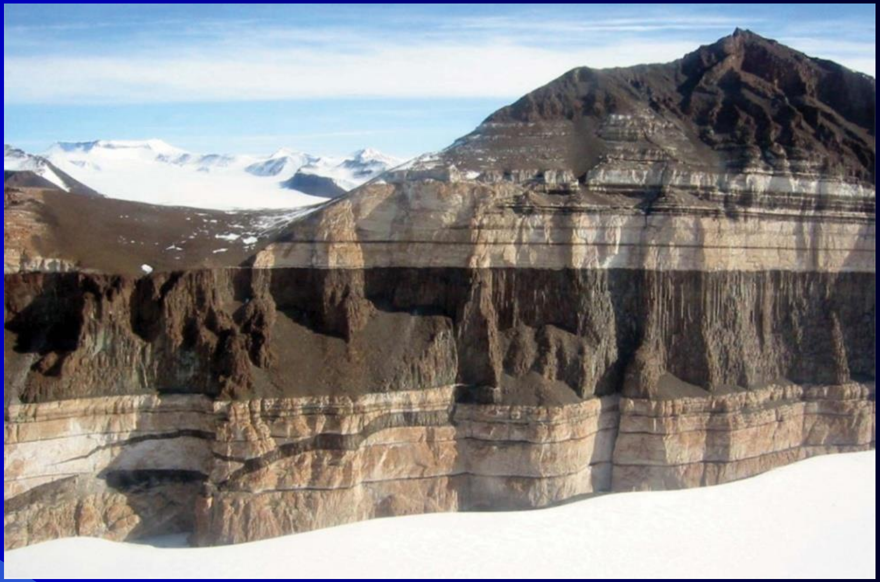
Igneous Rocks - Occurrence and Classification



Classification of Igneous Rocks

Rocks are classified on the basis of

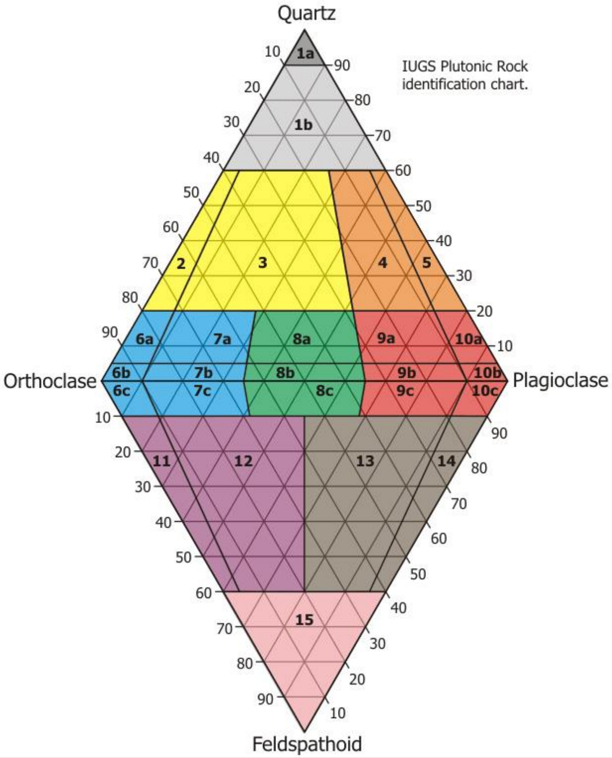
- Texture
- Mineralogy

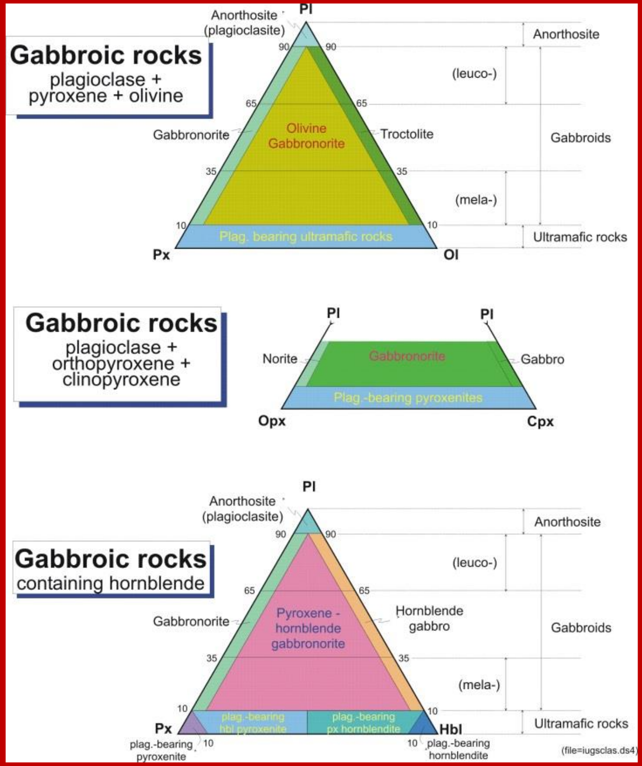
Very fine-grained or glassy rocks are classified on the basis of chemistry

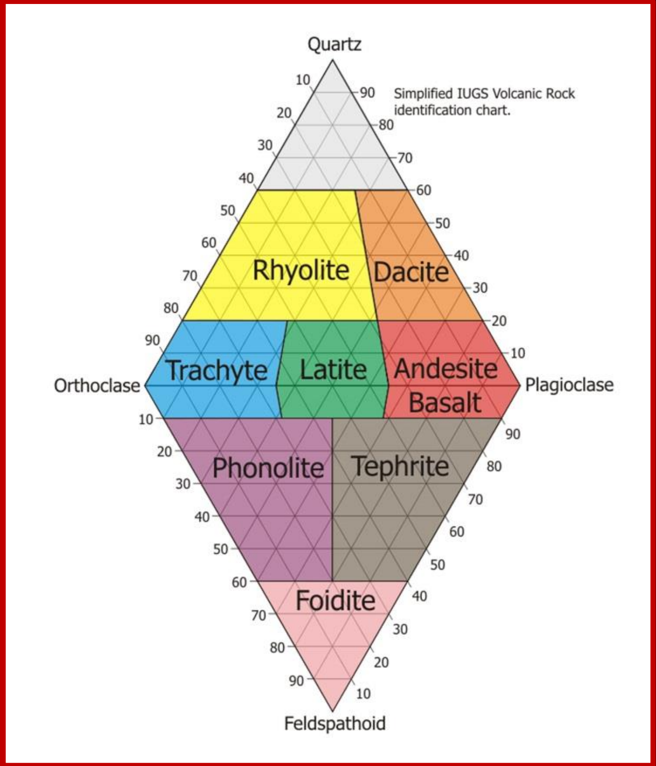
Mode – mineral content of rock on a volume basis. Either visually estimated or determined by point counting

Norm – calculated mineral content of a rock on a weight percent basis. Chemistry of the rock is converted to ideal minerals.

IUGS Classification of Igneous Rocks







Rock classification based on chemical composition. This classification scheme is used for volcanic rocks.

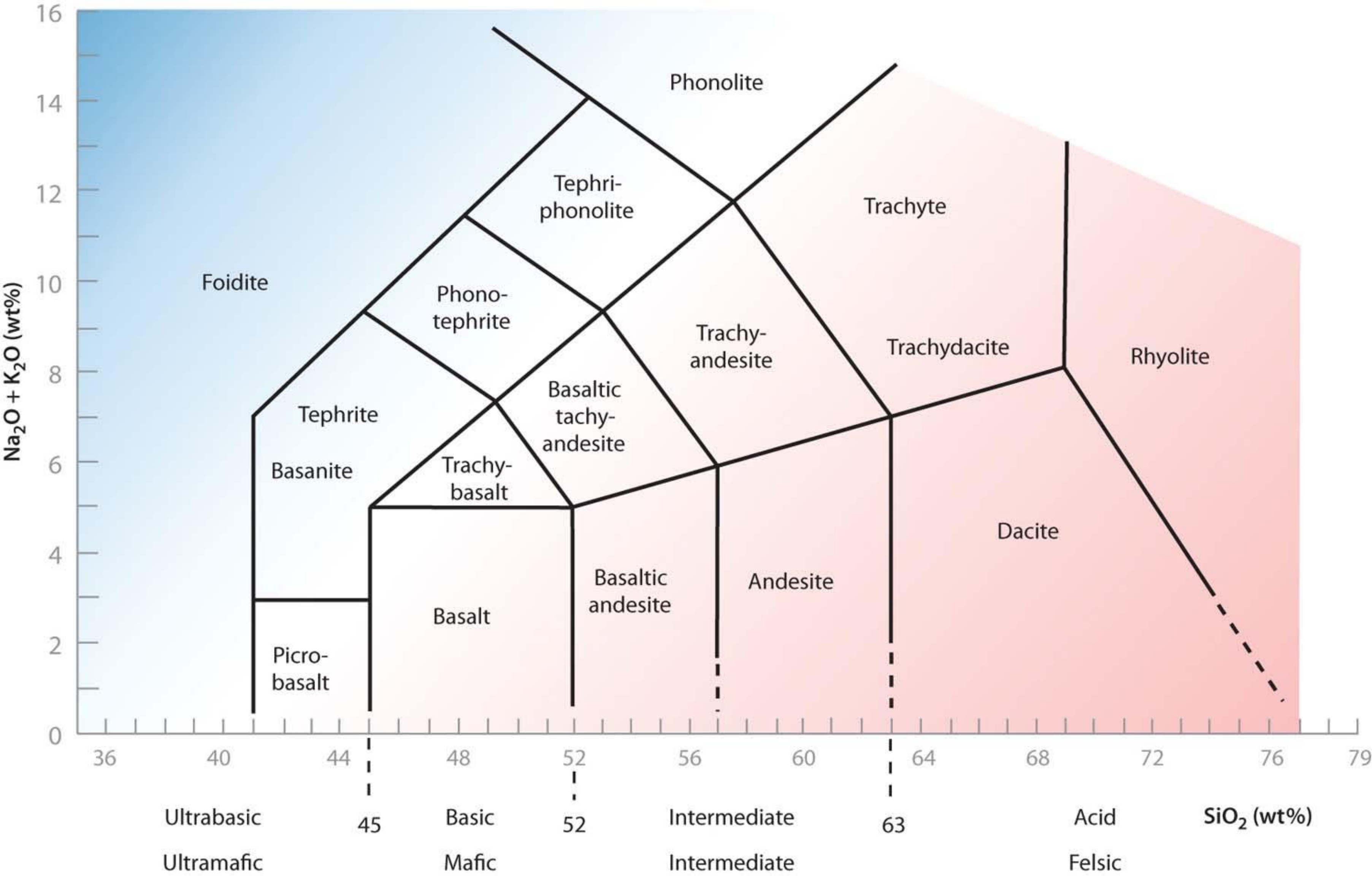


Table 9.1 Average compositions (weight %) of some common plutonic igneous rocks (after Le Maitre, 1976) and their CIPW norms.

	Granite	Nepheline syenite	Granodiorite	Monzonite	Tonalite	Diorite	Gabbro
Number of analyses averaged	2485	115	885	336	97	872	1451
SiO_2	71.30	54.99	66.09	62.60	61.52	57.48	50.14
TiO_2	0.31	0.60	0.54	0.78	0.73	0.95	1.12
Al_2O_3	14.32	20.96	15.73	15.67	16.48	16.67	15.48
Fe_2O_3	1.21	2.25	1.38	1.92	1.83	2.50	3.01
FeO	1.64	2.05	2.73	3.08	3.82	4.92	7.62
MnO	0.05	0.15	0.08	0.10	0.08	0.12	0.12
MgO	0.71	0.77	1.74	2.02	2.80	3.71	7.59
CaO	1.84	2.31	3.83	4.17	5.42	6.58	9.58
Na_2O	3.68	8.23	3.75	3.73	3.63	3.54	2.39
K_2O	4.07	5.58	2.73	4.06	2.07	1.76	0.93
P_2O_5	0.12	0.13	0.18	0.25	0.25	0.29	0.24
H_2O+[a]	0.64	1.30	0.85	0.90	1.04	1.15	0.75
Total	99.89	99.32	99.63	99.28	99.67	99.67	98.97

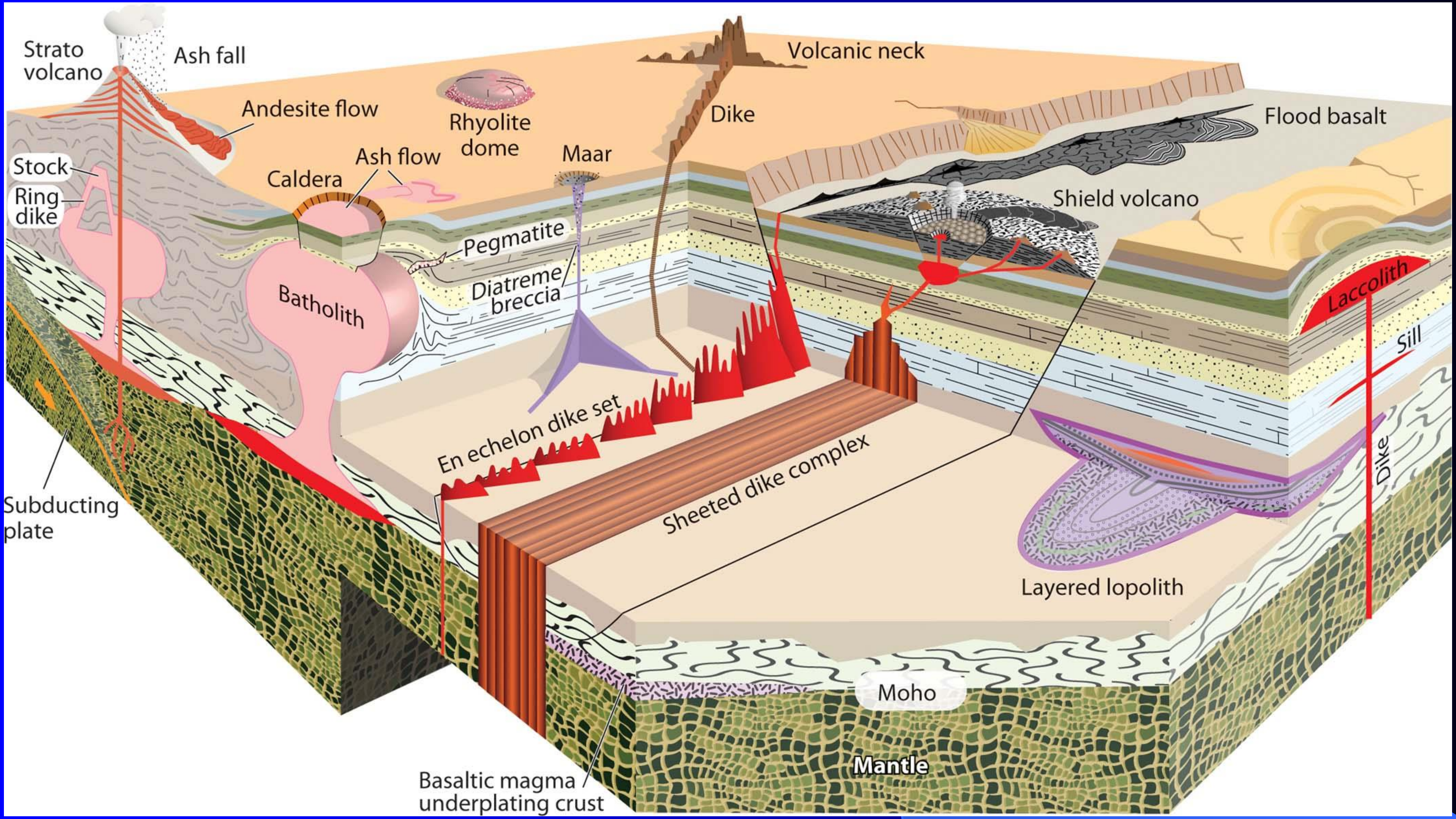
CIPW norms

Normative mineral[b]	Granite	Nepheline syenite	Granodiorite	Monzonite	Tonalite	Diorite	Gabbro
Q	28.93		22.11	13.86	15.96	10.15	0.73
C	0.80		0.07				
Or	24.05	32.98	16.13	23.99	12.23	10.40	5.50
Plag	39.48	29.45	49.56	45.58	53.27	54.35	48.99
Ne		22.37					
Di		5.58		4.09	2.20	5.17	13.94
Hy	3.36		7.46	6.01	10.35	12.34	22.03
Ol		0.29					
Mt	1.75	3.26	2.00	2.78	2.65	3.62	4.36
Il	0.59	1.14	1.03	1.48	1.39	1.80	2.13
Ap	0.28	0.30	0.42	0.58	0.58	0.67	0.56
Mg/Mg+Fe	0.593	0.679	0.645	0.690	0.673	0.683	0.715
Plag An%	20.2	11.1	34.6	29.5	40.9	43.4	57.3

[a] H_2O+ is water driven off by heating above 105°C.

