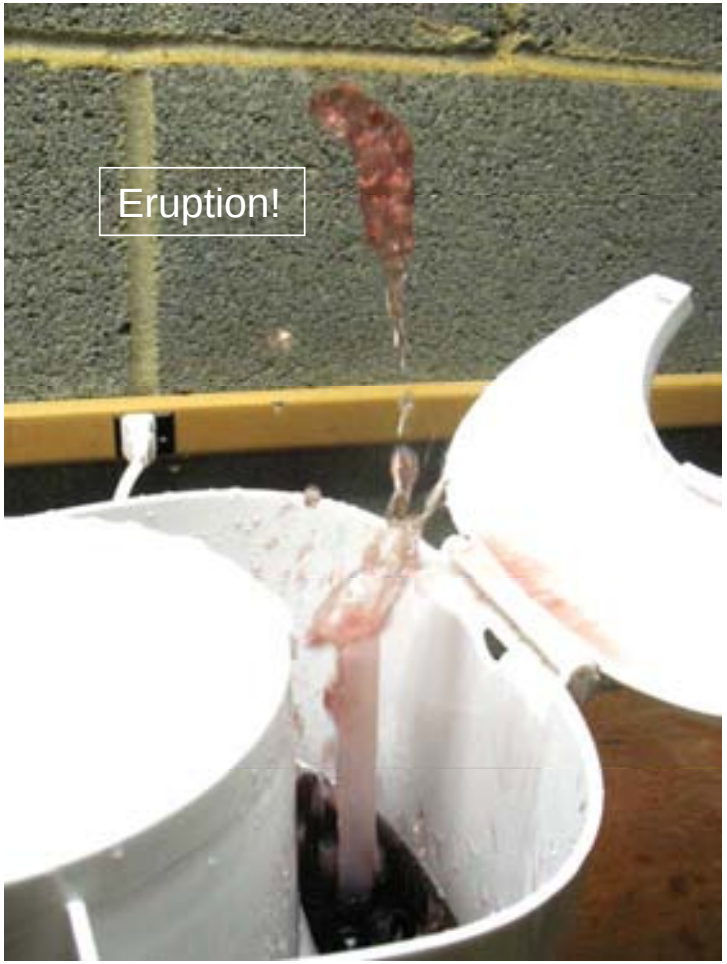
(Walmart, $9)




$P_{magma} = \rho_{water}\, g\, h$

$P_{conduit} = \rho_{water+steam}\, g\, h$


Conduit
Magma
chamber

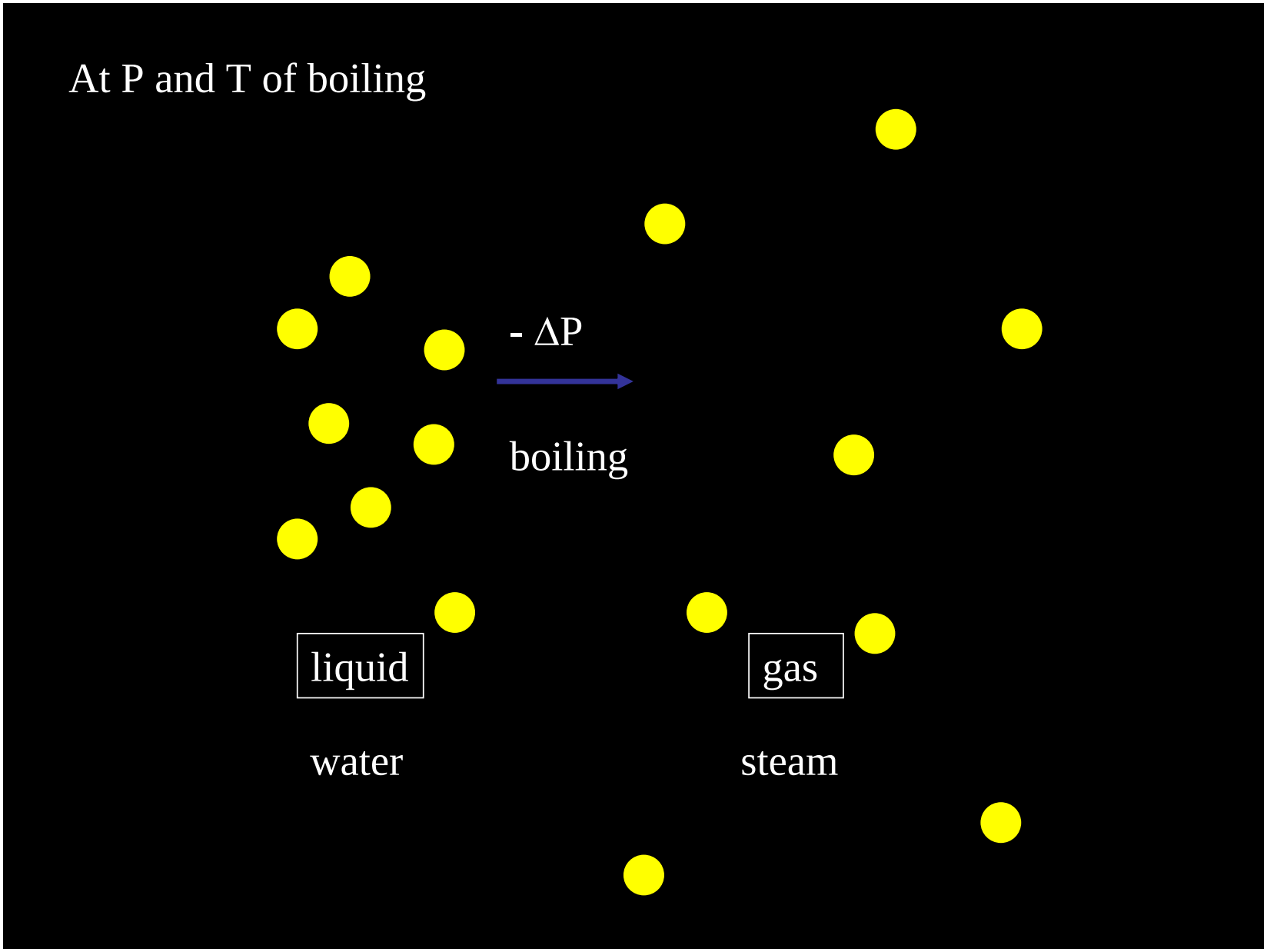

Eruption!

Pulsatory; not steady-state

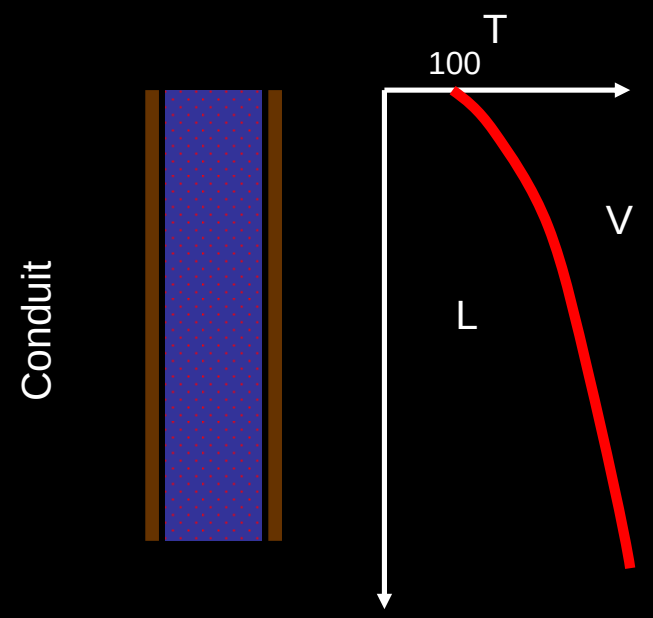
# What’s the difference between coffee makers vs. volcanoes and geysers?

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

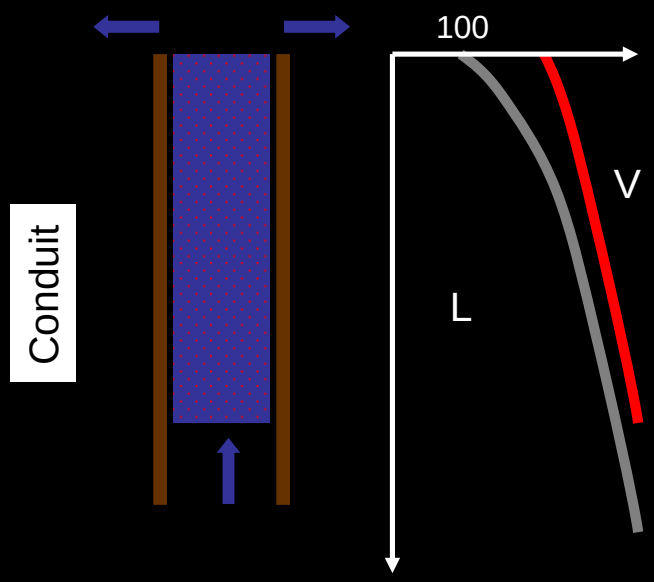
- Volcanoes and geysers (and gas-rich oil wells) are therefore self-pumping.


