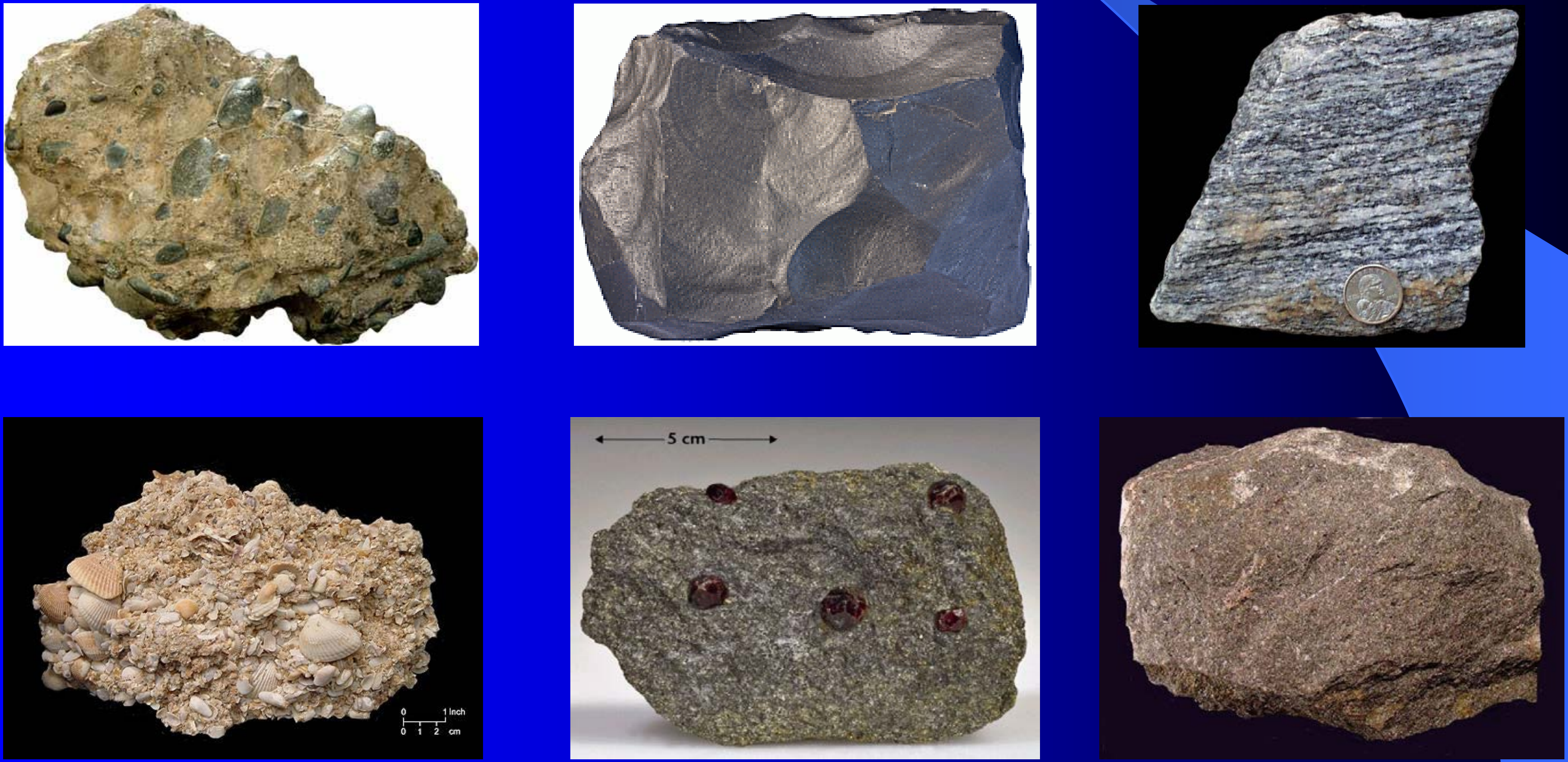
89.325 – Geology for Engineers
Igneous Rocks



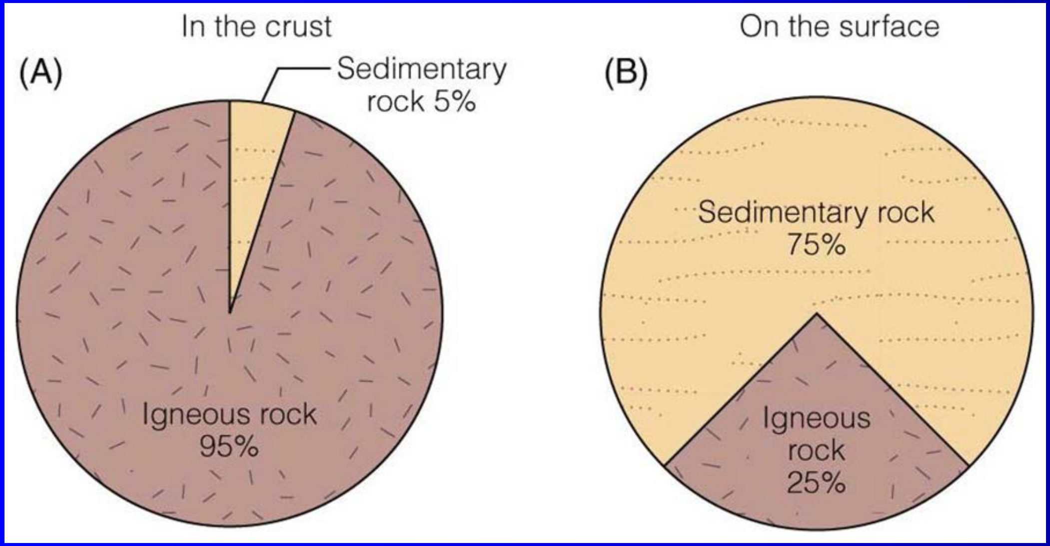

Rock – an aggregate of minerals, particles, glass

- **Igneous** – formed from the cooling and consolidation of magma or lava
- **Sedimentary** – formed from either chemical precipitation of material or deposition of particles transported in suspension
- **Metamorphic** – formed from changing a rock as a result of high temperatures, high pressures, or both



Classification of Rocks

- **Texture:** the overall appearance of a rock, resulting from the size, shape, and arrangement of its mineral grains
- **Mineral assemblage:** the kinds and relative amounts of minerals present



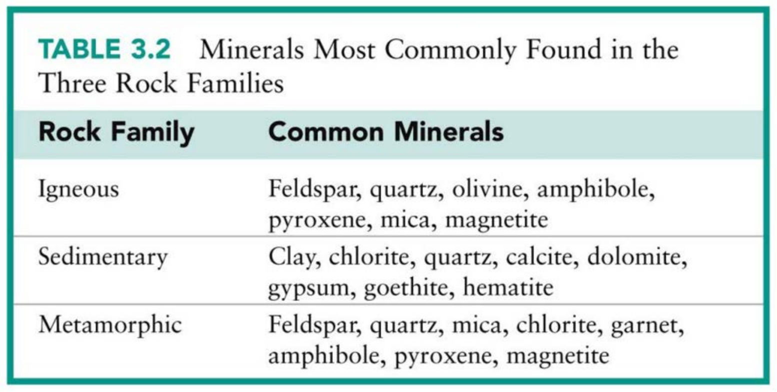
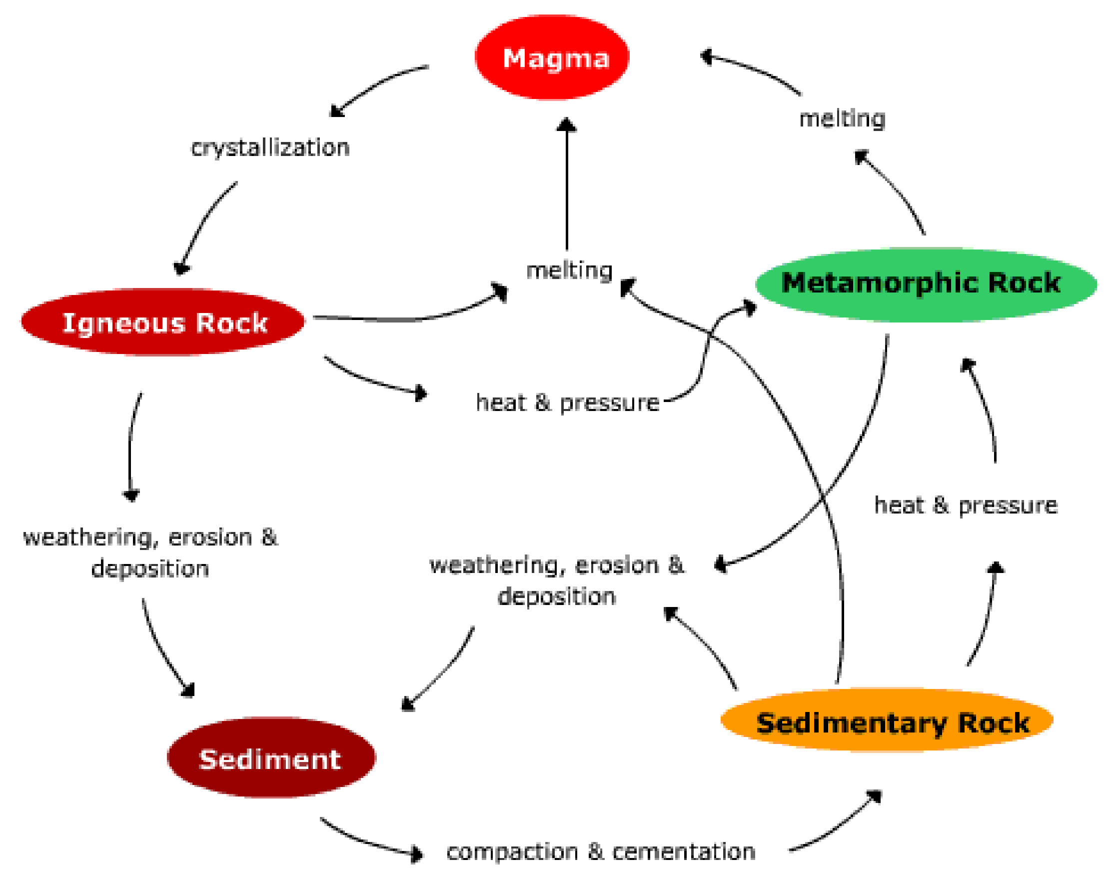


TABLE 3.2 Minerals Most Commonly Found in the Three Rock Families

Rock Family	Common Minerals
Igneous	Feldspar, quartz, olivine, amphibole, pyroxene, mica, magnetite
Sedimentary	Clay, chlorite, quartz, calcite, dolomite, gypsum, goethite, hematite
Metamorphic	Feldspar, quartz, mica, chlorite, garnet, amphibole, pyroxene, magnetite

The Rock Cycle



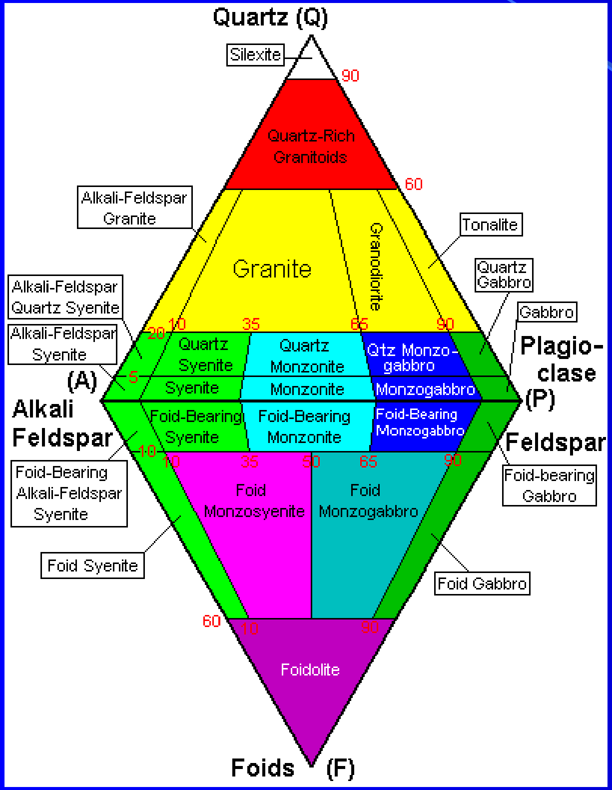
Igneous Rocks - Occurrence and Classification

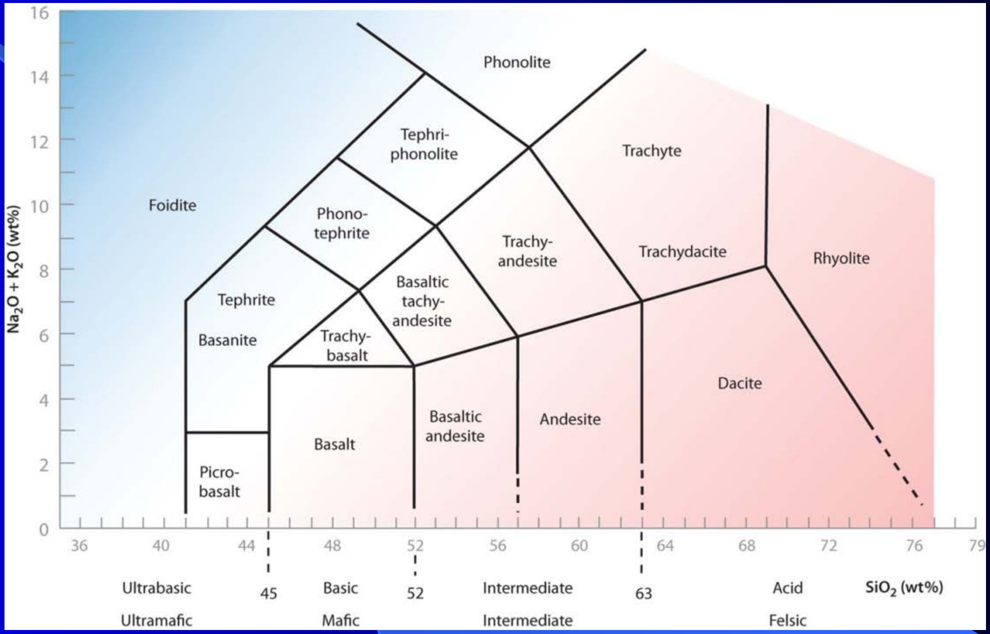
Classification of Igneous Rocks

Rocks are classified on the basis of

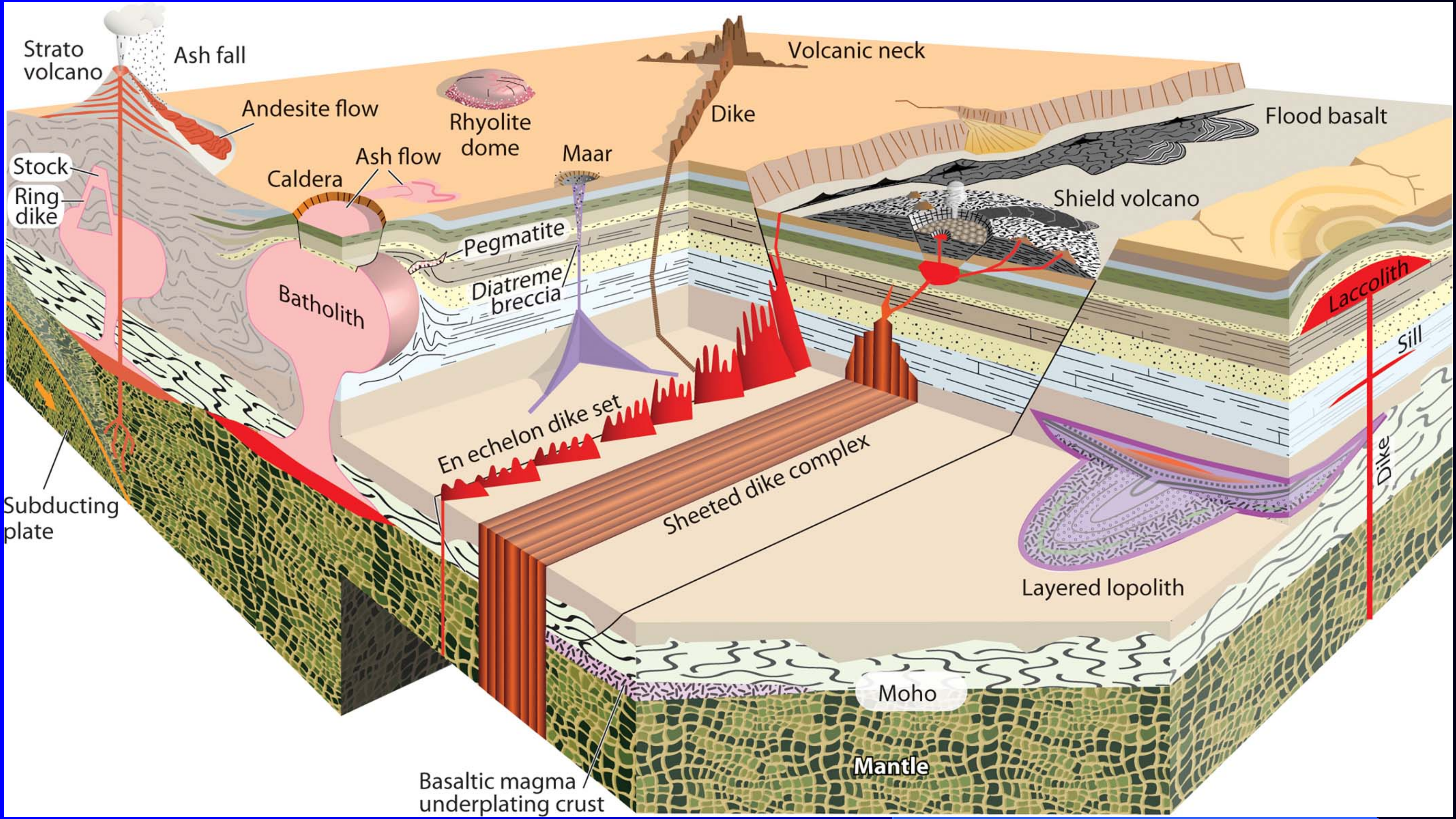
- Texture
- Mineralogy

Very fine-grained or glassy rocks are classified on the basis of chemistry





Mode of Occurrence of Igneous Rocks



Extrusive igneous rocks – fine-grained or glassy

- Lava flows
- Volcanoes

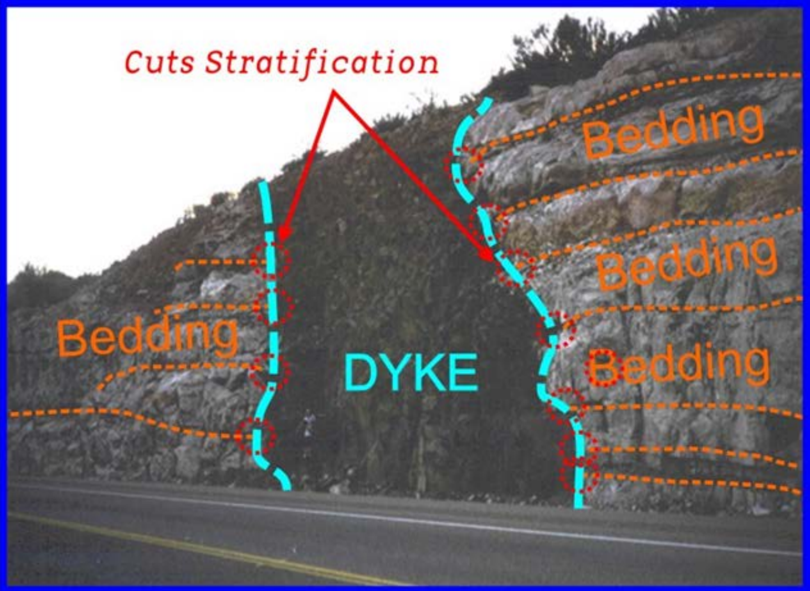
Intrusive igneous rocks – medium to coarse-grained

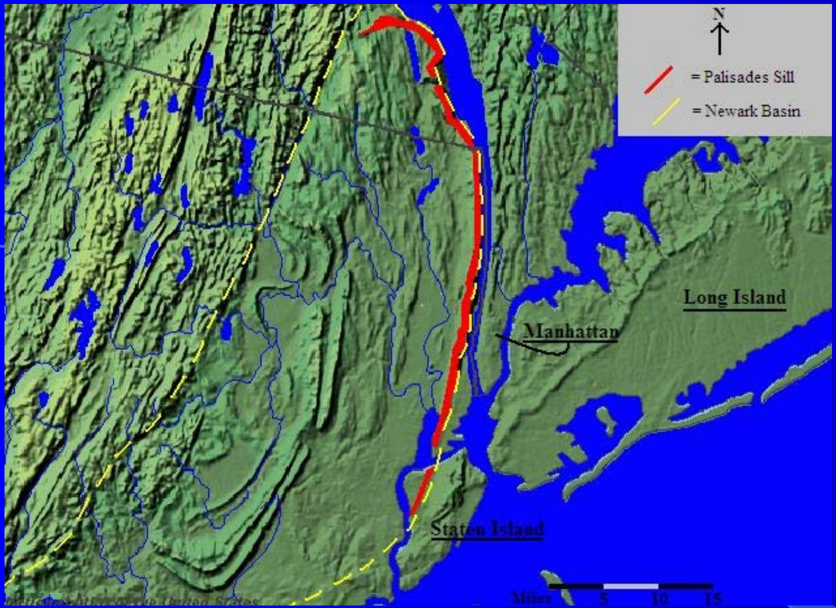
- Hypabyssal – transitional between fine- and coarse-grained. Often porphyritic.
- Plutonic – coarse-grained

Shallow intrusive igneous bodies

Dikes – tabular intrusions that cross-cut existing layering (discordant)