[b] Abbreviations for the normative minerals are as follows: quartz = Q, corundum = C, orthoclase = Or, plagioclase = Plag, nepheline = Ne, diopside (cpx) = Di, hypersthene (opx) = Hy, olivine = Ol, magnetite = Mt, ilmenite = Il, and apatite = Ap. Mg/Mg+Fe is the ratio of magnesium to magnesium + iron in the diopside, hypersthene, and olivine, and Plag An% is the percentage of anorthite in plagioclase.

Mode of Occurrence of Igneous Rocks



Extrusive igneous rocks – fine-grained or glassy

- Lava flows
- Volcanoes

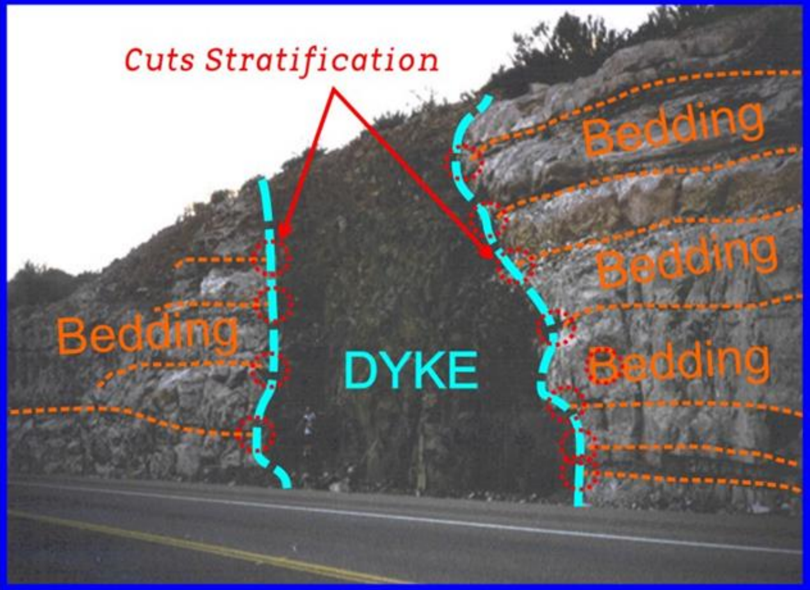
Intrusive igneous rocks

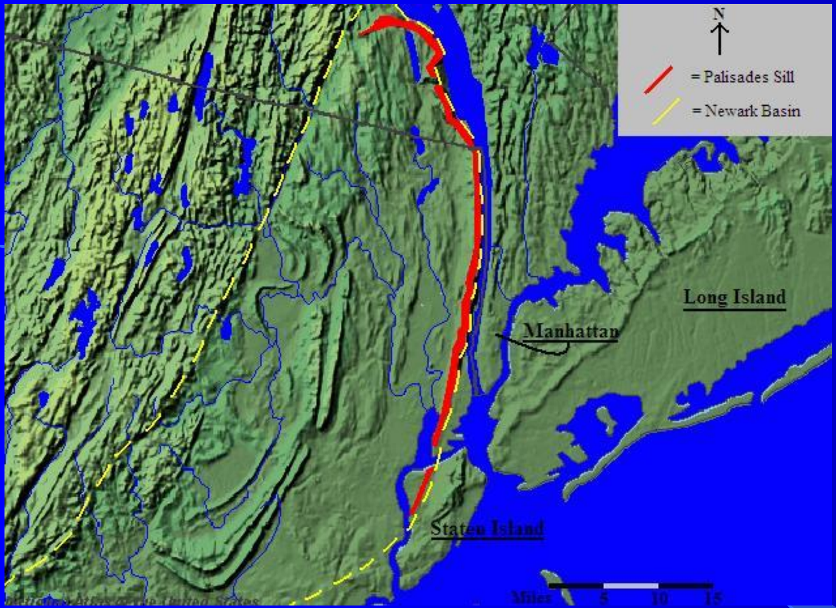
- Hypabyssal – transitional between fine- and coarse-grained. Often porphyritic.
- Plutonic – coarse-grained

Shallow intrusive igneous bodies

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

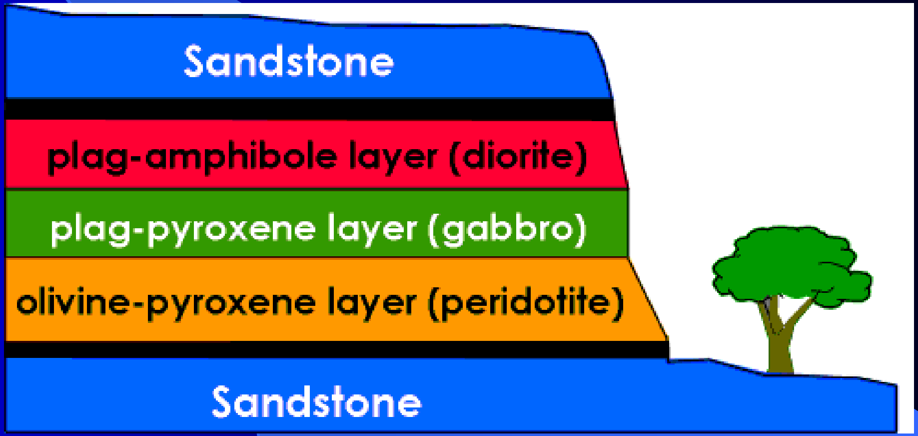
Sills – tablular intrusions that are parallel to existing layering (concordant)





Palisades Sill

Salisbury Crags – Arthur’s Seat



Sandstone

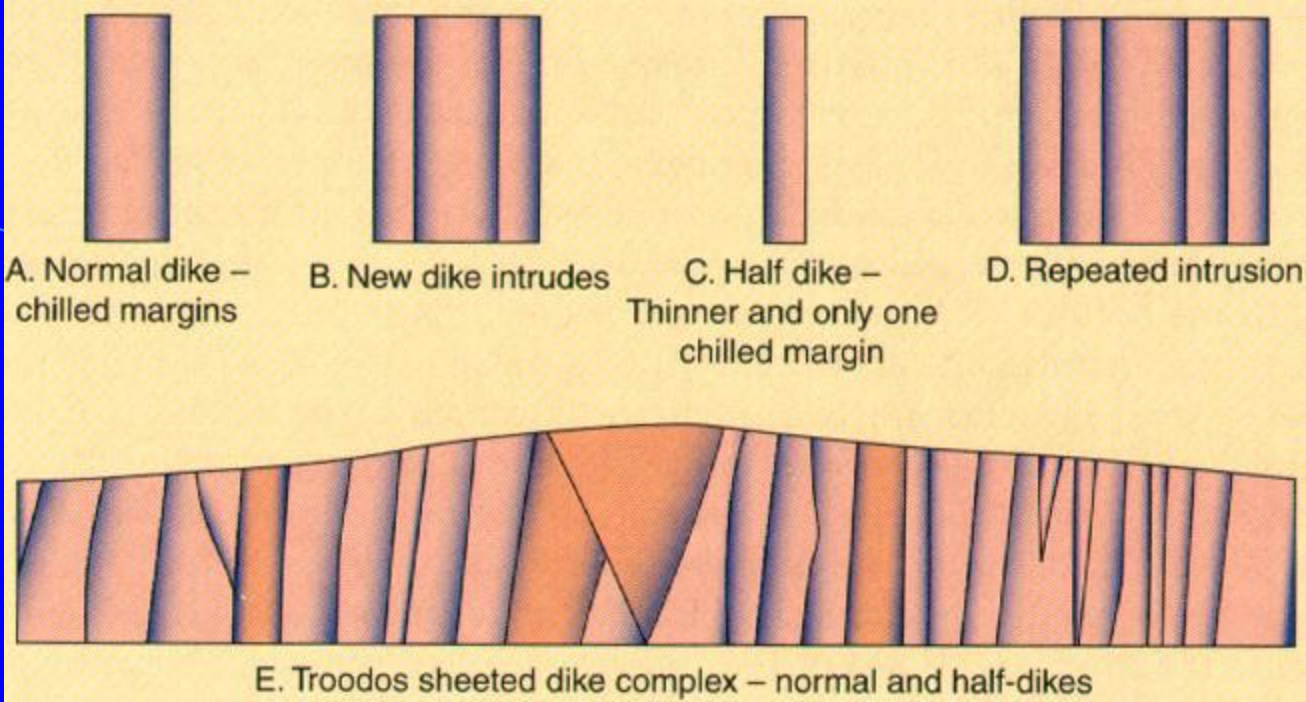
plag-amphibole layer (diorite)

plag-pyroxene layer (gabbro)

olivine-pyroxene layer (peridotite)

Sandstone

Sheeted dike complexes



A. Normal dike – chilled margins

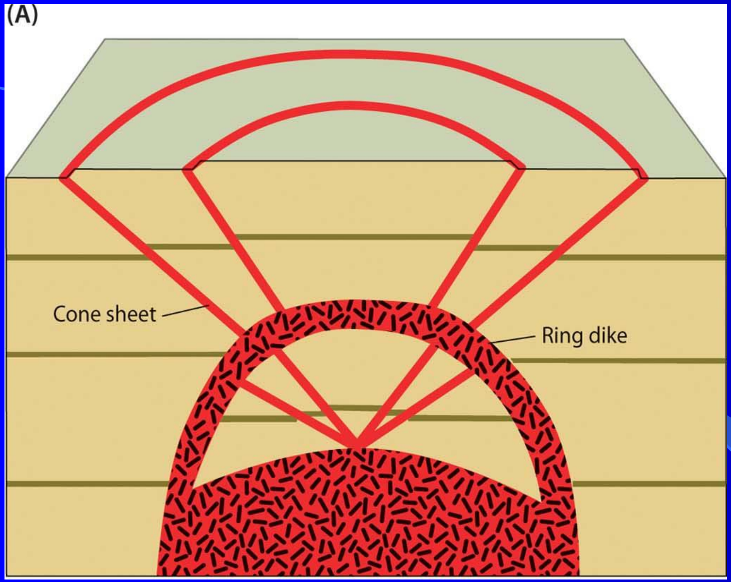
B. New dike intrudes

C. Half dike – Thinner and only one chilled margin

D. Repeated intrusion

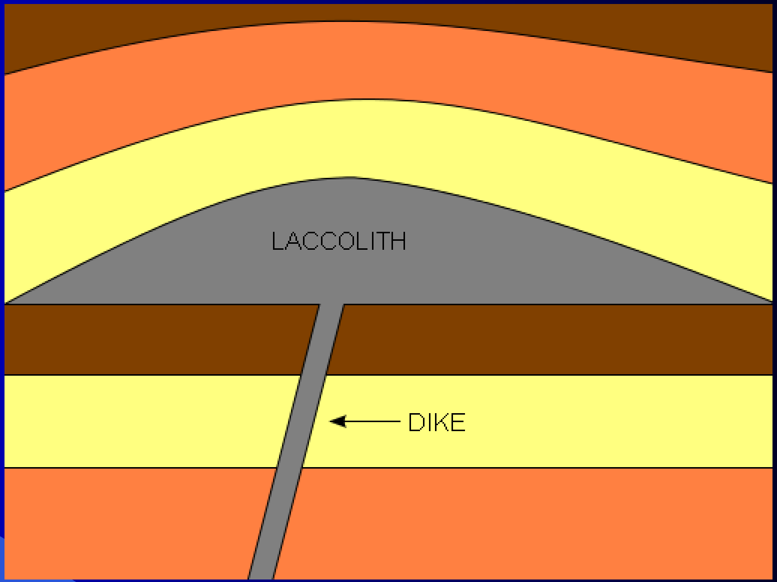
E. Troodos sheeted dike complex – normal and half-dikes

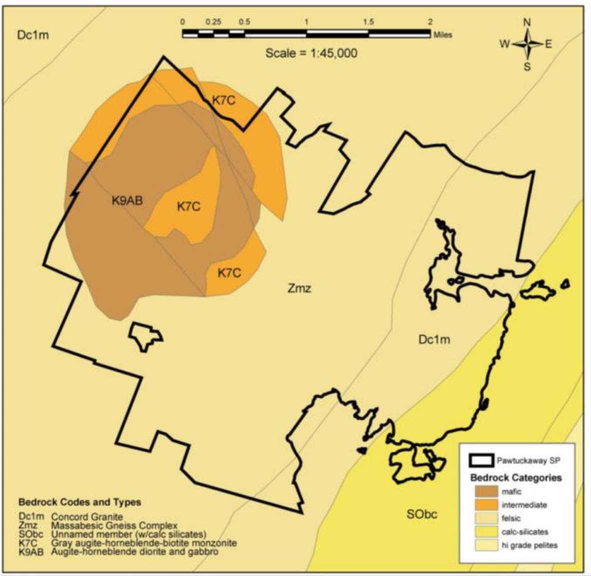
Ring dikes and cone sheets



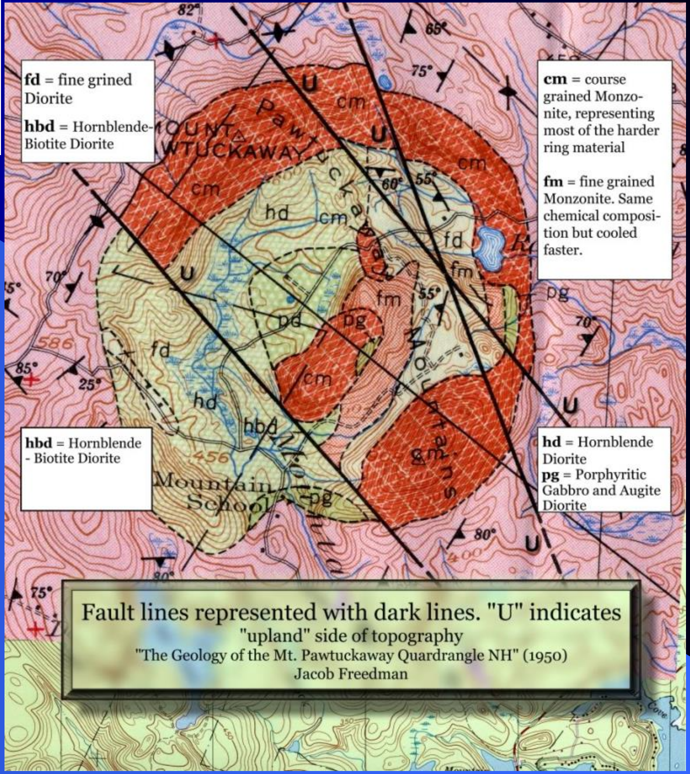
Dikes are intruded by magma fracturing and sills involve lifting of the overlying rock (bouyancy). These are hypabyssal intrusions and imply that the crust showed brittle behavior.