At P and T of boiling
- ΔP
boiling
liquid
gas
water
steam

Boiling water geyser

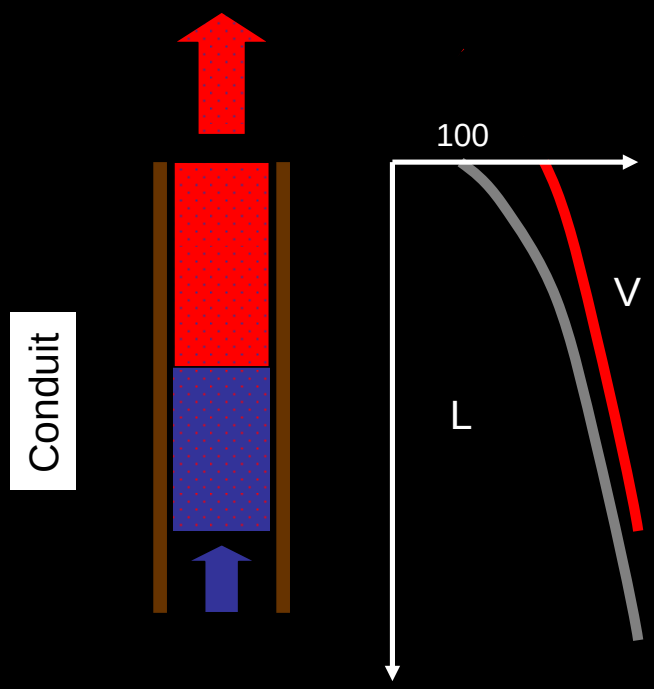



$P_V = P_L$

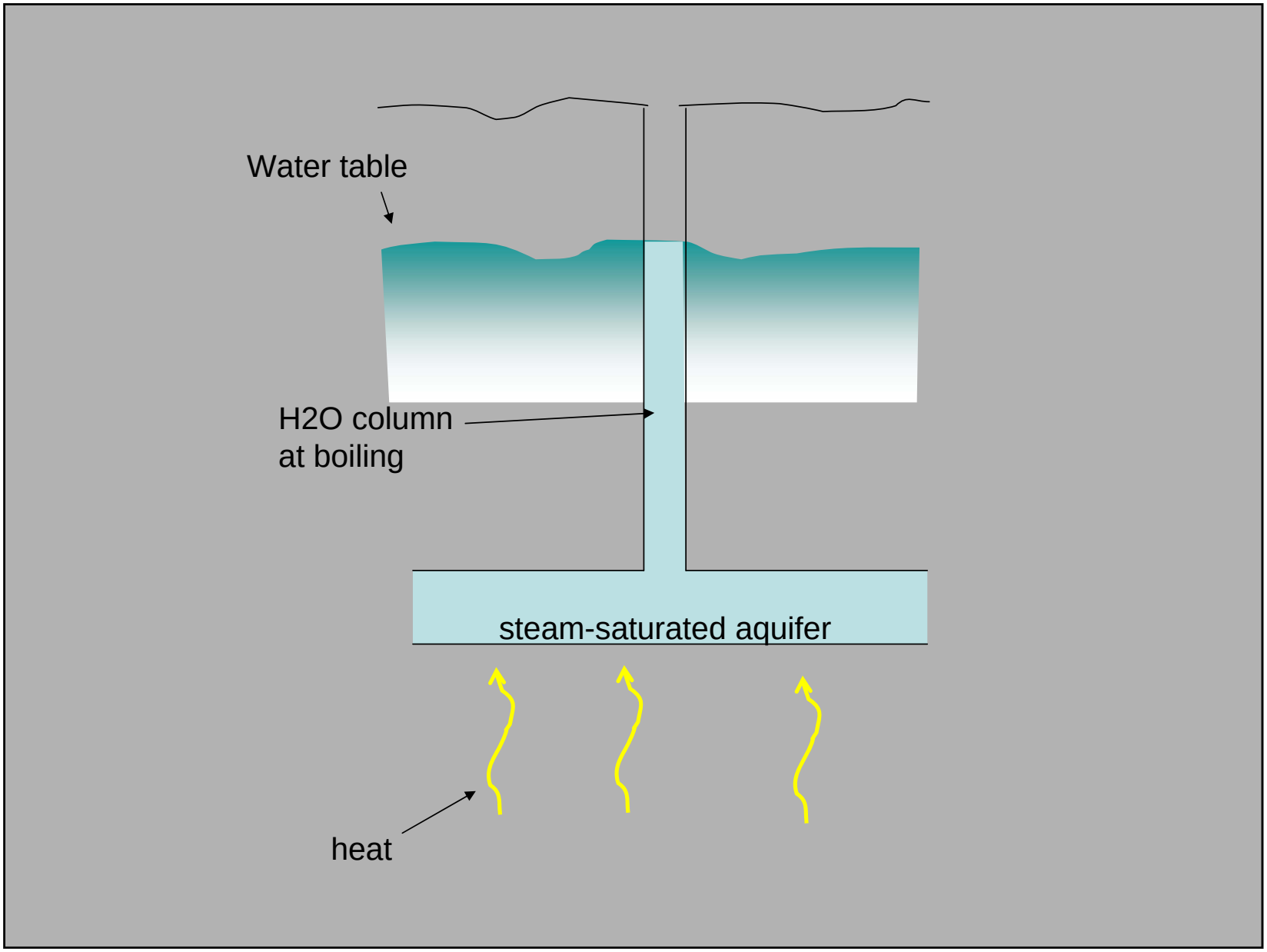


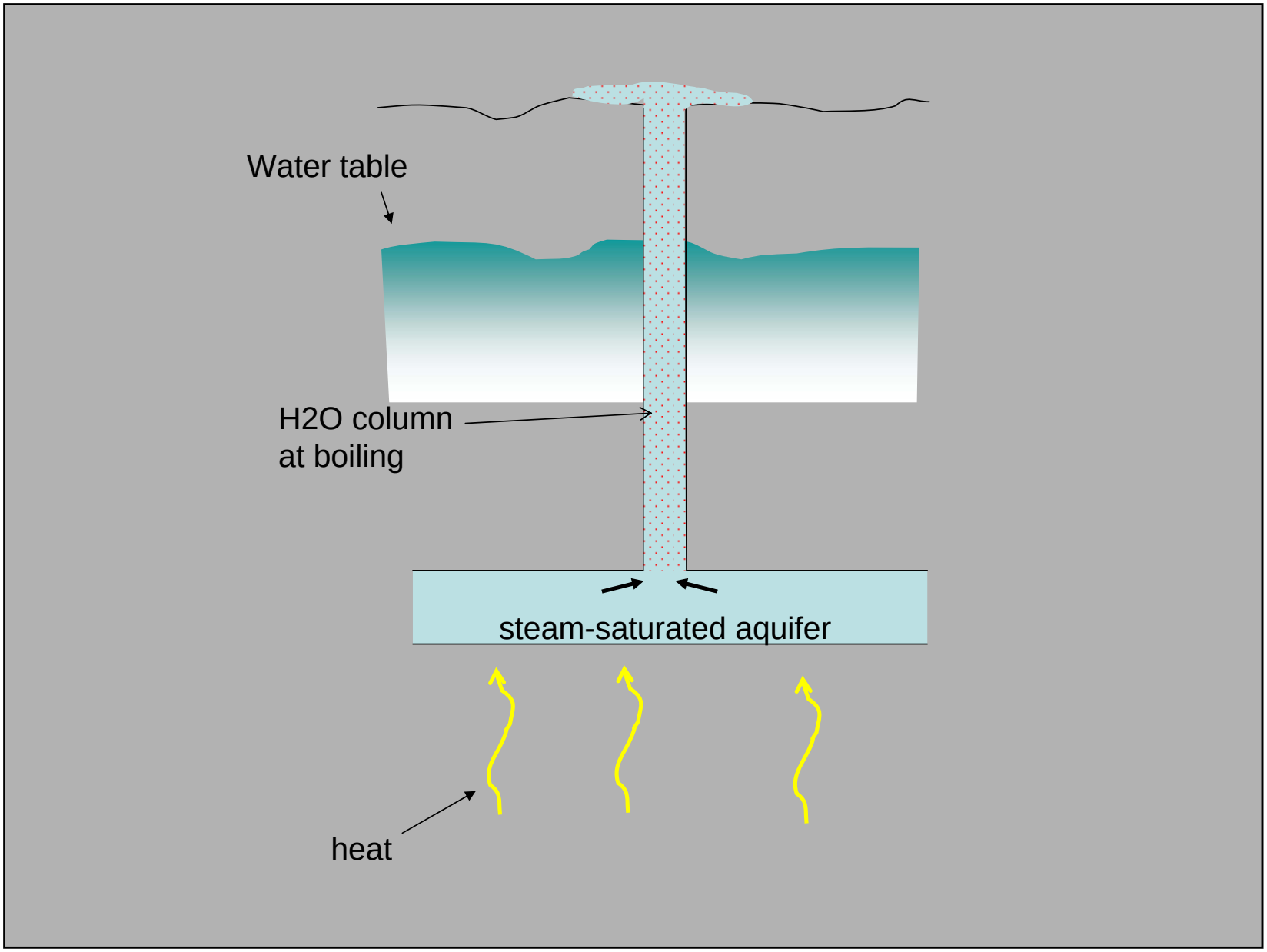

Iceland

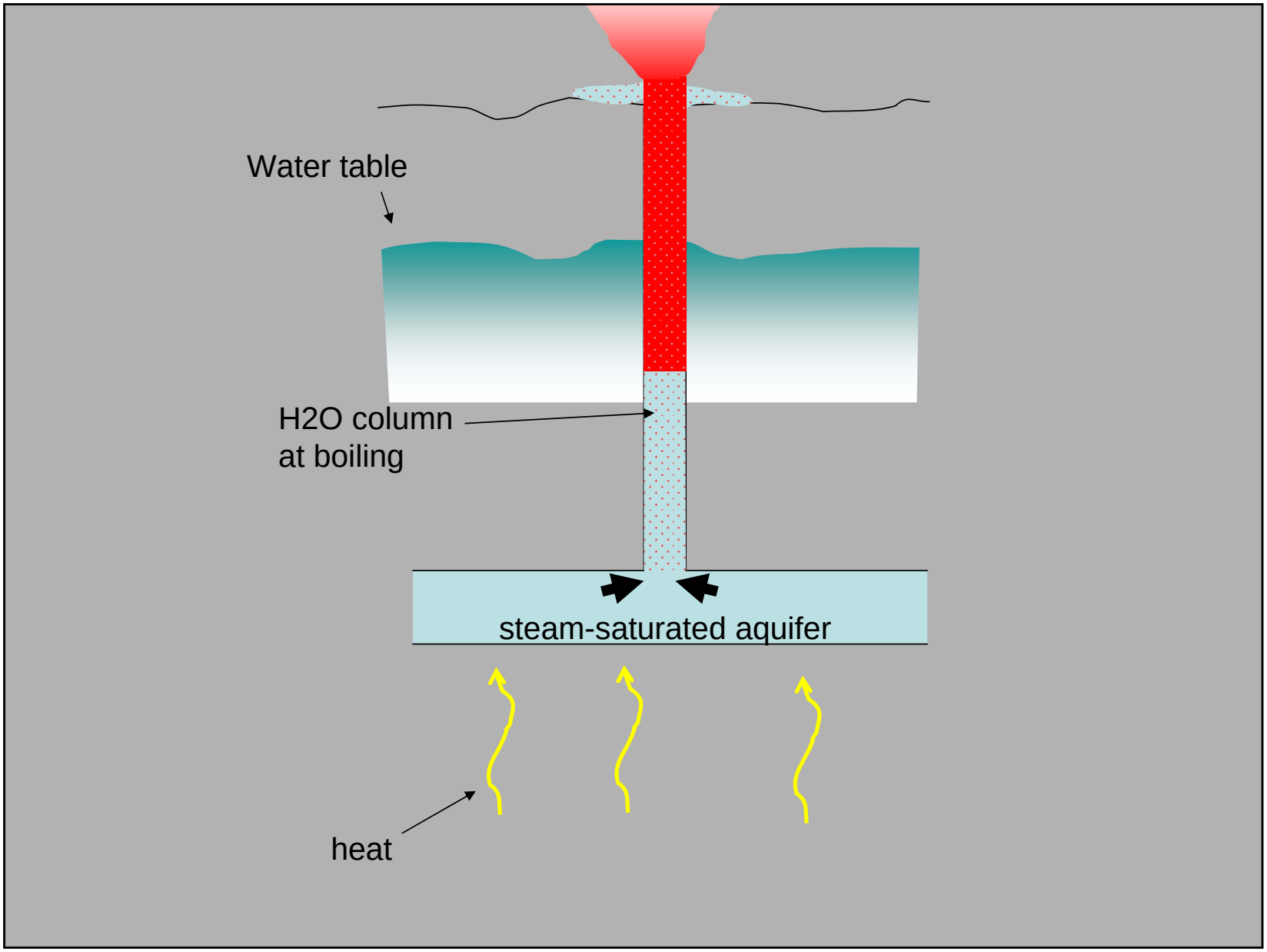
$P_V > P_L$




$P_V > P_L$


Water table
H2O column
at boiling
steam-saturated aquifer
heat

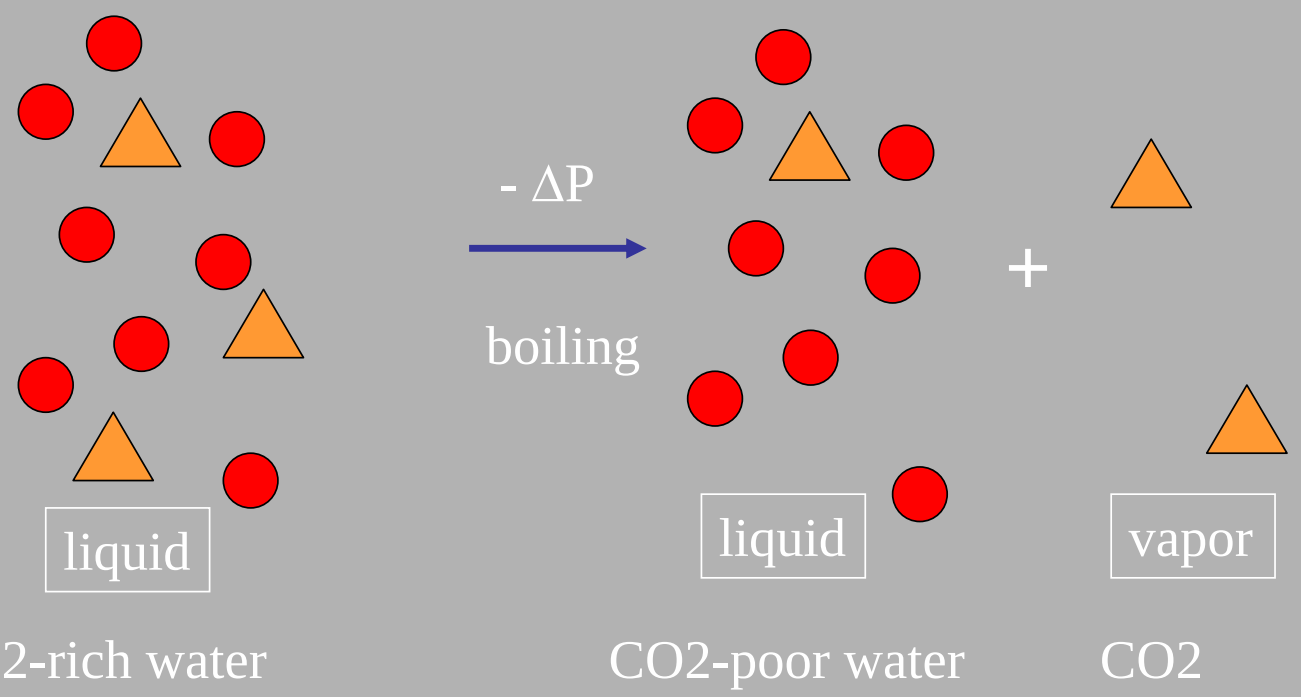

Water table
H2O column
at boiling
steam-saturated aquifer
heat

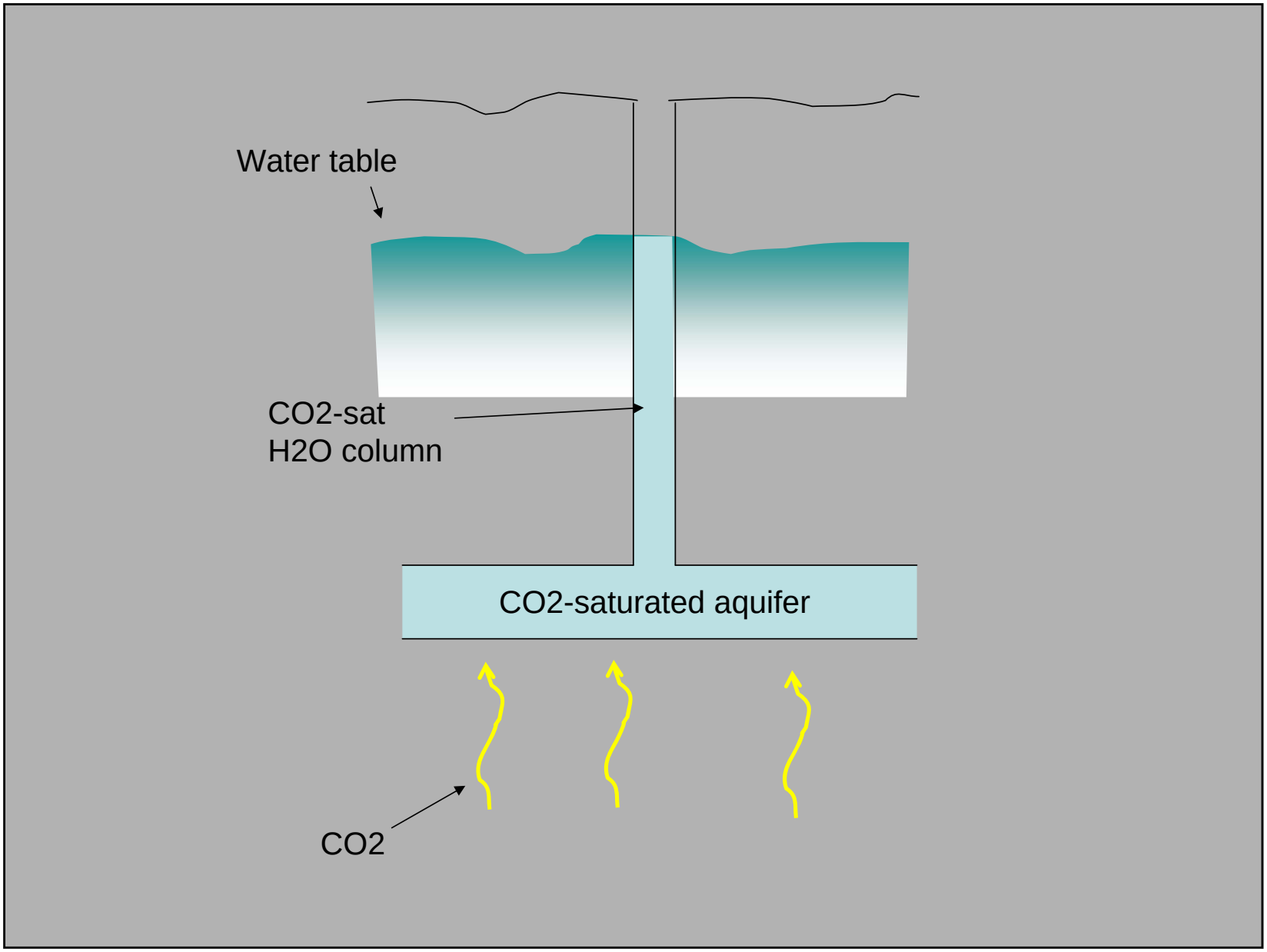

Water table
H2O column
at boiling
steam-saturated aquifer
heat

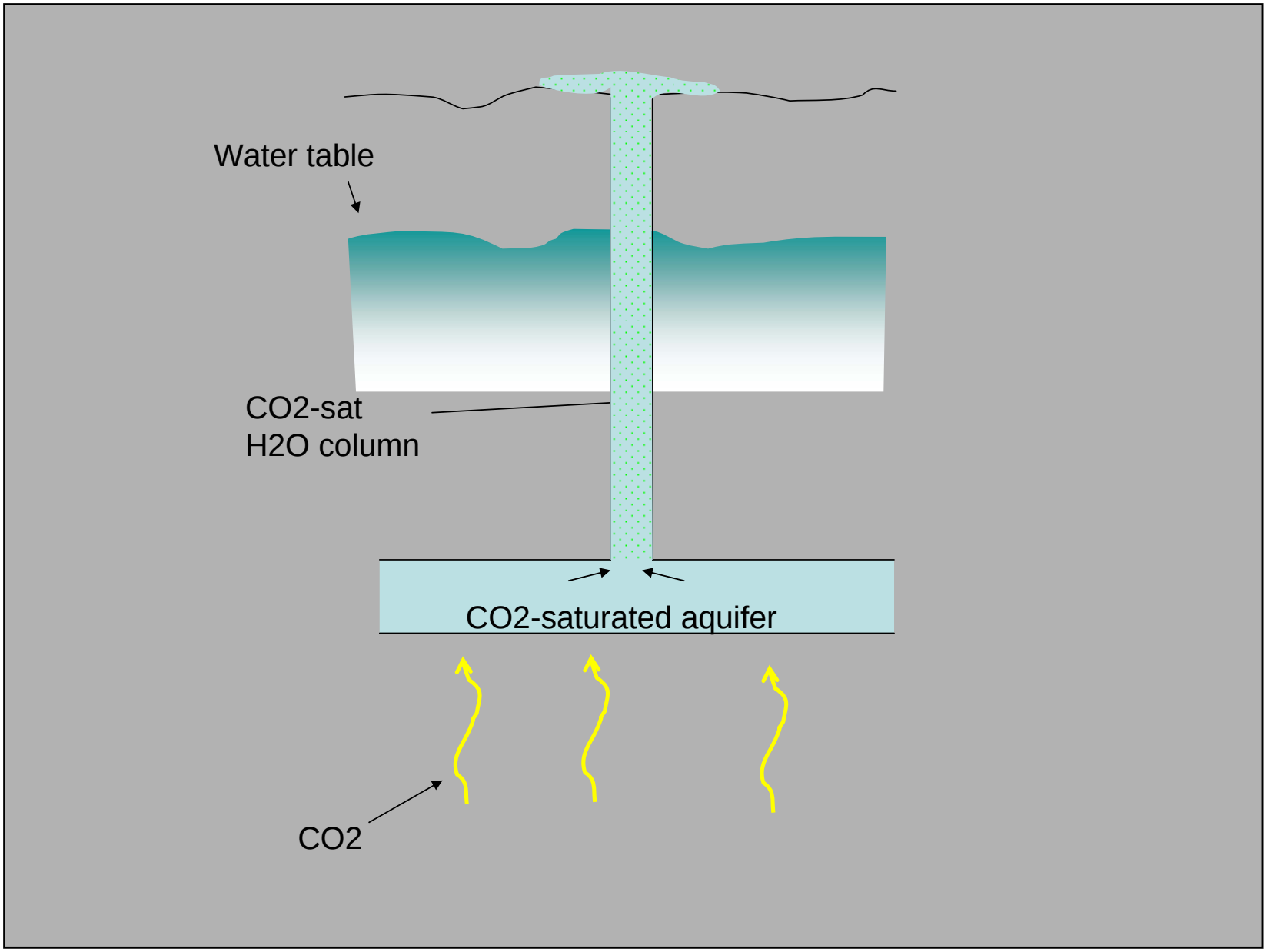
This is cold water!

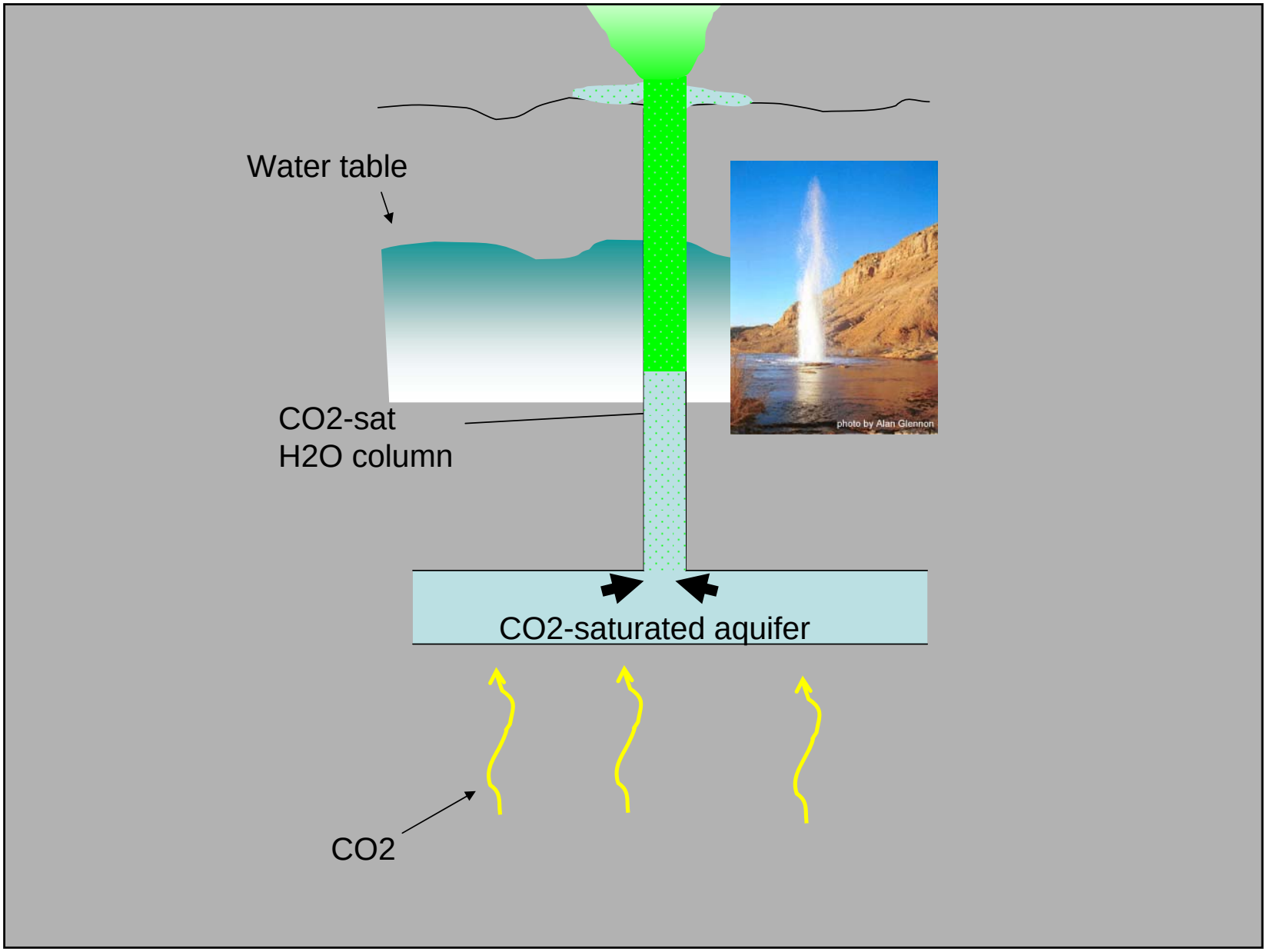
Carbonated water geyser.