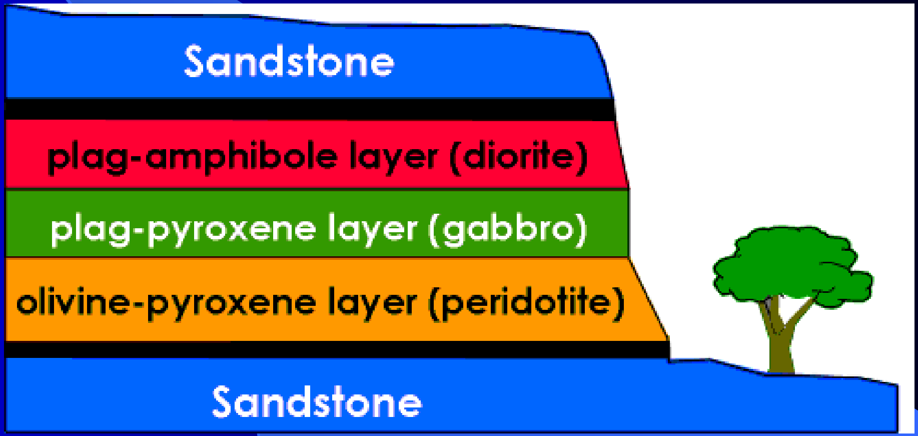
Sills – tablular intrusions that are parallel to existing layering (concordant)





Salisbury Crags – Arthur’s Seat

Palisades Sill



Sandstone

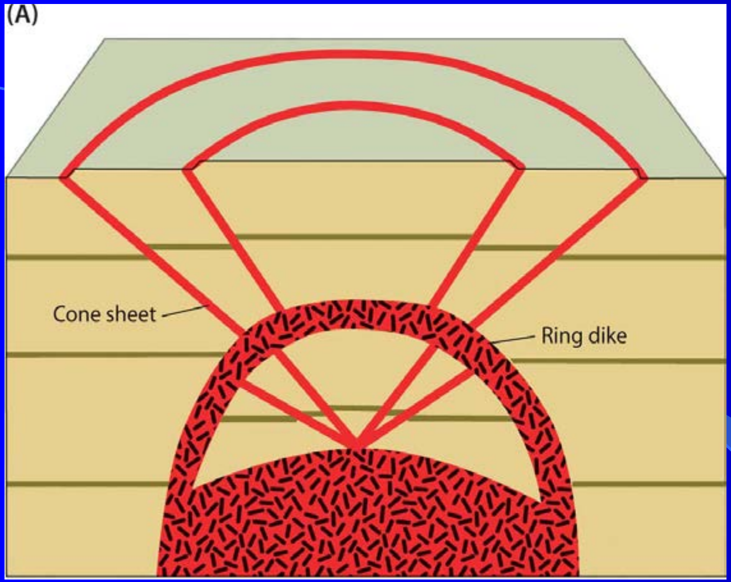
plag-amphibole layer (diorite)

plag-pyroxene layer (gabbro)

olivine-pyroxene layer (peridotite)

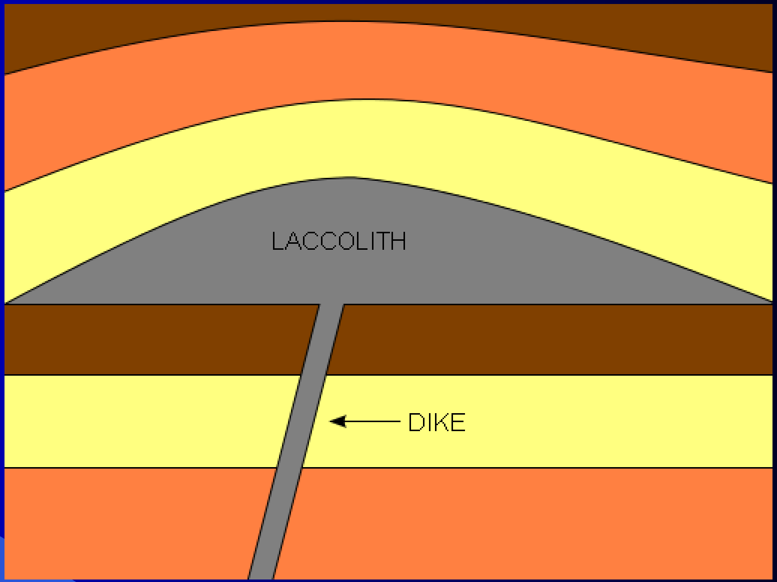
Sandstone

Ring dikes and cone sheets

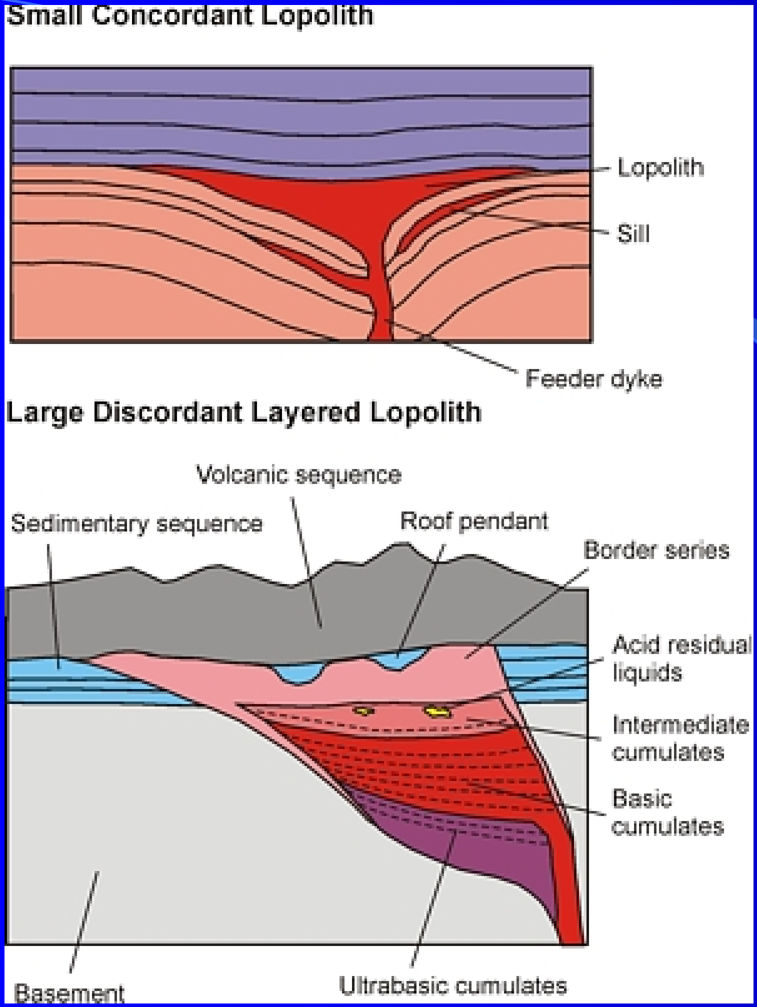


Dikes are intruded by magma fracturing and sills involve lifting of the overlying rock (bouyancy). These are hypabyssal intrusions and imply that the crust showed brittle behavior.

Laccolith – domes up overlying strata – concordant intrusion



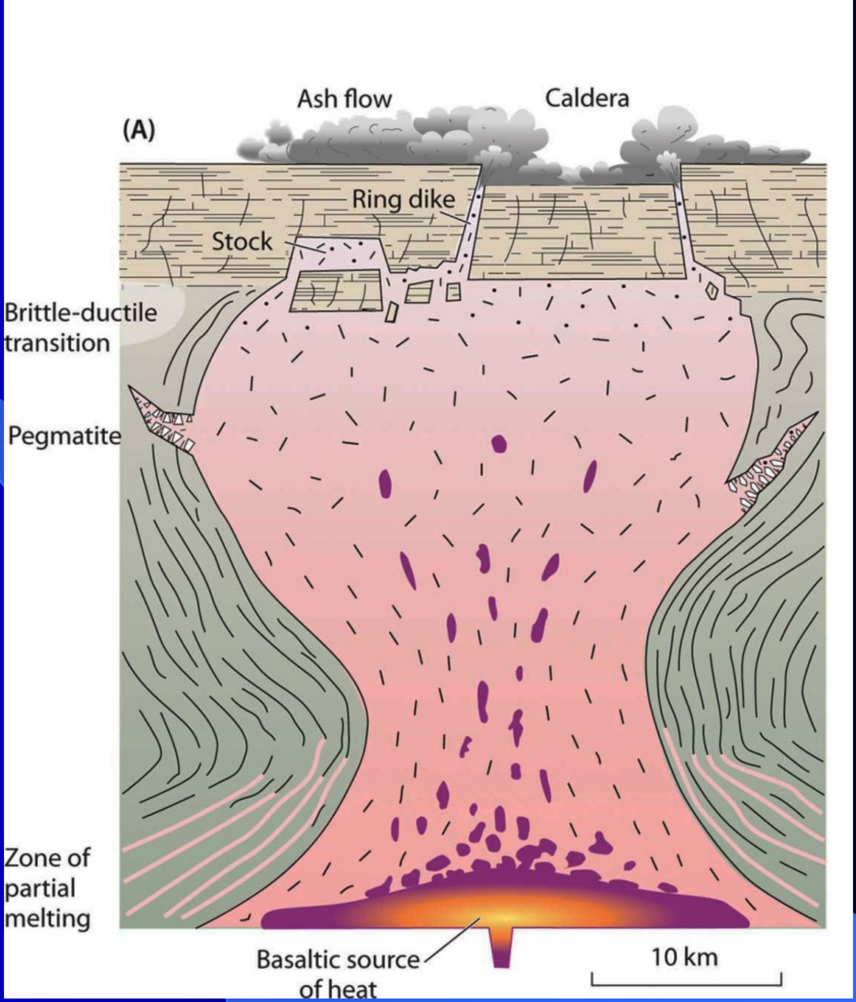
Lopolith



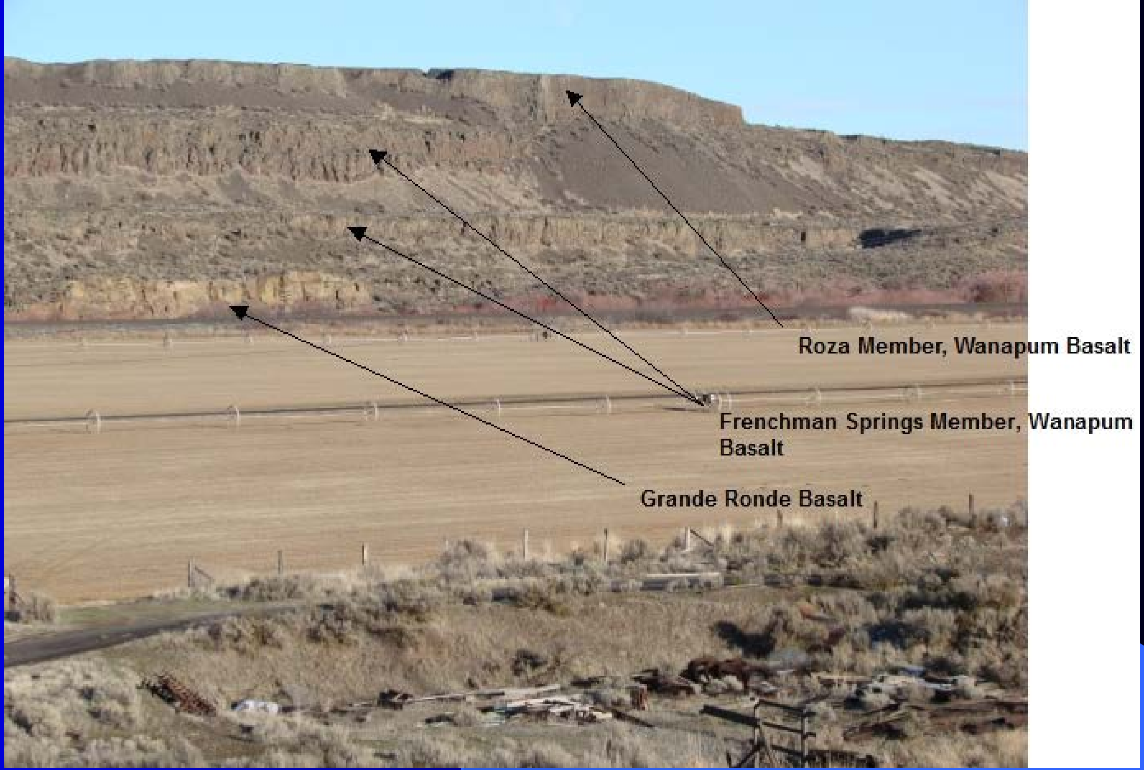
Batholith > 100 km^2

Stock < 100 km^2

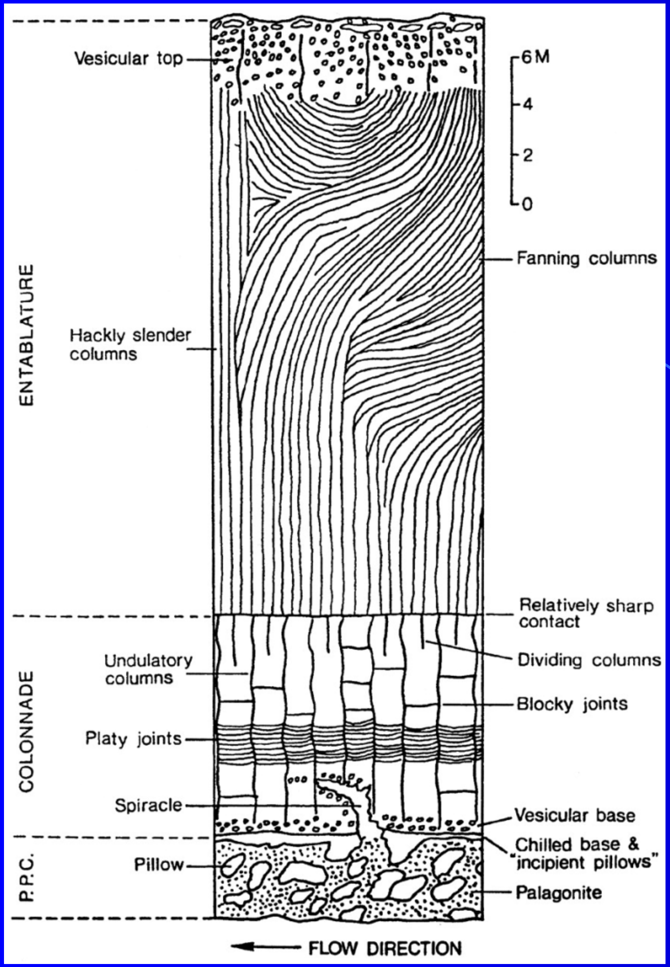
Batholiths are everywhere



Flood Basalts



Lava Flows and Columnar Joints



Physical Properties and Behavior of Various Types of Magmas

Magma type	Basaltic	Andesitic	Dacitic	Rhyolitic
SiO_2 (wt. %)	50.83	54.20	63.58	73.66
Eruptive T (^oC)	1150	1000	900	800
Viscosity (Pa s)	50	1×10^3	4×10^3	4×10^8

Eruptive behavior Fluid → Explosive

Magma Viscosity

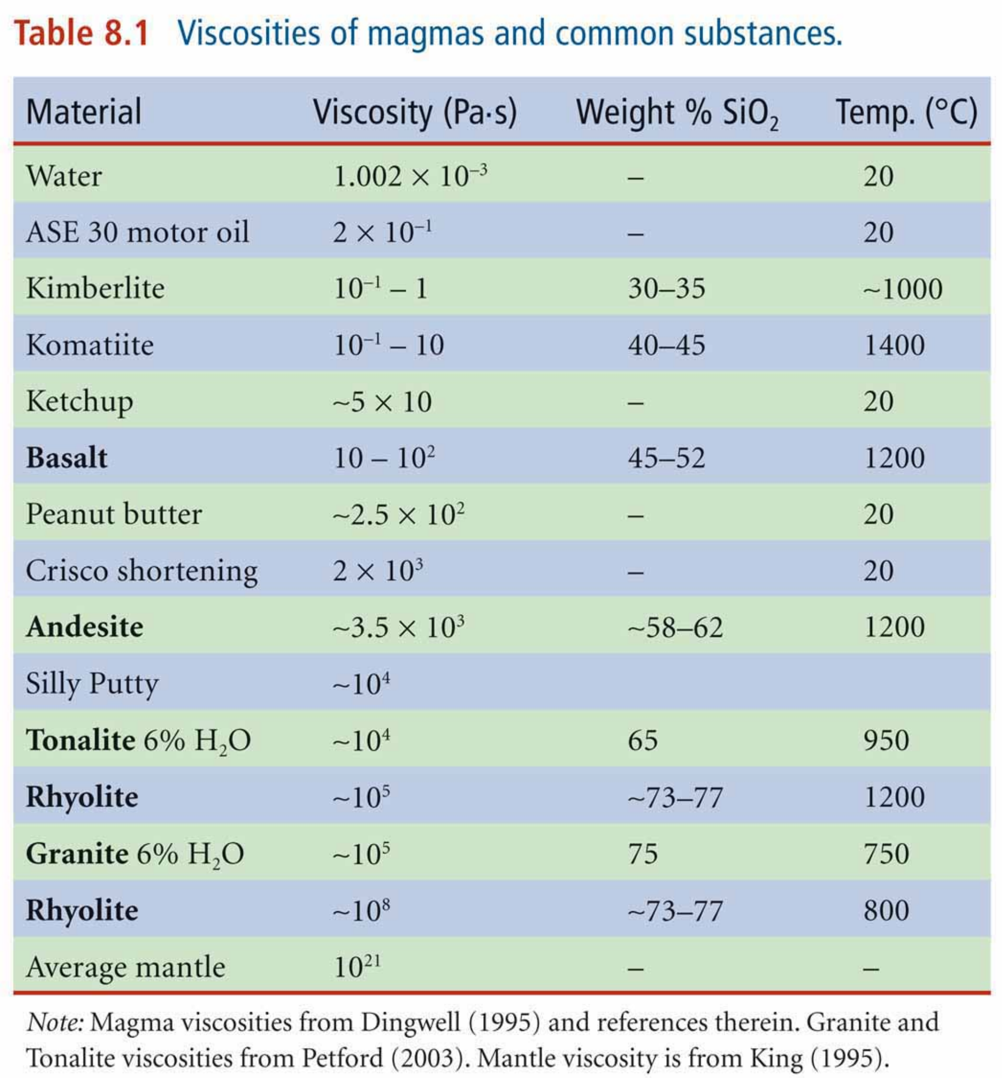


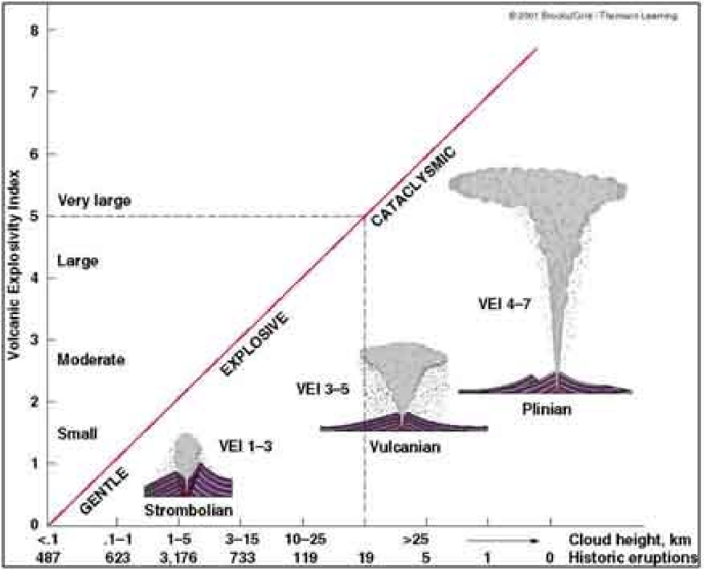
Table 8.1 Viscosities of magmas and common substances.