Laccolith – domes up overlying strata – concordant intrusion

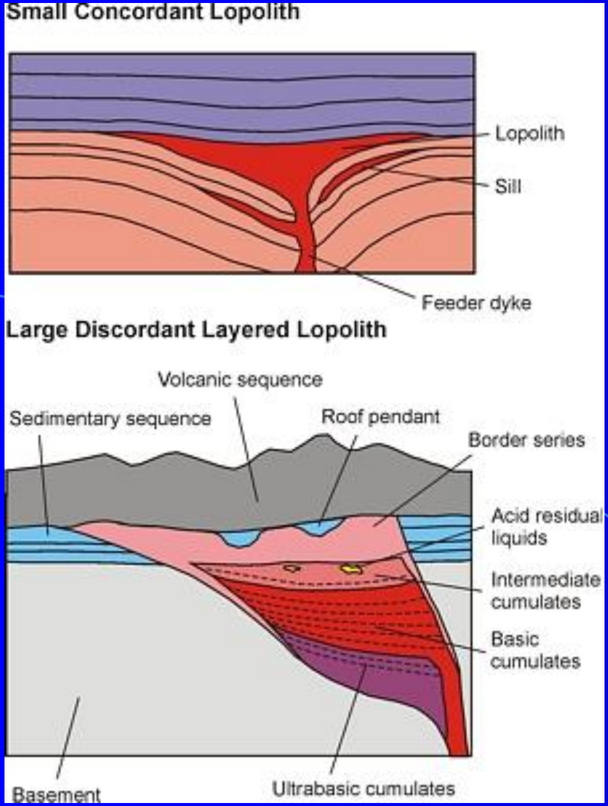




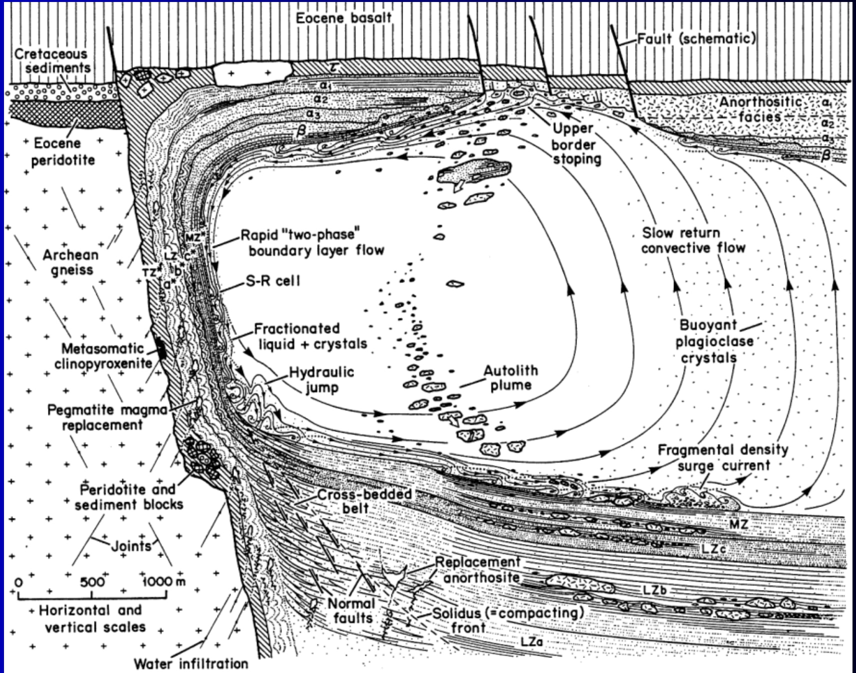
Pawtuckaway State Park, NH, and Pawtuckaway Mountains. A classic ring-complex and a nice place for a fall foliage/geology hike.



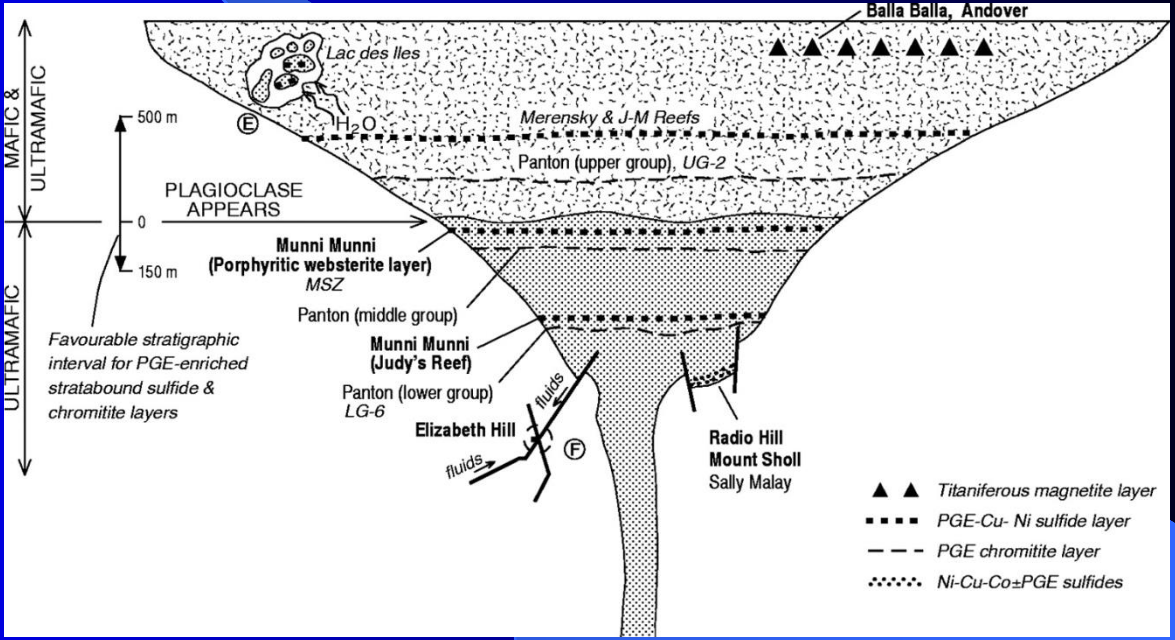
Fault lines represented with dark lines. "U" indicates "upland" side of topography
"The Geology of the Mt. Pawtuckaway Quardrangle NH" (1950)
Jacob Freedman



Skaergaard



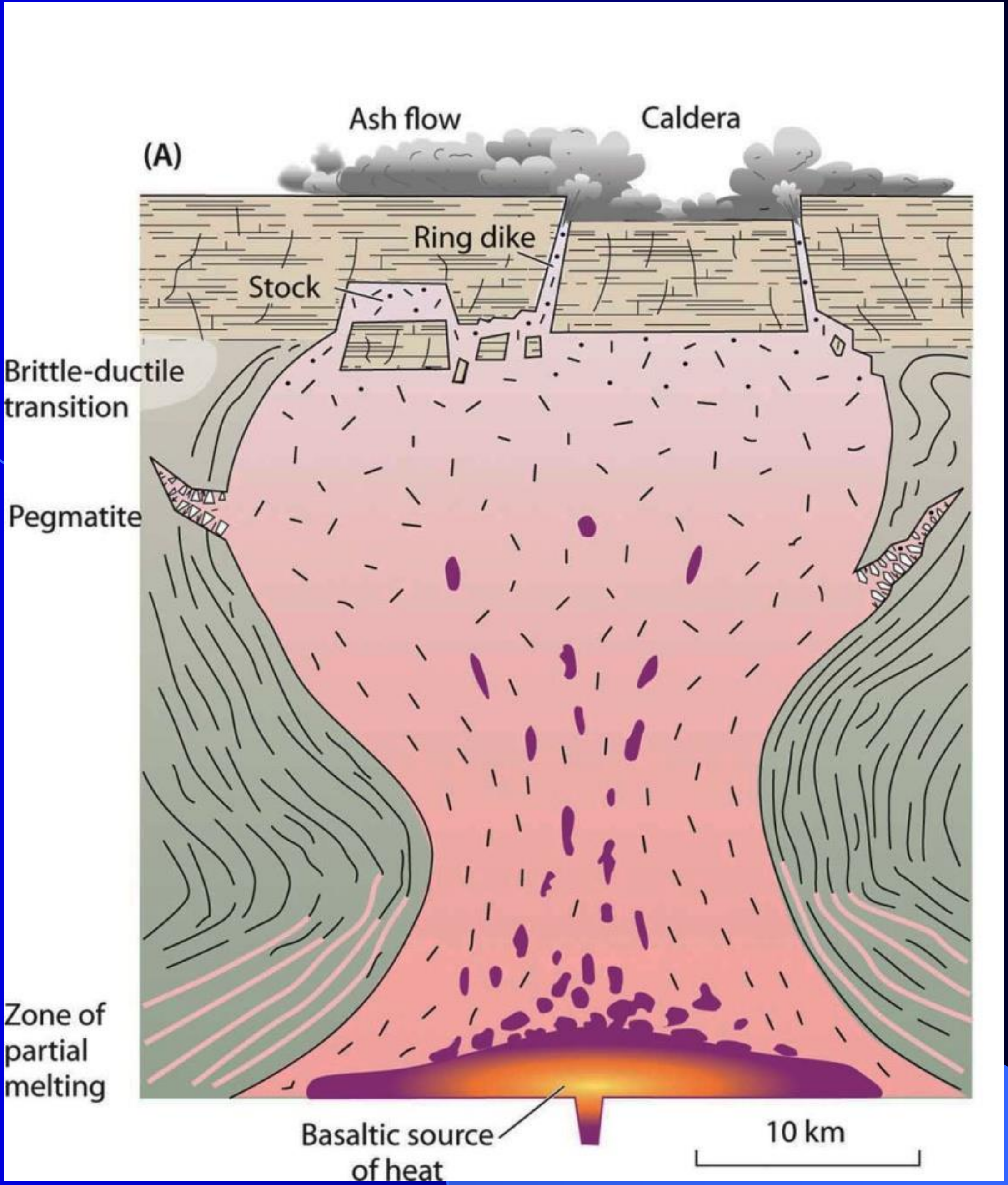
Bushveld



Batholith > 100 km^2

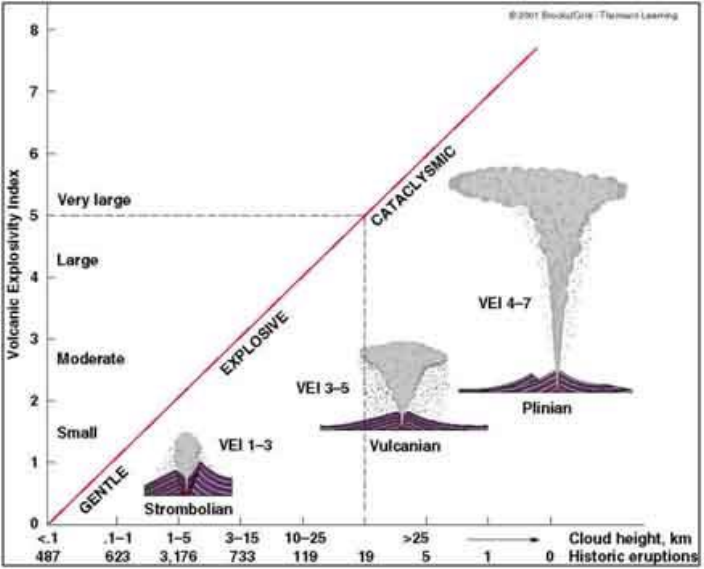
Stock < 100 km^2

Batholiths are everywhere



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).

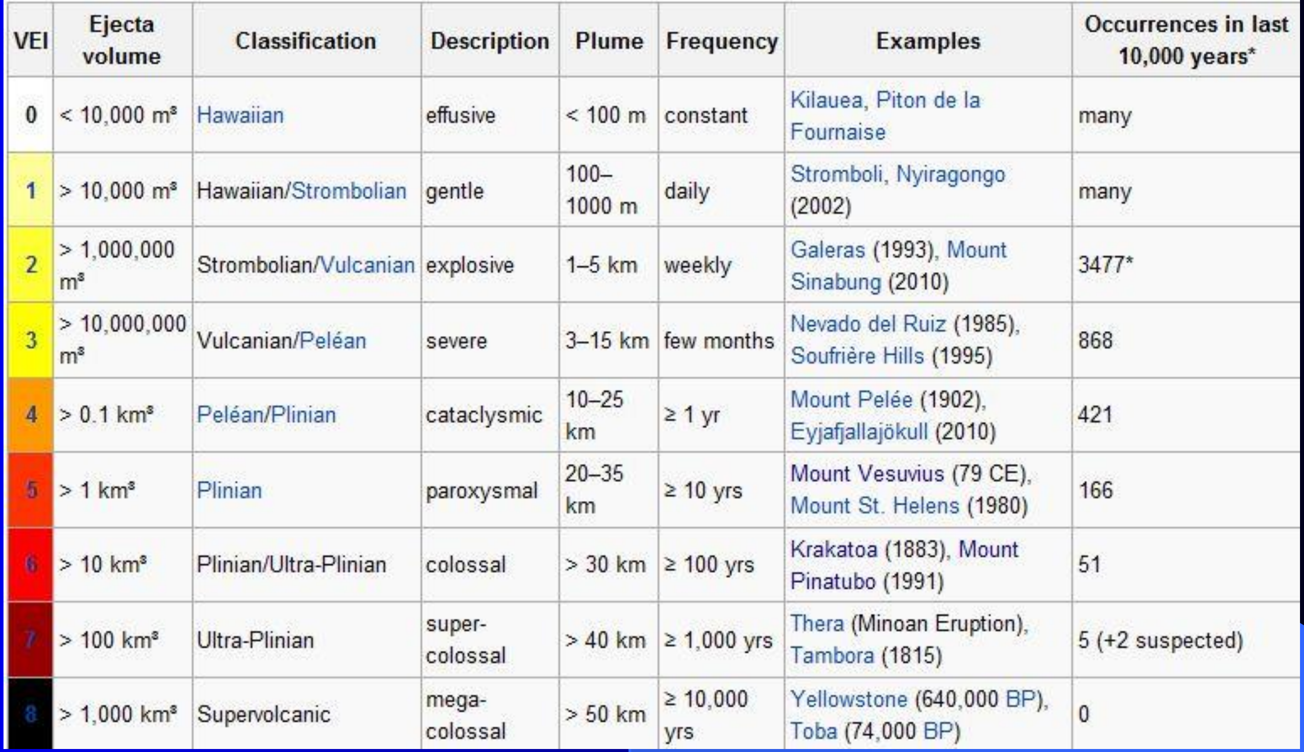


Tephra – any fragmental volcanic material.

Ash (< 2mm)