At P and T of “Boiling” (vapor saturation)

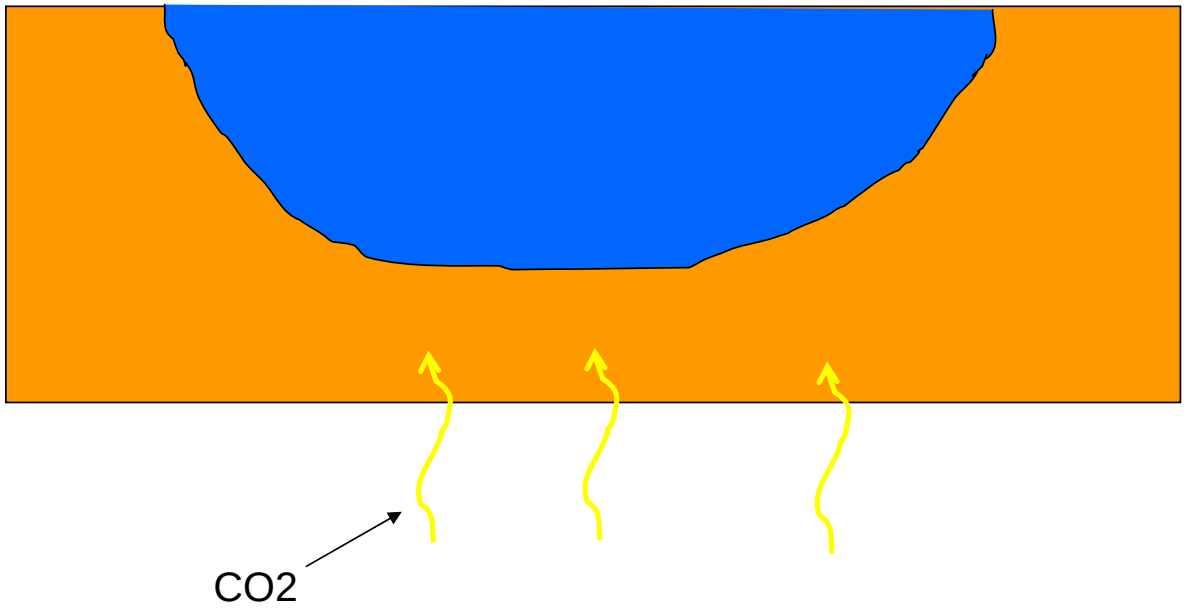


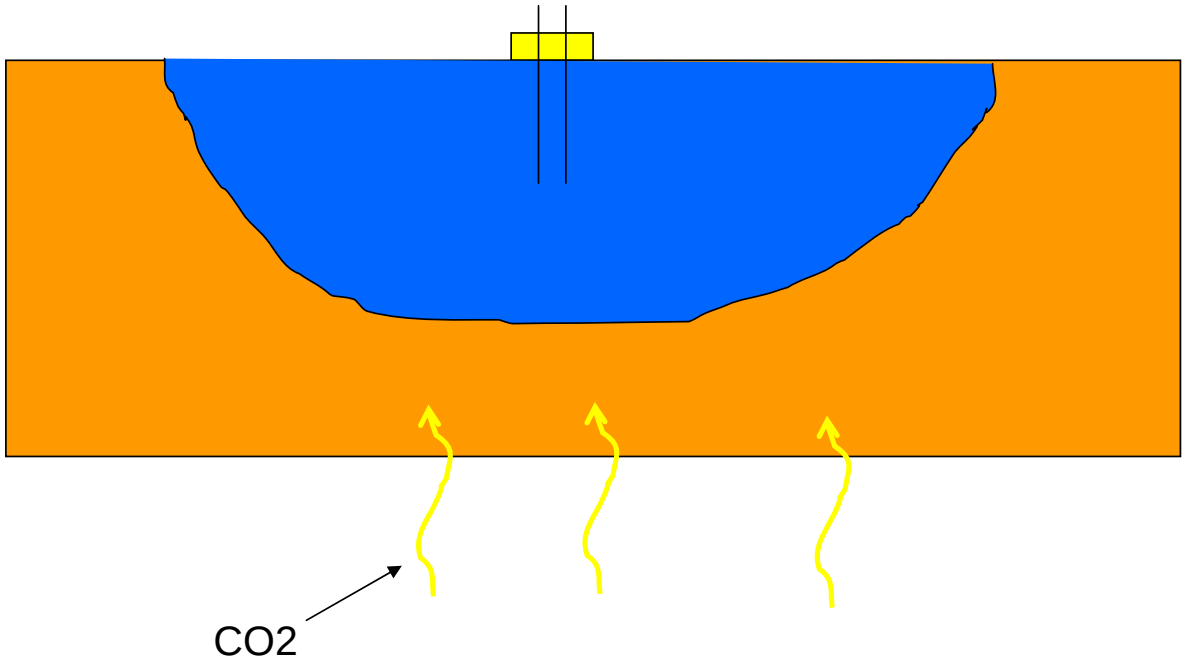

Water table
CO2-sat
H2O column
CO2-saturated aquifer
CO2

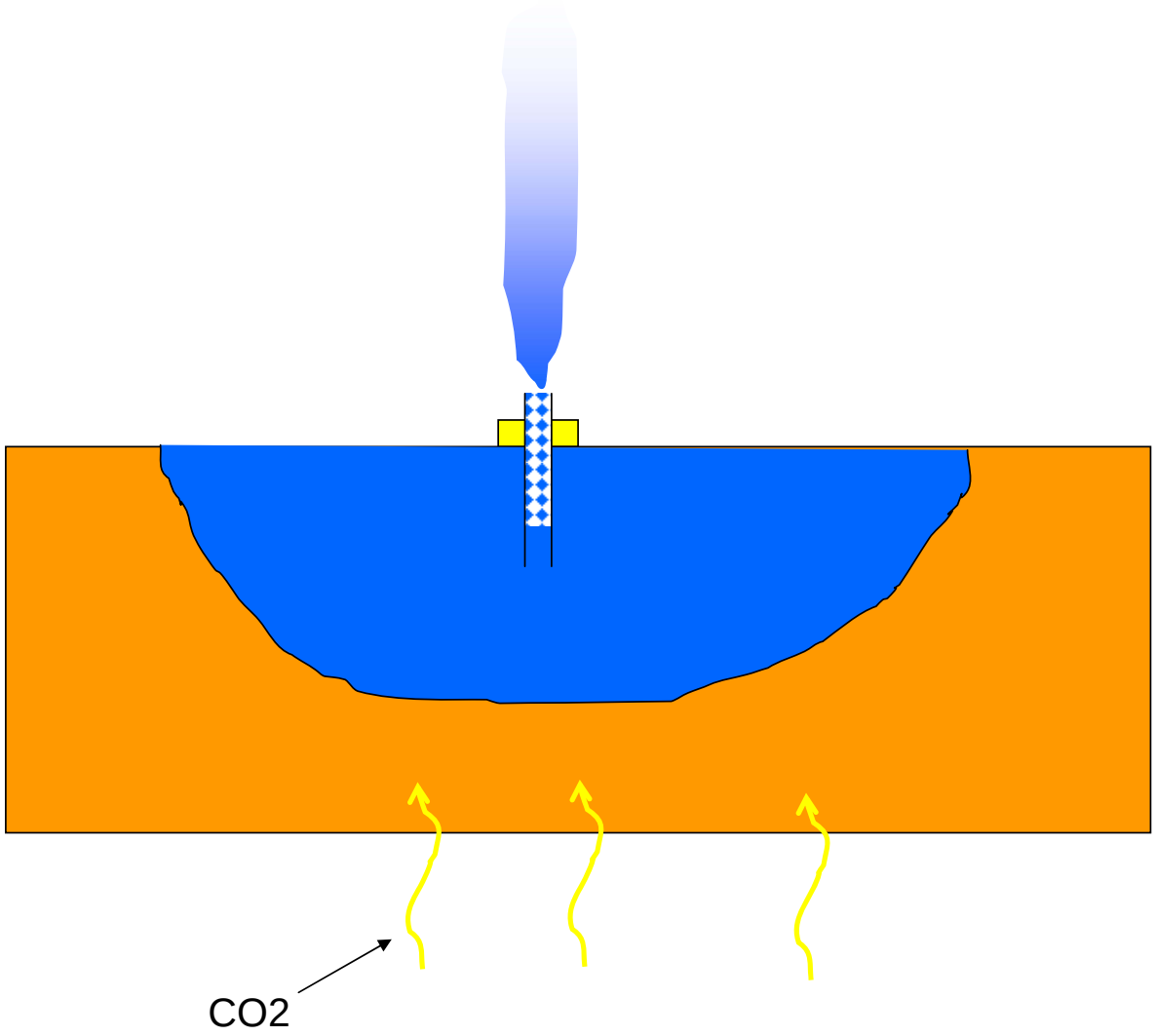

Water table
CO2-sat
H2O column
CO2-saturated aquifer
CO2

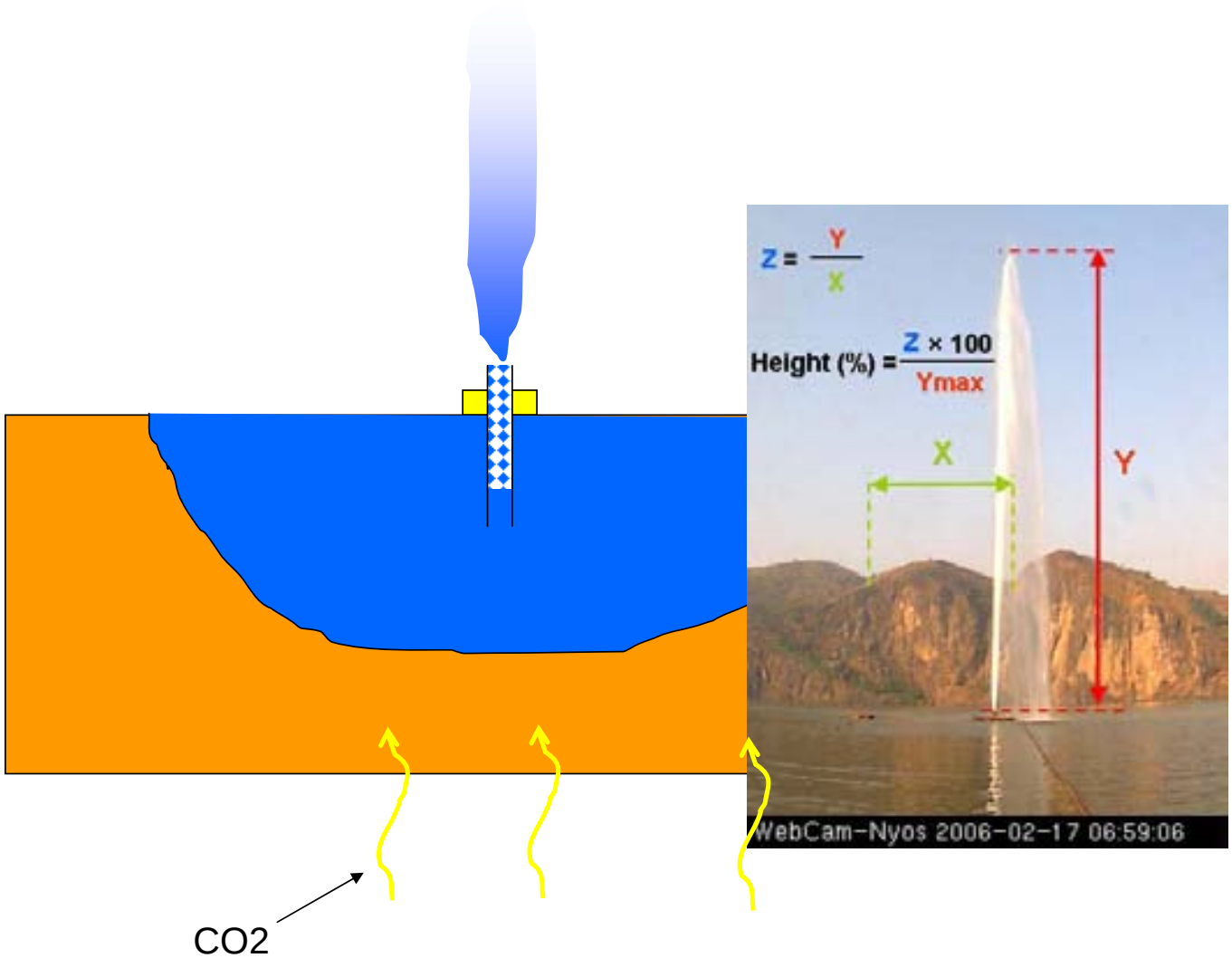

Water table
CO2-sat
H2O column
photo by Alan Glennon
CO2-saturated aquifer
CO2

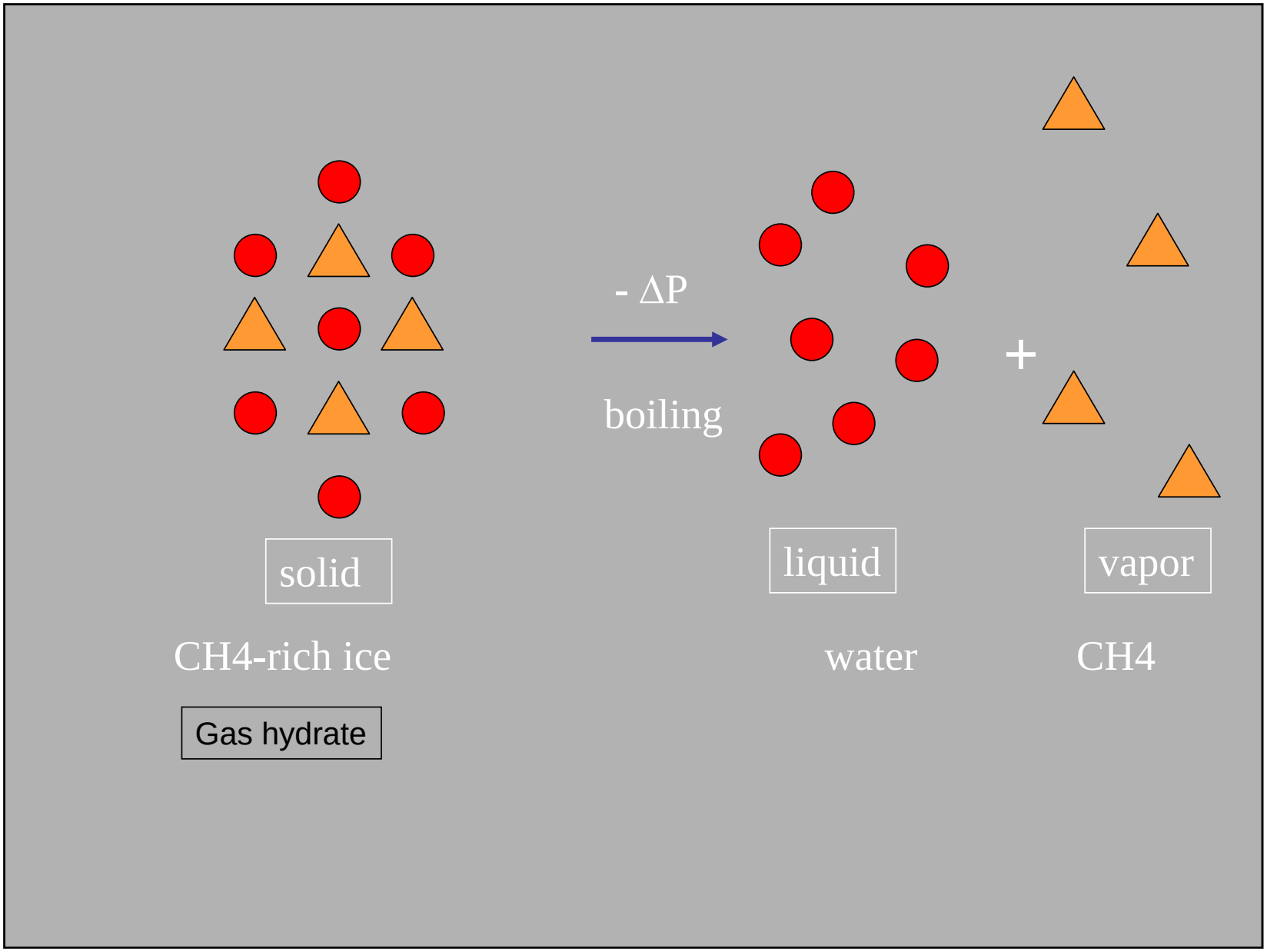
Lake Nyos, Cameroon: CO2-staurated crater lake