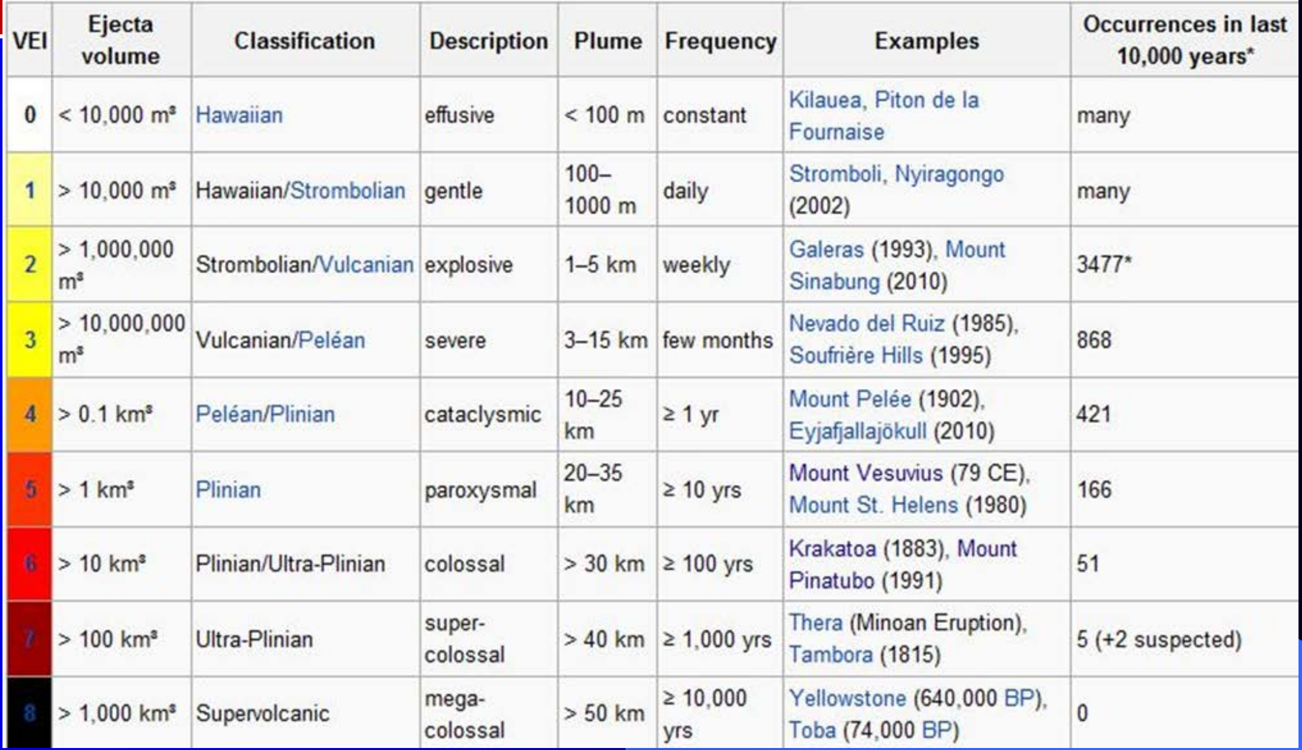
Material	Viscosity (Pa·s)	Weight % SiO_2	Temp. (°C)
Water	1.002×10^{-3}	–	20
ASE 30 motor oil	2×10^{-1}	–	20
Kimberlite	$10^{-1} – 1$	30–35	~1000
Komatiite	$10^{-1} – 10$	40–45	1400
Ketchup	$\sim 5 \times 10$	–	20
Basalt	$10 – 10^{2}$	45–52	1200
Peanut butter	$\sim 2.5 \times 10^{2}$	–	20
Crisco shortening	2×10^{3}	–	20
Andesite	$\sim 3.5 \times 10^{3}$	~58–62	1200
Silly Putty	$\sim 10^{4}$		
Tonalite 6% H_2O	$\sim 10^{4}$	65	950
Rhyolite	$\sim 10^{5}$	~73–77	1200
Granite 6% H_2O	$\sim 10^{5}$	75	750
Rhyolite	$\sim 10^{8}$	~73–77	800
Average mantle	10^{21}	–	–

Note: Magma viscosities from Dingwell (1995) and references therein. Granite and Tonalite viscosities from Petford (2003). Mantle viscosity is from King (1995).

Types of volcanic eruptions

- Hawaiian – fluid basaltic lava is thrown into the air in jets from a vent or line of vents (a fissure) at the summit or on the flank of a volcano.
- Strombolian – distinct bursts of fluid lava (usually basalt or basaltic andesite) from the mouth of a magma-filled summit conduit.
- Vulcanian - short, violent, relatively small explosion of viscous magma (usually andesite, dacite, or rhyolite).
- Pelean - explosive outbursts that generate pyroclastic flows, dense mixtures of hot volcanic fragments and gas.
- Plinian - caused by the fragmentation of gassy magma, and are usually associated with very viscous magmas (dacite and rhyolite).





VEI	Ejecta volume	Classification	Description	Plume	Frequency	Examples	Occurrences in last 10,000 years*
0	< 10,000 m^3	Hawaiian	effusive	< 100 m	constant	Kilauea, Piton de la Fournaise	many
1	> 10,000 m^3	Hawaiian/Strombolian	gentle	100–1000 m	daily	Stromboli, Nyiragongo (2002)	many
2	> 1,000,000 m^3	Strombolian/Vulcanian	explosive	1–5 km	weekly	Galeras (1993), Mount Sinabung (2010)	3477*
3	> 10,000,000 m^3	Vulcanian/Peléan	severe	3–15 km	few months	Nevado del Ruiz (1985), Soufrière Hills (1995)	868
4	> 0.1 km^3	Peléan/Plinian	cataclysmic	10–25 km	≥ 1 yr	Mount Pelée (1902), Eyjafjallajökull (2010)	421
5	> 1 km^3	Plinian	paroxysmal	20–35 km	≥ 10 yrs	Mount Vesuvius (79 CE), Mount St. Helens (1980)	166
6	> 10 km^3	Plinian/Ultra-Plinian	colossal	> 30 km	≥ 100 yrs	Krakatoa (1883), Mount Pinatubo (1991)	51
7	> 100 km^3	Ultra-Plinian	super-colossal	> 40 km	≥ 1,000 yrs	Thera (Minoan Eruption), Tambora (1815)	5 (+2 suspected)
8	> 1,000 km^3	Supervolcanic	mega-colossal	> 50 km	≥ 10,000 yrs	Yellowstone (640,000 BP), Toba (74,000 BP)	0

Tephra – volcanic ash (< 2mm)

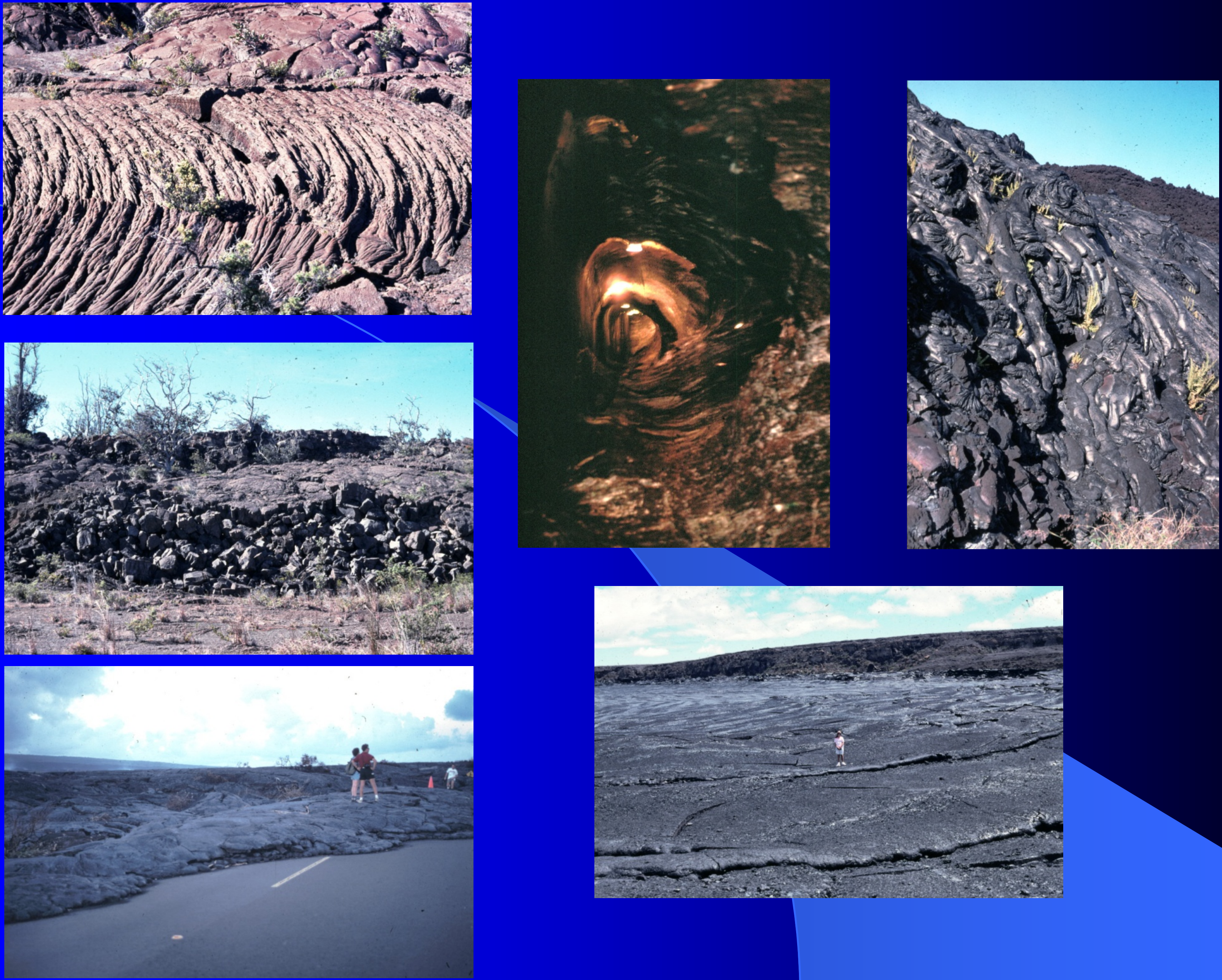
Lapilli – 2 to 64 mm

Bombs - >64 mm. Bombs form a cow pancake on landing

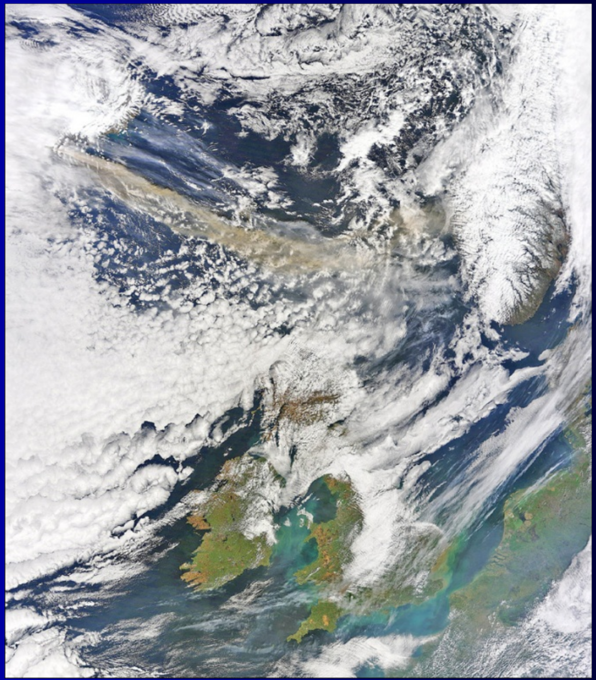
Shield Volcanoes

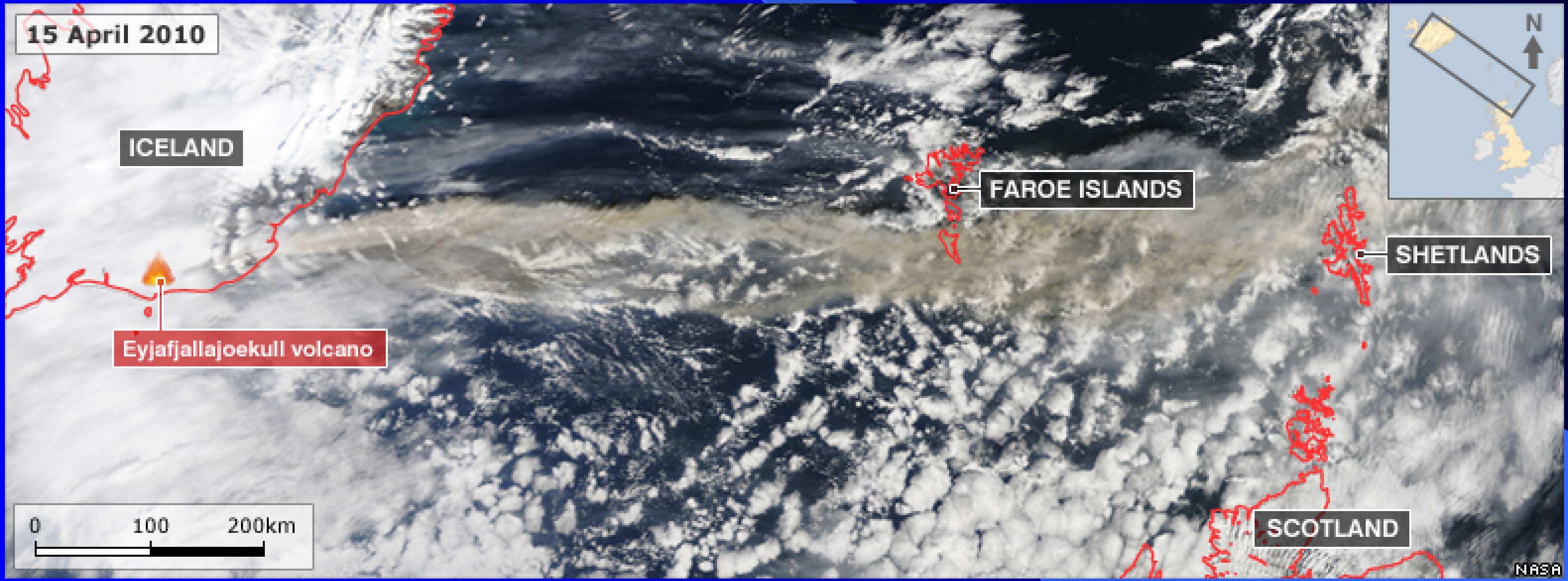
Mauna Kea

Mauna Loa



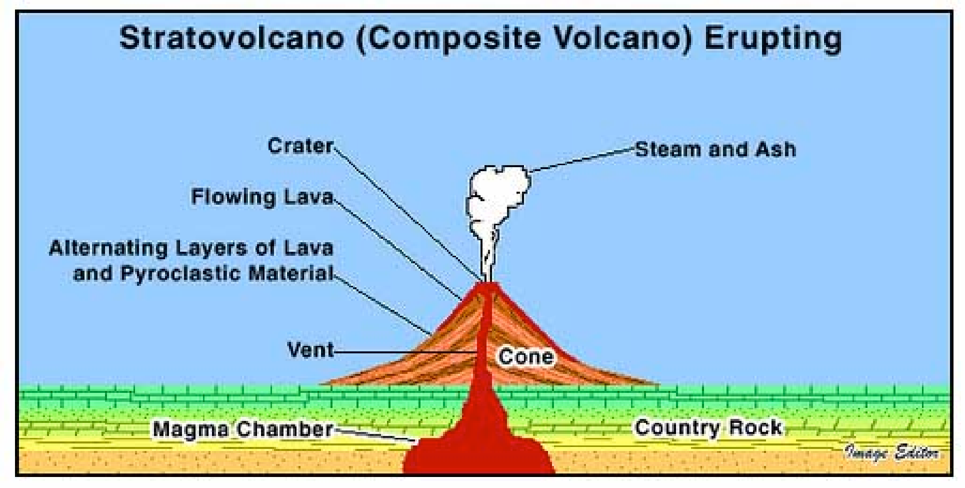

16 April 0000GMT
Scope of ash
ICELAND
Eyjafjallajoekull Glacier
NORWAY
FINLAND
RUSSIA
SWEDEN
UNITED KINGDOM
SOURCE: Met Office




15 April 2010
ICELAND
Eyjafjallajoekull volcano
FAROE ISLANDS
SHETLANDS
SCOTLAND
N
0
100
200km
NASA

Jökulhlaup - glacial outburst flood. Generally, large and abrupt release of water from a subglacial or proglacial lake/reservoir.

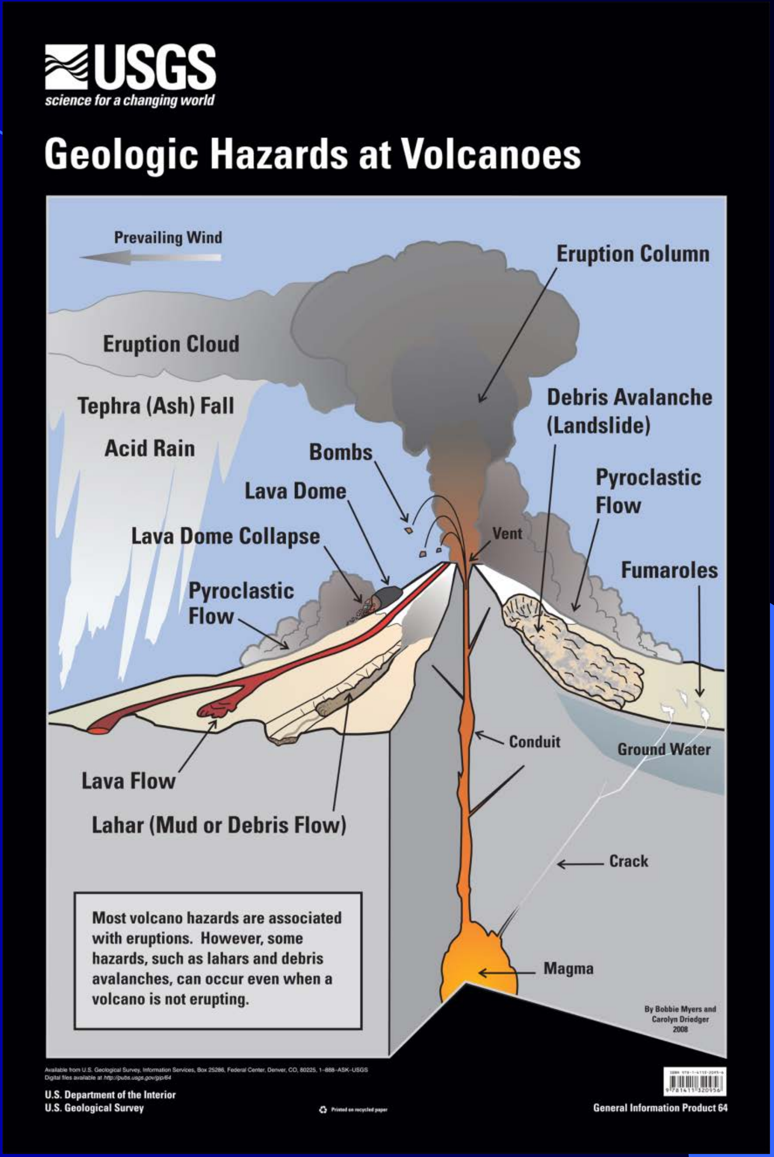
Composite Volcano (Strato-volcano)



Types of Volcanic Hazards

Types of Volcanic Hazards

- Lava flows: e.g. Hawaii, 1998
- Gas: e.g. Lake Nyos (Cameroon), 1984 (1700 people killed)
- Ash fall: e.g. Mt. Pinatubo, 1991
- Pyroclastic flows: e.g. Mt. Pelee, 1902 (28,000 killed)
- Lahars (mudflows): e.g. Nevado del Ruiz, 1985 (23,000 killed)
- Tsunami: e.g. Krakatoa, 1883 (36,417 killed)



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Geologic Hazards at Volcanoes

Most volcano hazards are associated with eruptions. However, some hazards, such as lahars and debris avalanches, can occur even when a volcano is not erupting.

By Bobbie Myers and
Carolyn Driedger
2008

Available from U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO, 80225, 1-888-ASK-USGS
Digital files available at *http://pubs.usgs.gov/gip/64*

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U.S. Geological Survey

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General Information Product 64

Lava Flows

Property damage

Don’t fall in

Mount Cameroon lava flow cutting road

Tephra

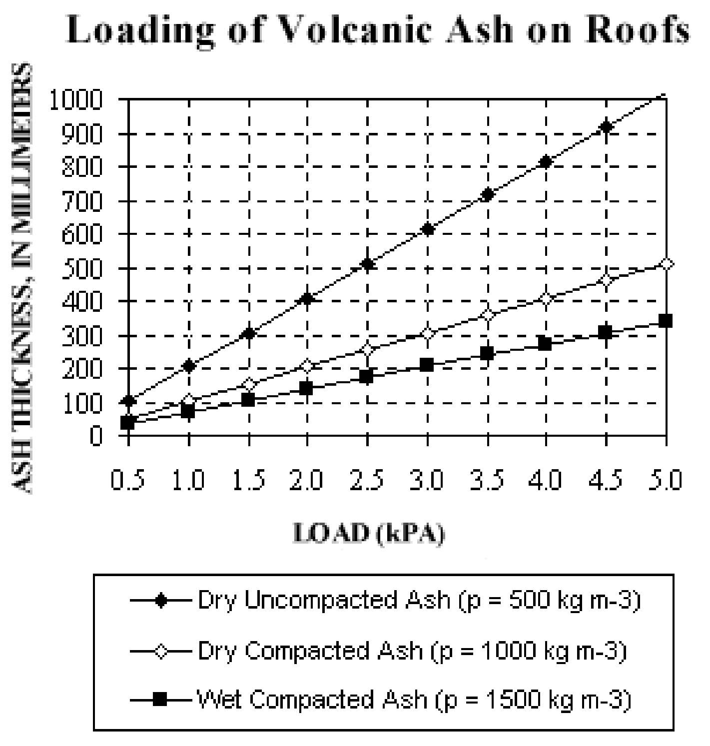
Power outages

Reduced visibility

Roof collapse

Slippery roads

Ash Loading on Roofs



$$L = \frac{dpg}{1000}$$

L is volcanic ash load (pressure in kPa)
d is ash depth (m)
p is ash density (kg/m^3)
g is the gravitational acceleration (9.8 m/s^2)