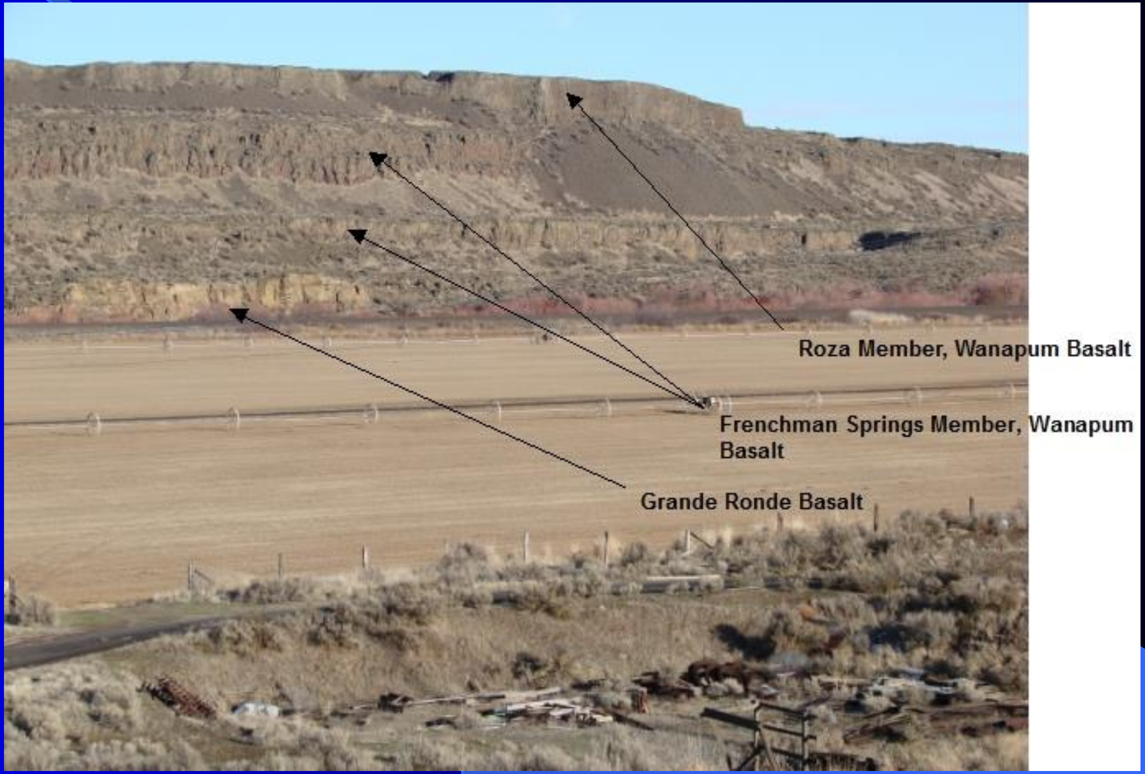
Lapilli – 2 to 64 mm

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

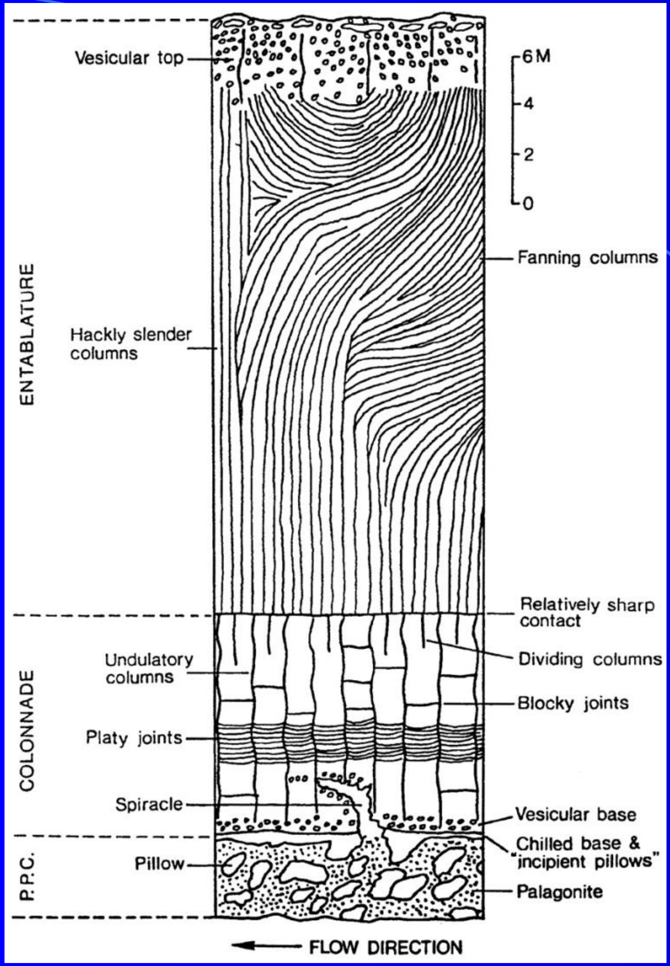


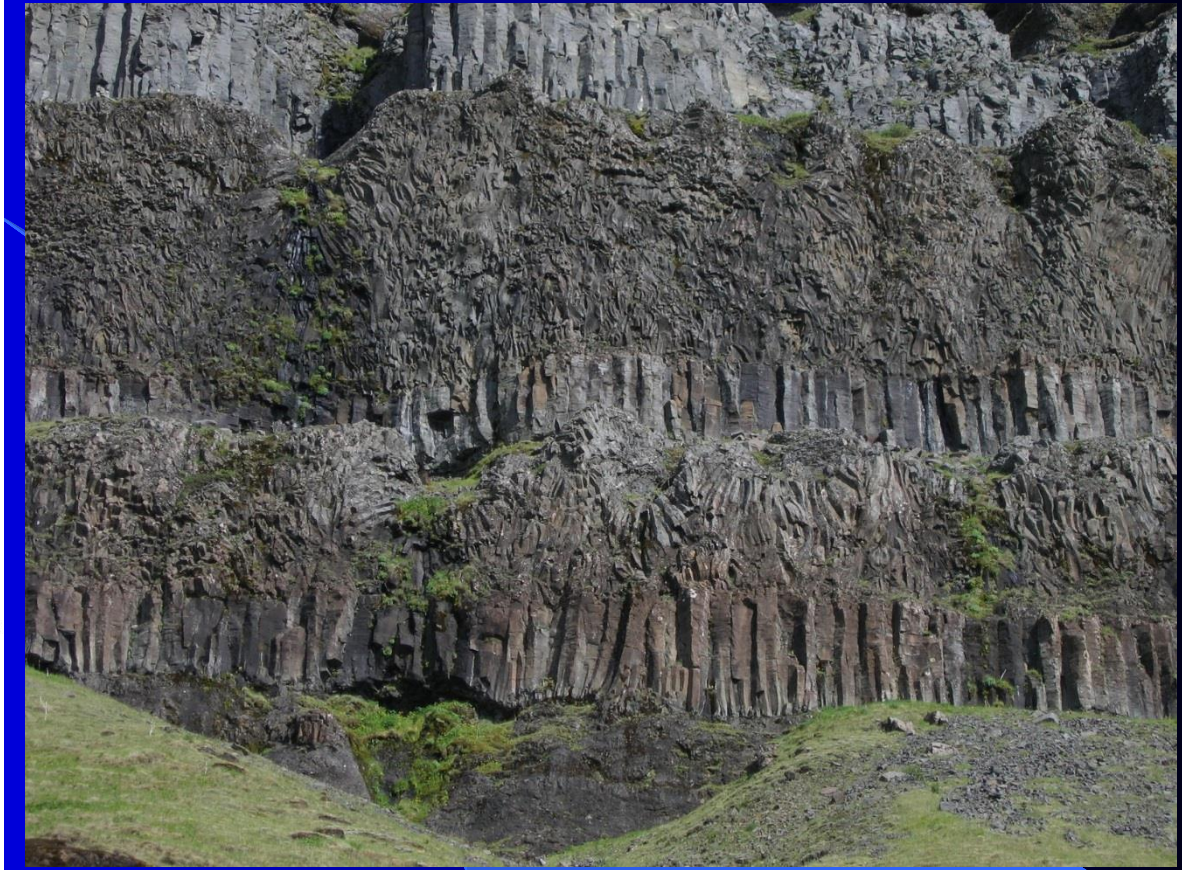
VEI	Ejecta volume	Classification	Description	Plume	Frequency	Examples	Occurrences in last 10,000 years*
0	< 10,000 m³	Hawaiian	effusive	< 100 m	constant	Kilauea, Piton de la Fournaise	many
1	> 10,000 m³	Hawaiian/Strombolian	gentle	100–1000 m	daily	Stromboli, Nyiragongo (2002)	many
2	> 1,000,000 m³	Strombolian/Vulcanian	explosive	1–5 km	weekly	Galeras (1993), Mount Sinabung (2010)	3477*
3	> 10,000,000 m³	Vulcanian/Peléan	severe	3–15 km	few months	Nevado del Ruiz (1985), Soufrière Hills (1995)	868
4	> 0.1 km³	Peléan/Plinian	cataclysmic	10–25 km	≥ 1 yr	Mount Pelée (1902), Eyjafjallajökull (2010)	421
5	> 1 km³	Plinian	paroxysmal	20–35 km	≥ 10 yrs	Mount Vesuvius (79 CE), Mount St. Helens (1980)	166
6	> 10 km³	Plinian/Ultra-Plinian	colossal	> 30 km	≥ 100 yrs	Krakatoa (1883), Mount Pinatubo (1991)	51
7	> 100 km³	Ultra-Plinian	super-colossal	> 40 km	≥ 1,000 yrs	Thera (Minoan Eruption), Tambora (1815)	5 (+2 suspected)
8	> 1,000 km³	Supervolcanic	mega-colossal	> 50 km	≥ 10,000 yrs	Yellowstone (640,000 BP), Toba (74,000 BP)	0


CANADA
PACIFIC OCEAN
WASHINGTON
Columbia River Basalt Group
MONTANA
IDAHO
OREGON


Roza Member, Wanapum Basalt
Frenchman Springs Member, Wanapum Basalt
Grande Ronde Basalt

Lava Flows and Columnar Joints

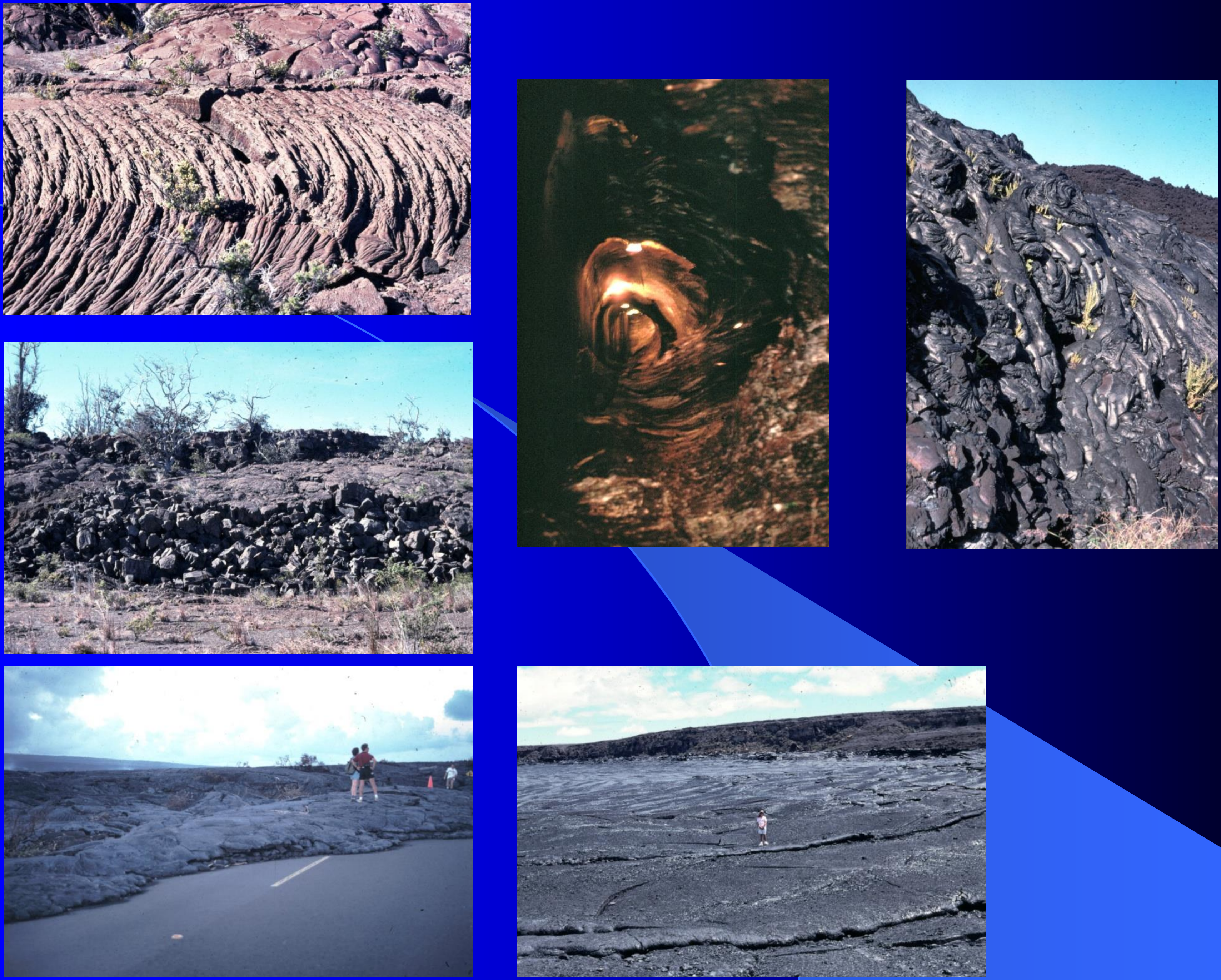




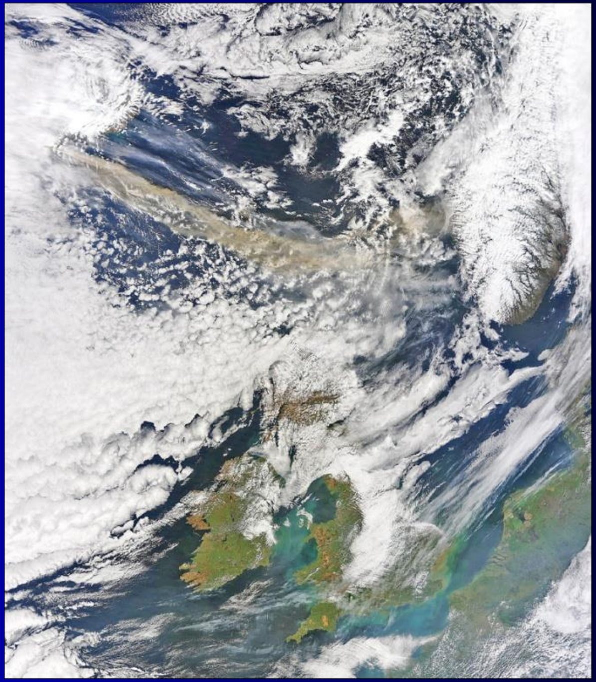
Shield Volcanoes

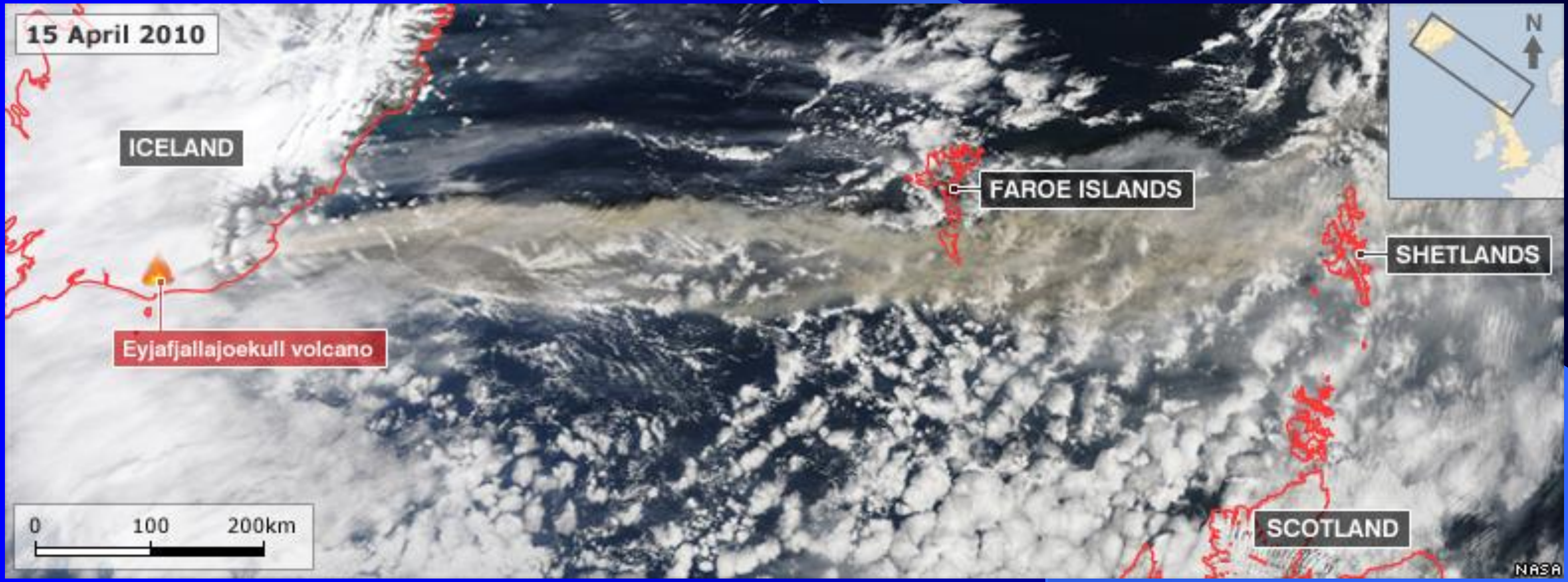
Mauna Kea

Mauna Loa



SOURCE: Met Office





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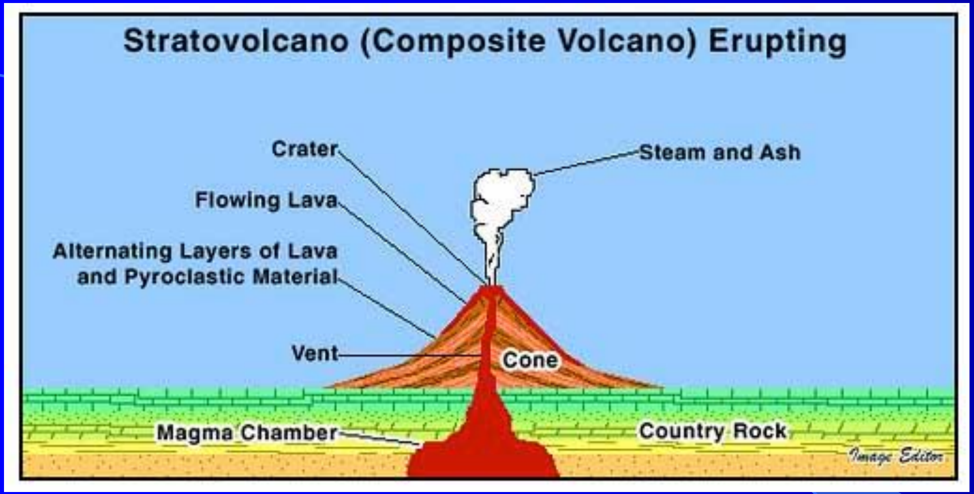
Jökulhlaup - glacial outburst flood. Generally, large and abrupt release of water from a subglacial or proglacial lake/reservoir.