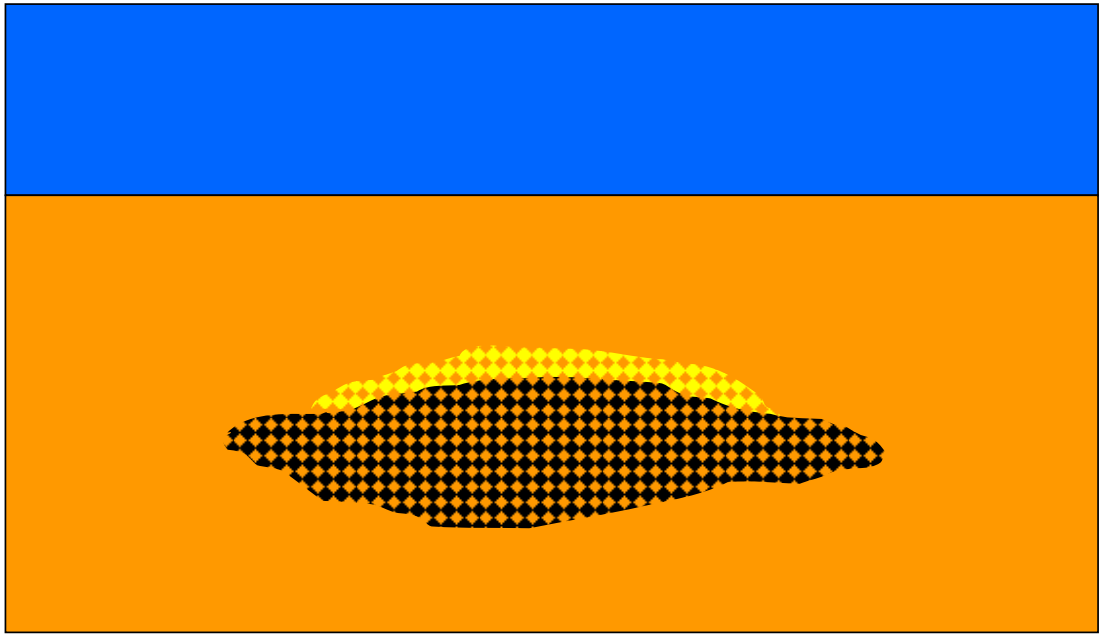

CO2

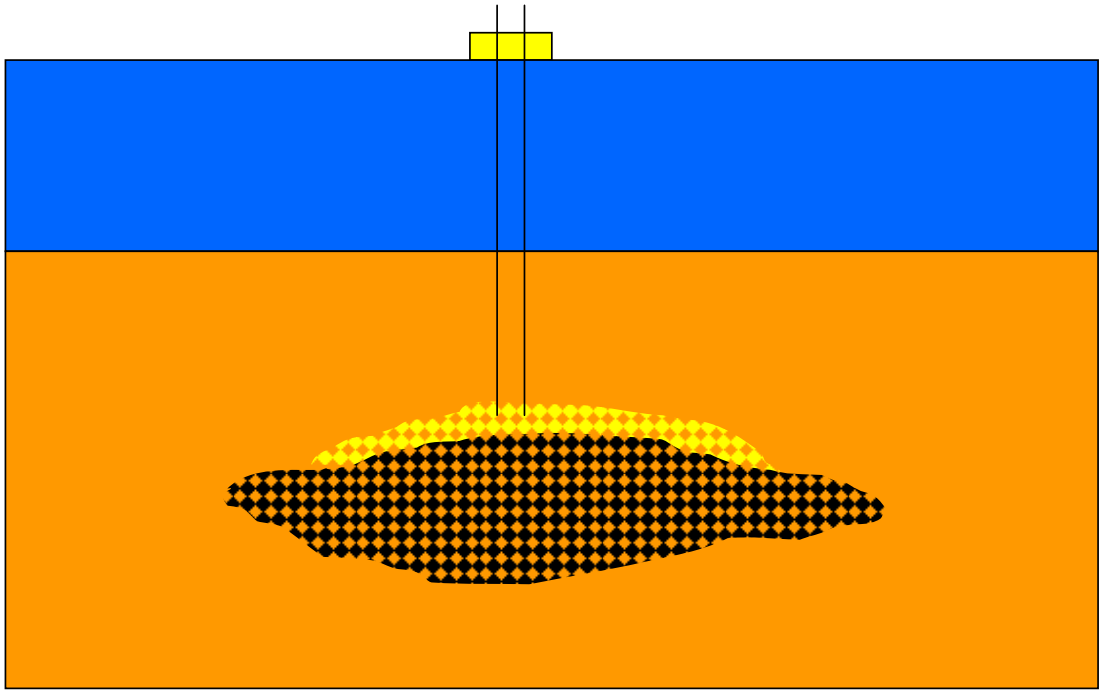

CO2

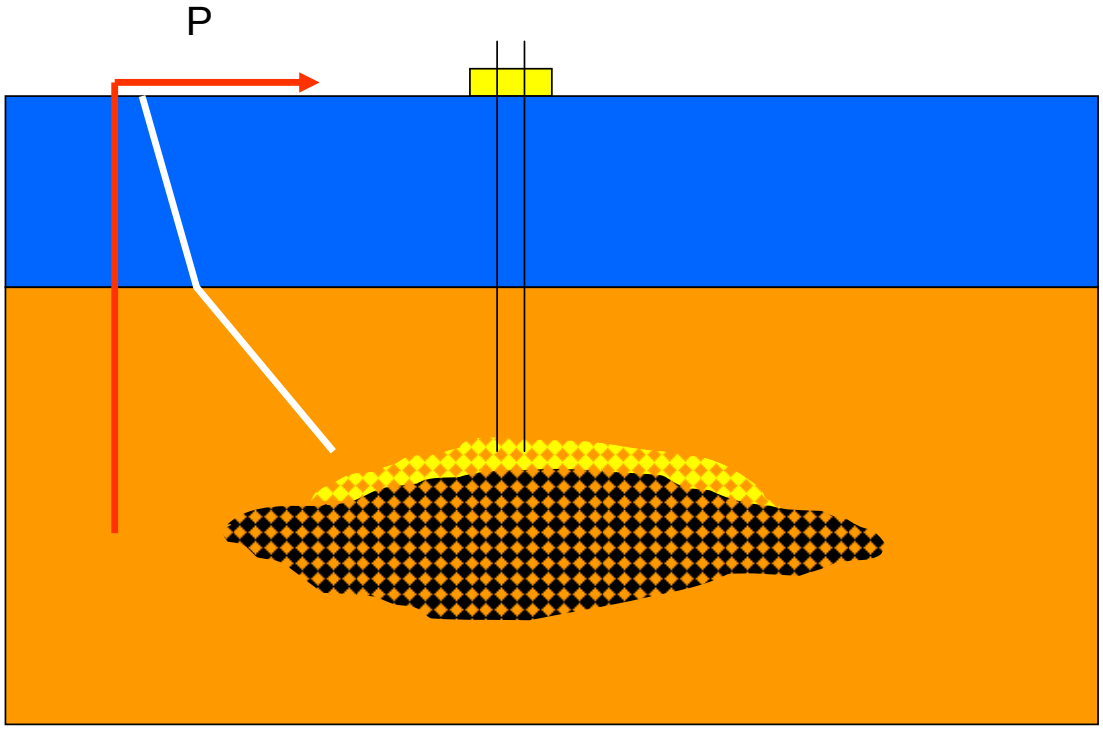

Z = Y / X
Height (%) = Z × 100 / Ymax
X
Y
WebCam-Nyos 2006-02-17 06:59:06
CO2

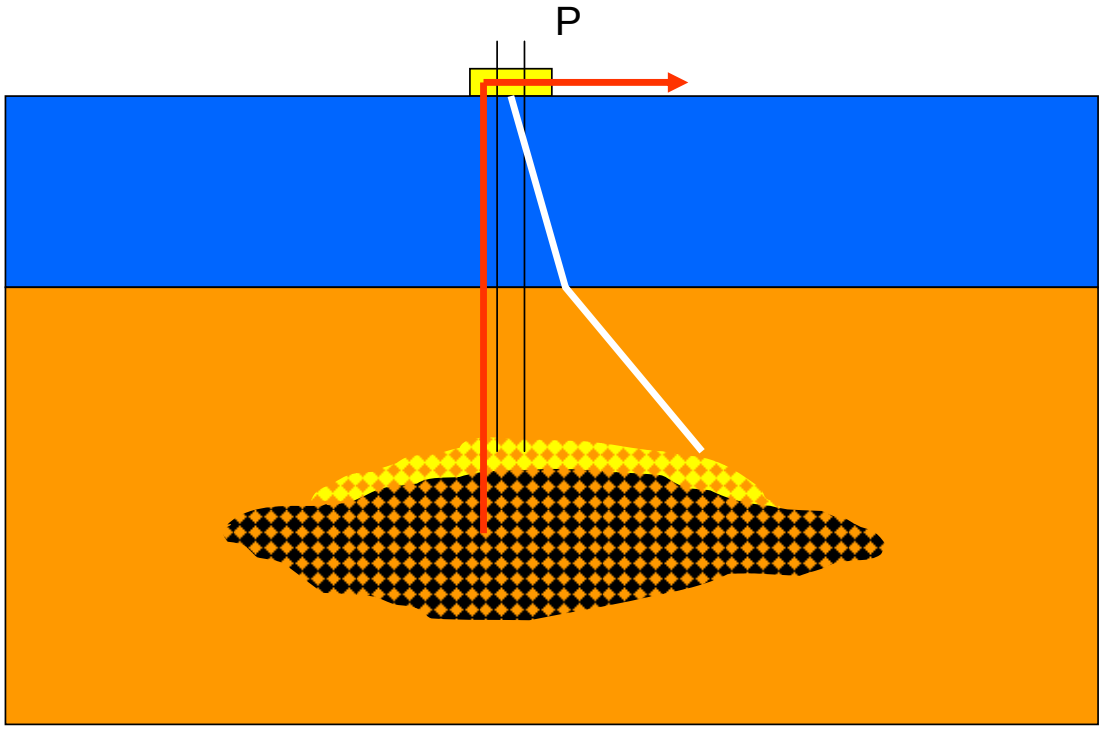

- ΔP
boiling
+
solid
liquid
vapor
CH4-rich ice
water
CH4
Gas hydrate

Gas-rich oil geyser (artificial)






P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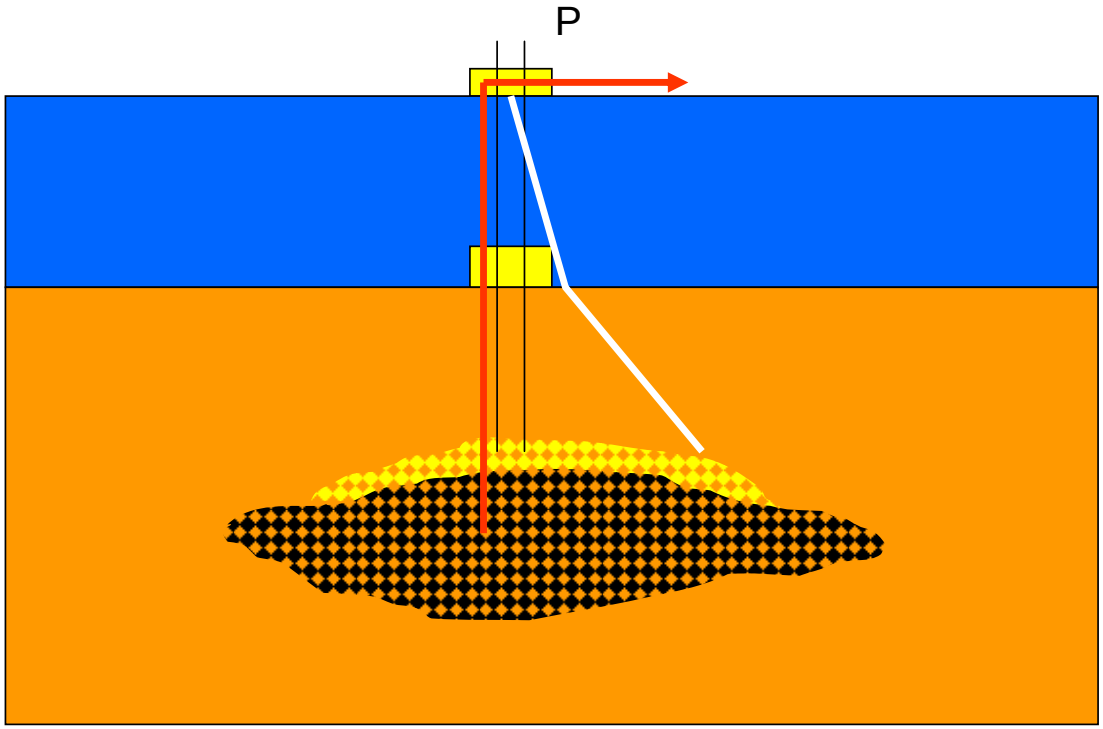
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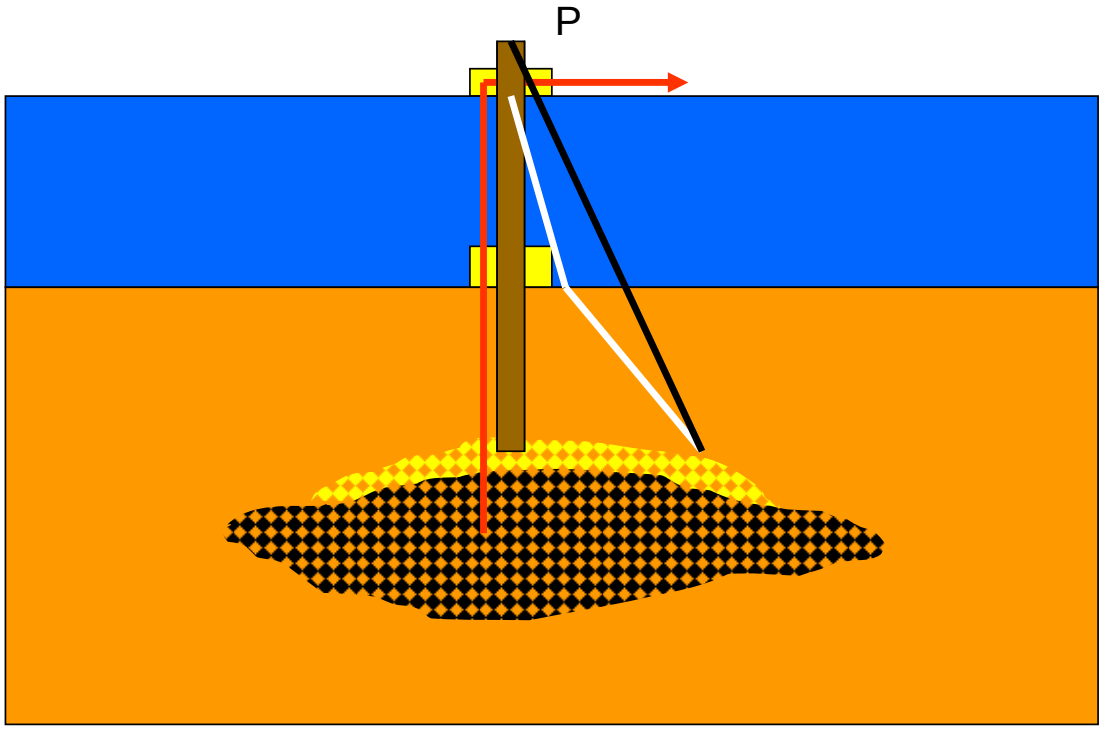
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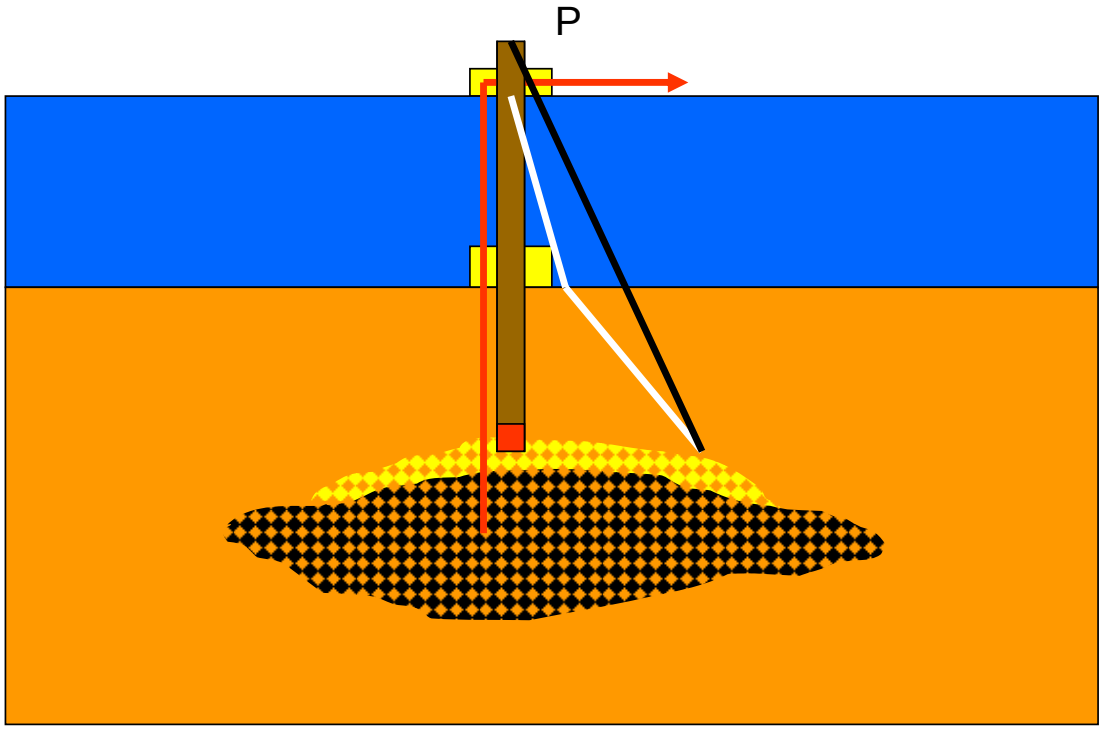
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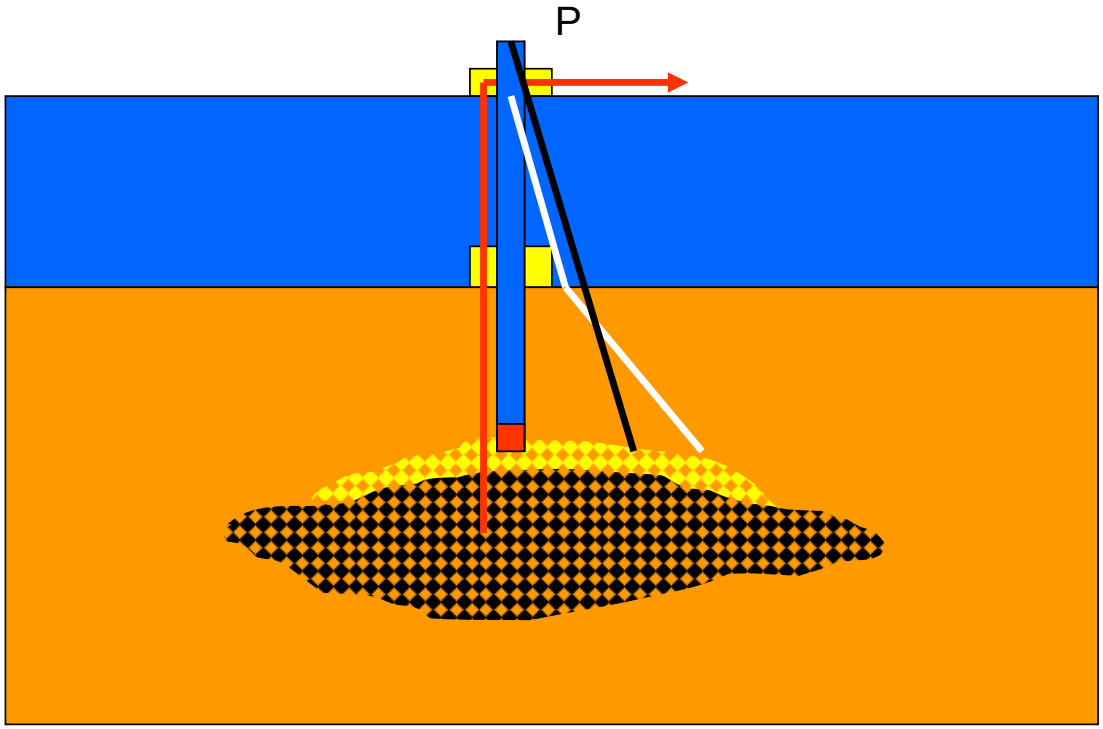
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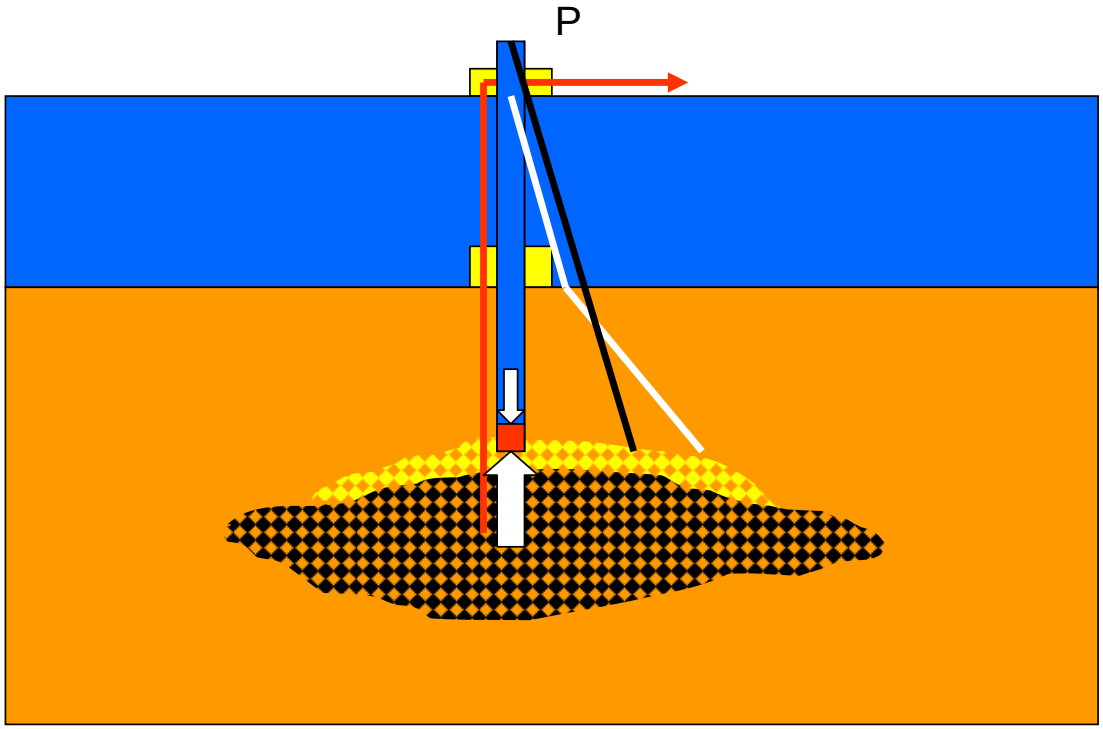
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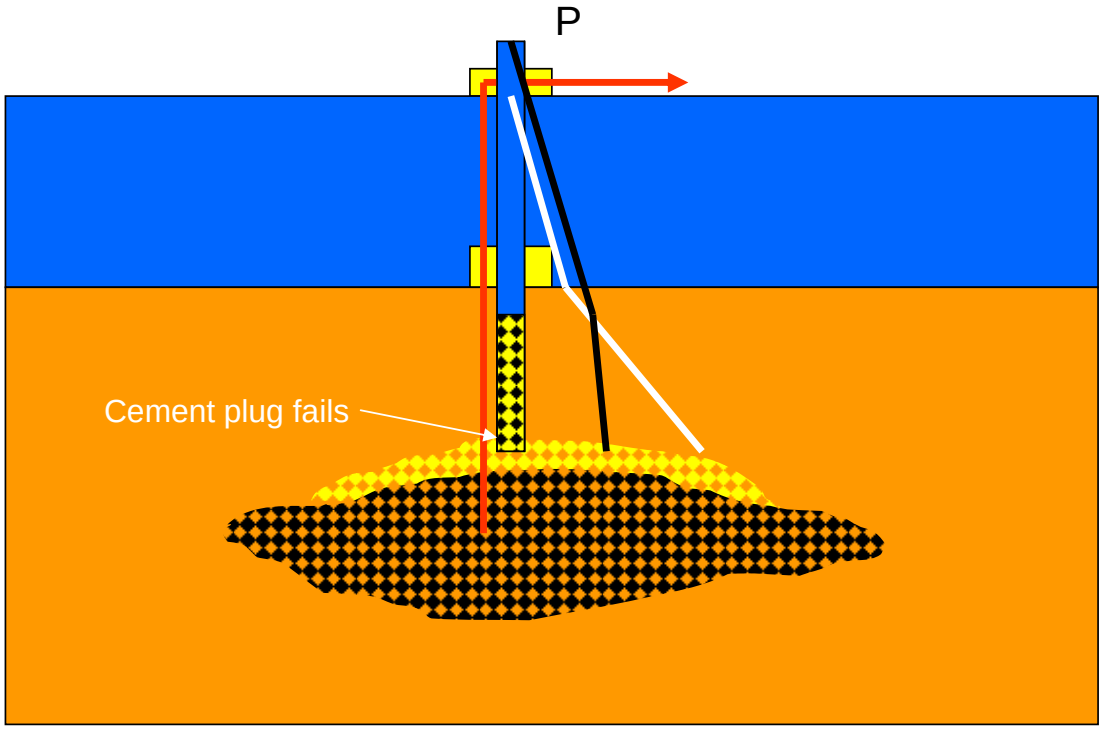
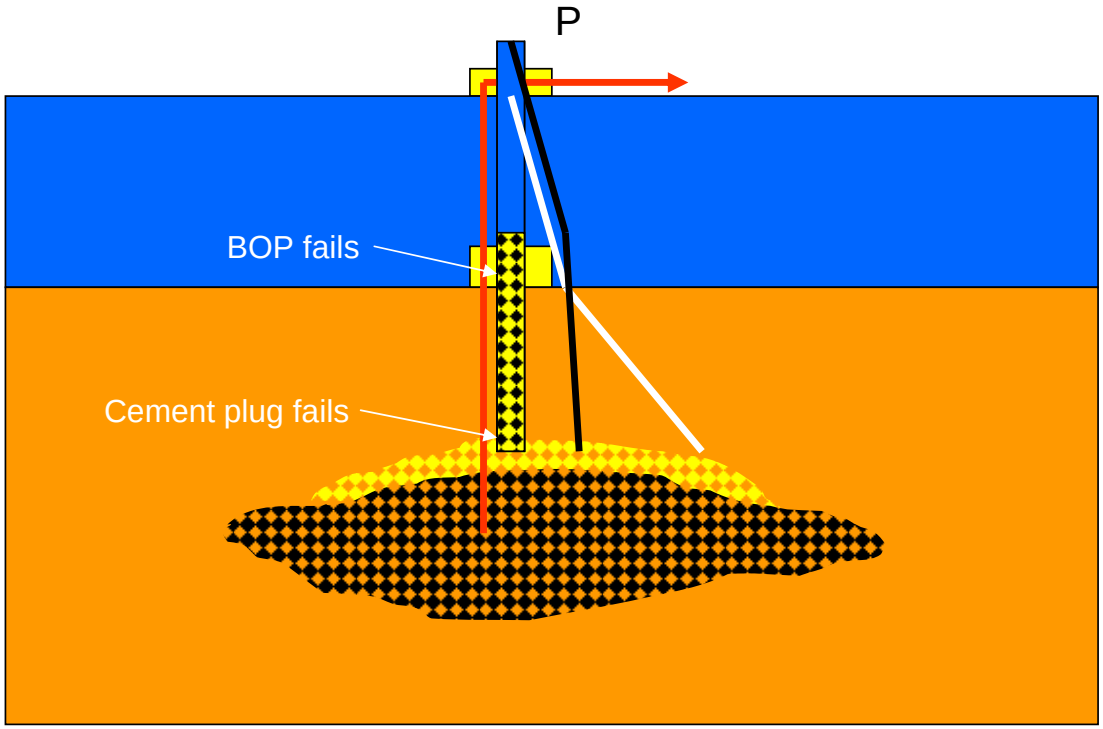
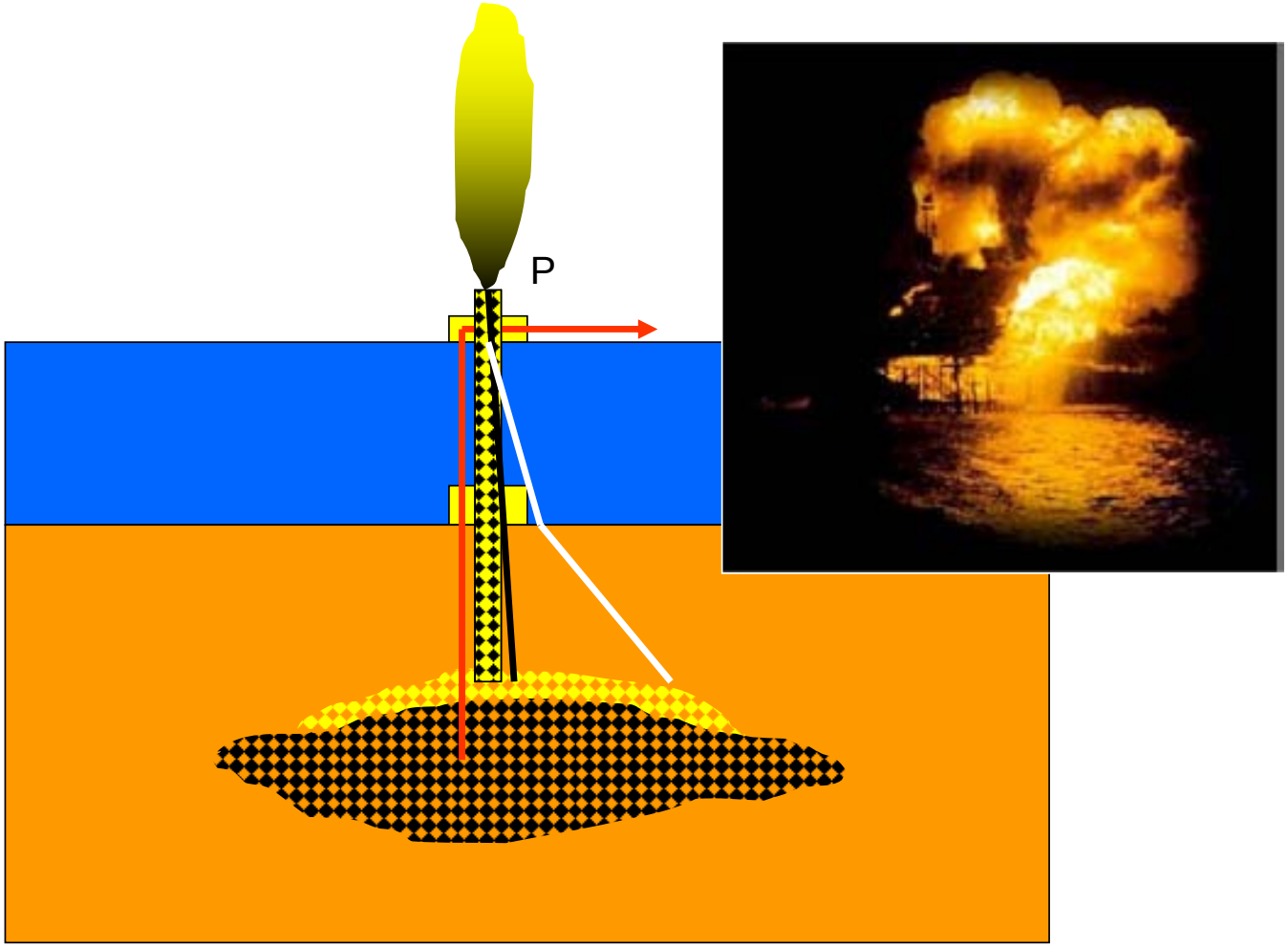
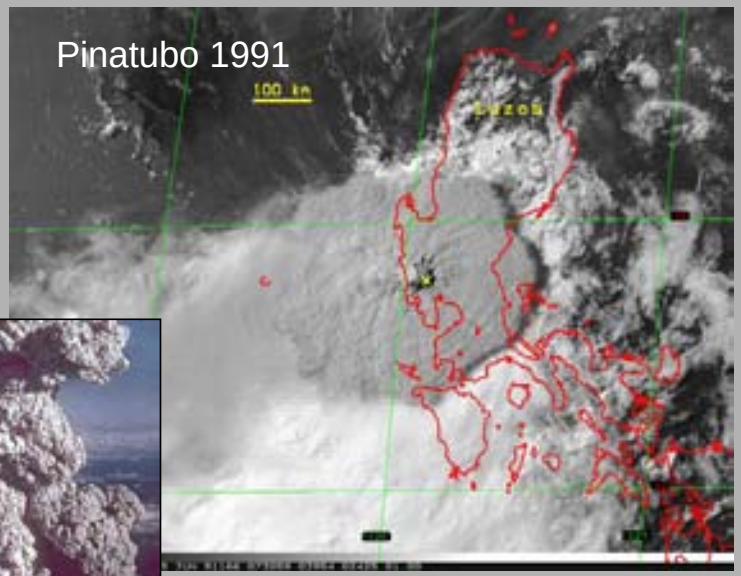