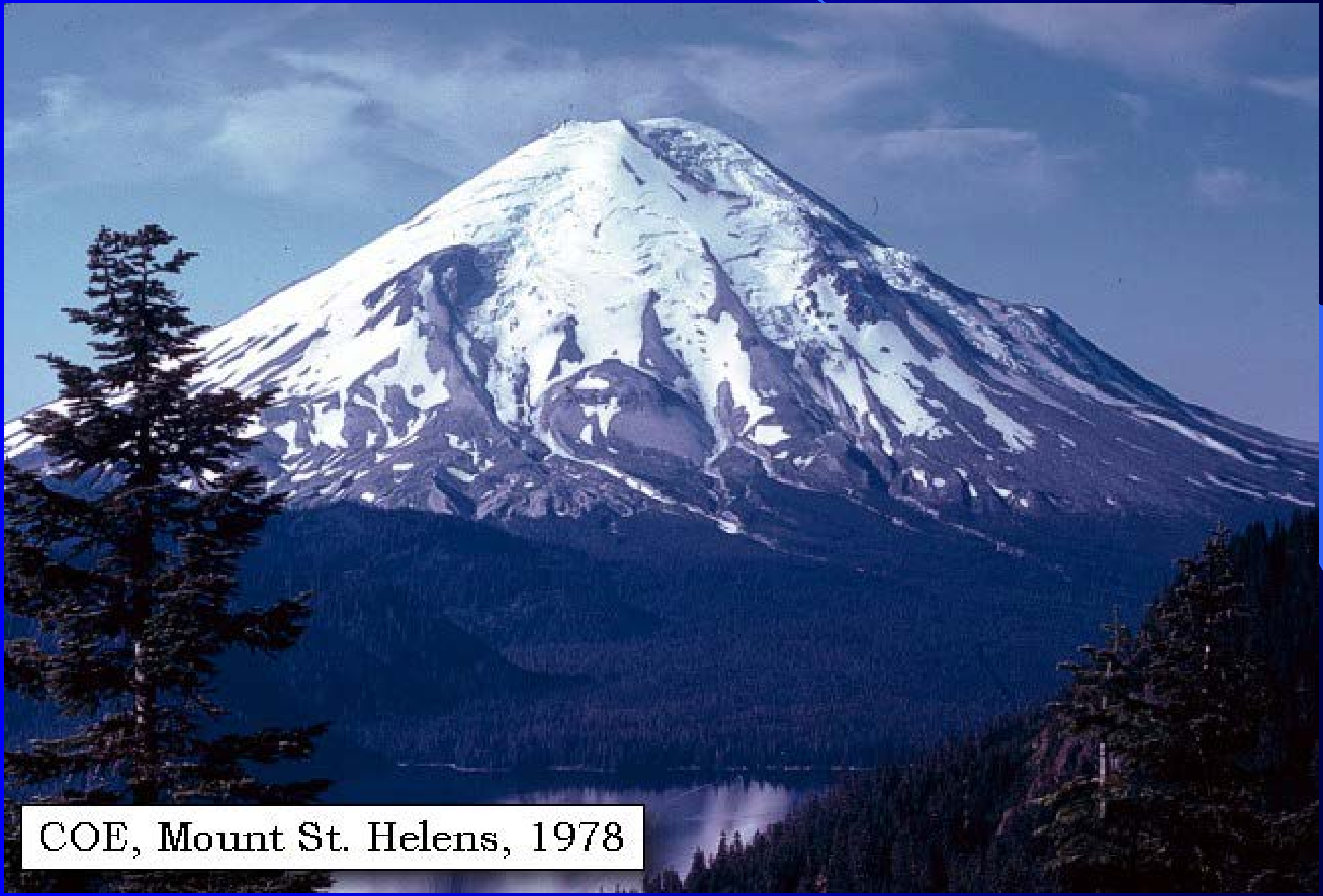
Chile
Restaurant

Raboul

Philippines
Clark Air
Force Base

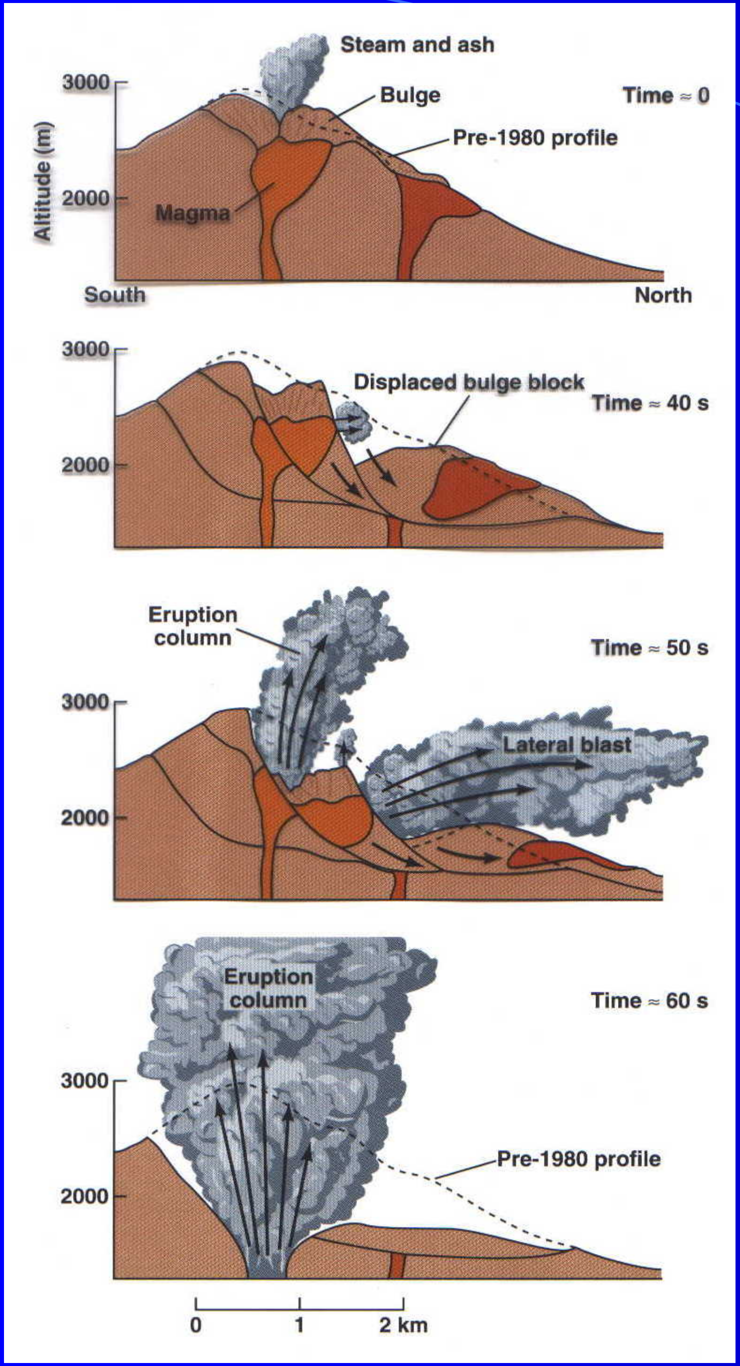
Pyroclastics and Landslides

Mt. St. Helens (May 18, 1980)



COE, Mount St. Helens, 1978

Mt. St. Helens start of eruption

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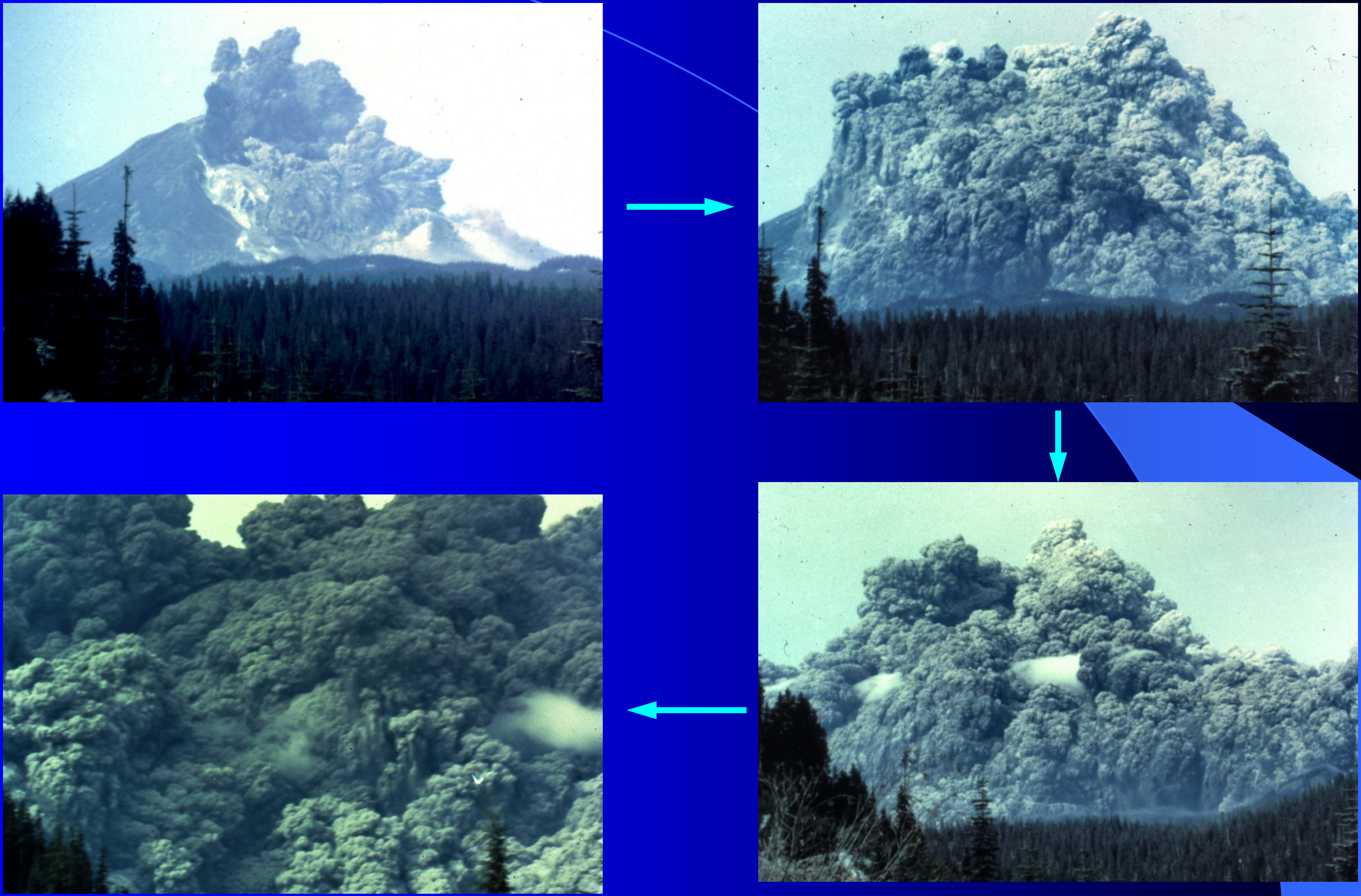
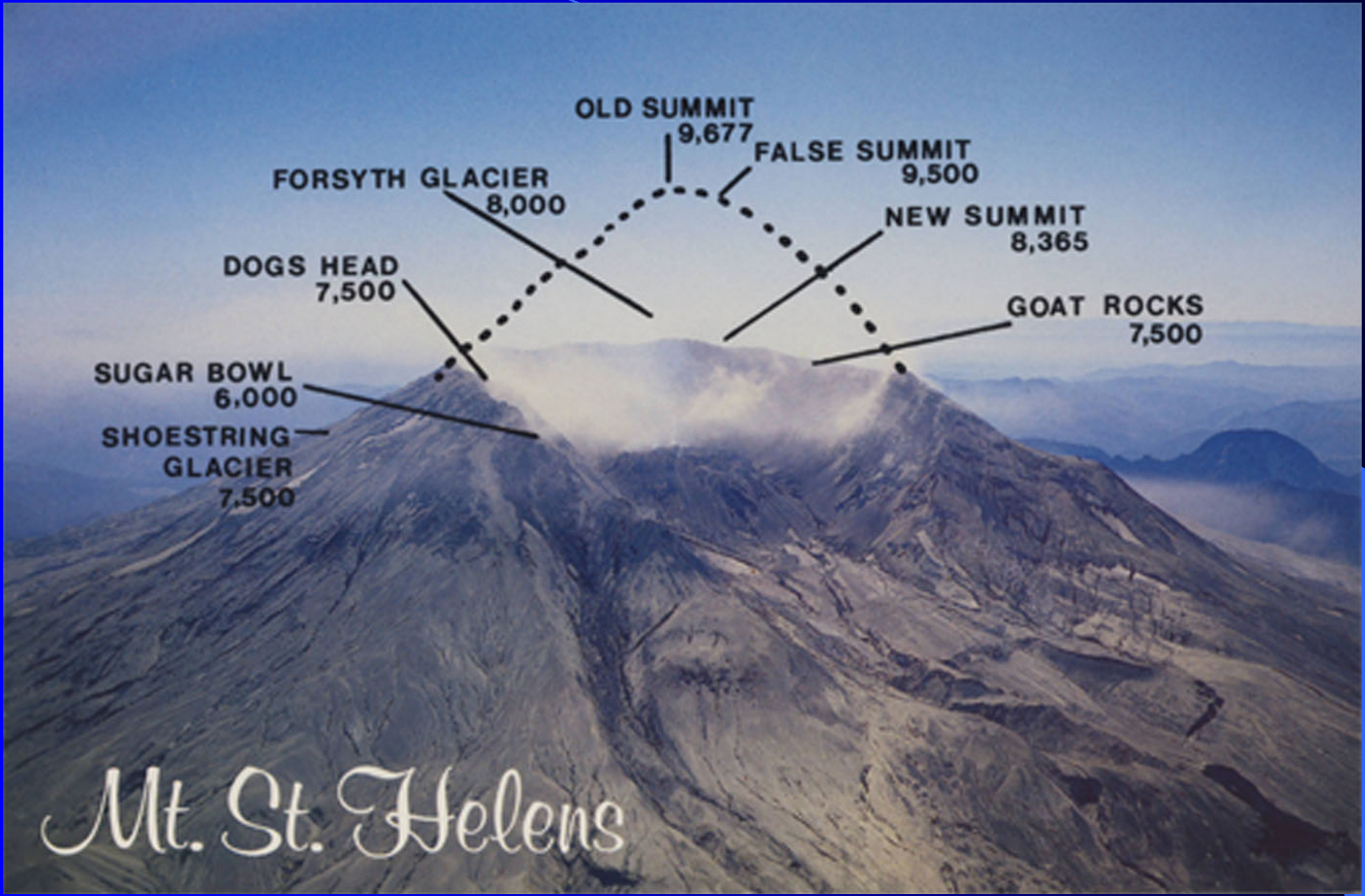
Mt. St. Helens Eruption



Mt. St. Helens after the eruption



Mt. St. Helens - the aftermath

Landslide deposits

Flattened trees

Trees in Cowlitz river

Destroyed logging trucks

Mt. St. Helens - today

Mt. St. Helens today

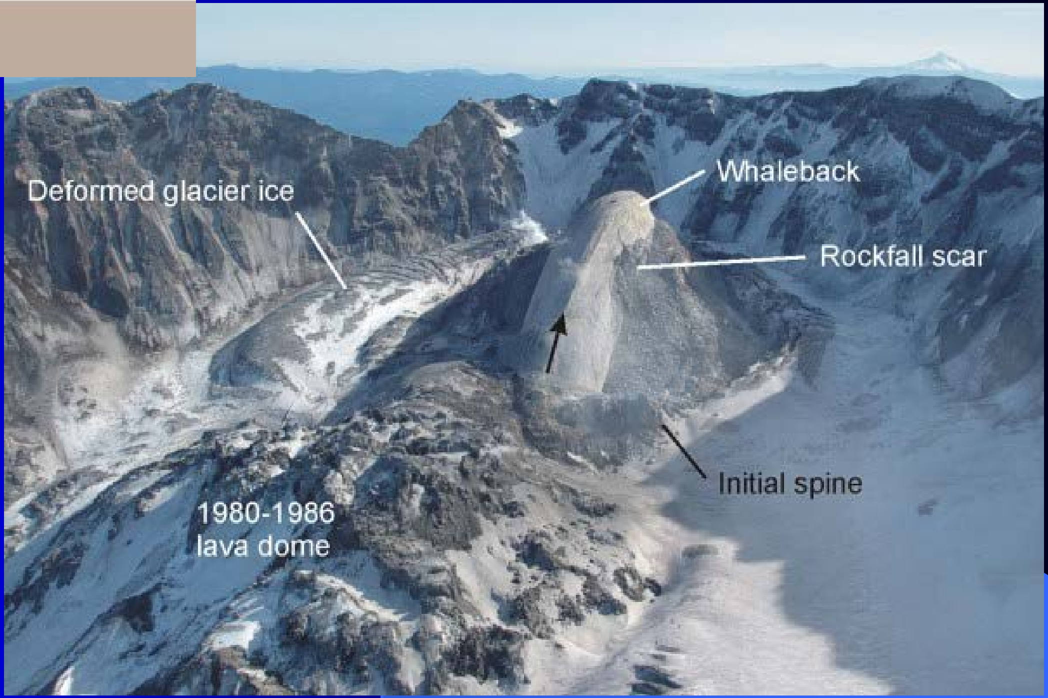
Regrowth

Spirit Lake

Demolished car

Growth of lava dome in the Mt. St. Helens crater.

Crater and dome of Mount Saint Helens in 1989.
Photo by Lyn Topinka, U. S. Geological Survey

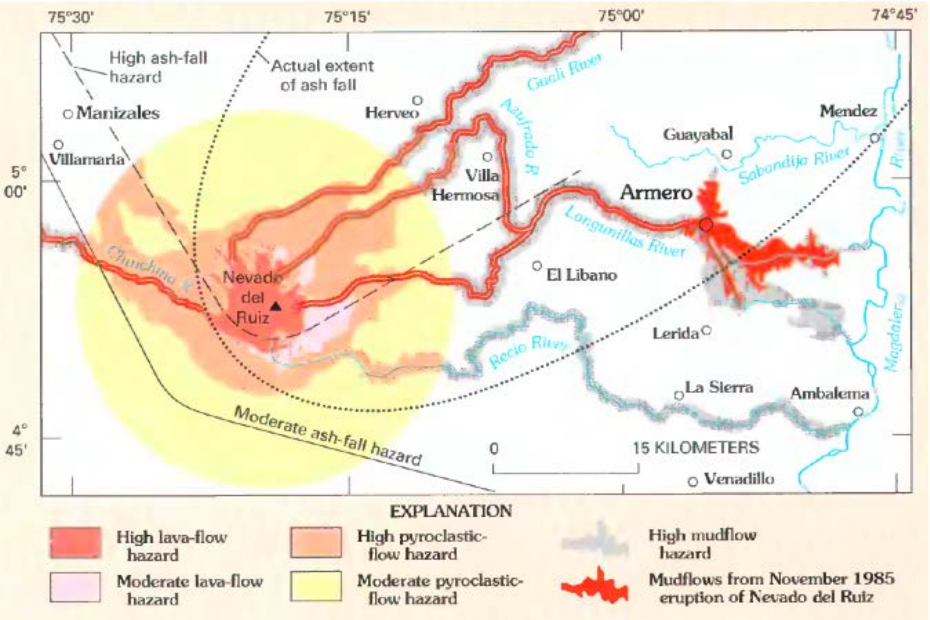


Lahars

Nevado del Ruiz (November 13, 1985)

An explosive eruption from Ruiz's summit crater at 9:08 PM generated an eruption column and sent a series of pyroclastic flows and surges across the volcano's broad ice-covered summit. In this view, the dark pyroclastic-flow deposits are partly covered with fresh snow.

Hot rock fragments of the pyroclastic flows and surges quickly eroded and mixed with Ruiz's snow and ice, melting about ten percent of the volcano's ice cover. Flowing mixtures of water, ice, pumice and other rock debris poured from the summit and sides of the volcano into rivers draining the volcano.



Lahars merge at the base of the volcano. Headwaters of the Gualí river.

Lahars grow in size through erosion. Gualí river valley

High ground means safety. Gualí river.

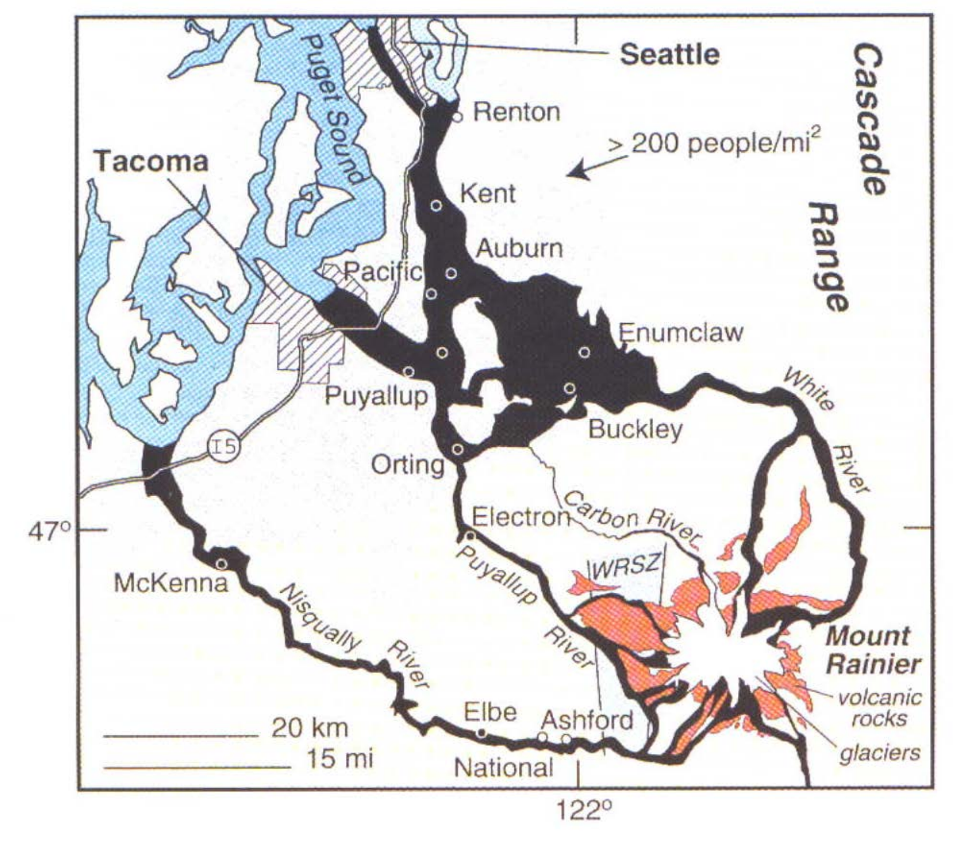
Río Lagunillas, former location of Armero. Bottom, remains of Armero. 75% of the population of 28,700 perished when lahars buried the town. There were multiple pulses with flow depths of 2 to 5 m.