Composite Volcano (Strato-volcano)



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

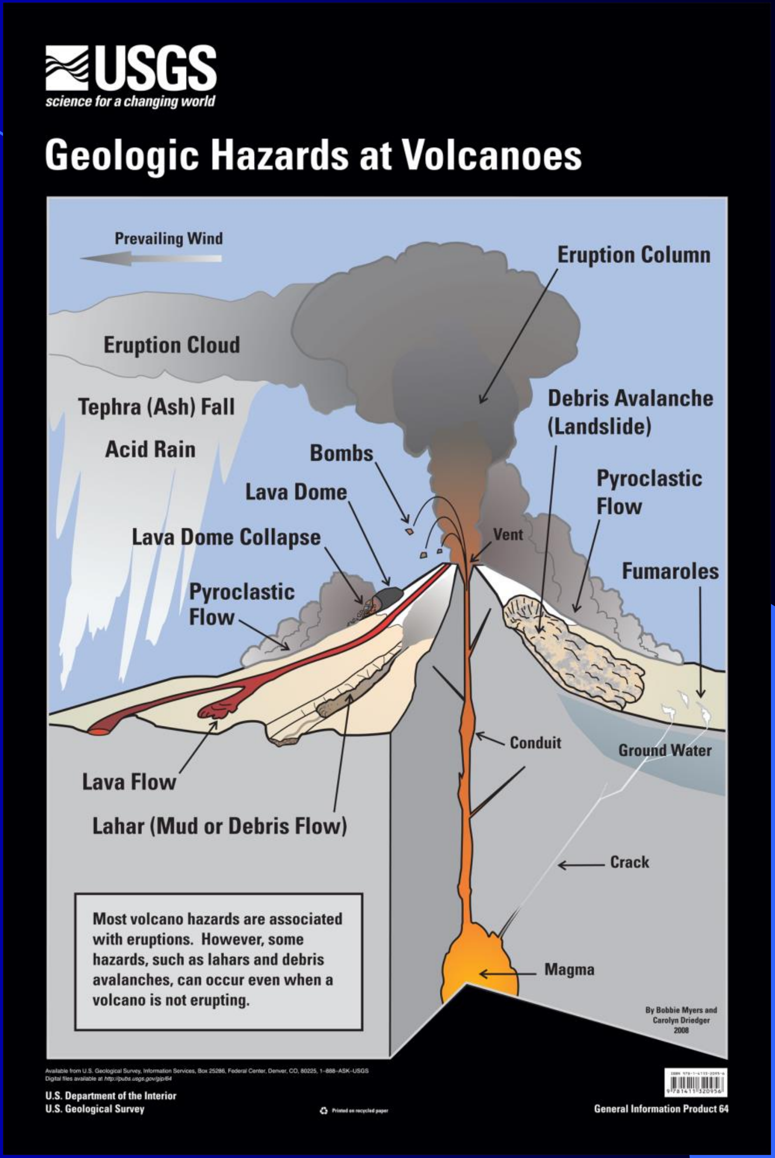
Eruptive behavior

Fluid → Explosive

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)**



USGS science for a changing world

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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General Information Product 64

Lava Flows

Property damage

Don’t fall in

Mount Cameroon lava flow cutting road

Tephra

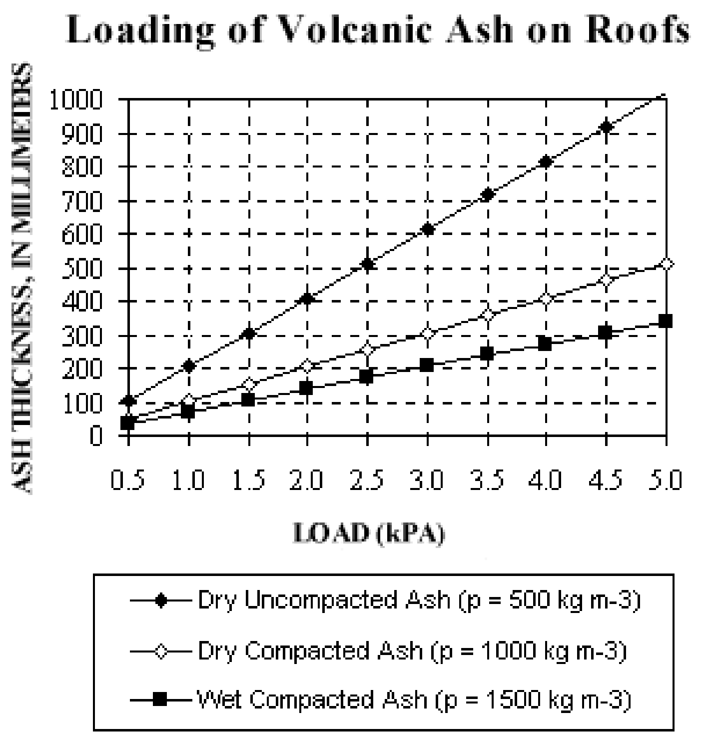
Power outages

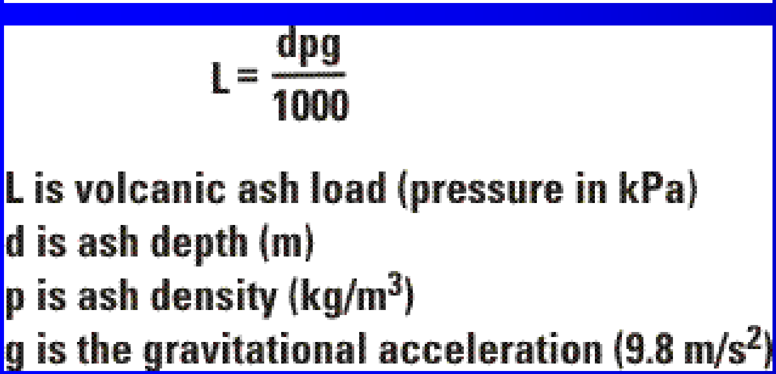
Reduced visibility

Roof collapse

Slippery roads

Ash Loading on Roofs





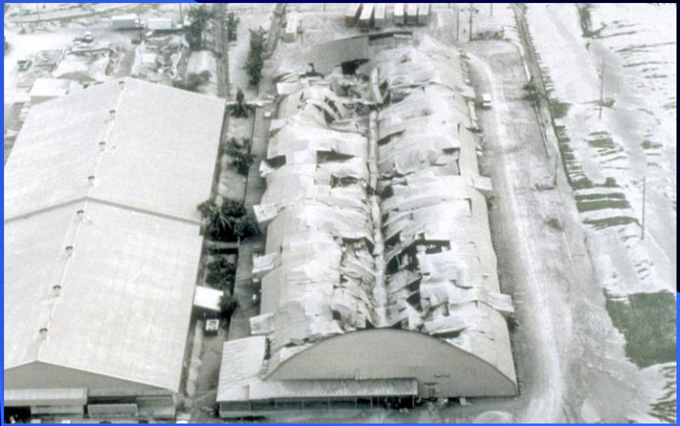
$$L = \frac{dpg}{1000}$$

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

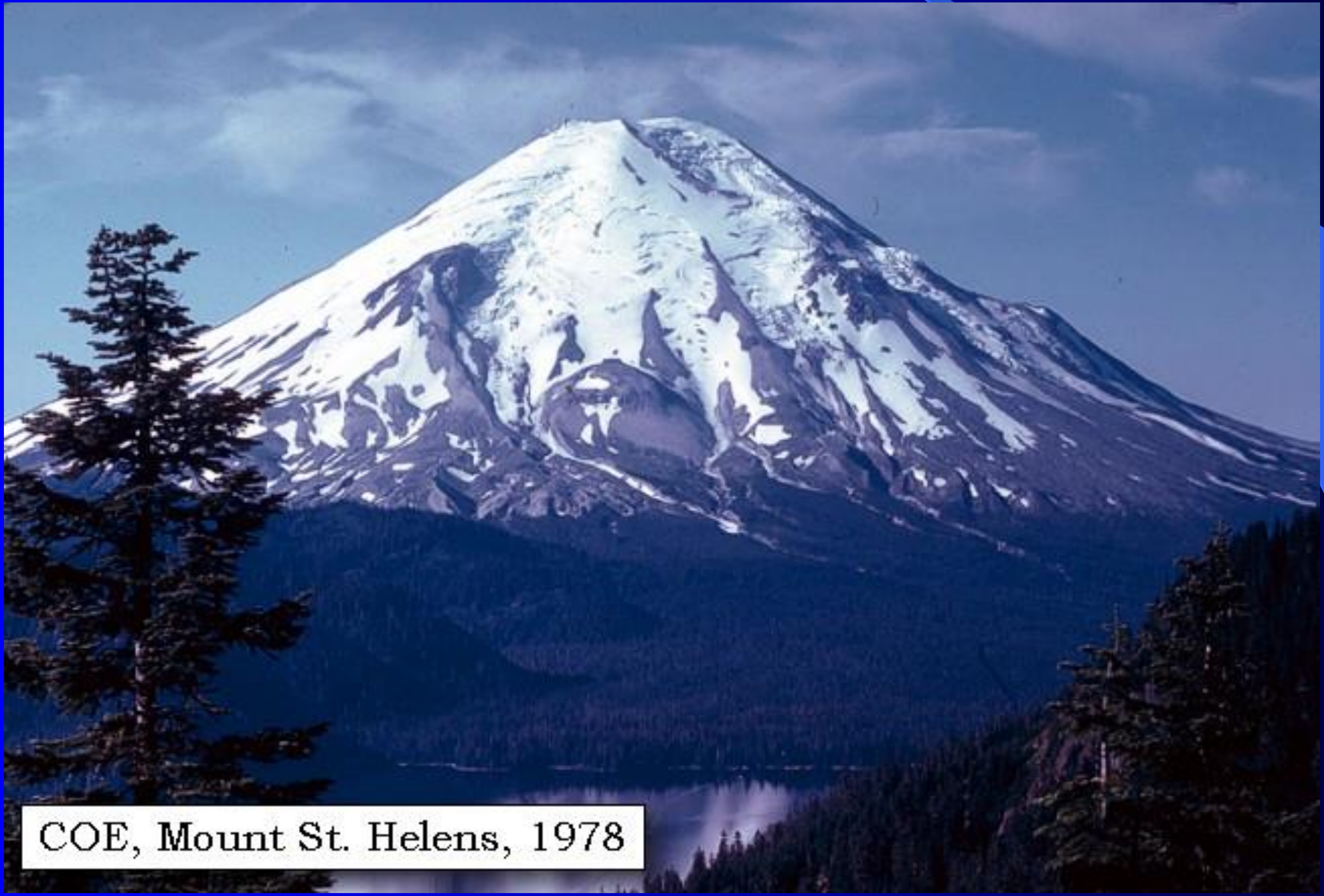
Raboul

Philippines
Clark Air
Force Base



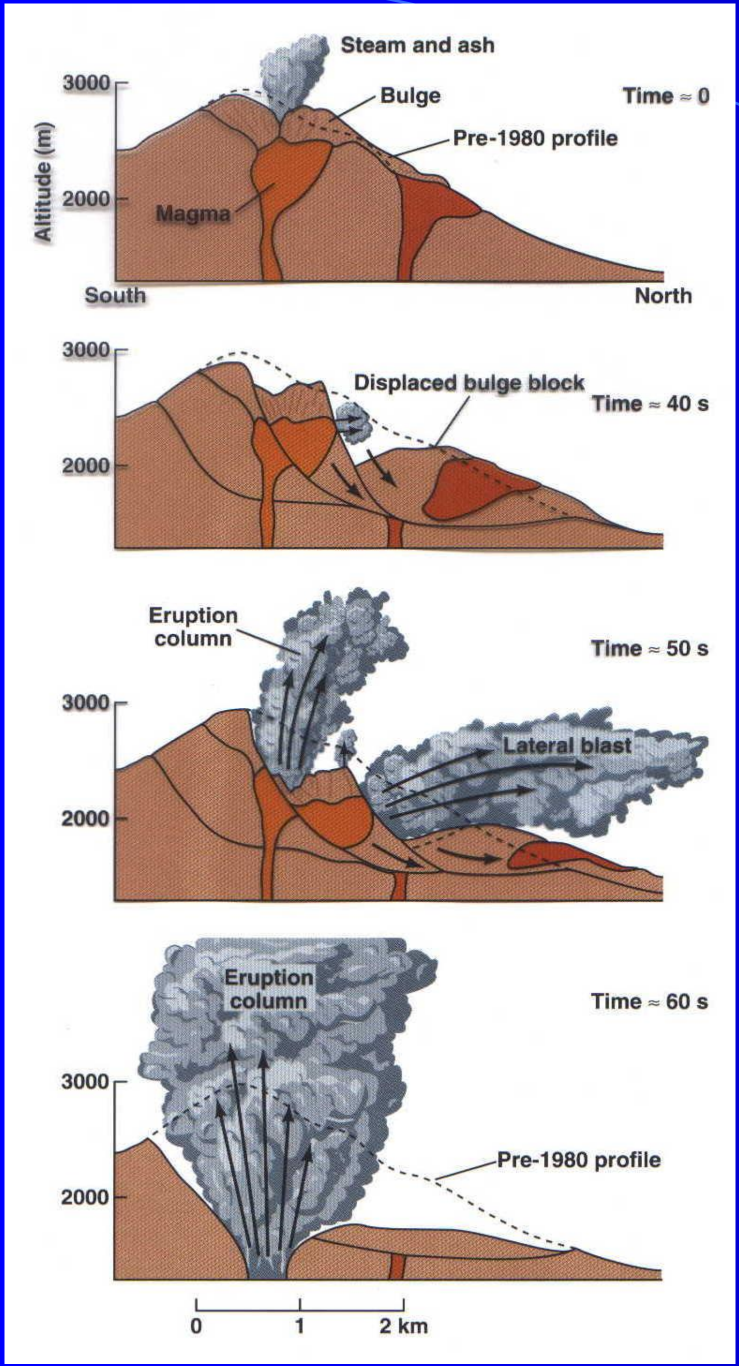
Pyroclastics and Landslides

Mt. St. Helens (May 18, 1980)