P
Cement plug fails

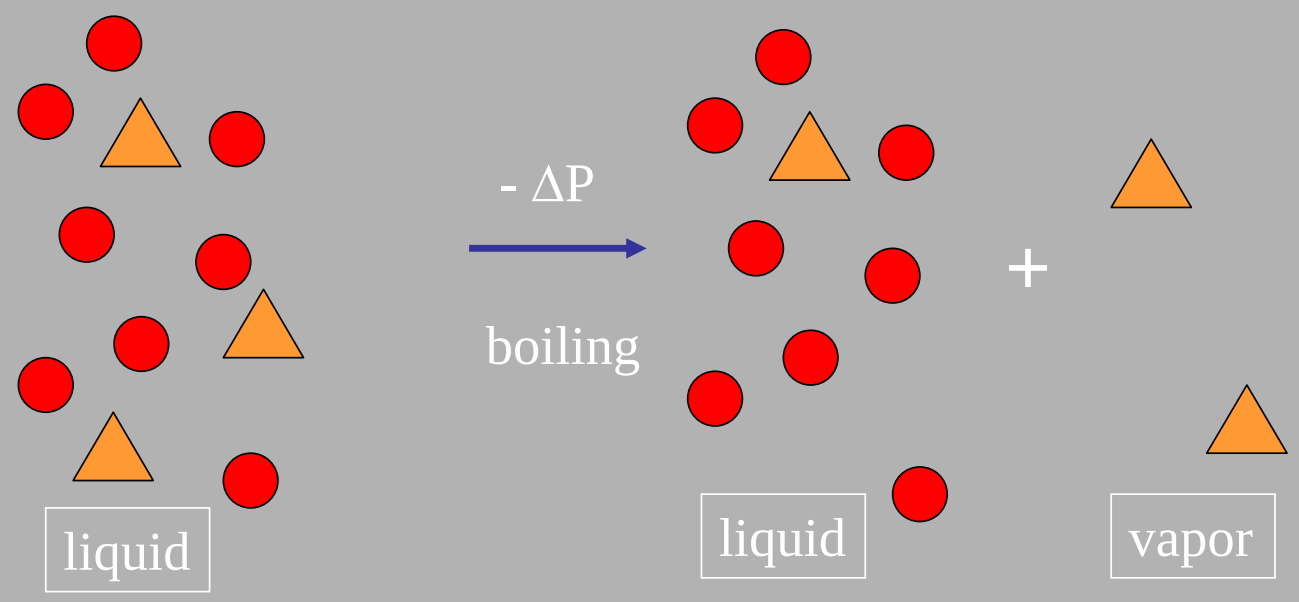

P
BOP fails
Cement plug fails


P

- So what does this have to do with volcanoes?

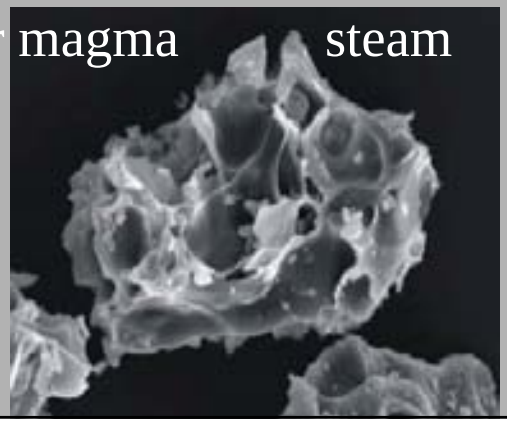


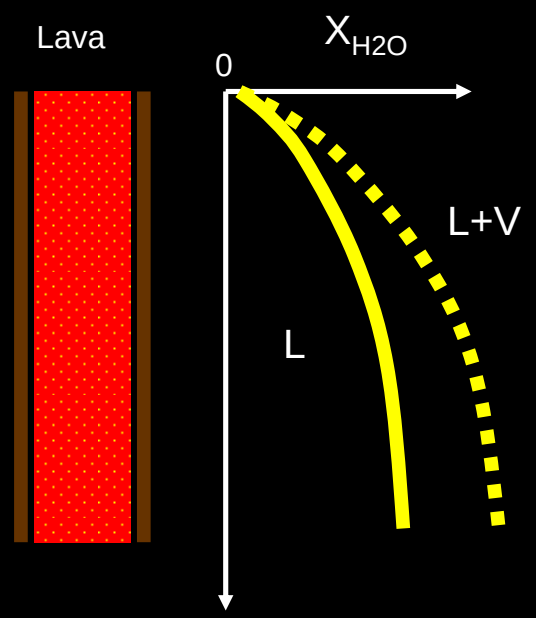

At P and T of “Boiling” (vapor saturation)