Lahars


Mt. Rainier

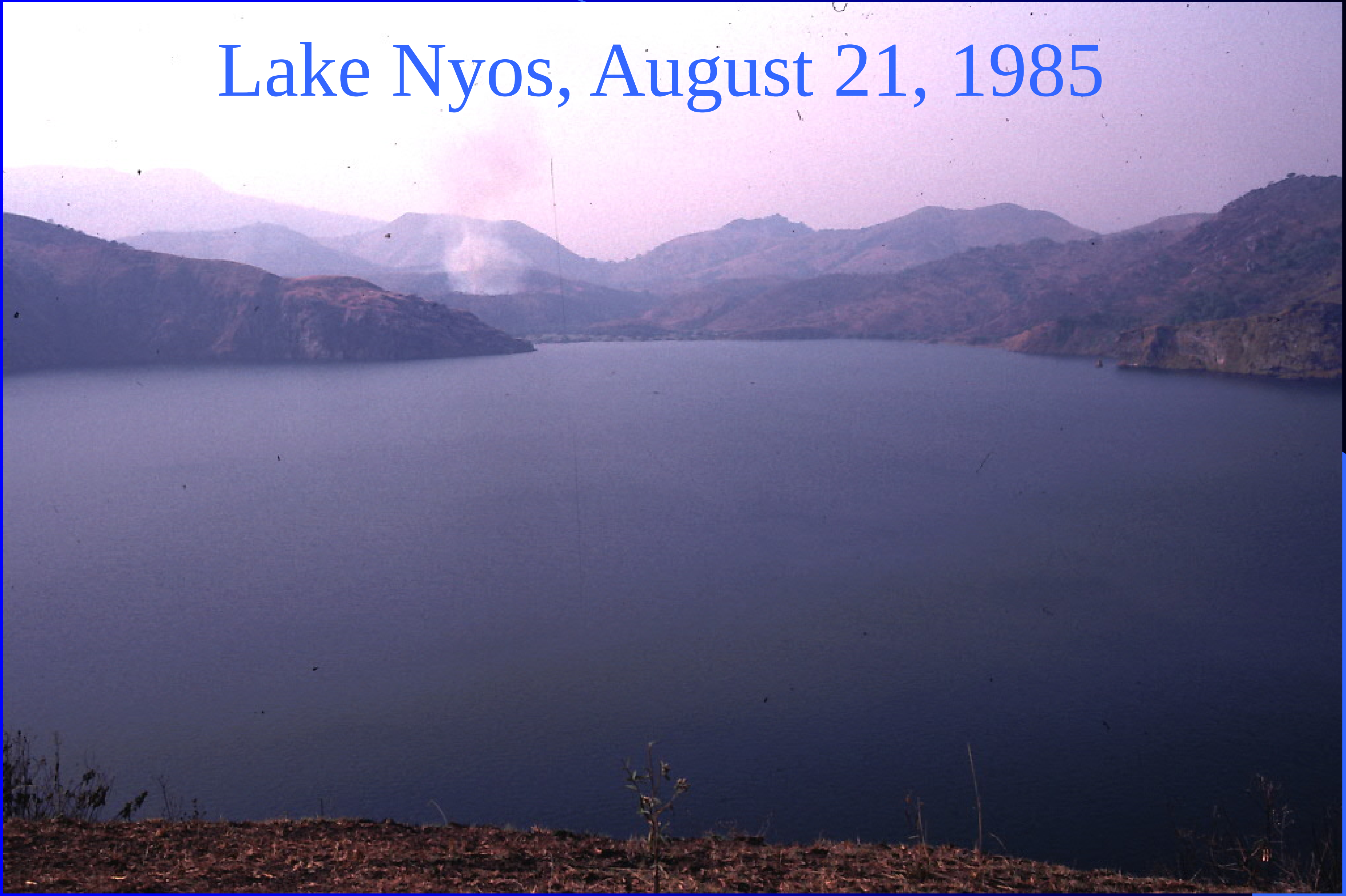
Paleo-lahars surround Mt. Rainier. Recent developments are built on these lahars.

Lahar near Enumclaw. 1 m thick layer at top of quarry. Note distance to Mt. Rainier



Lahars can originate from Mt. Rainier without volcanic activity. Hydrothermal alteration of volcanic rocks by acid gases oxidizes the ferromagnesian silicates and converts the feldspars to clay minerals. The resulting weak altered layers can fail under gravitational loading. Downslope movement of material with entrainment and melting of glacial ice and snow leads to the formation of a volcanic mudflow (lahar).

Gas release

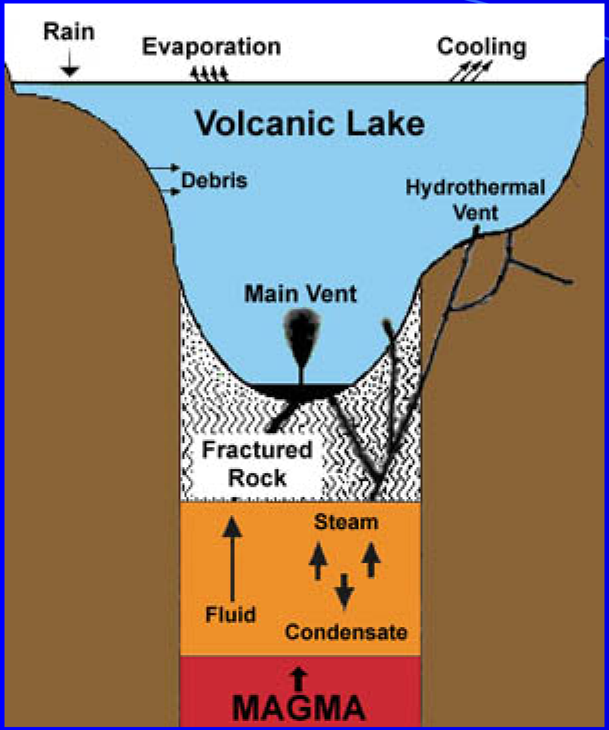

Lake Nyos, August 21, 1985

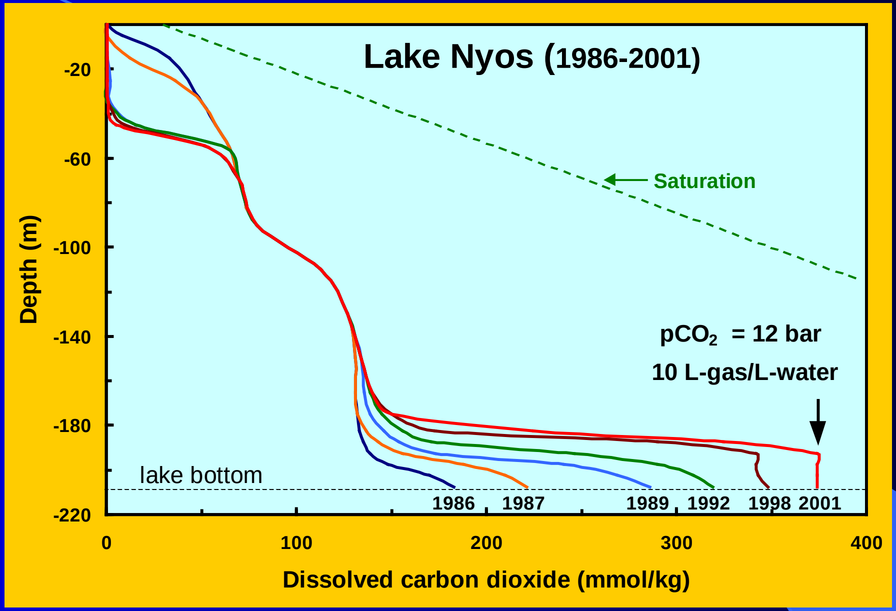
Lake Nyos pyroclastic dam, valley and town of Nyos.

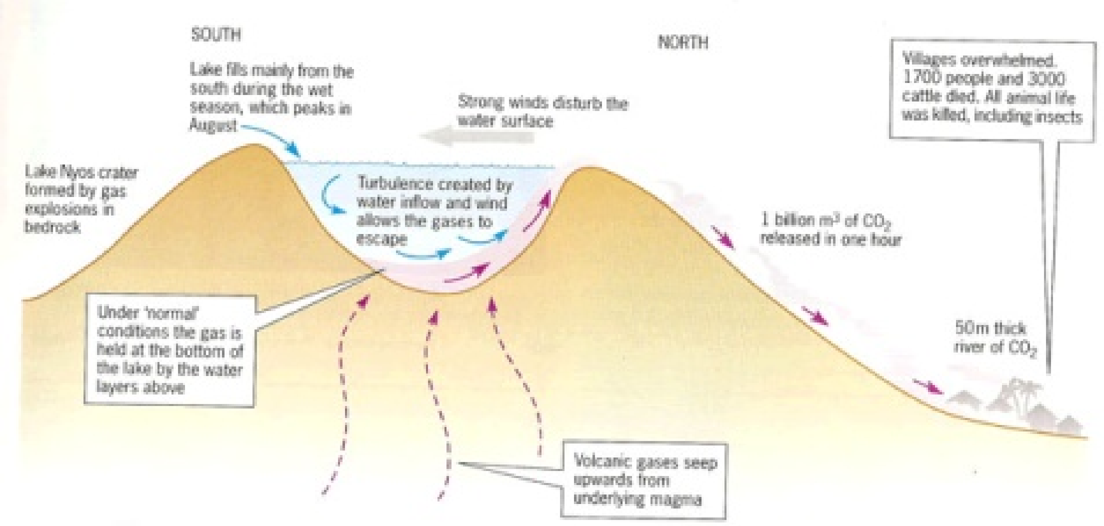
Orange color of Lake Nyos immediately after the gas release. The color is due to the oxidation of iron and the formation of ferric hydroxides

Dead cows in Nyos village. Over 1700 people perished as a result of the CO_2 release.

Disaster due to build-up of CO_2 in deep waters. Overturn leads to catastrophic release of CO_2.





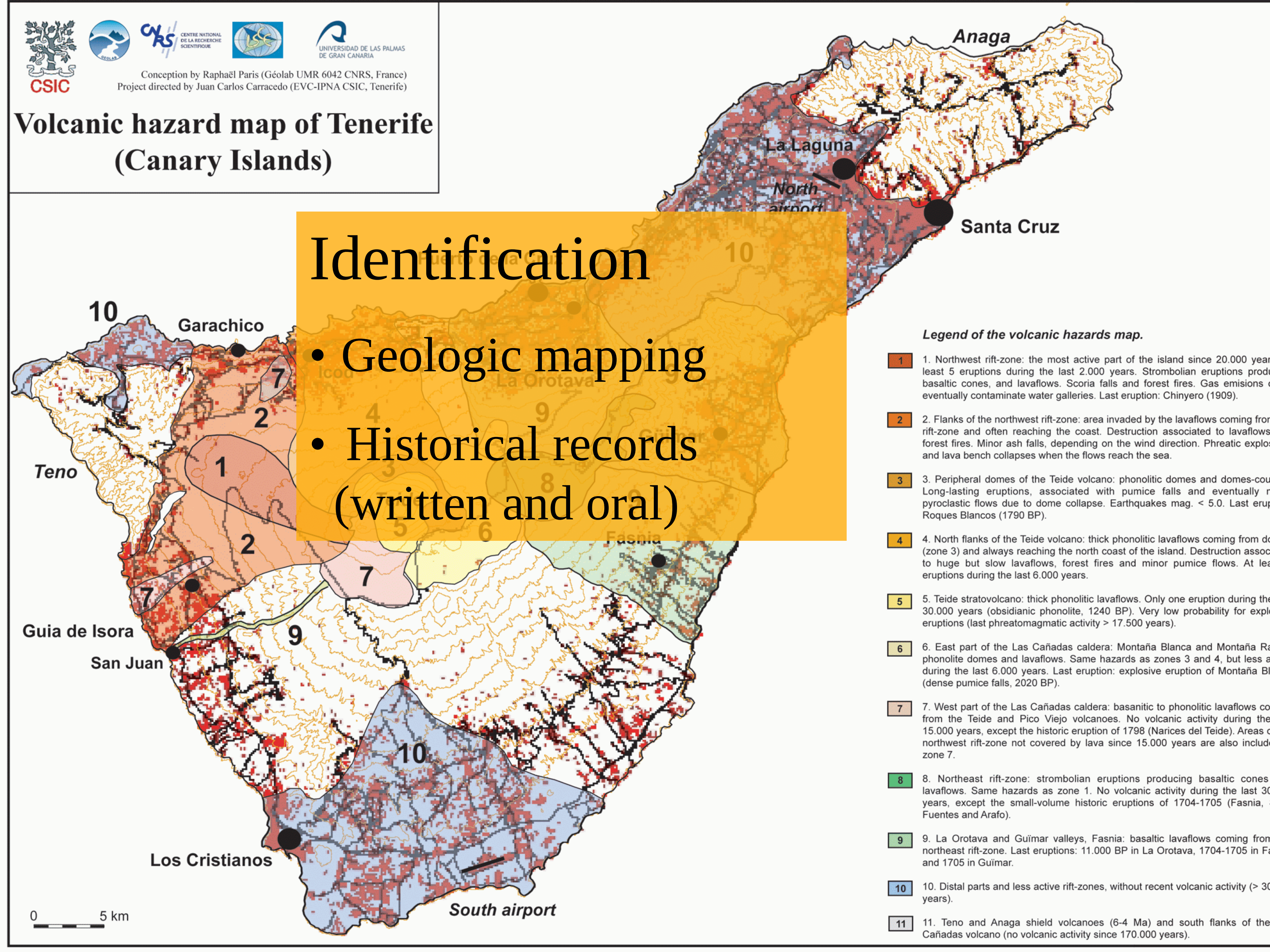


Volcanic Hazards

- Identification
- Monitoring and prediction
- Response

Identification

- Geologic mapping
- Historical records (written and oral)



Conception by Raphaël Paris (Géolab UMR 6042 CNRS, France)
Project directed by Juan Carlos Carracedo (EVC-IPNA CSIC, Tenerife)

Volcanic hazard map of Tenerife (Canary Islands)

Legend of the volcanic hazards map.

1 — 1. Northwest rift-zone: the most active part of the island since 20.000 year
least 5 eruptions during the last 2.000 years. Strombolian eruptions produ
basaltic cones, and lavaflows. Scoria falls and forest fires. Gas emisions c
eventually contaminate water galleries. Last eruption: Chinyero (1909).

2 — 2. Flanks of the northwest rift-zone: area invaded by the lavaflows coming fror
rift-zone and often reaching the coast. Destruction associated to lavaflows
forest fires. Minor ash falls, depending on the wind direction. Phreatic explos
and lava bench collapses when the flows reach the sea.

3 — 3. Peripheral domes of the Teide volcano: phonolitic domes and domes-cou
Long-lasting eruptions, associated with pumice falls and eventually r
pyroclastic flows due to dome collapse. Earthquakes mag. < 5.0. Last erup
Roques Blancos (1790 BP).

4 — 4. North flanks of the Teide volcano: thick phonolitic lavaflows coming from do
(zone 3) and always reaching the north coast of the island. Destruction assoc
to huge but slow lavaflows, forest fires and minor pumice flows. At lea
eruptions during the last 6.000 years.

5 — 5. Teide stratovolcano: thick phonolitic lavaflows. Only one eruption during the
30.000 years (obsidianic phonolite, 1240 BP). Very low probability for explo
eruptions (last phreatomagmatic activity > 17.500 years).

6 — 6. East part of the Las Cañadas caldera: Montaña Blanca and Montaña Ra
phonolite domes and lavaflows. Same hazards as zones 3 and 4, but less a
during the last 6.000 years. Last eruption: explosive eruption of Montaña Bl
(dense pumice falls, 2020 BP).

7 — 7. West part of the Las Cañadas caldera: basanitic to phonolitic lavaflows co
from the Teide and Pico Viejo volcanoes. No volcanic activity during the
15.000 years, except the historic eruption of 1798 (Narices del Teide). Areas o
northwest rift-zone not covered by lava since 15.000 years are also include
zone 7.

8 — 8. Northeast rift-zone: strombolian eruptions producing basaltic cones
lavaflows. Same hazards as zone 1. No volcanic activity during the last 30
years, except the small-volume historic eruptions of 1704-1705 (Fasnia,
Fuentes and Arafo).

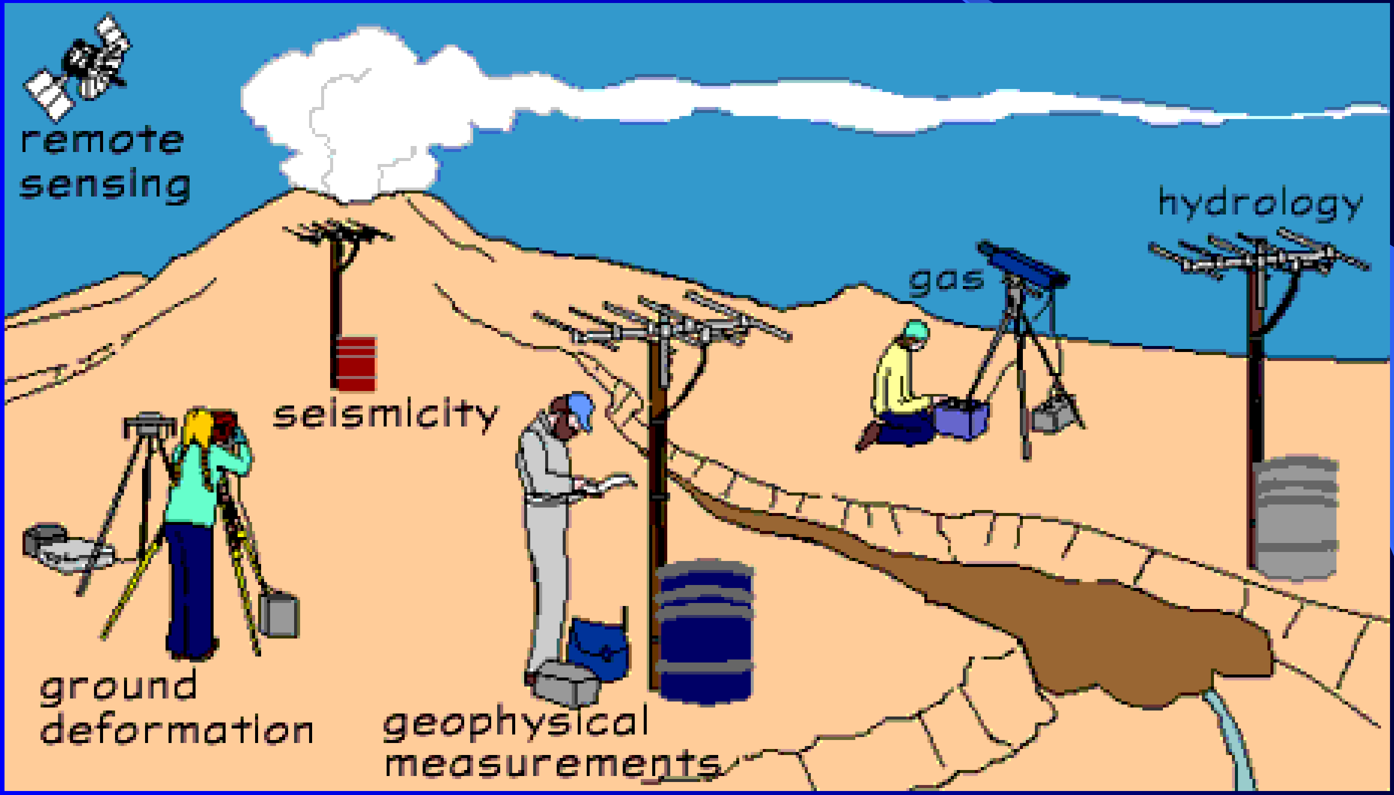
9 — 9. La Orotava and Guïmar valleys, Fasnia: basaltic lavaflows coming from
northeast rift-zone. Last eruptions: 11.000 BP in La Orotava, 1704-1705 in Fa
and 1705 in Guïmar.

10 — 10. Distal parts and less active rift-zones, without recent volcanic activity (> 30
years).

11 — 11. Teno and Anaga shield volcanoes (6-4 Ma) and south flanks of the
Cañadas volcano (no volcanic activity since 170.000 years).