COE, Mount St. Helens, 1978

Mt. St. Helens start of eruption

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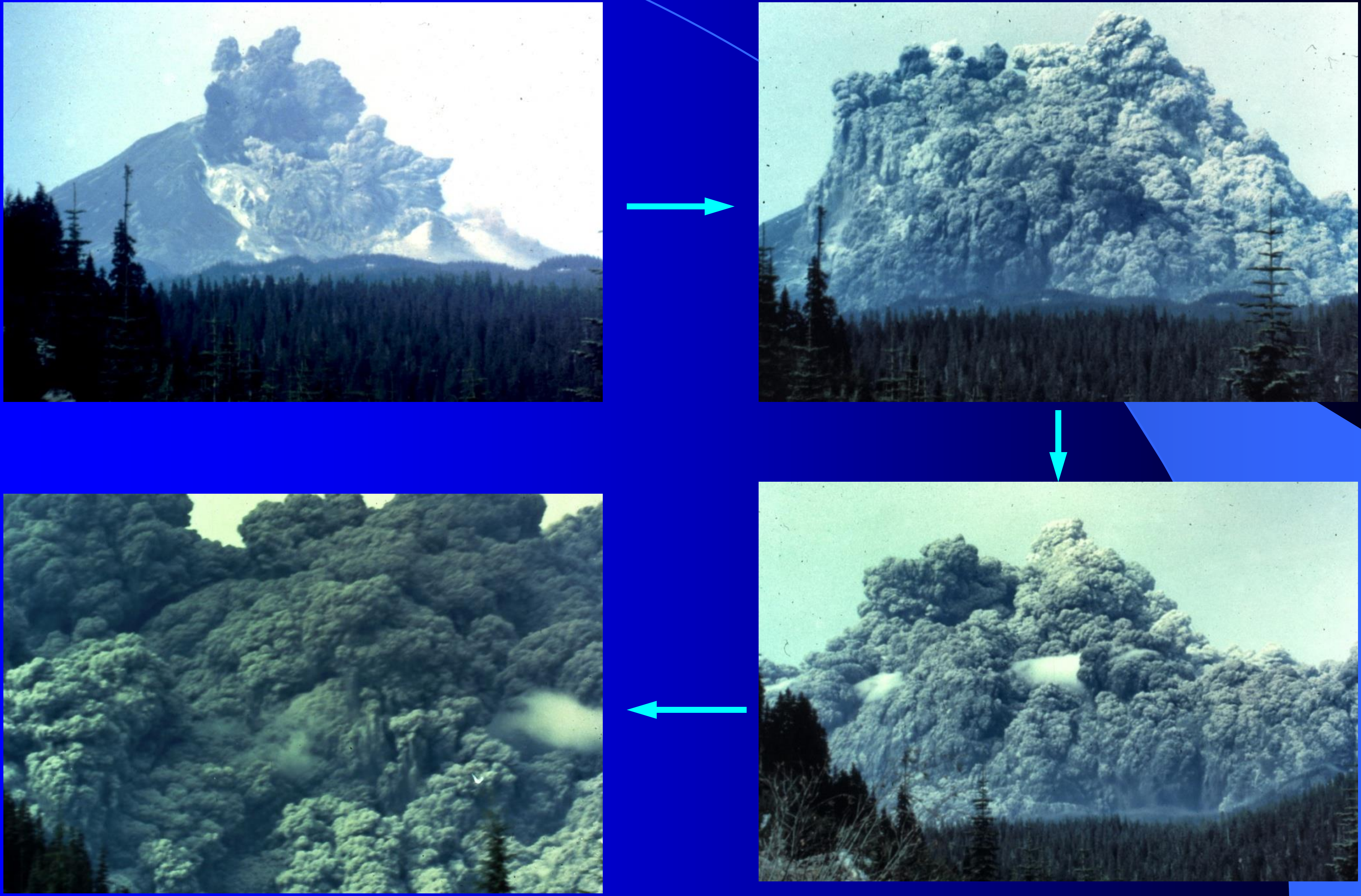
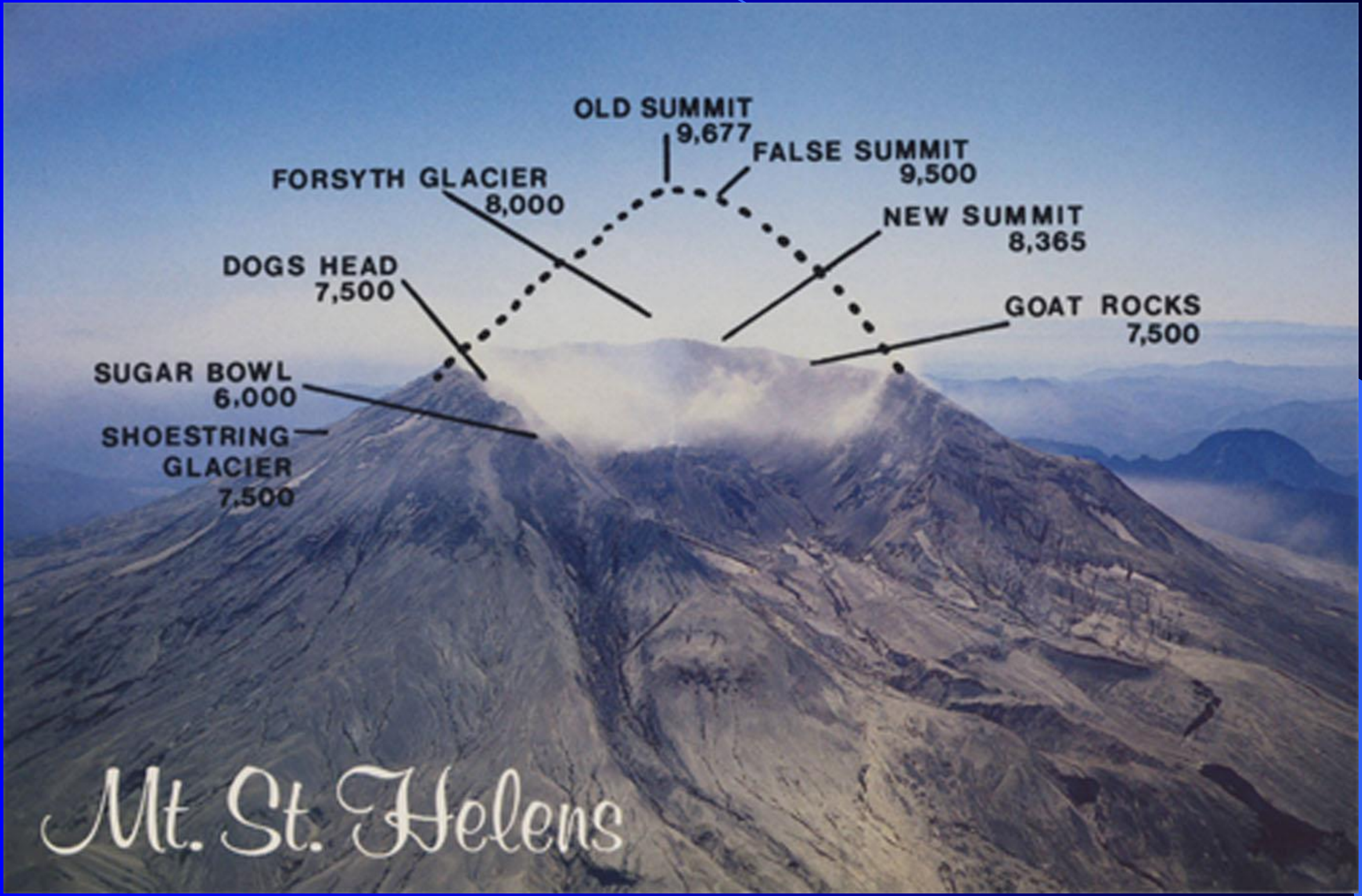
Mt. St. Helens Eruption



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

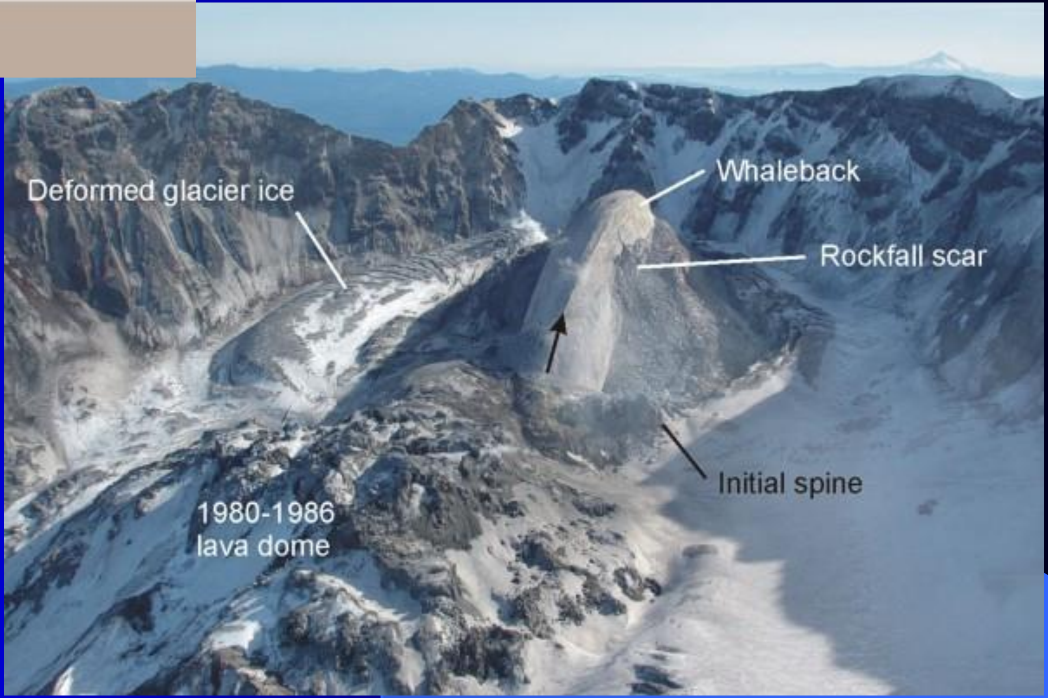
Regrowth

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

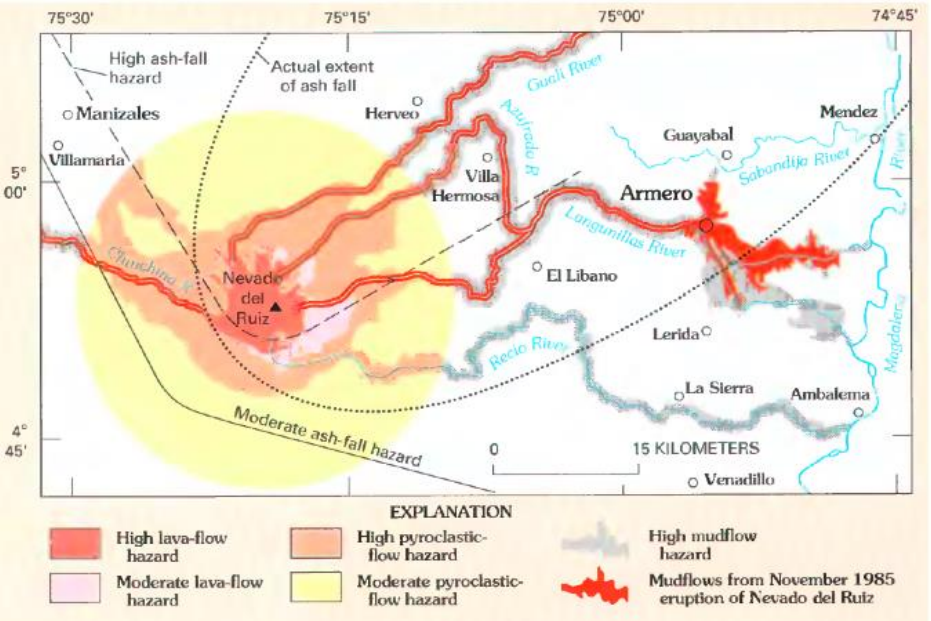


Lahars

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

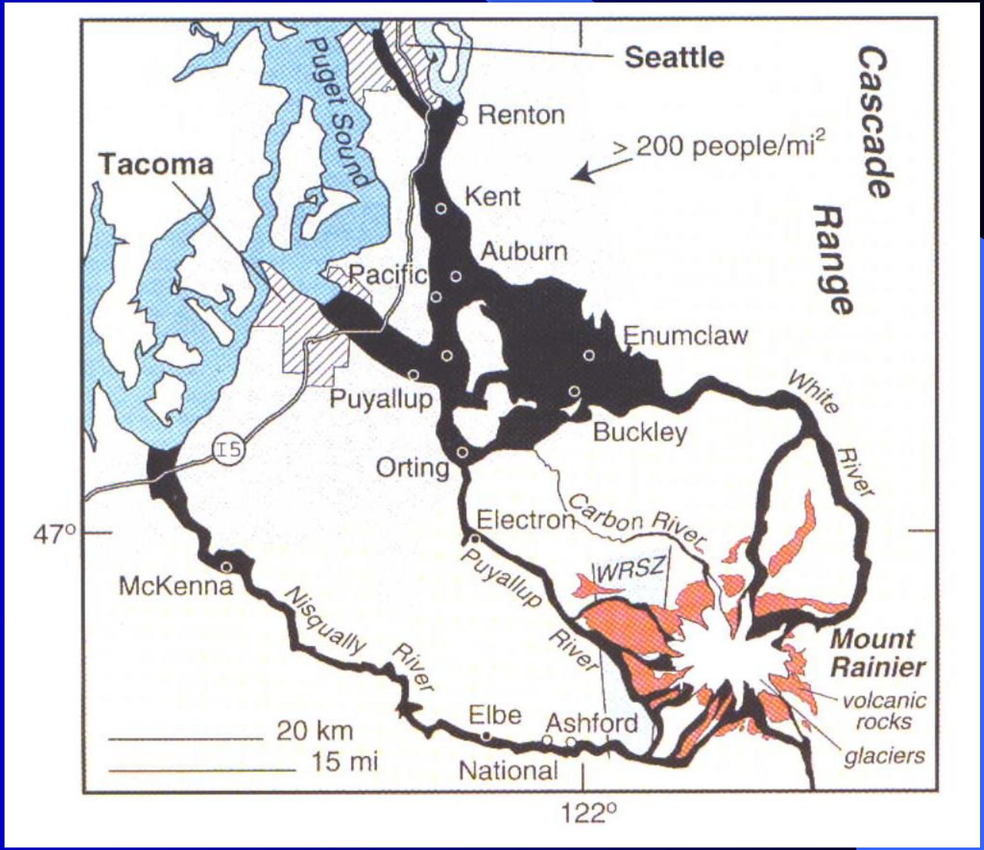
High ground means safety. Gualí river.

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

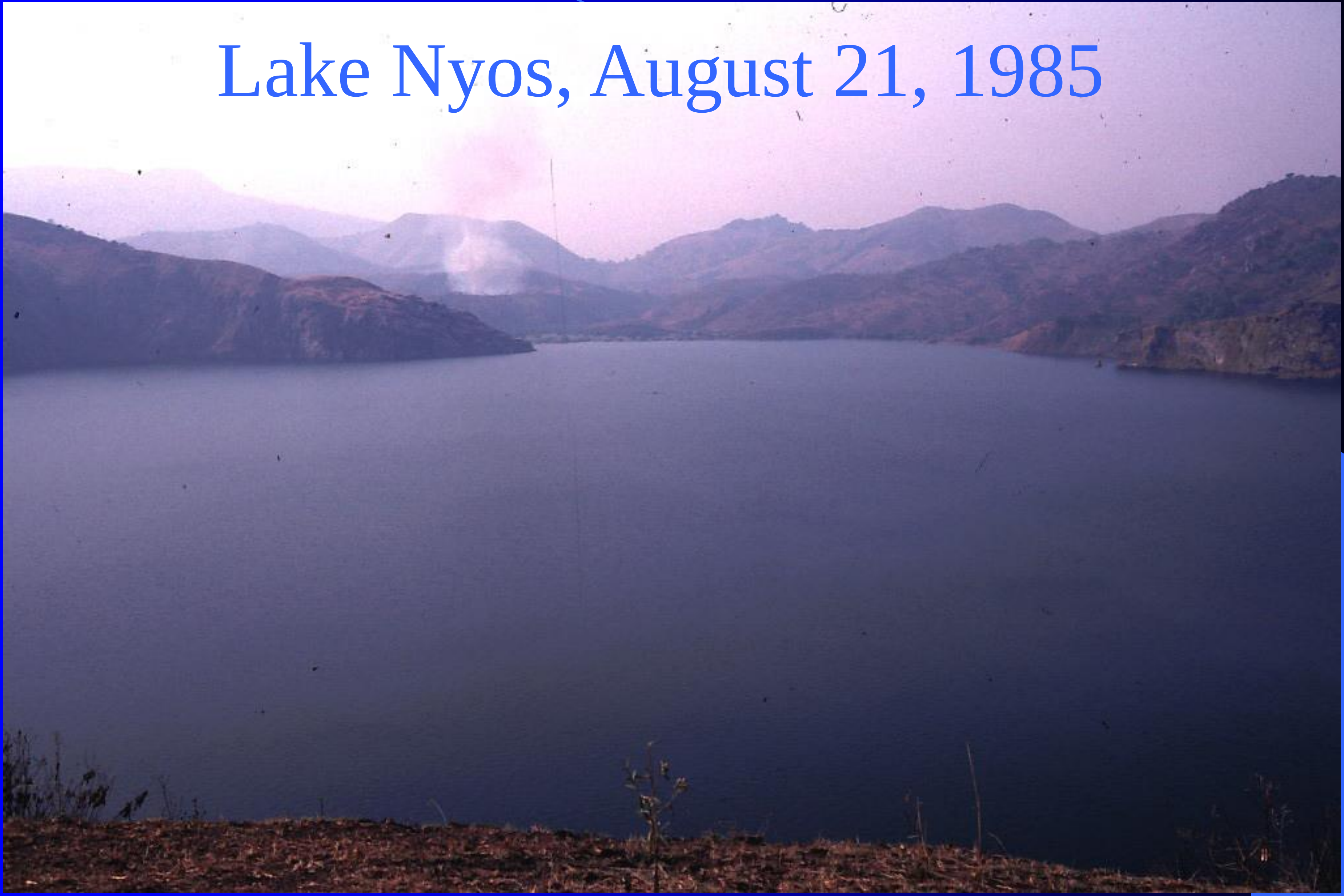
Paleo-lahars surround Mt. Rainier. Recent developments are built on these lahars.