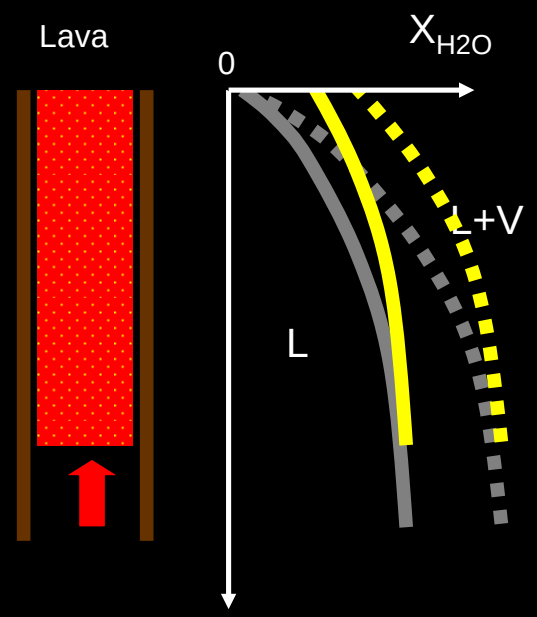

water-rich magma

water-poor magma steam

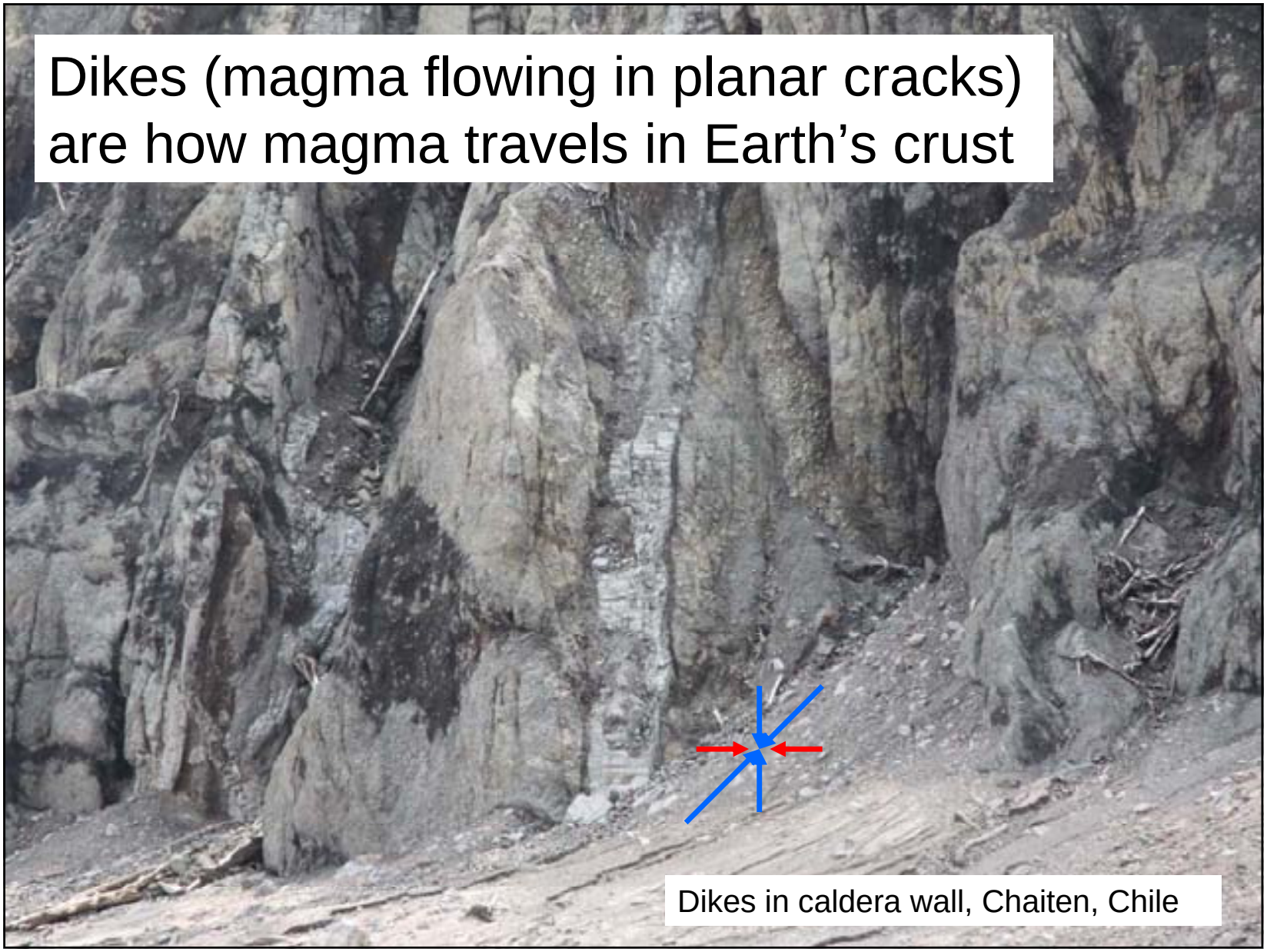


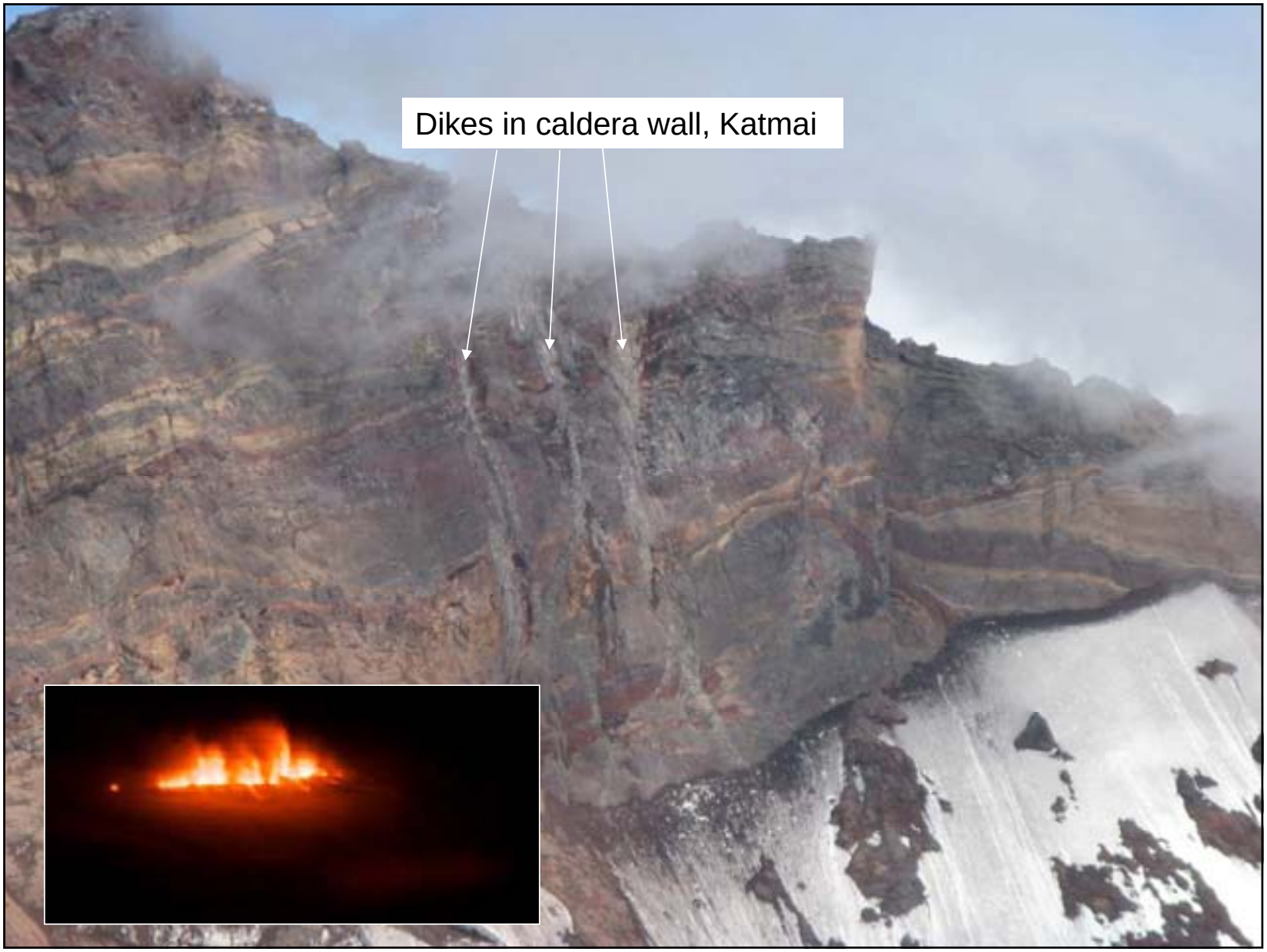


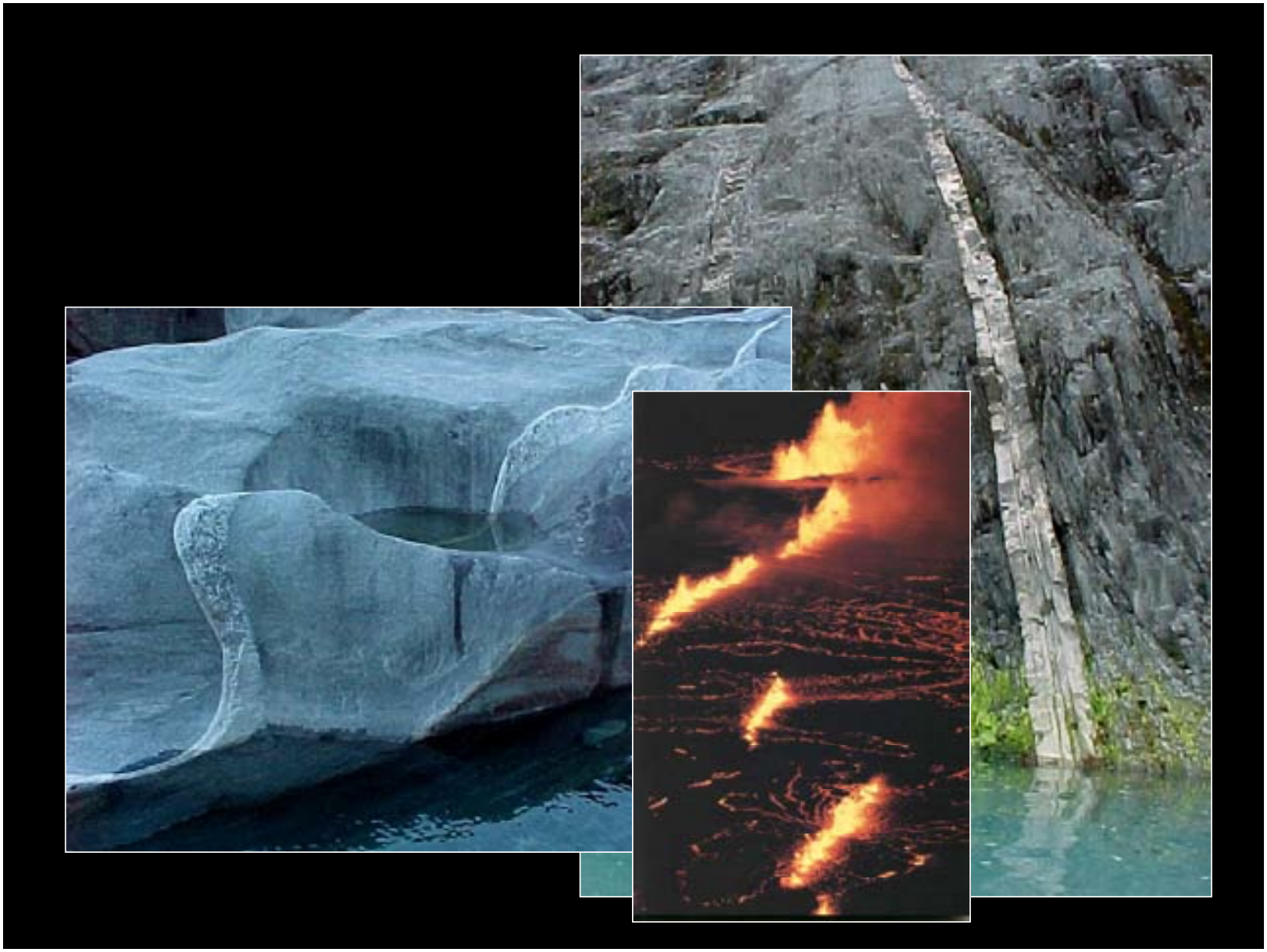

$P_V = P_L$

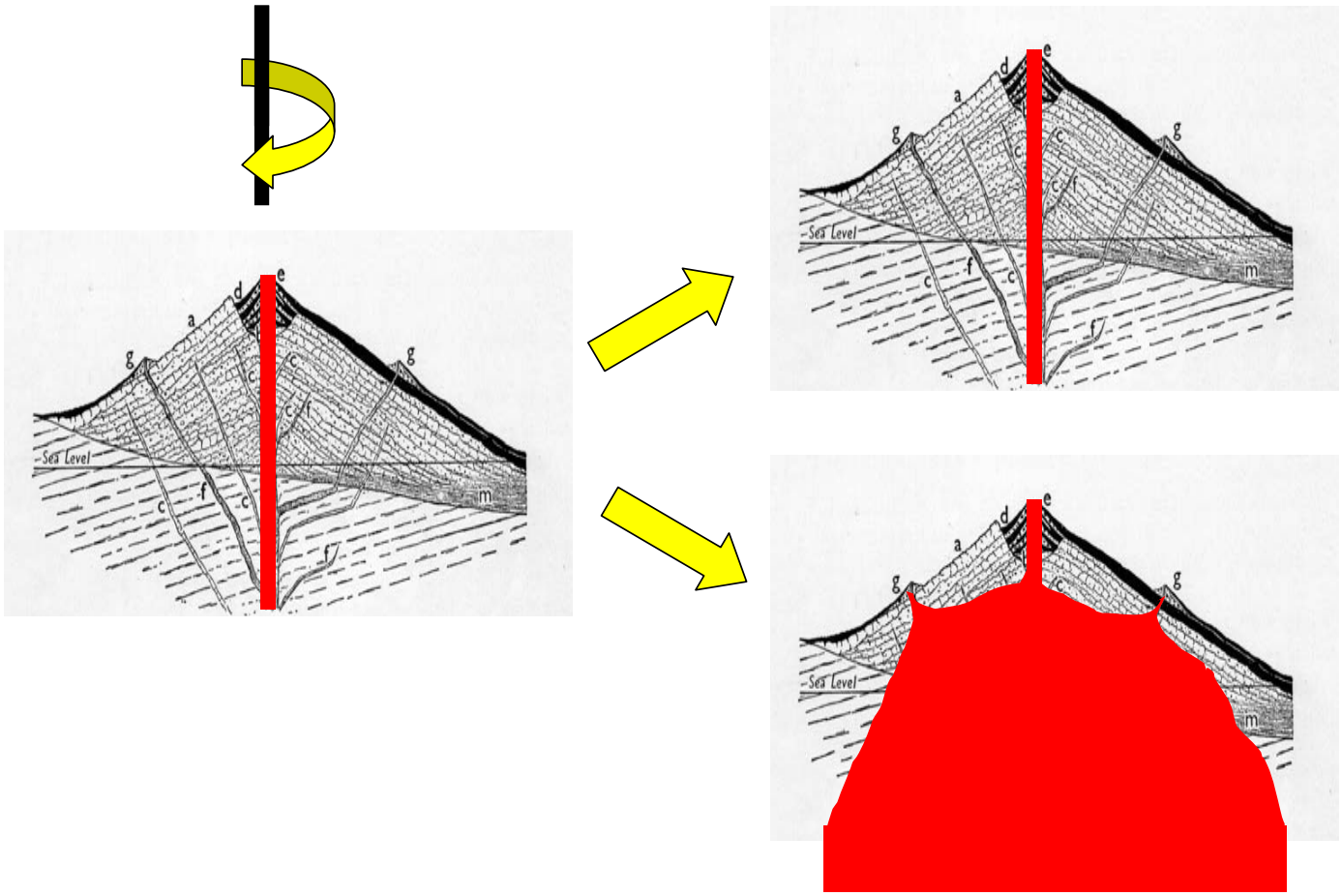


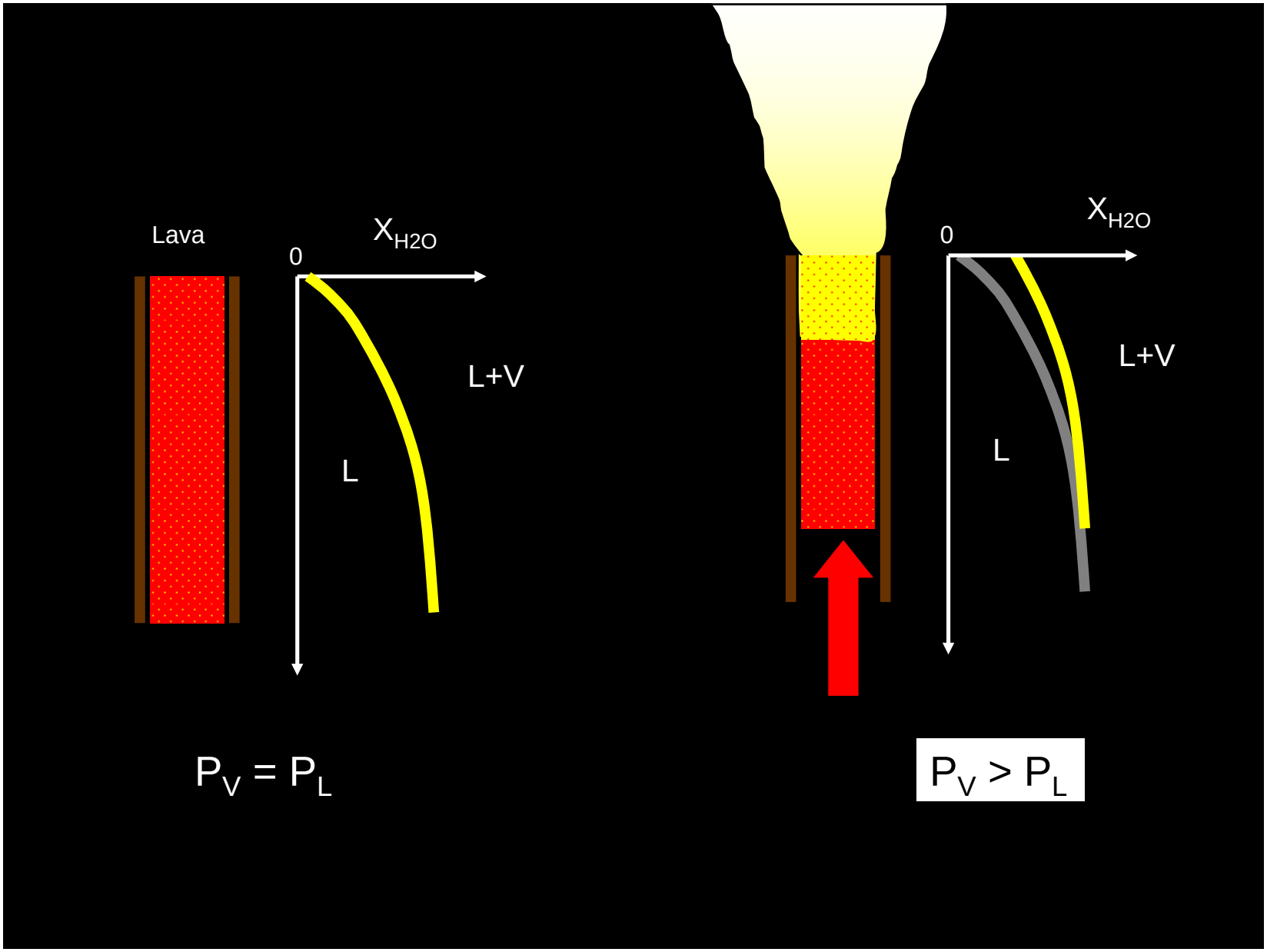

$P_V > P_L$

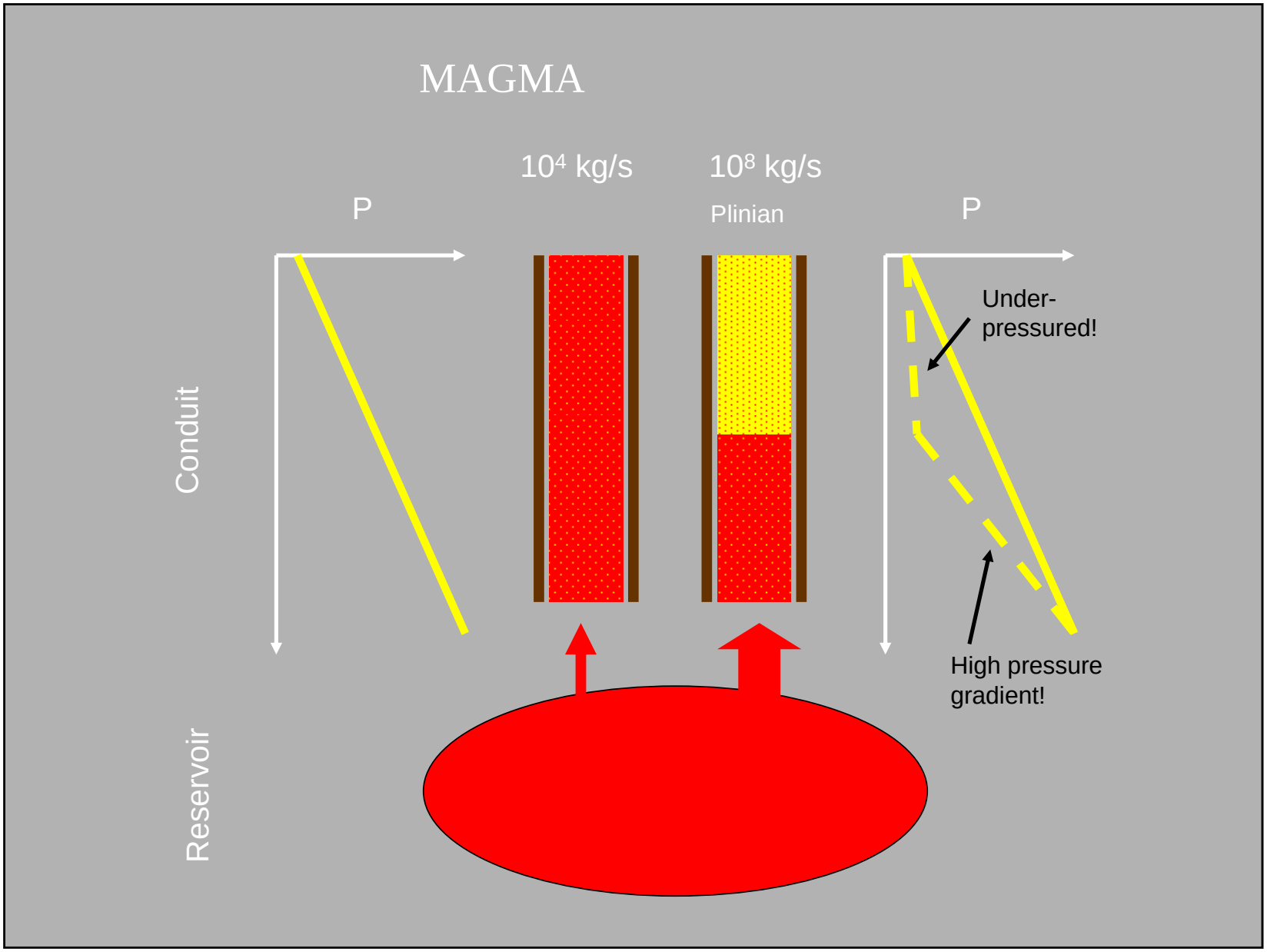

Dikes (magma flowing in planar cracks) are how magma travels in Earth's crust
Dikes in caldera wall, Chaiten, Chile