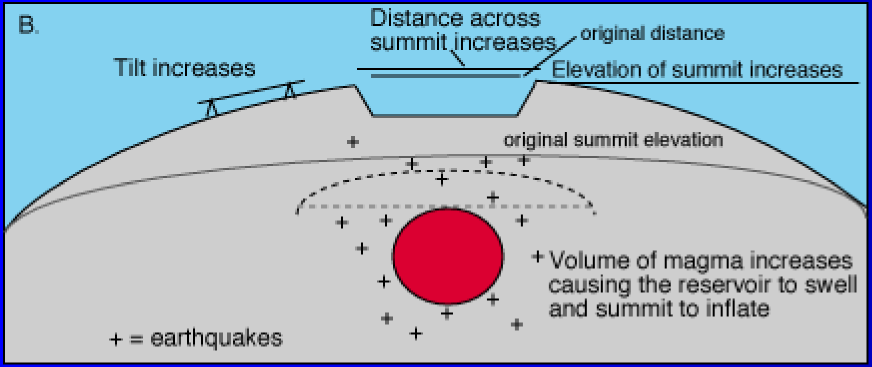
Monitoring and Predicting

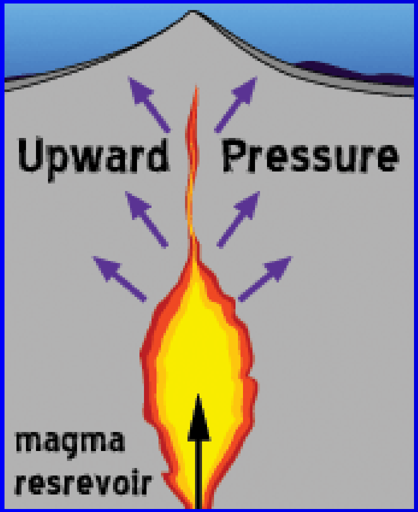
Volcanic Eruptions



Ground deformation

Rising magma intrudes volcano and changes its shape



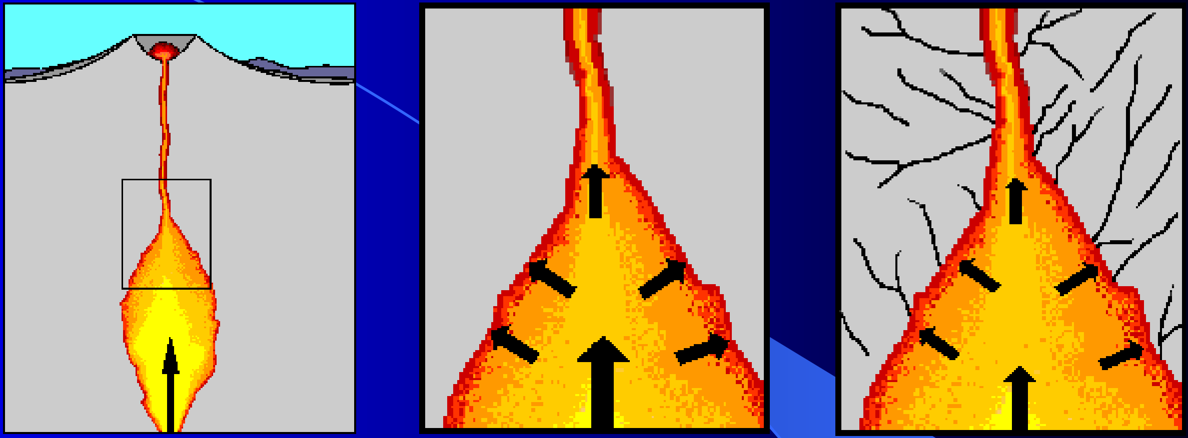


Installing tiltmeter

Tiltmeter

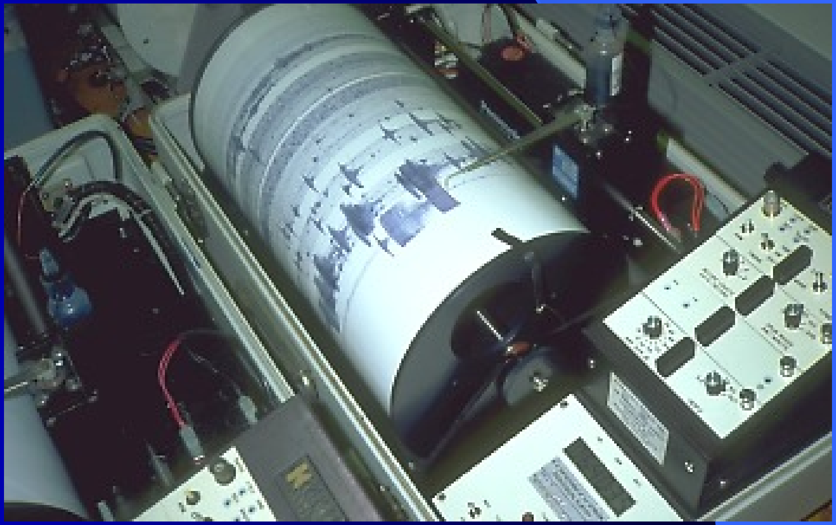
Seismicity

Rising magma exerts pressure on the surrounding rock which leads to fracturing and small earthquakes



Installing seismometer

Seismograph, Mt. Pinatubo

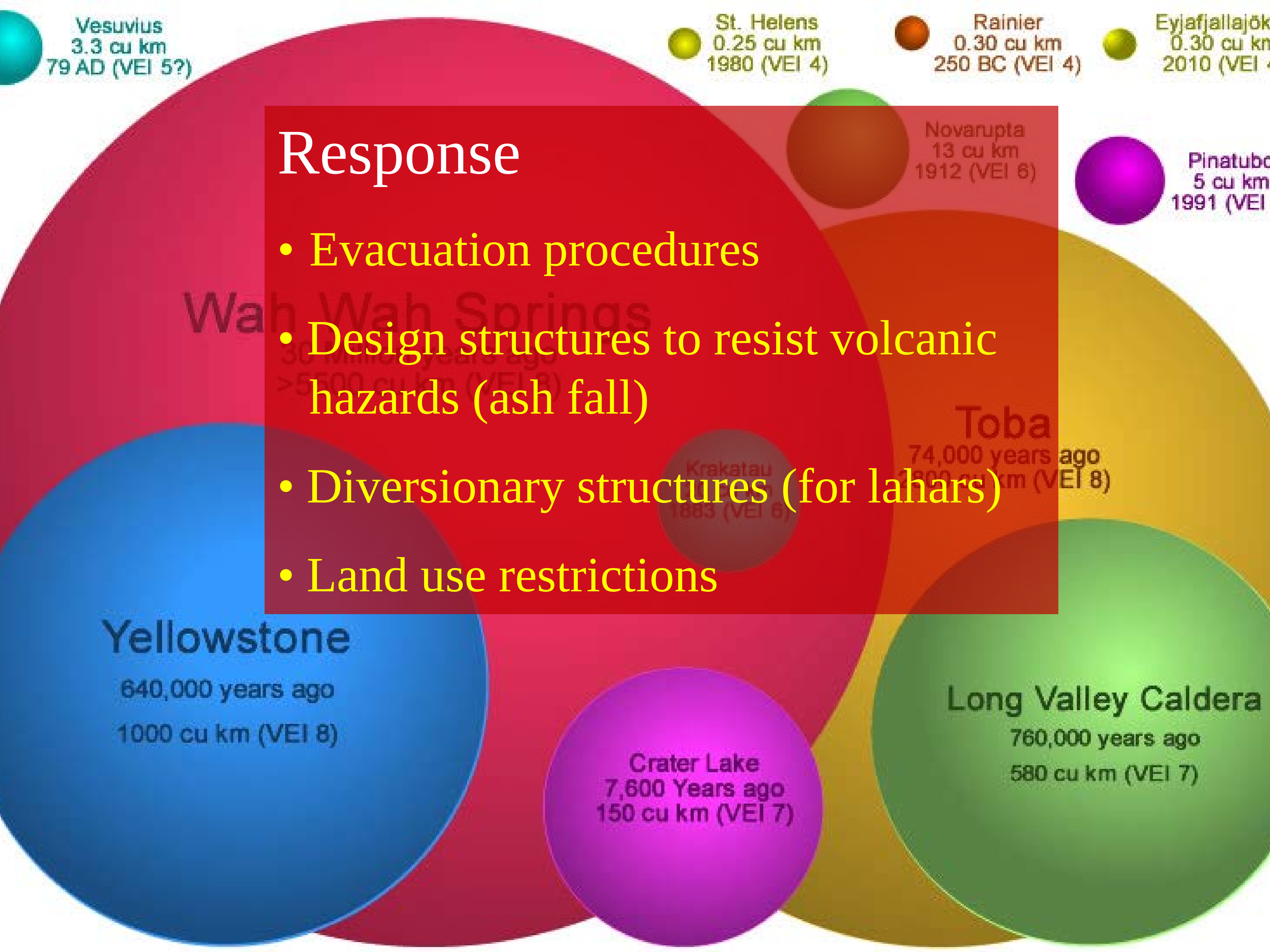


Gas monitoring

Monitor emission of carbon dioxide and sulfur dioxide. The emission rate may increase immediately before a volcanic eruption and sulfur dioxide may become a more important component of the gas stream.

Response

- Evacuation procedures
- Design structures to resist volcanic hazards (ash fall)
- Diversionary structures (for lahars)
- Land use restrictions

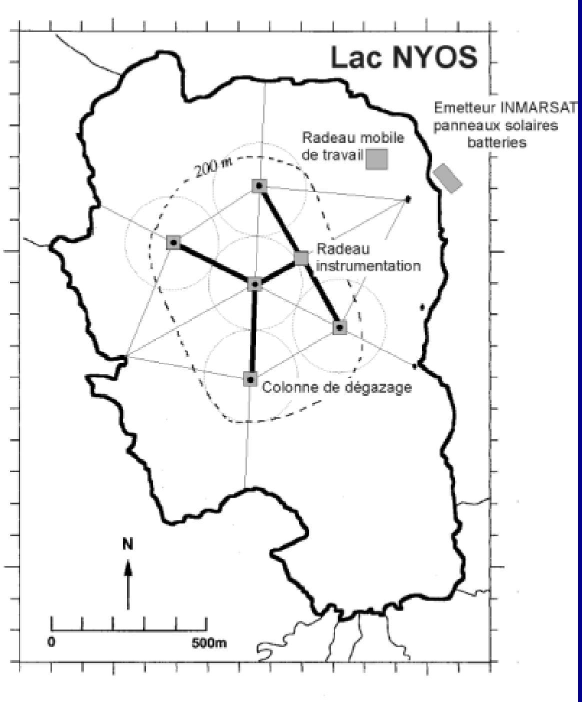


Monitoring and alert system (Lake Nyos)

- CO_2 gas monitoring system
  - Solar powered with battery back-up
  - Infrared sensor
  - Both visual and audio alert
- Response plan and designation of responsible individuals


Carbon dioxide
continuous monitoring
NYOS MONOUN DEGASSING PROJECT
WEST
westsystems.com

Remediation – Degassing Lake Nyos



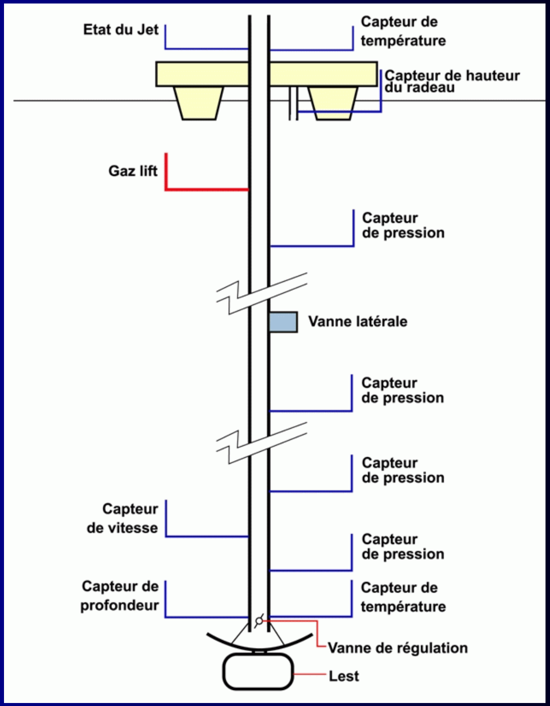
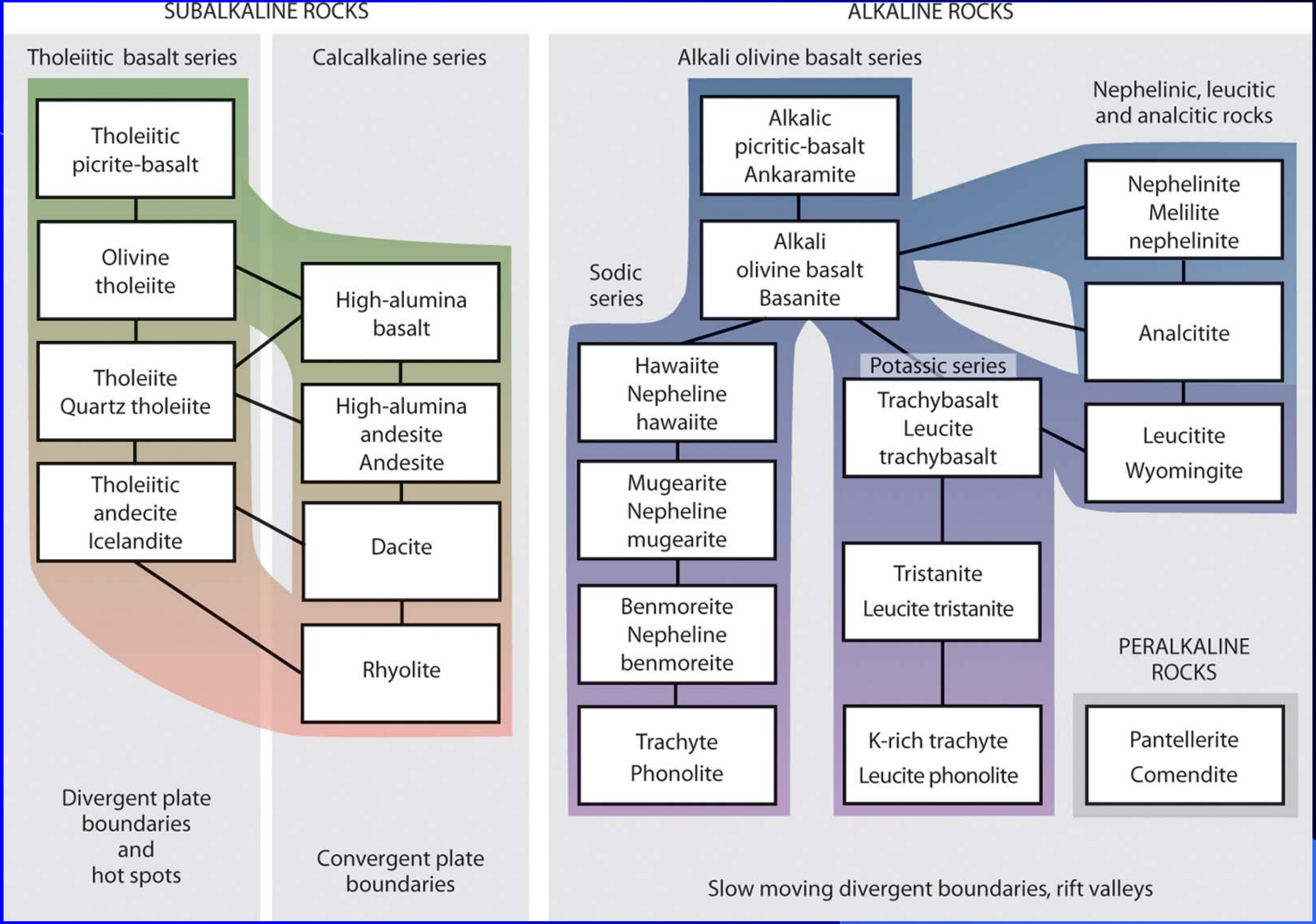


Plate Tectonics and Igneous Rock Associations



SUBALKALINE ROCKS

Tholeiitic basalt series

Tholeiitic picrite-basalt

Olivine tholeiite

Tholeiite
Quartz tholeiite

Tholeiitic andecite
Icelandite

Calcalkaline series

High-alumina basalt

High-alumina andesite
Andesite

Dacite

Rhyolite

Divergent plate boundaries and hot spots

Convergent plate boundaries

ALKALINE ROCKS

Alkali olivine basalt series

Alkalic picritic-basalt
Ankaramite

Alkali olivine basalt
Basanite

Sodic series

Hawaiite
Nepheline hawaiite

Mugearite
Nepheline mugearite

Benmoreite
Nepheline benmoreite

Trachyte
Phonolite

Potassic series

Trachybasalt
Leucite trachybasalt

Tristanite
Leucite tristanite

K-rich trachyte
Leucite phonolite

Nephelinic, leucitic and analcitic rocks

Nephelinite
Melilite nephelinite

Analcitite

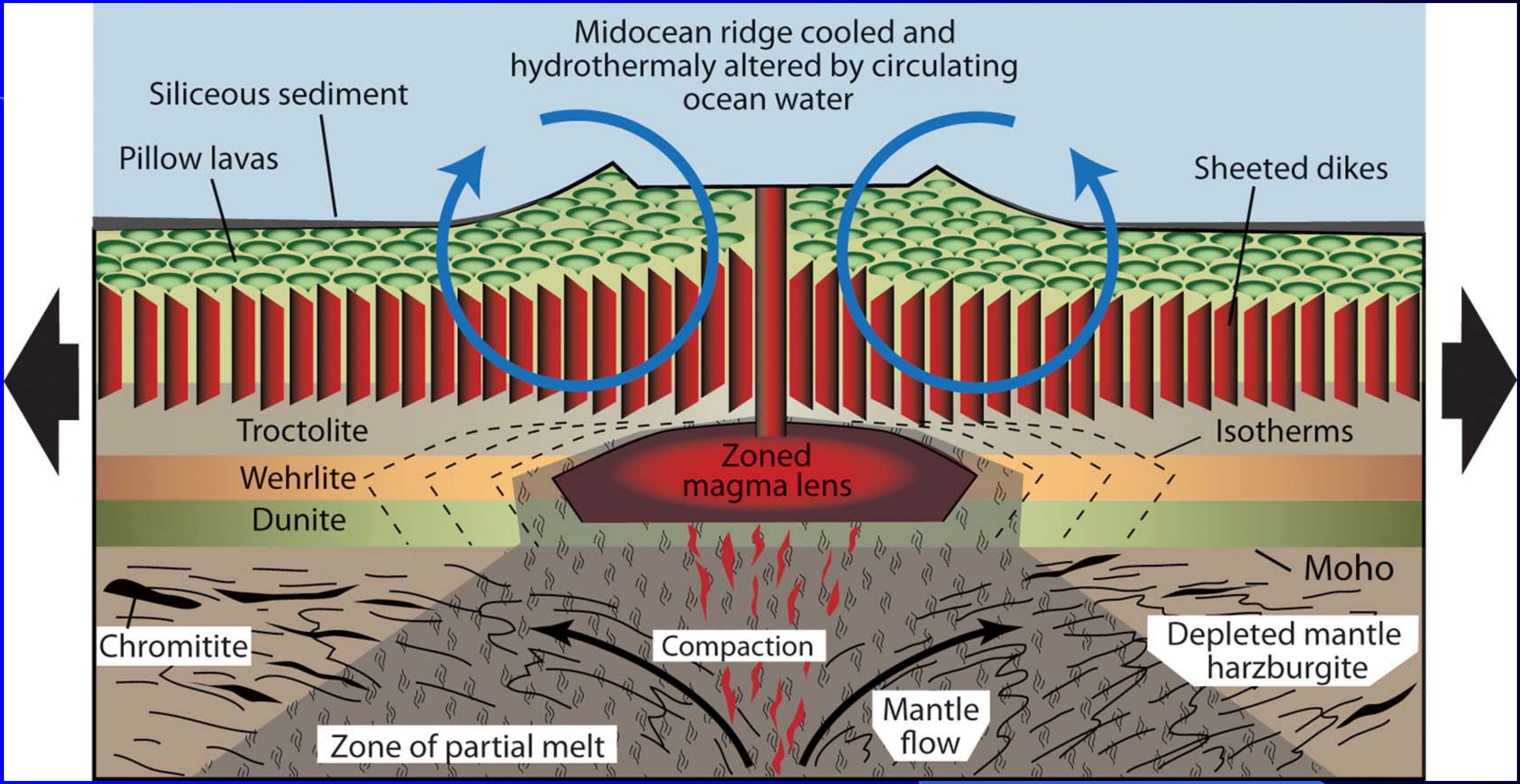
Leucitite
Wyomingite

PERALKALINE ROCKS

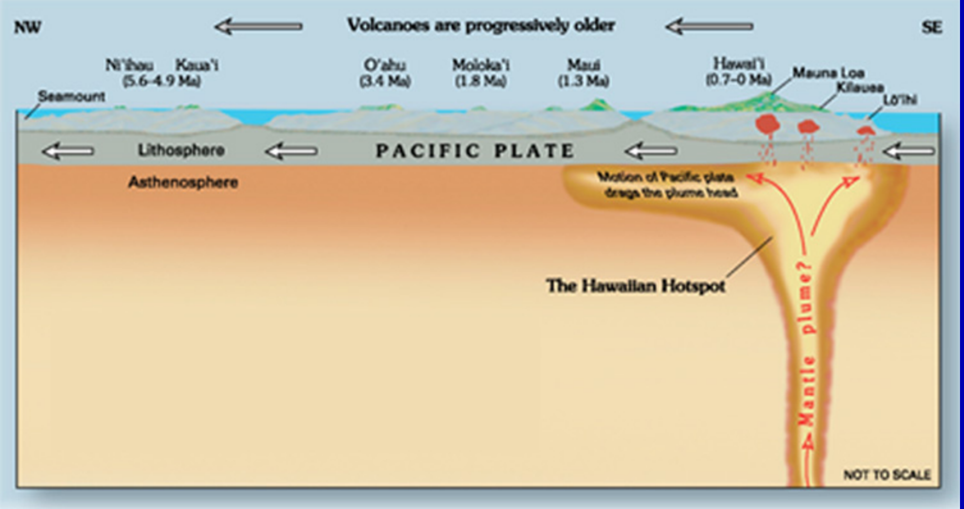
Pantellerite
Comendite

Slow moving divergent boundaries, rift valleys

The mid-ocean ridge system. The Earth's great basalt generator.