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



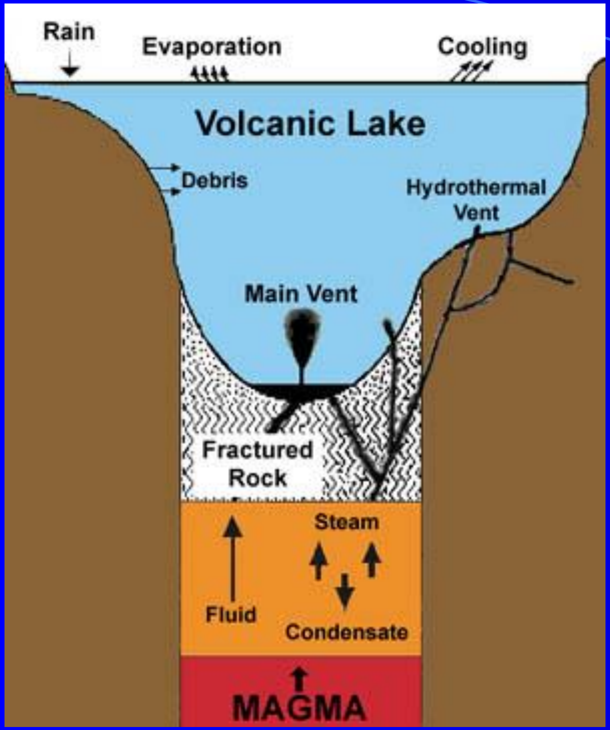
Lake Nyos, August 21, 1985

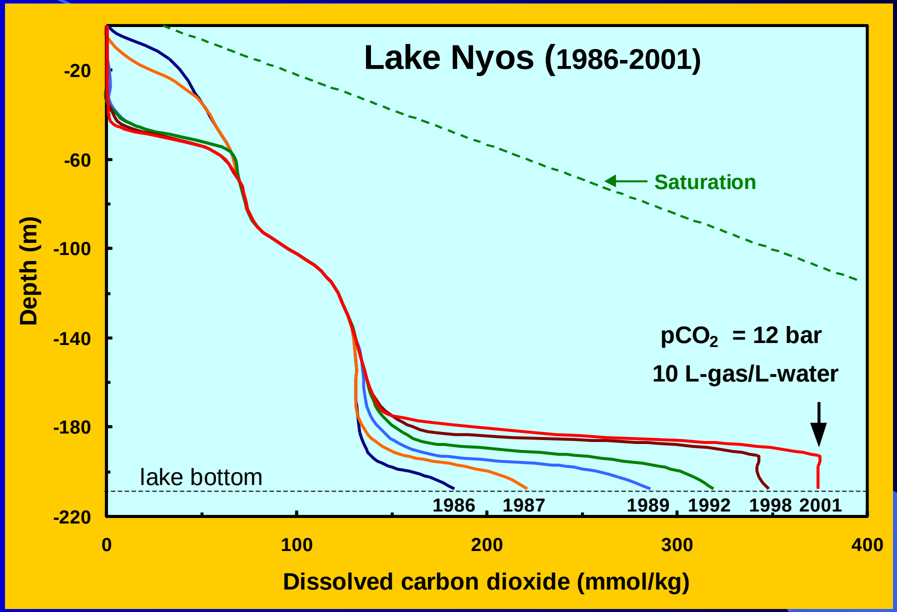
Lake Nyos pyroclastic dam, valley and town of Nyos.

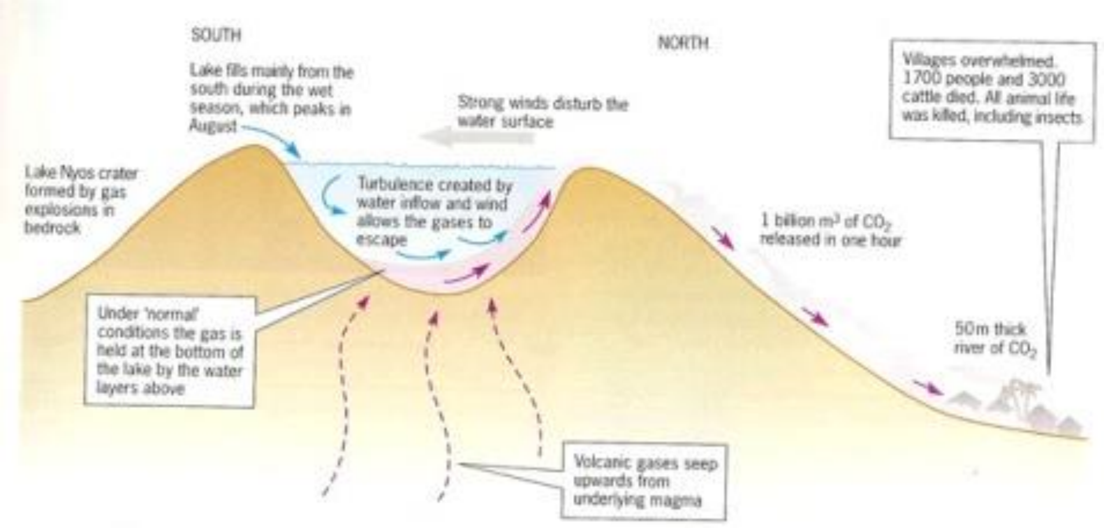
Orange color of Lake Nyos immediately after the gas release. The color is due to the oxidation of iron and the formation of ferric hydroxides

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.







Lake fills mainly from the south during the wet season, which peaks in August

Strong winds disturb the water surface

Villages overwhelmed. 1700 people and 3000 cattle died. All animal life was killed, including insects.

Lake Nyos crater formed by gas explosions in bedrock

Turbulence created by water inflow and wind allows the gases to escape

1 billion m^3 of CO_2 released in one hour

Under 'normal' conditions the gas is held at the bottom of the lake by the water layers above

50m thick river of CO_2

Volcanic gases seep upwards from underlying magma

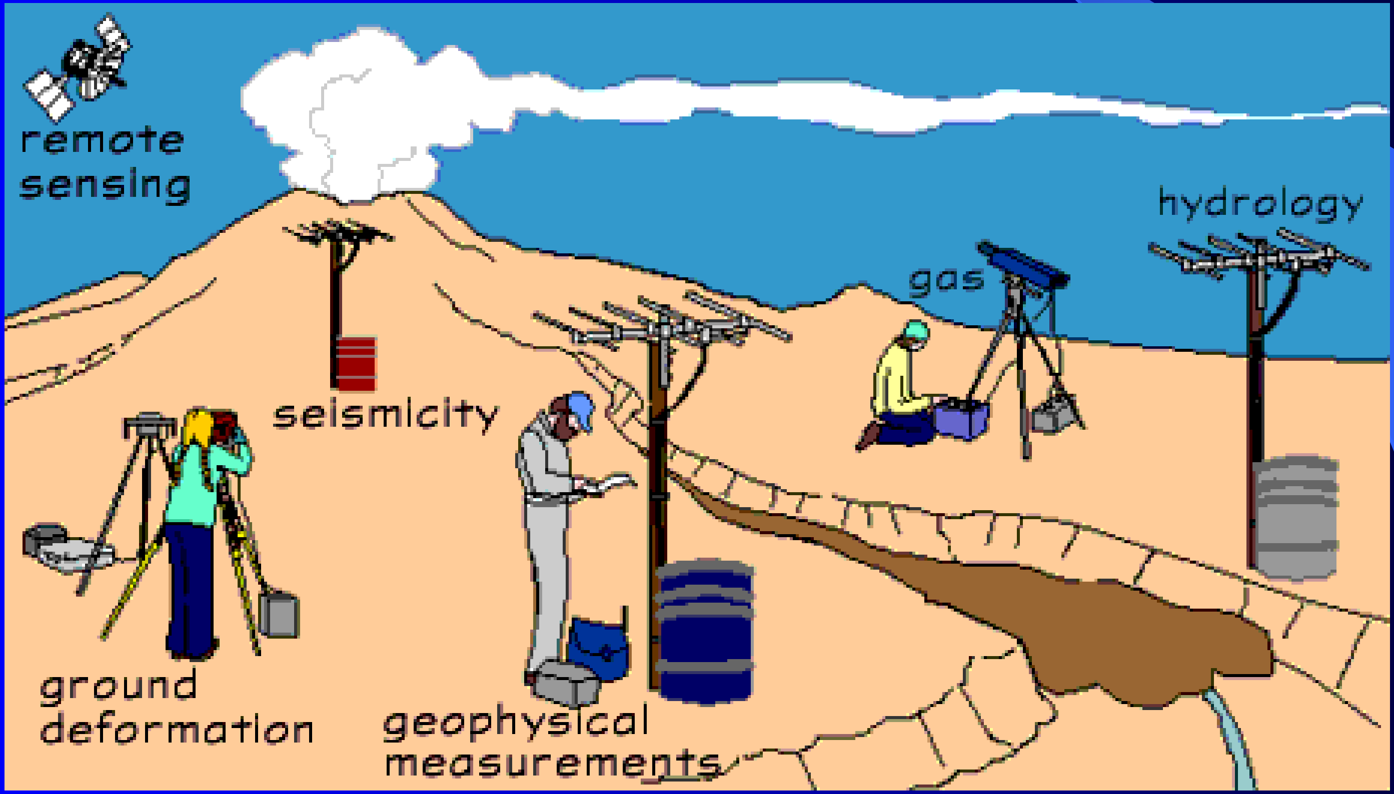
Volcanic Hazards

- Identification
- Monitoring and prediction
- Response

Identification

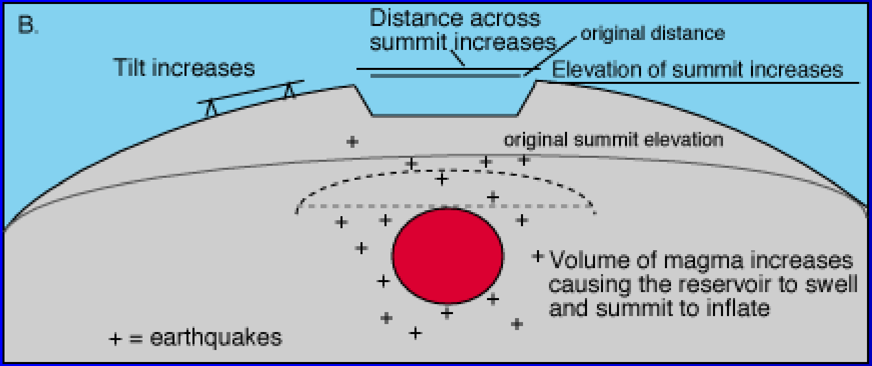
- Geologic mapping
- Historical records (written and oral)

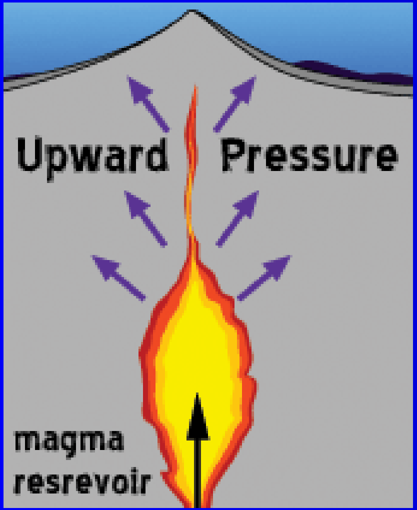
Monitoring and Predicting Volcanic Eruptions



Ground deformation

Rising magma intrudes volcano and changes its shape



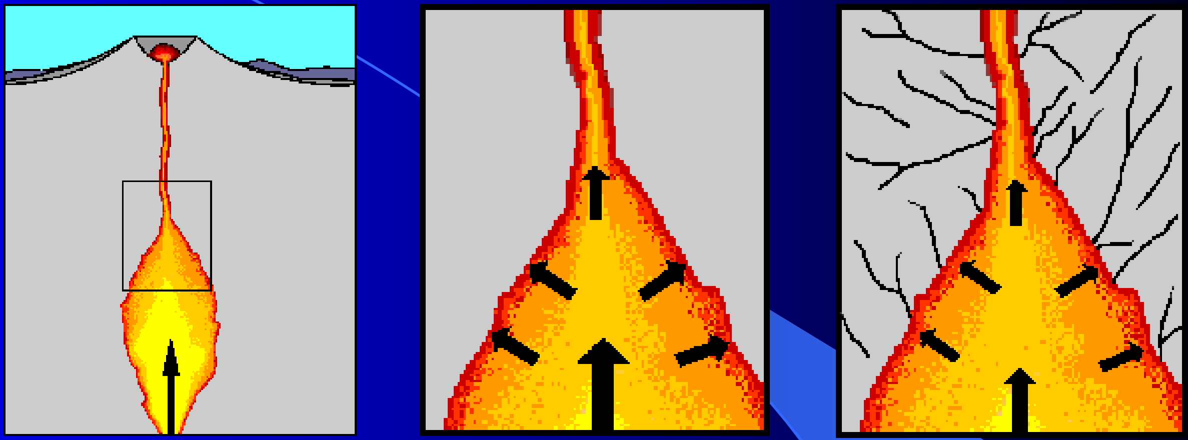


Installing tiltmeter

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)

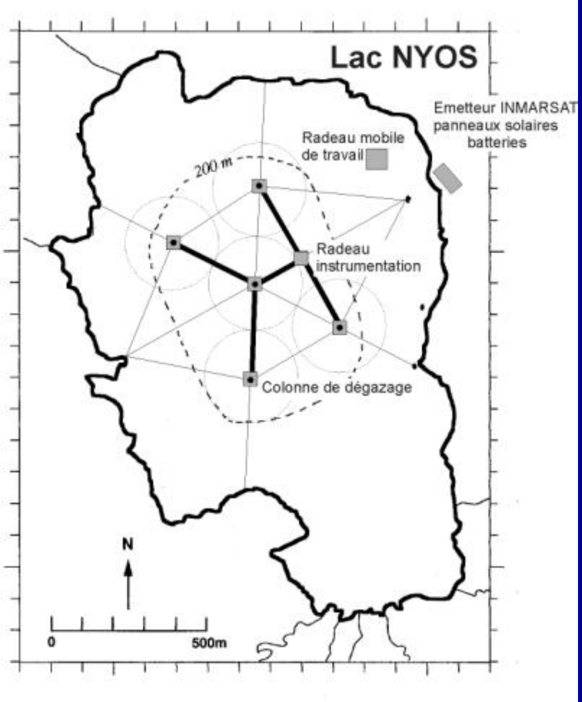
CO2 gas monitoring system

- Solar powered with battery back-up
- Infrared sensor
- Both visual and audio alert

Response plan and designation of responsible individuals


Carbon dioxide
continuous monitoring
WEST
westsystems.com

Remediation – Degassing Lake Nyos



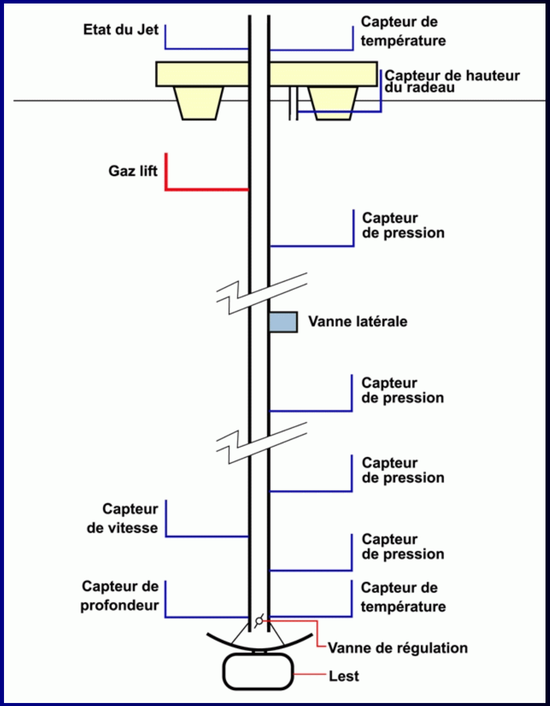
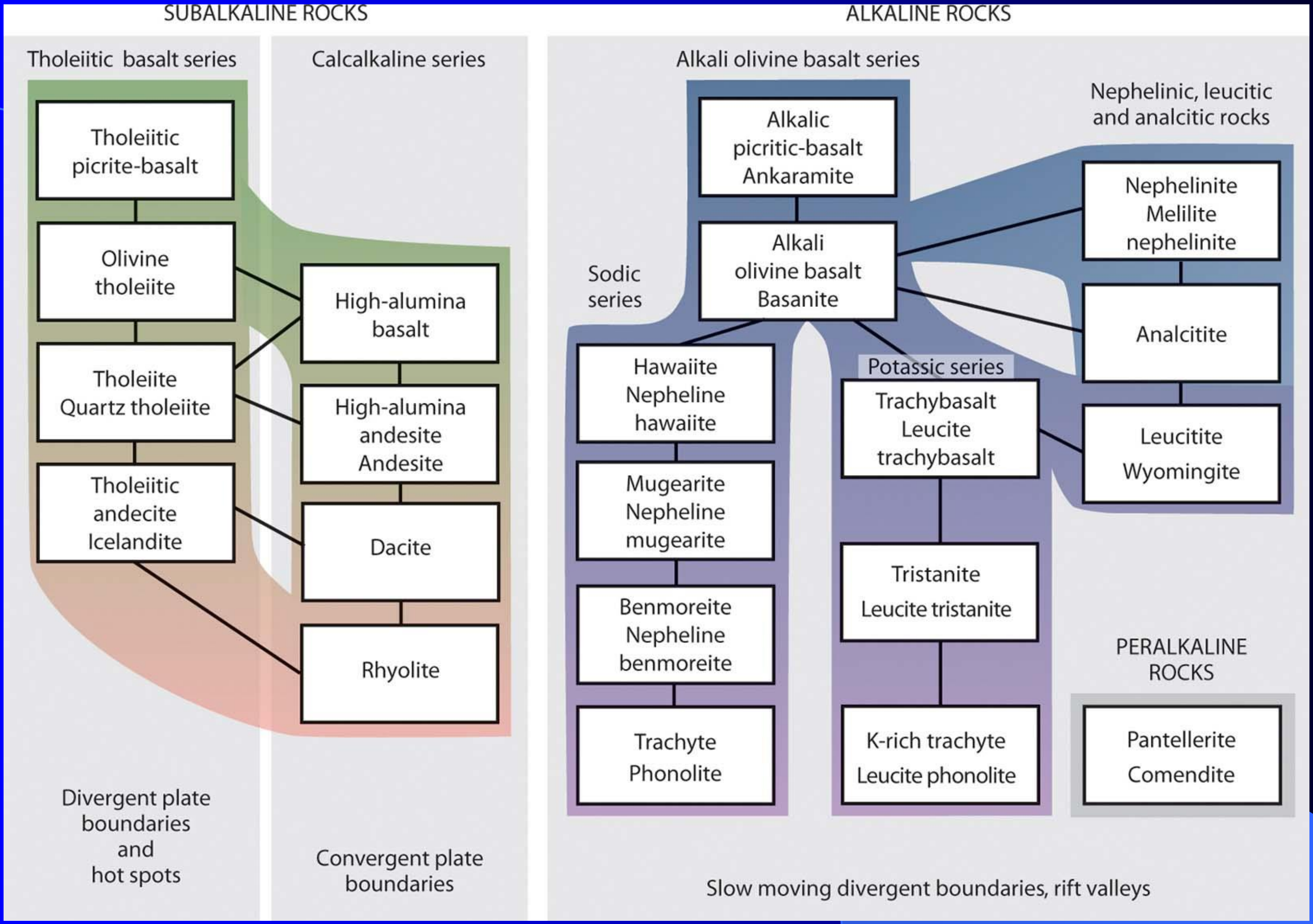