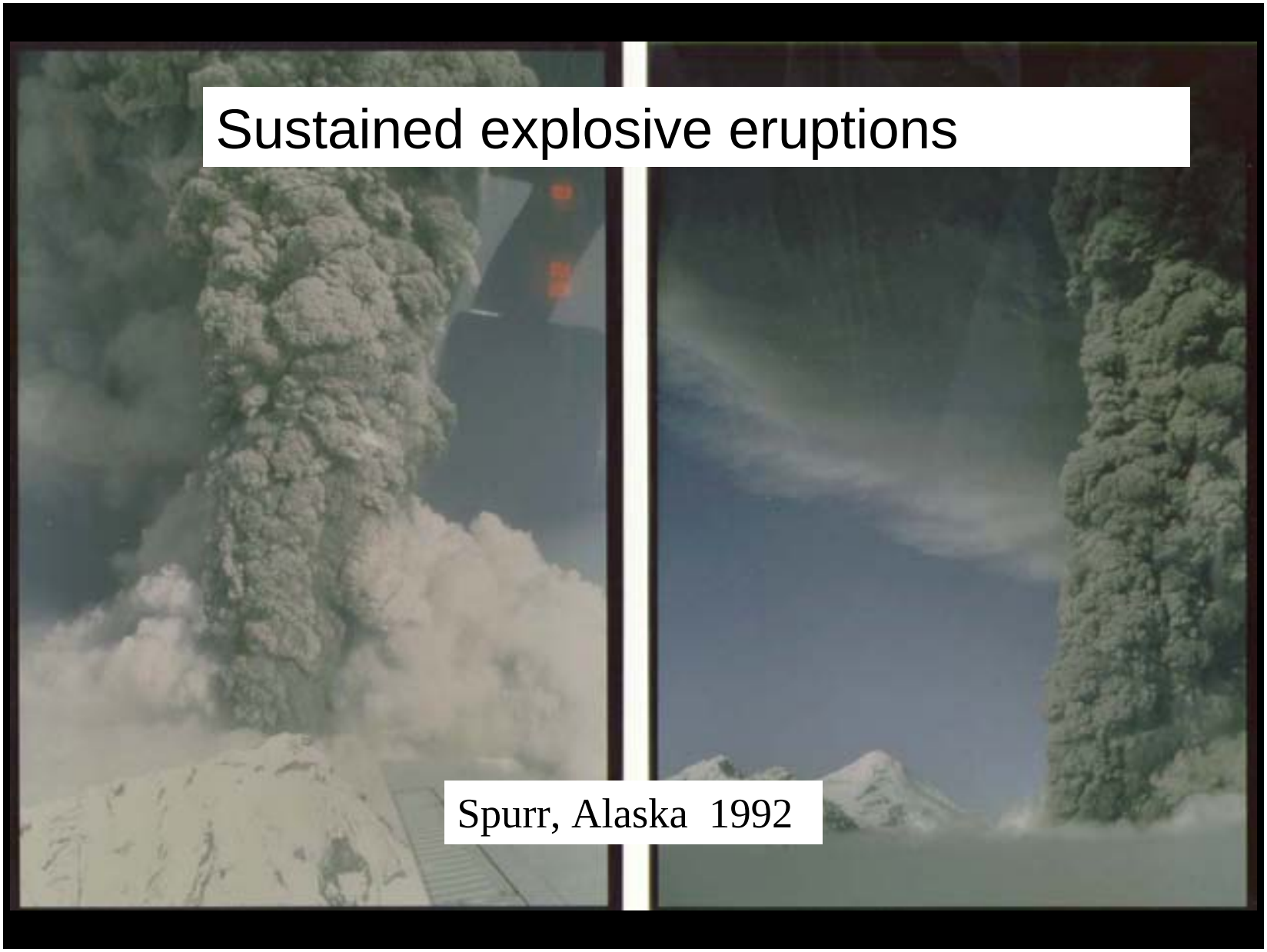

Dikes in caldera wall, Katmai



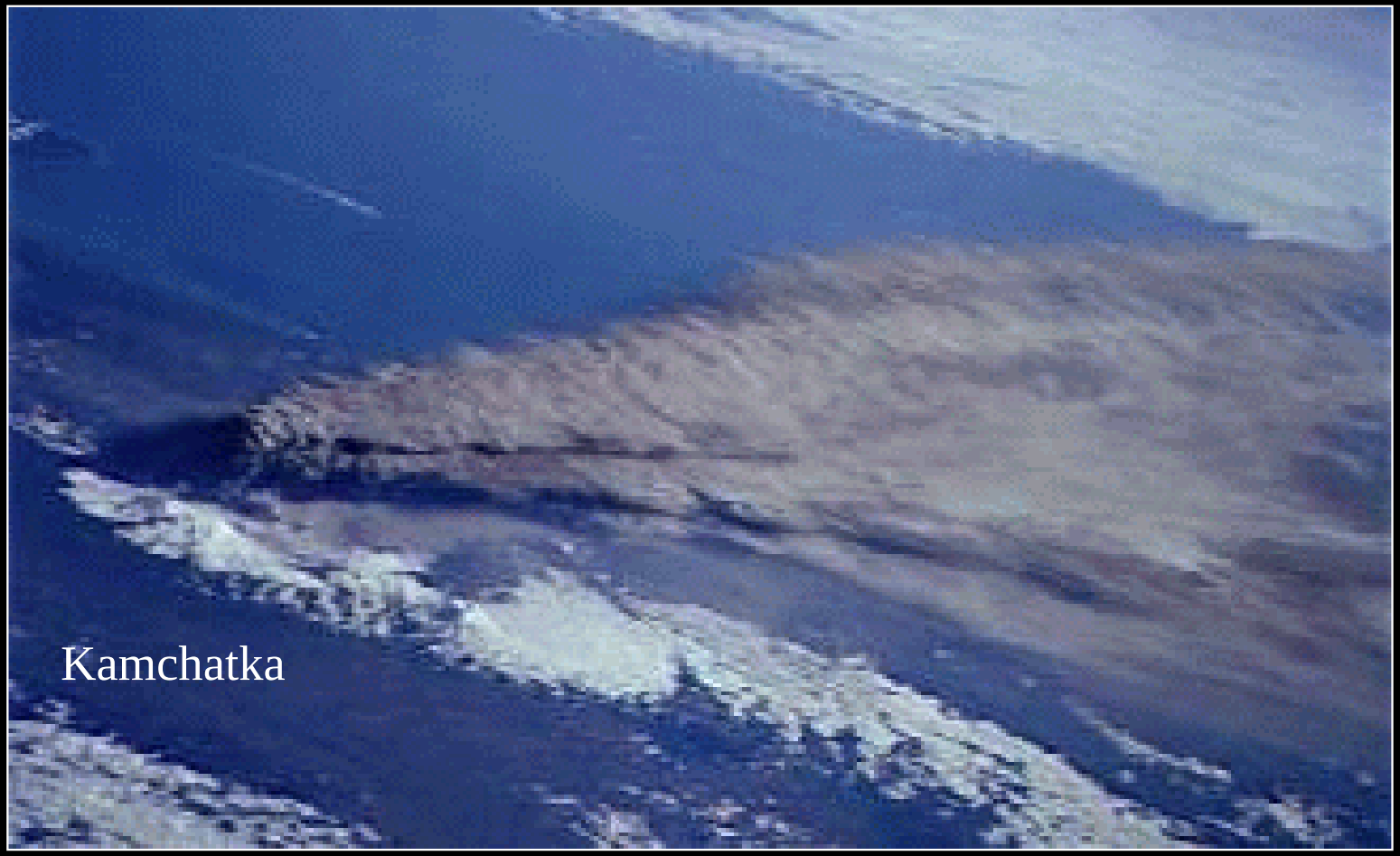

Sea Level
a
c
d
e
f
g
m

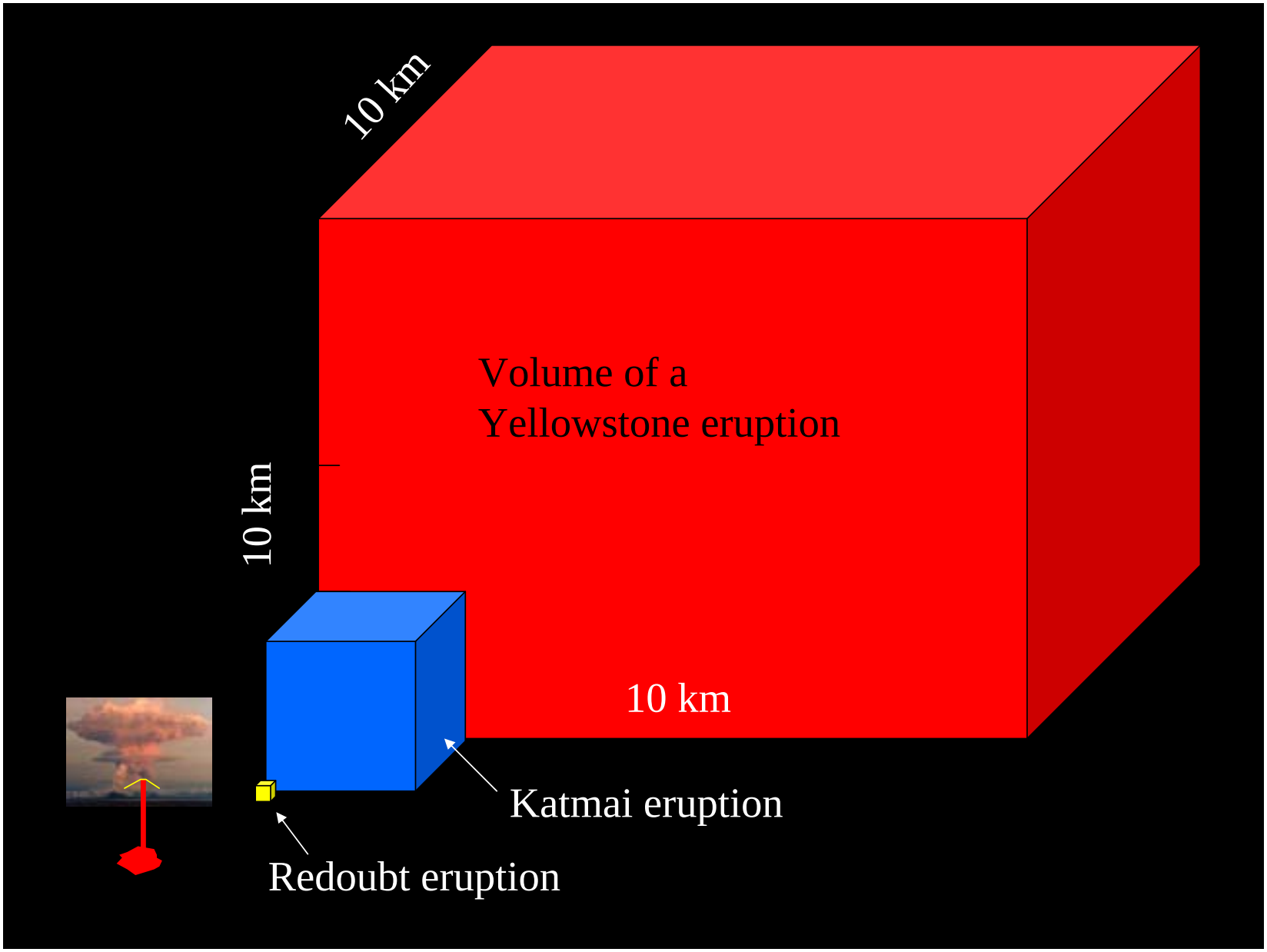

Lava
0
$X_{H2O}$
L+V
L
$P_V = P_L$
0
$X_{H2O}$
L+V
L
$P_V > P_L$


MAGMA
$10^4$ kg/s
$10^8$ kg/s
Plinian
P
P
Under-
pressured!
High pressure
gradient!
Conduit
Reservoir

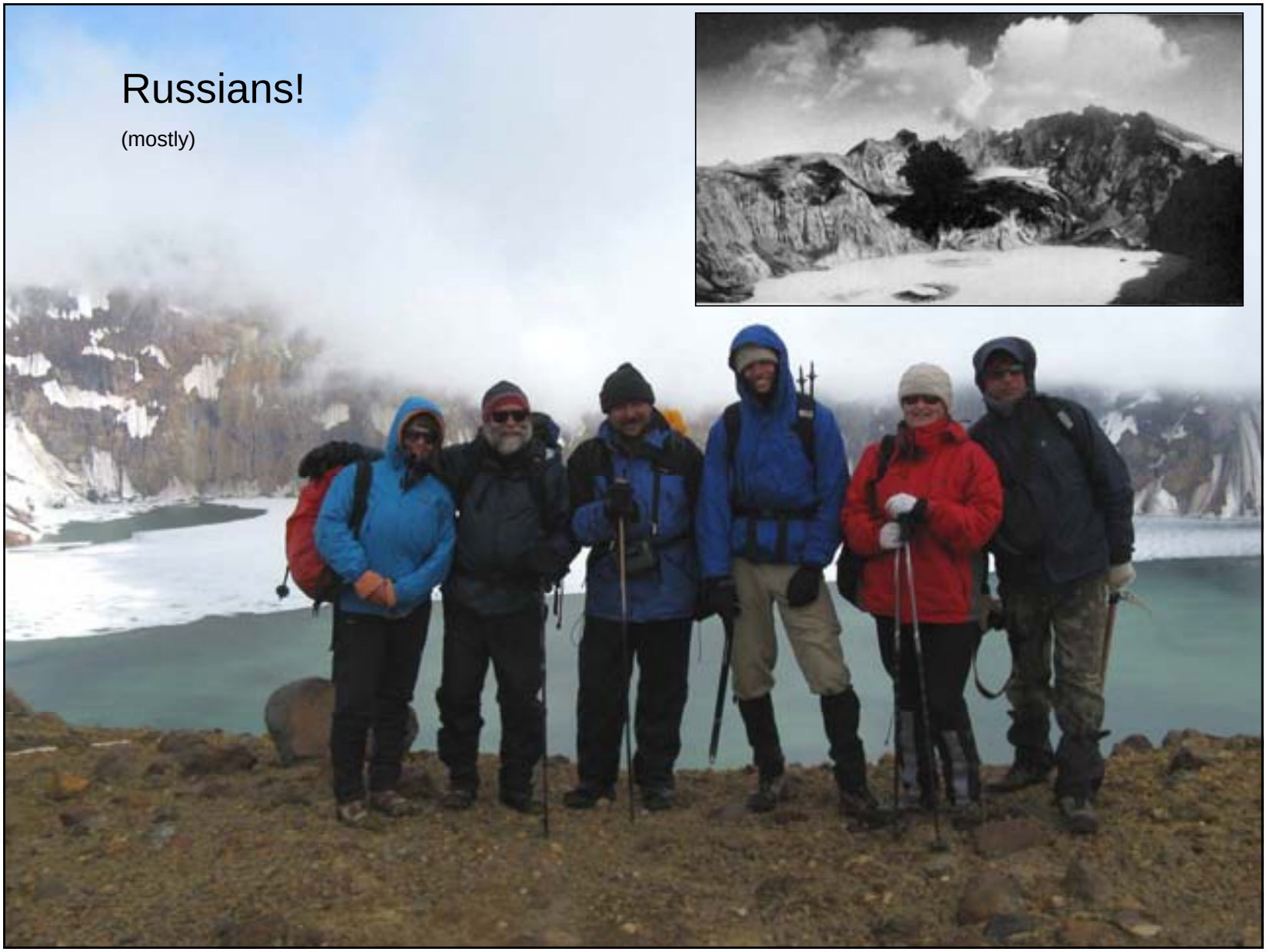

Sustained explosive eruptions
Spurr, Alaska 1992

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.

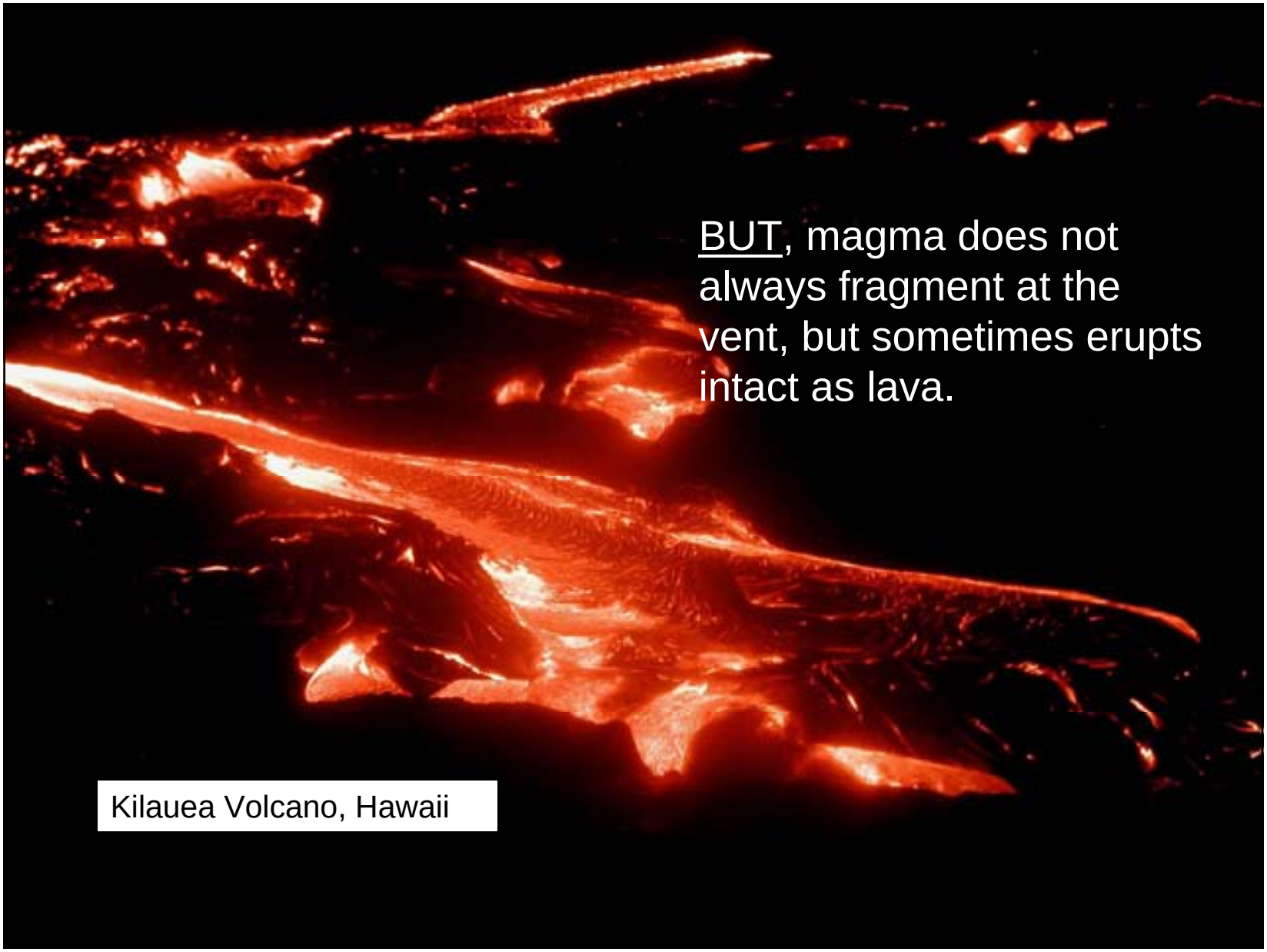

Kamchatka


10 km
10 km
Volume of a
Yellowstone eruption
10 km
Katmai eruption
Redoubt eruption


Katmai Caldera, Alaska, formed in 1912: Eruptions of ≥ 10 km³ of magma usually result in collapse of the magma chamber's roof, forming a caldera.