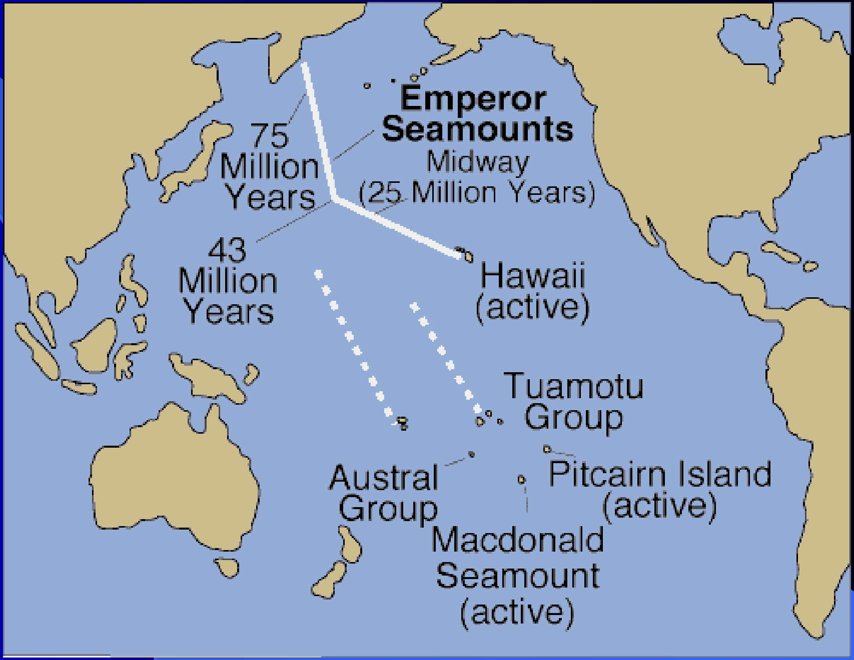
Oceanic Islands and Hot Spots



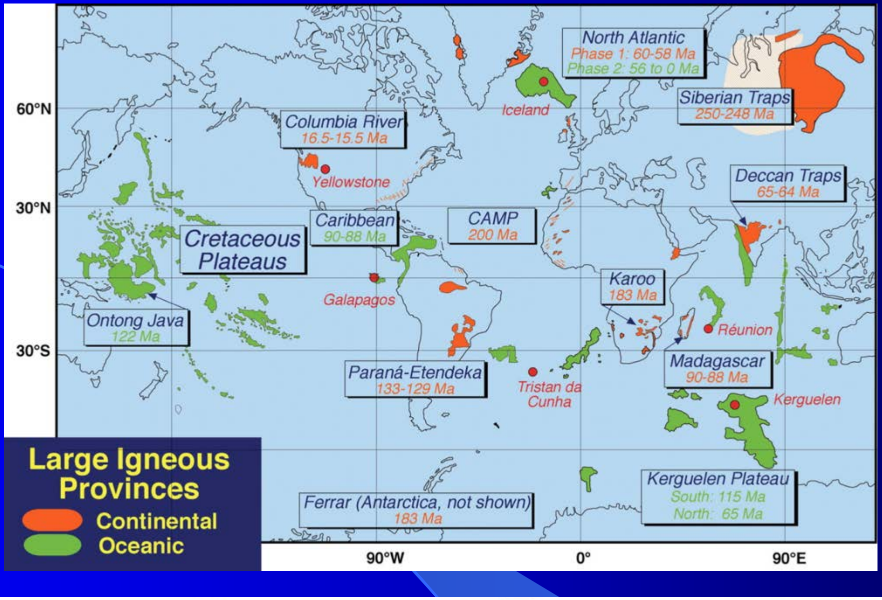
Oceanic islands are mostly composed of tholeiitic basalt with a late stage alkaline sequence (alkali olivine basalt).

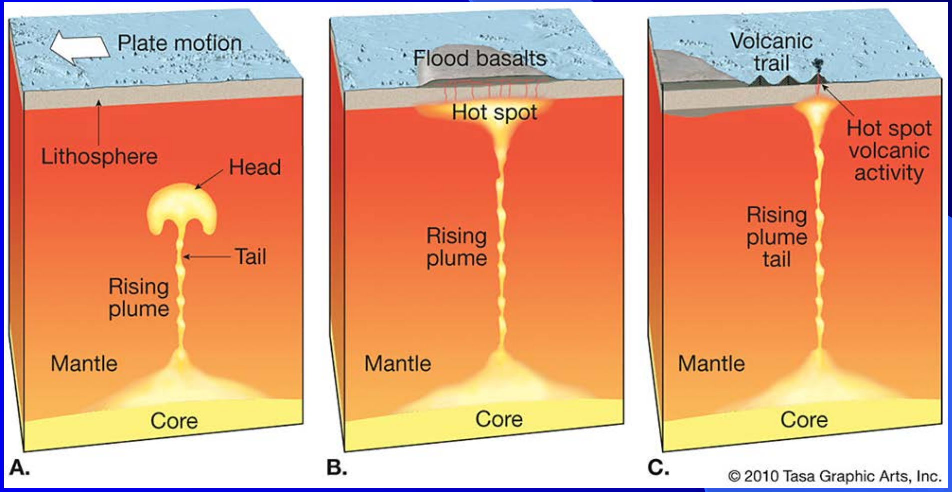
MORB and oceanic island tholeiites consist of olivine + two pryoxenes (Ca-rich and Ca-poor).

Alkali olivine basalt has one pryoxene (a Ca-rich pyroxene)



Flood basalts are associated with large plumes. The major basalt type is a quartz tholeiite. Note difference between MORB and oceanic island tholeiites versus flood basalt tholeiites.





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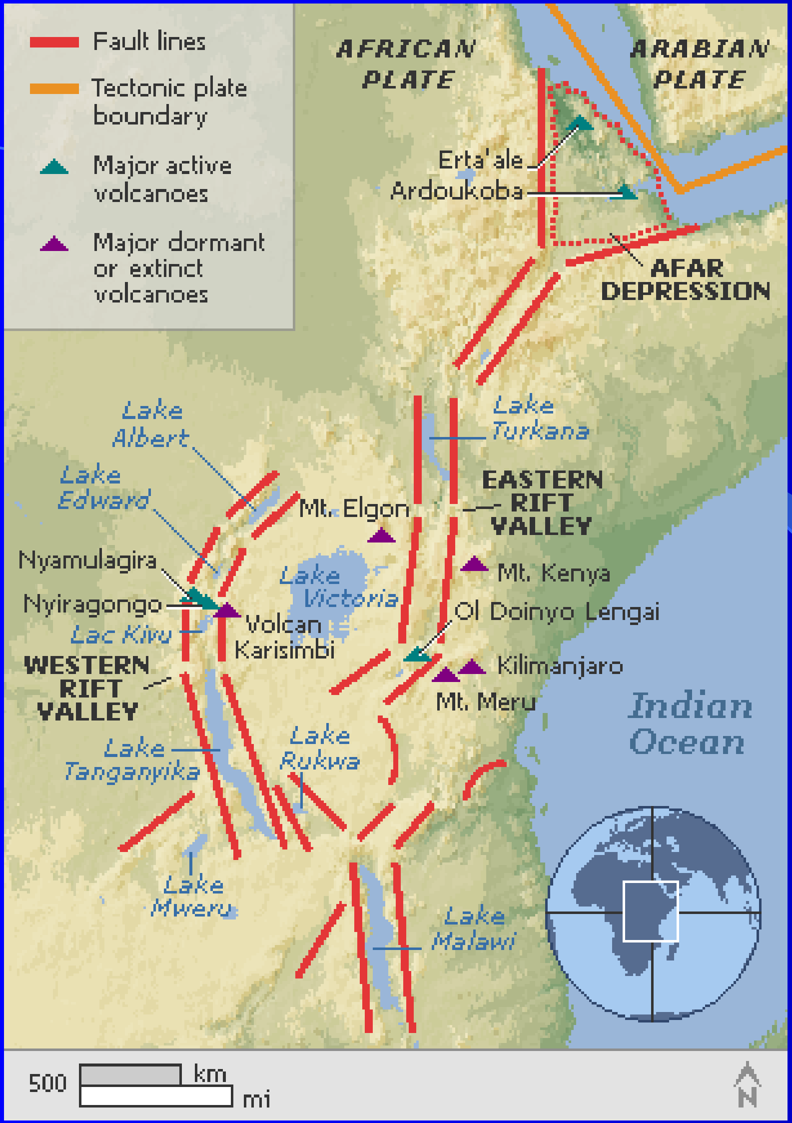
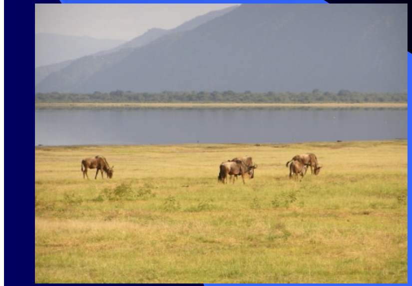
Alkaline Igneous Rocks Associated with Continental Rift Valleys



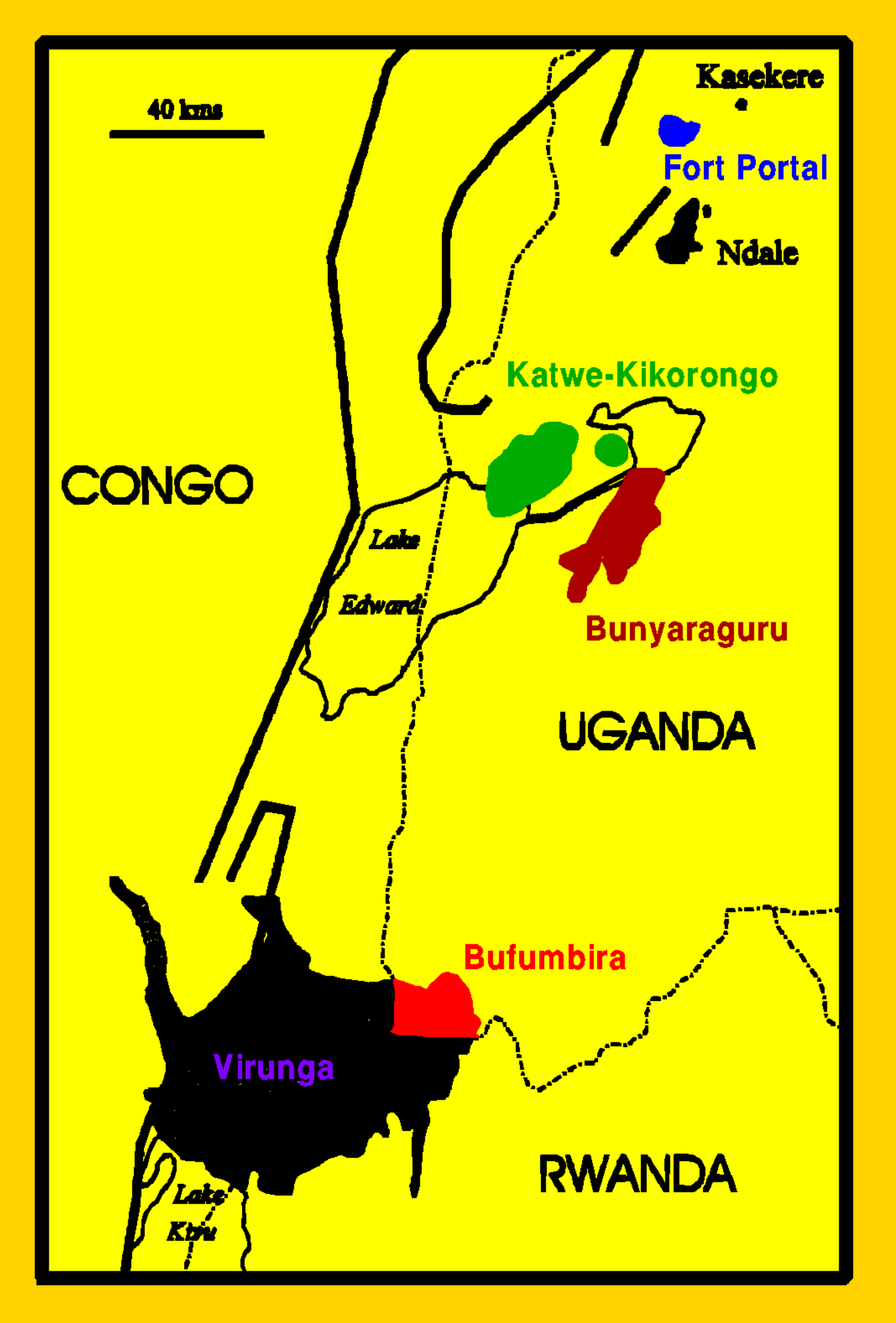
Kilimanjaro is a snow-covered mountain 19,710 feet high, and is said to be the highest mountain in Africa. Its western summit is called the Masai "Ngaje Ngai," the House of God. Close to the western summit there is the dried and frozen carcass of a leopard. No one has explained what the leopard was seeking at that altitude. (Hemmingway, The Snows of Kilimanjaro)


OMO N.P.
Omo River
ETHIOPIA
Nile River
SUDAN
MAGO N.R.
Lake Turkana
SIBILOI N.P
KIDEPO N.P.
D.R.CONGO
MURCHISON FALLS N.P.
SOMALIA
Lake Albert
UGANDA
KENYA
MARSABIT N.P.
KIBALE FOREST N.P.
Lake Baringo
LAIKIPIA
SAMBURU, SHABA BUFFALO SPRINGS
Kampala
Kakamega
MOUNT KENYA N.P.
Lake Edward
QUEEN ELIZABETH N.P.
Lake Nakuru
L.MBURU
MAASAI MARA N.R.
ABERDARES
BWINDI
Lake Kivu
VOLCANOES N.P.
Lake Victoria
Nairobi
Kigali
RWANDA
Lake Natron
AMBOSELI N.R.
TSAVO EAST N.P.
Lamu
SERENGETI N.P.
NGORONGORO
Kilimanjaro
BURUNDI
Bujumbura
Lake Eyasi
Arusha
TSAVO WEST N.P.
SEYCHELLES
Moshi
L.MANYARA N.P.
Mombasa
TARANGIRE N.P.
GOMBE STREAM N.P.
TANZANIA
Pemba
ZANZIBAR
MAHALE MTNS N.P.
Dodoma
Dar-es-Salaam
KATAVI N.P.
RUAHA N.P.
MIKUMI N.P.
Lake Tanganyika
Lake Rukwa
Rufiji River
SELOUS G.R.
Mbeya
SUMBU
Indian Ocean
ZAMBIA
NYIKA
200 km
200 miles
Lake Malawi
MOZAMBIQUE
N.LUANGWA
NIASSA
Pemba



Bunyaraguru Olivine-bearing tephras & rare lavas. Leucite + augite (ugandite), augite + kalsilite (mafurite) and melilite + leucite (katungite)

Bufumbira Basanite, leucitite, leucite-phonolite, latite & trachyte



Fort Portal Extrusive carbonatites

Katwe-Kikorongo Olivine-melilitite and feldspathoidal cpx-rich tephras & subordinate flows