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.
Kilauea Volcano, Hawaii


Unzen Volcano, Kyushu, Japan, 1991-1995

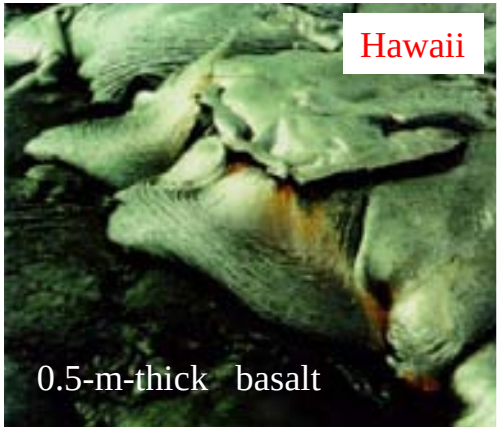
Hot

Fluid

Effect of composition and temperature on viscosity of lava.

Cool

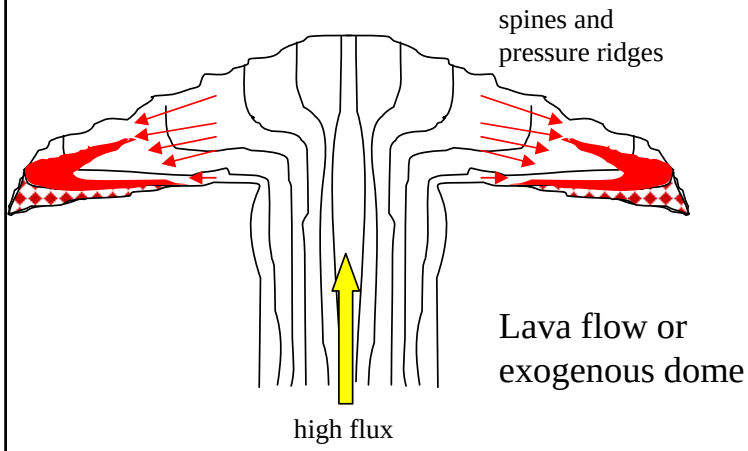
Viscous

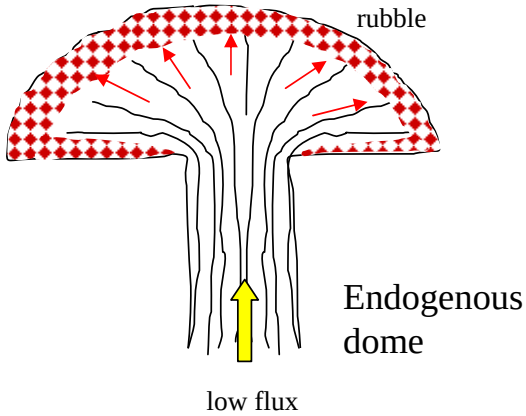




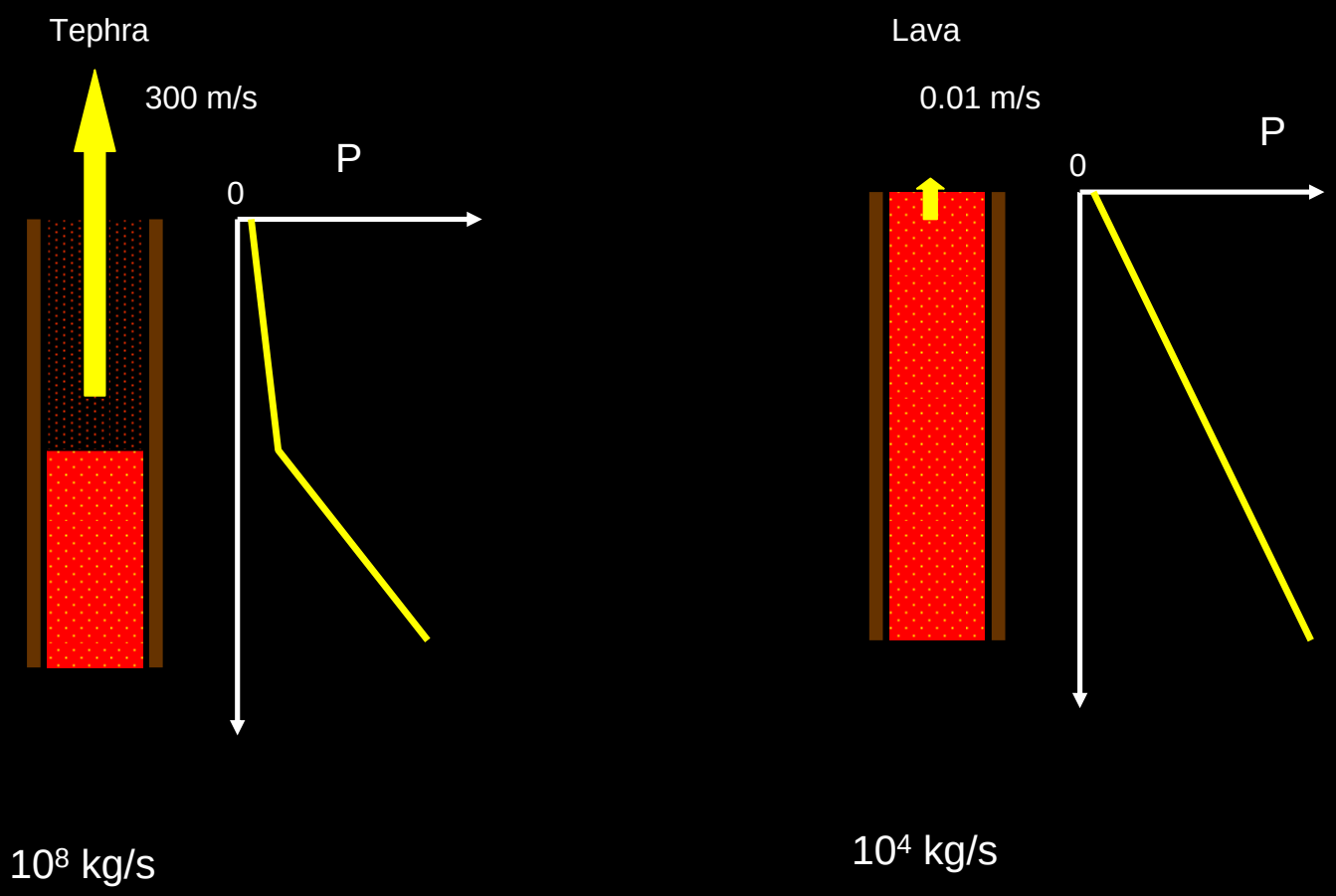

50 60 70 80

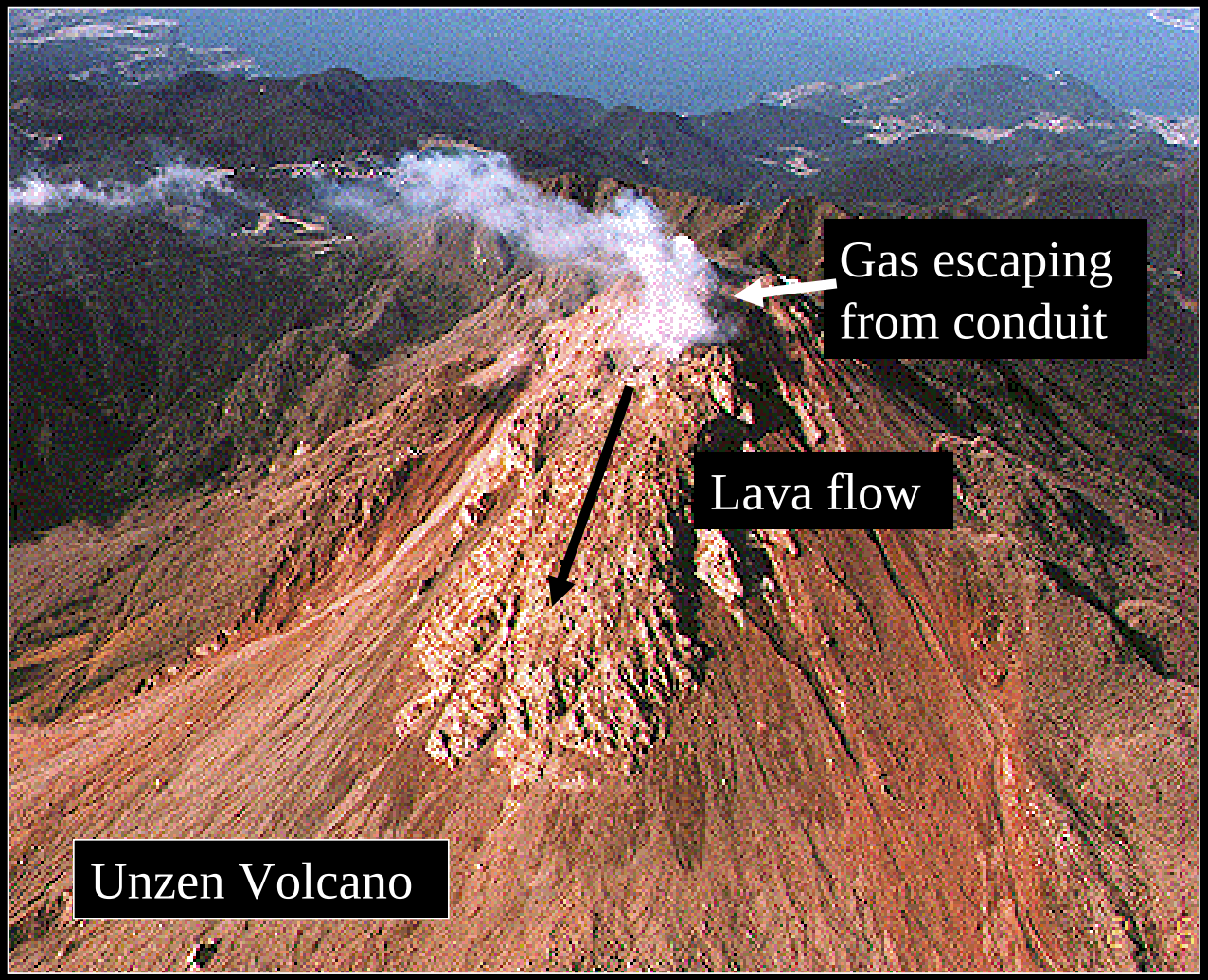
Wt.% SiO2

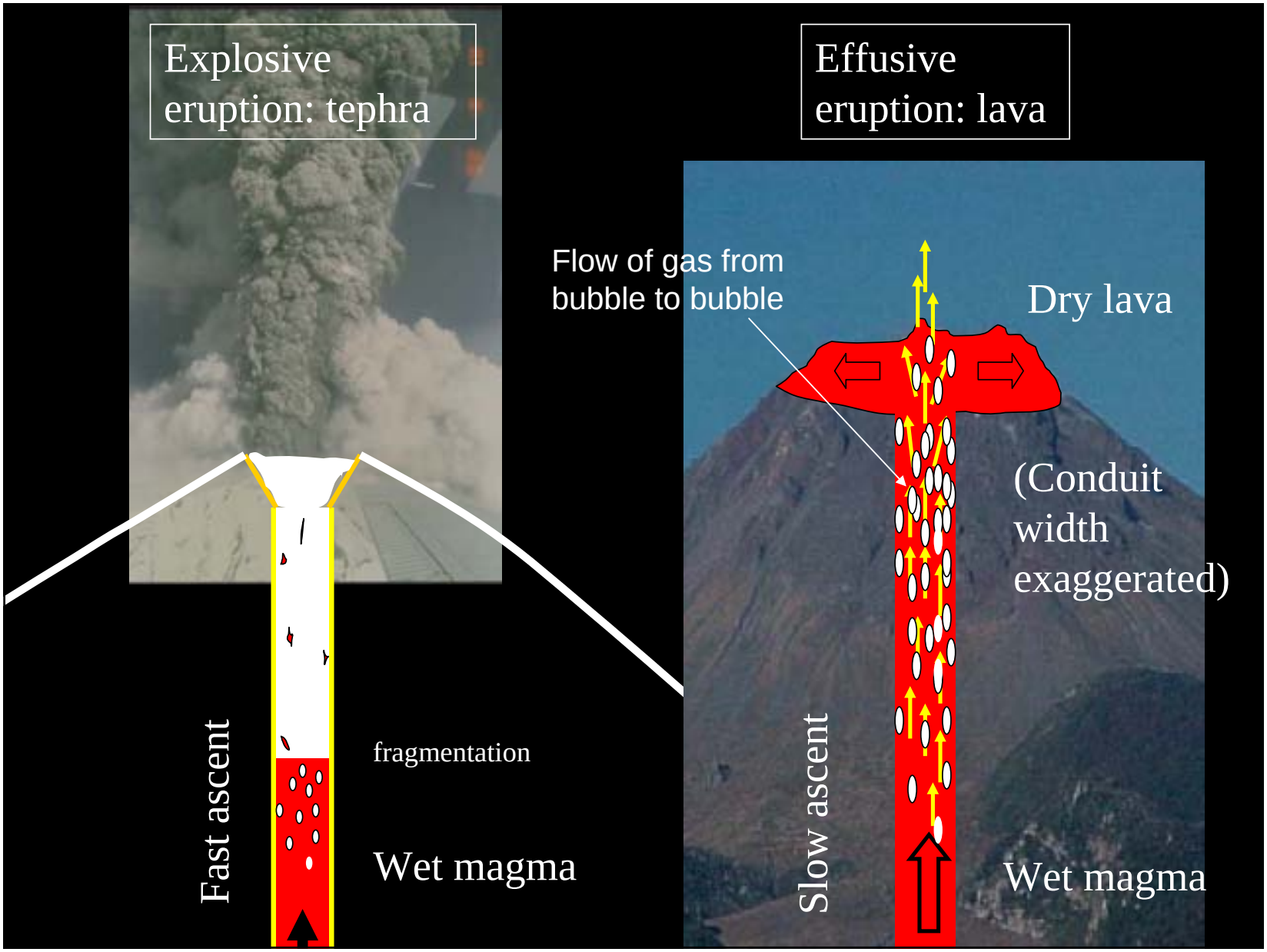

spines and
pressure ridges
Lava flow or
exogenous dome
high flux


rubble
Endogenous
dome
low flux

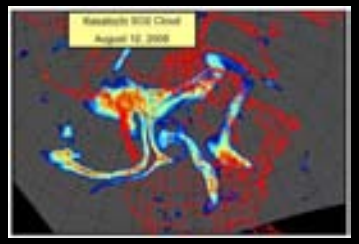
# Contrasting behaviors




Gas escaping
from conduit
Lava flow
Unzen Volcano

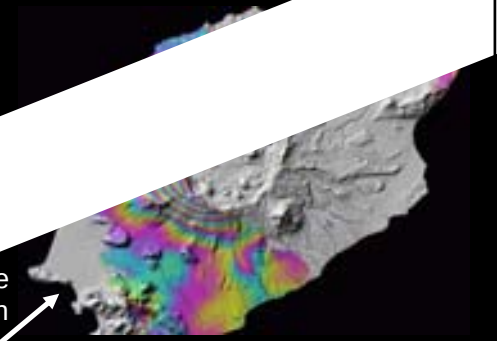

Explosive eruption: tephra
Effusive eruption: lava
Flow of gas from bubble to bubble
Dry lava
(Conduit width exaggerated)
Fast ascent
fragmentation
Wet magma
Slow ascent
Wet magma

# HOW WE MONITOR VOLCANOES



Gas cloud from satellite UV sensor

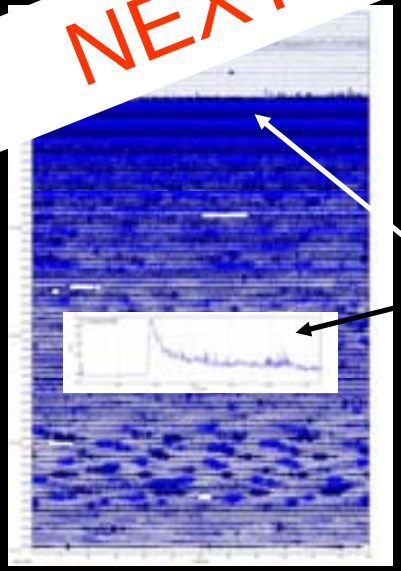
AVO oper



cillance
spots and ash

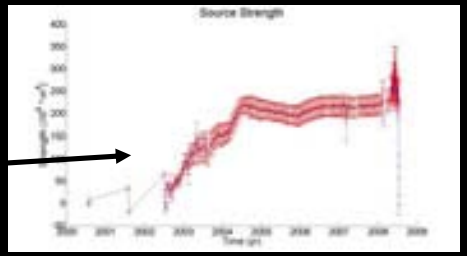
NEXT WEEK

AVO field installation



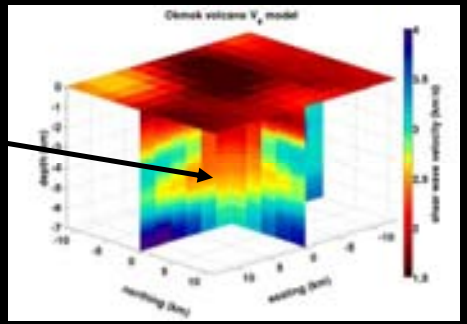
Volcano deformation from radar satellites

Volcano deformation from GPS




Eruption onset from seismic network

Magma chamber location from seismic tomography



Volcano Hazards