Field party

Bush camp

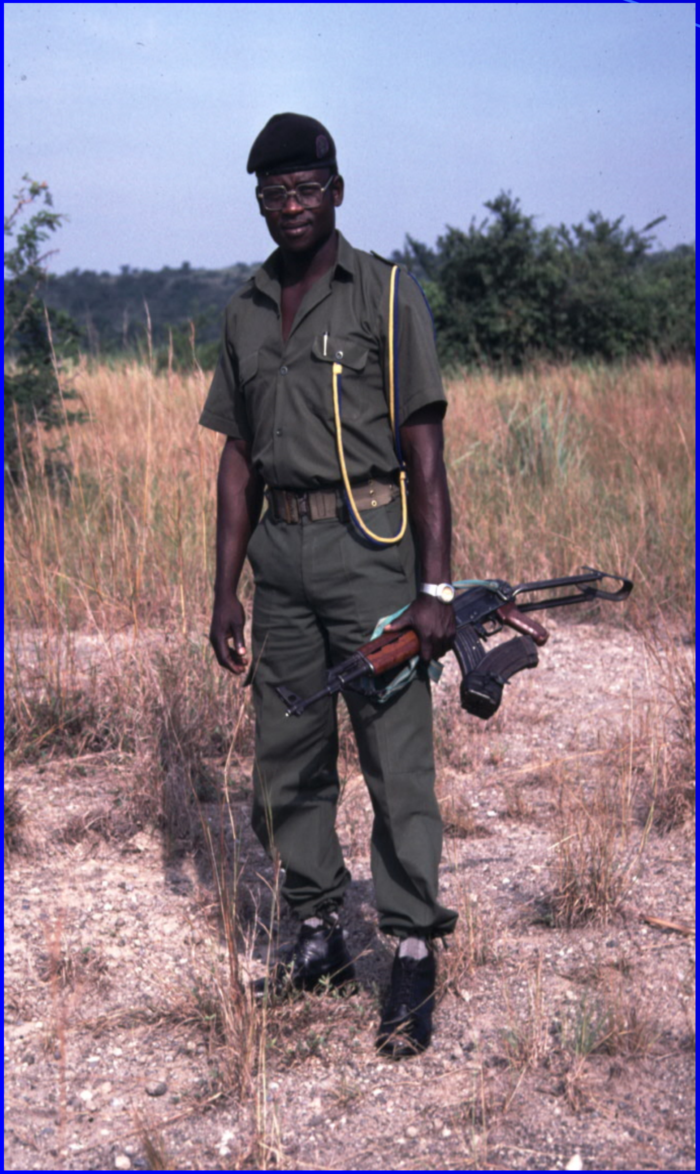
Lunch time

Tuff cones in the Fort Portal field

Fort Portal

Tuff cone and
crater lake

Tuff cone



Katwe-Kikorongo

Guide - Joseph Machati, Chief Ranger, Queen Elizabeth National Park

Katwe-Kikorongo

Crater

Rim is composed of tuffs and agglomerates

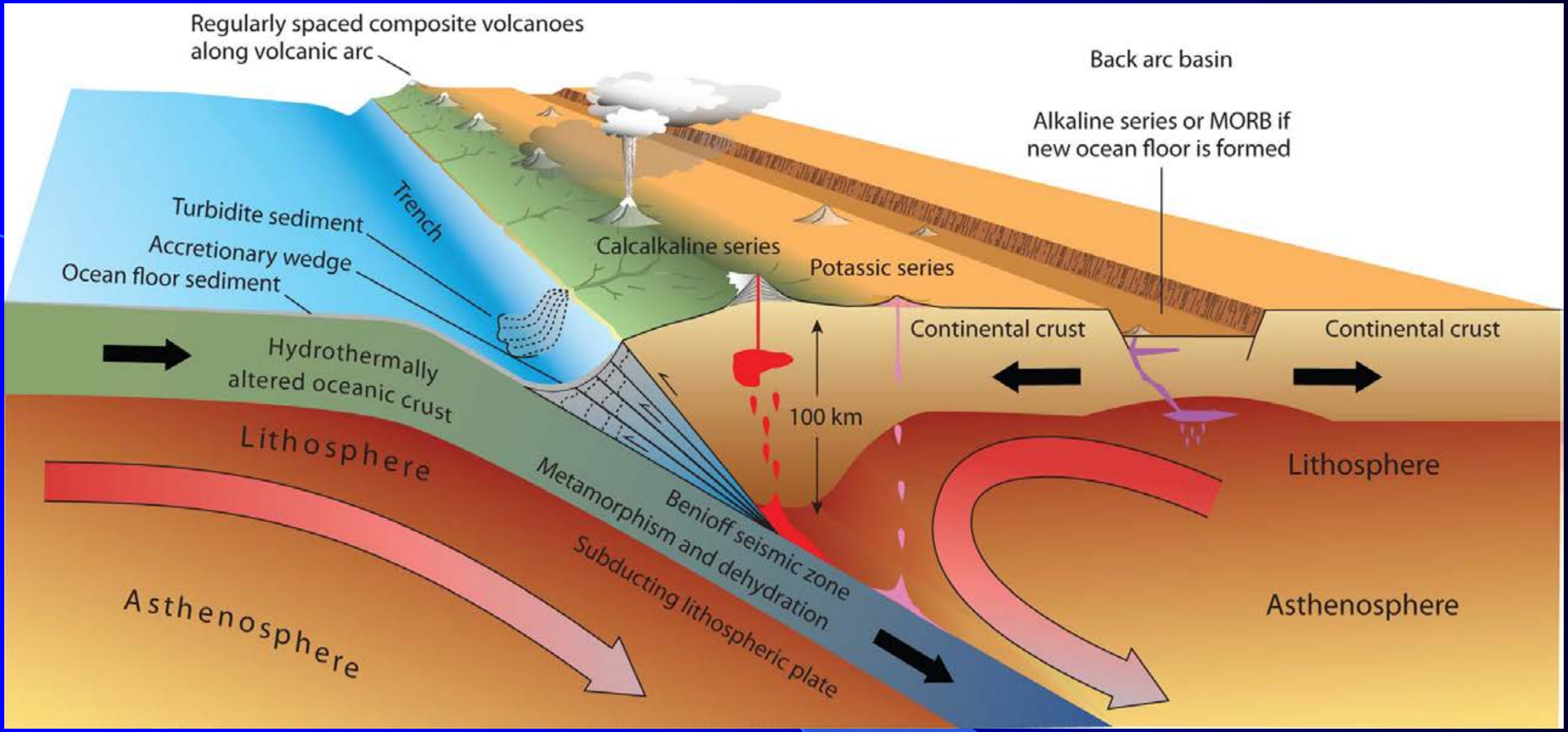
Crater lake

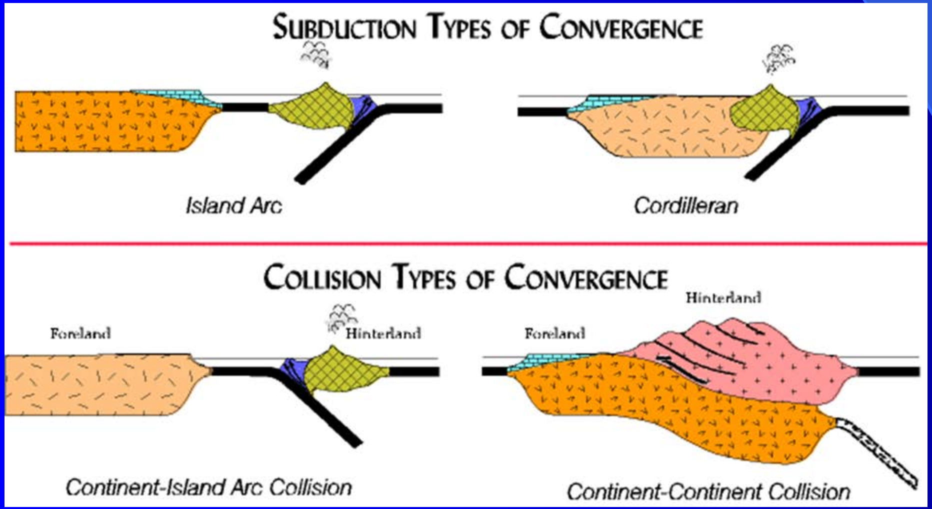
Bufumbira

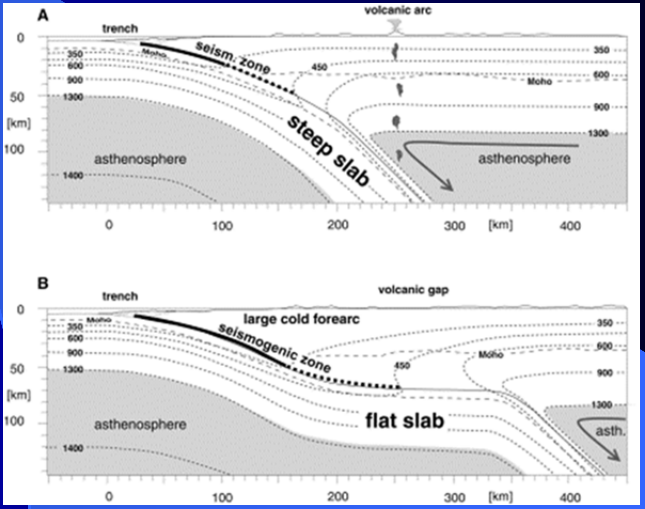
Mgahinga and Sabinio volcanoes

Trachyte plug

The Subduction Zone Factory

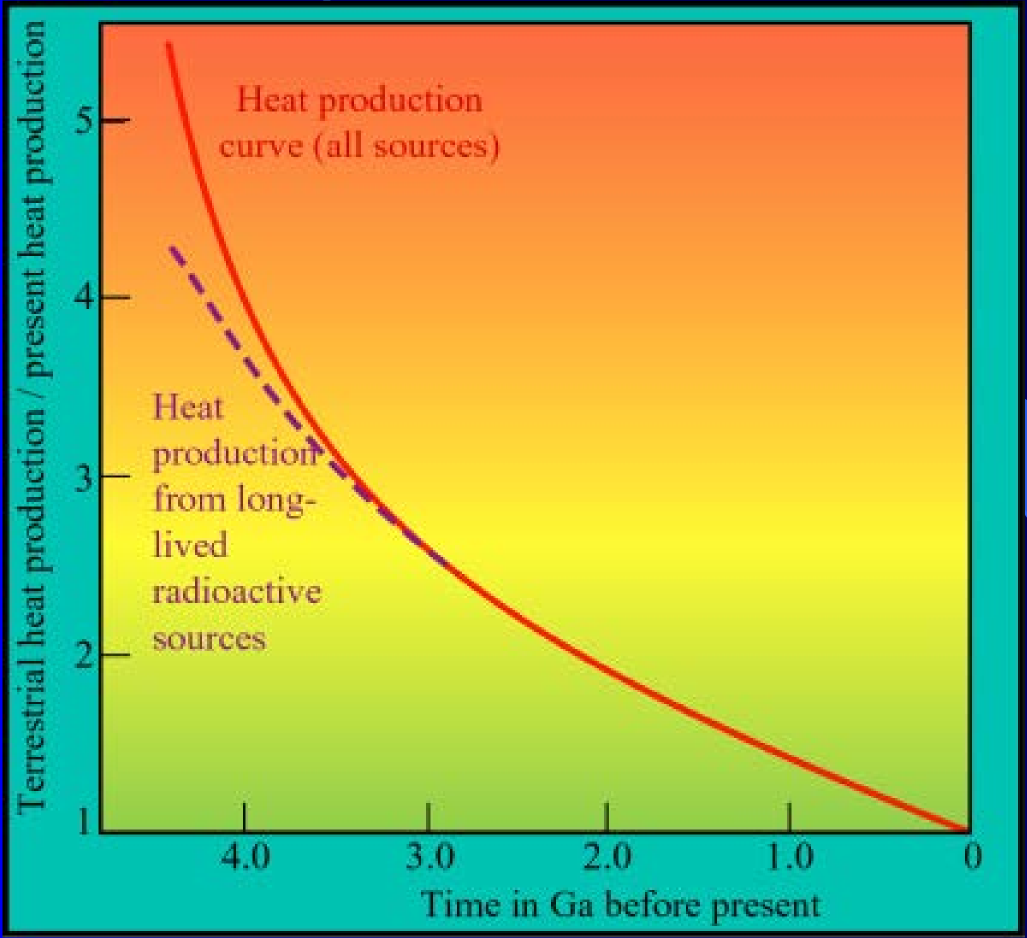




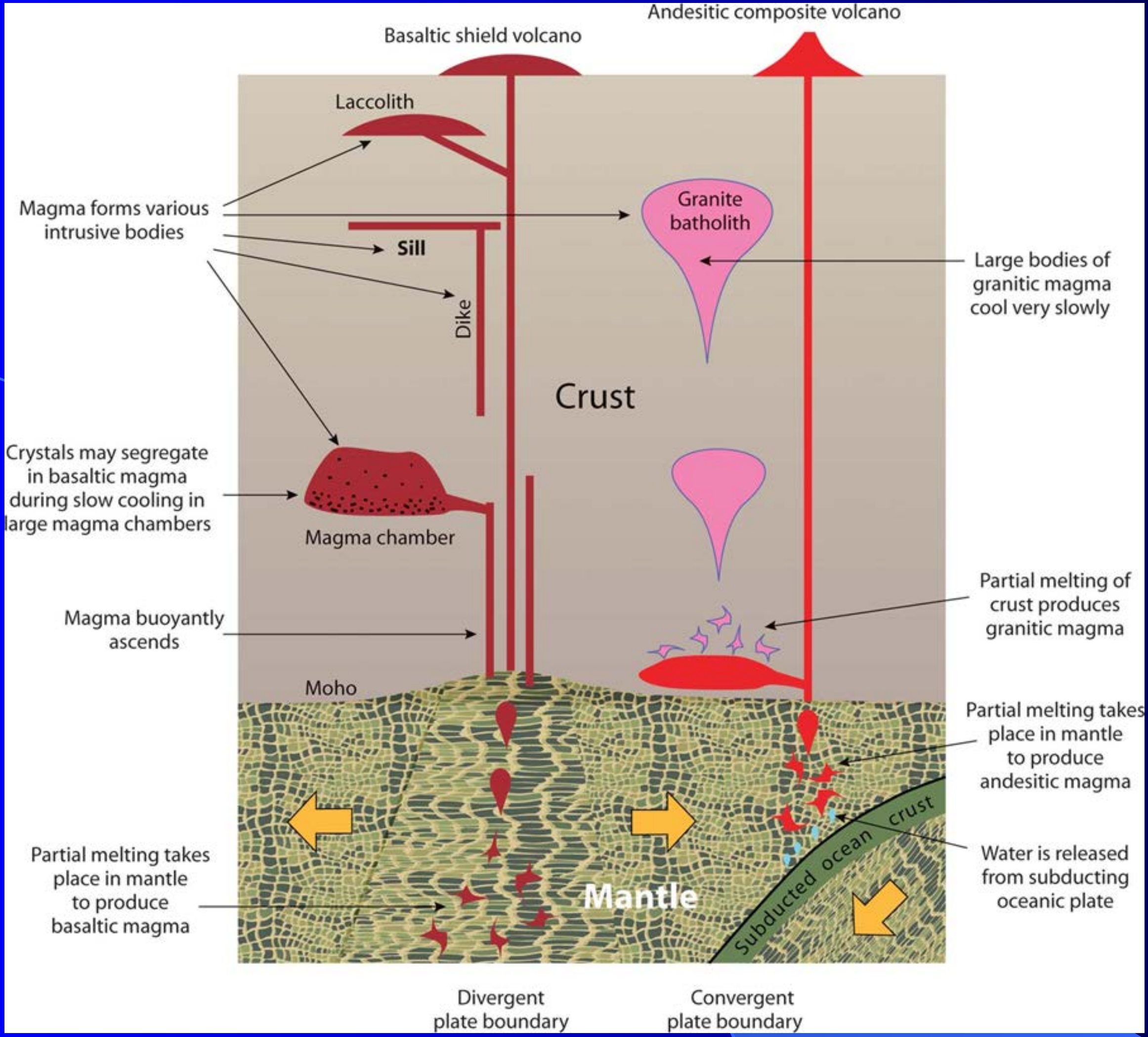


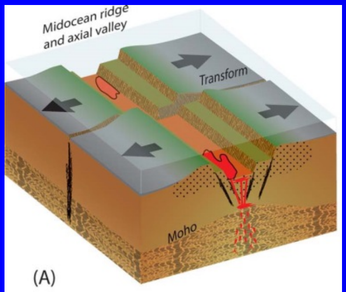
Formation of Igneous Rocks

Earth’s heat production

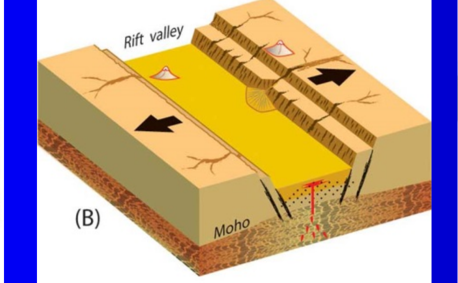


A 2- to 4-fold decrease from the Archean to now

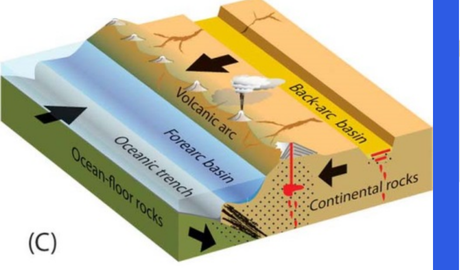




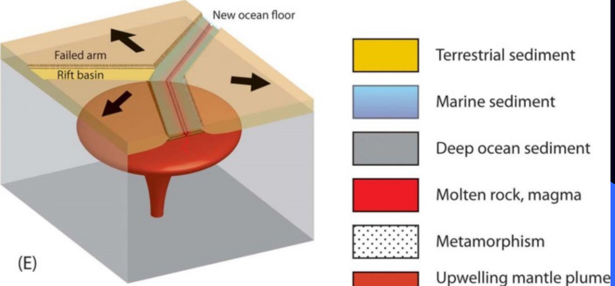
Divergent oceanic plates



Divergent continental plates



Convergent oceanic and continental plates



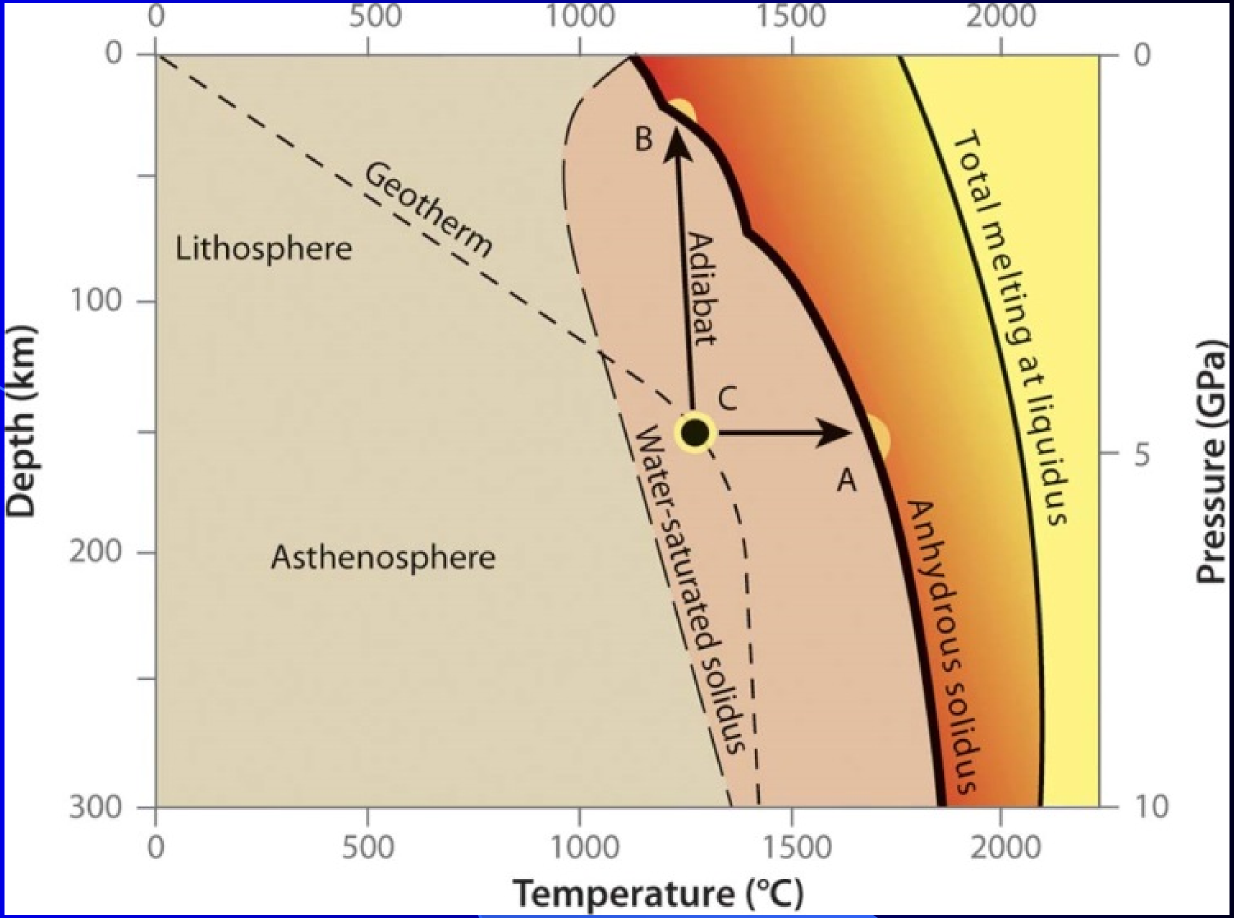
Mantle plume and triple junction

Why do rocks melt?

- Increasing temperature
- Decreasing pressure
- Adding water

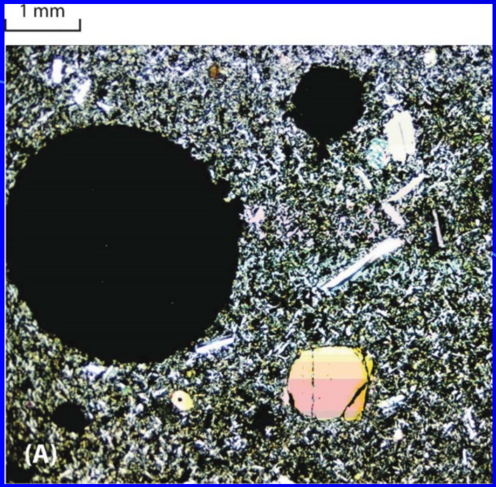
Types of Mantle rocks

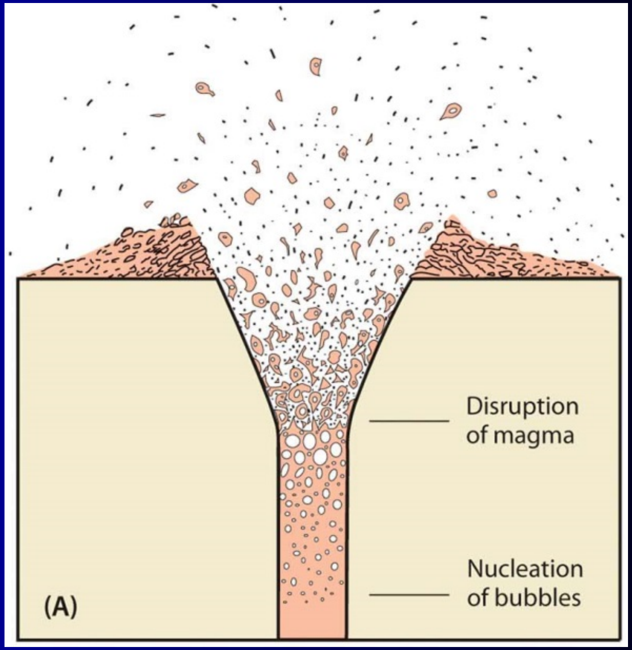
- Plagioclase lherzolite
- Spinel lherzolite
- Garnet lherzolite

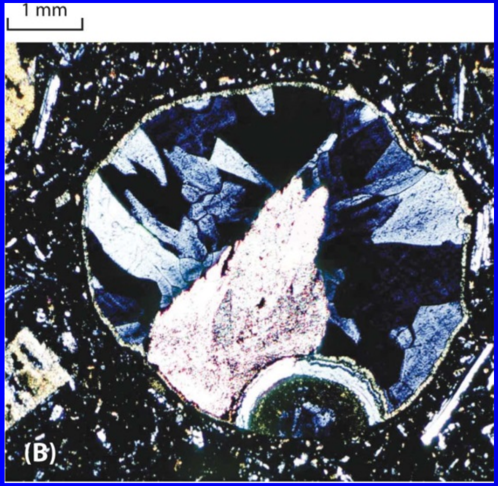


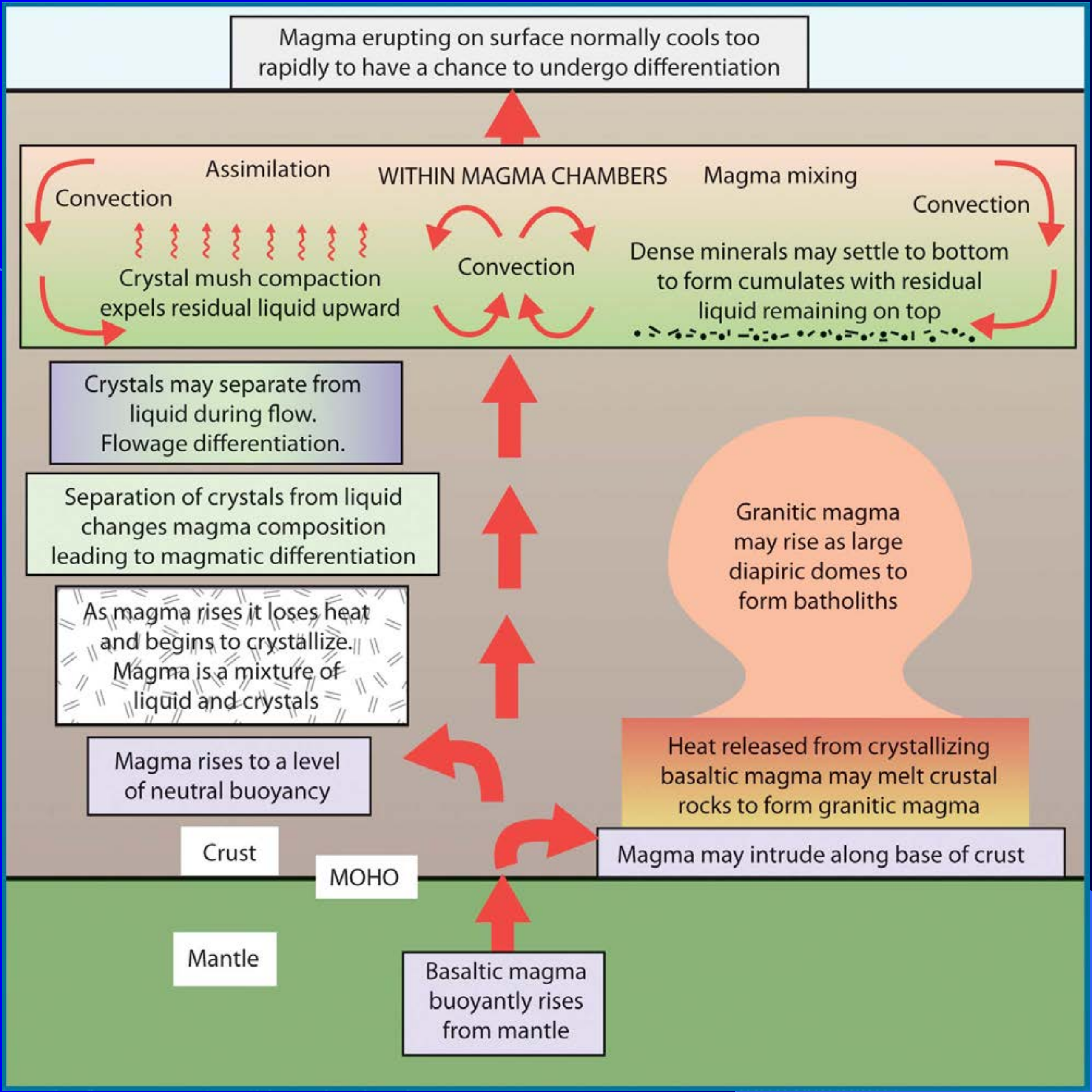
Lherzolite ⟶ olivine > orthopyroxene > Ca-pyroxene > aluminous phase

Exsolution of magmatic gases and explosive volcanism








Magma erupting on surface normally cools too rapidly to have a chance to undergo differentiation
Assimilation
WITHIN MAGMA CHAMBERS
Magma mixing
Convection
Convection
Crystal mush compaction expels residual liquid upward
Convection
Dense minerals may settle to bottom to form cumulates with residual liquid remaining on top
Crystals may separate from liquid during flow. Flowage differentiation.
Separation of crystals from liquid changes magma composition leading to magmatic differentiation
As magma rises it loses heat and begins to crystallize. Magma is a mixture of liquid and crystals
Granitic magma may rise as large diapiric domes to form batholiths
Magma rises to a level of neutral buoyancy
Heat released from crystallizing basaltic magma may melt crustal rocks to form granitic magma
Magma may intrude along base of crust
Crust
MOHO
Mantle
Basaltic magma buoyantly rises from mantle