Plate Tectonics and Igneous Rock Associations



SUBALKALINE ROCKS

ALKALINE ROCKS

Tholeiitic basalt series

Calcalkaline series

Alkali olivine basalt series

Tholeiitic picrite-basalt

Olivine tholeiite

Tholeiite Quartz tholeiite

Tholeiitic andecite Icelandite

High-alumina basalt

High-alumina andesite Andesite

Dacite

Rhyolite

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

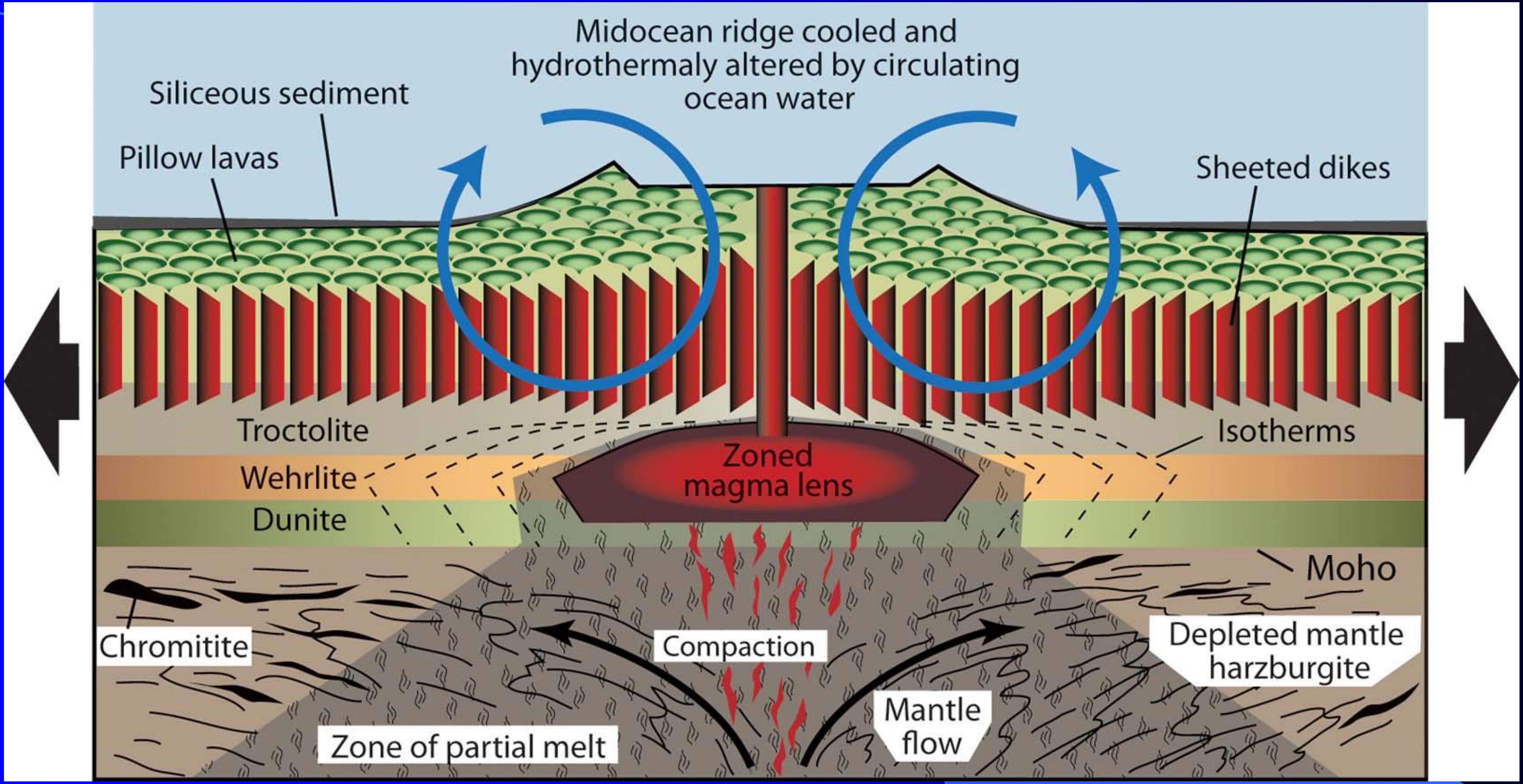
Pantellerite Comendite

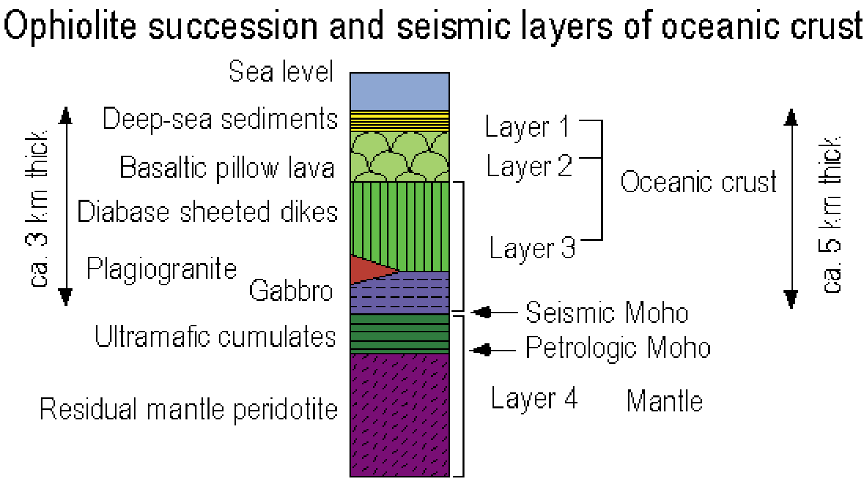
Divergent plate boundaries and hot spots

Convergent plate boundaries

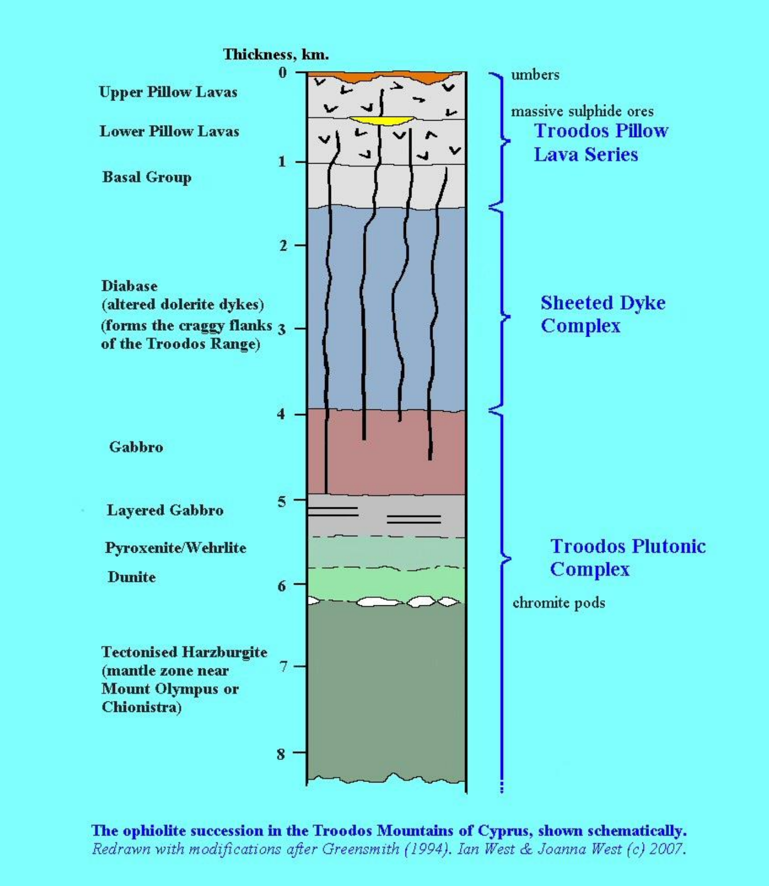
Slow moving divergent boundaries, rift valleys

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



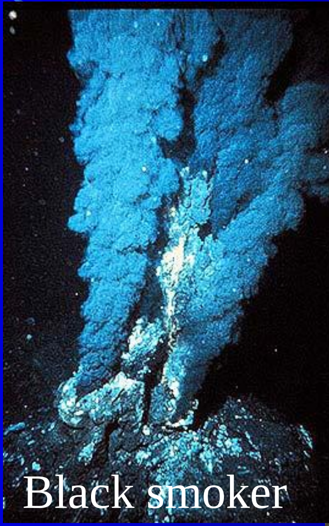


Ophiolite succession and seismic layers of oceanic crust



The ophiolite succession in the Troodos Mountains of Cyprus, shown schematically.
Redrawn with modifications after Greensmith (1994). Ian West & Joanna West (c) 2007.

Pillows

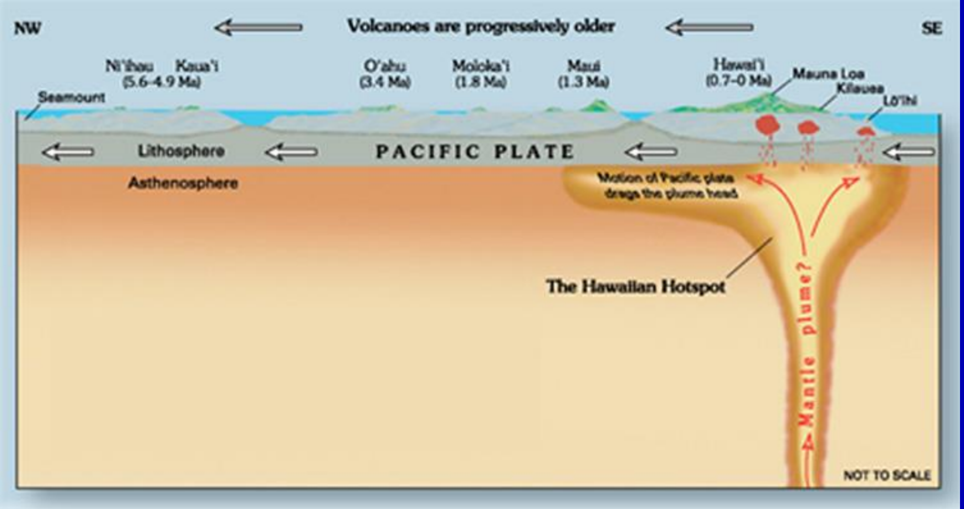


Black smoker

Sheeted dikes

- Ophiolites
- Spilites
- Serpentinites (chrysotile)
- Smokers and base metal deposits
- MORBs

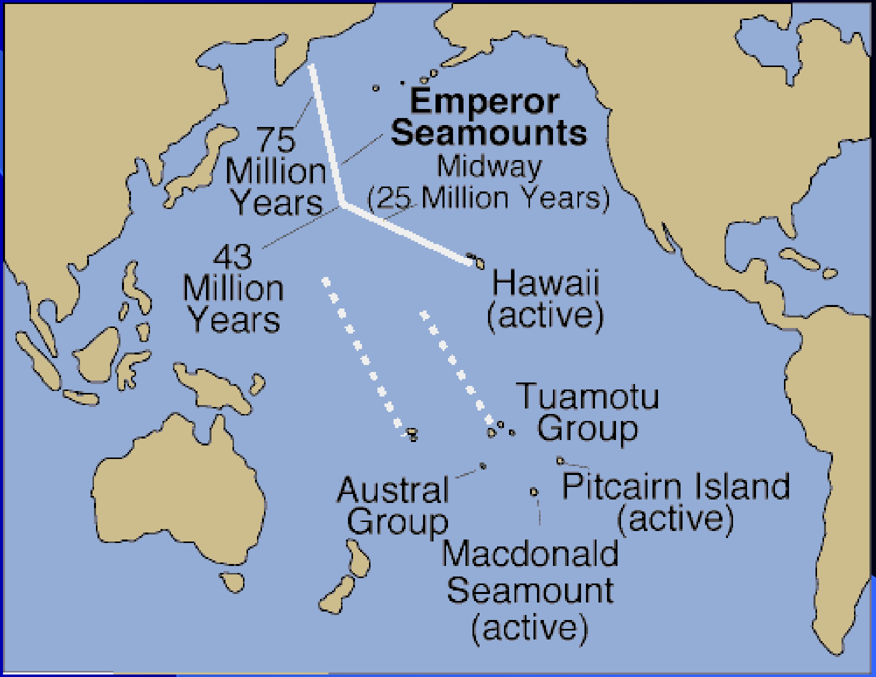
Oceanic Islands and Hot Spots



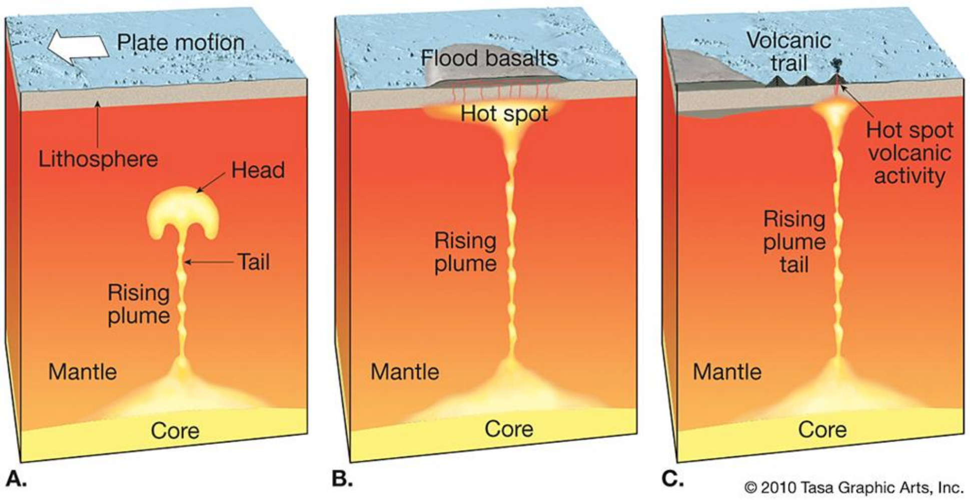
Oceanic islands are mostly composed of tholeiitic basalt with a late stage alkaline sequence (alkali olivine basalt).

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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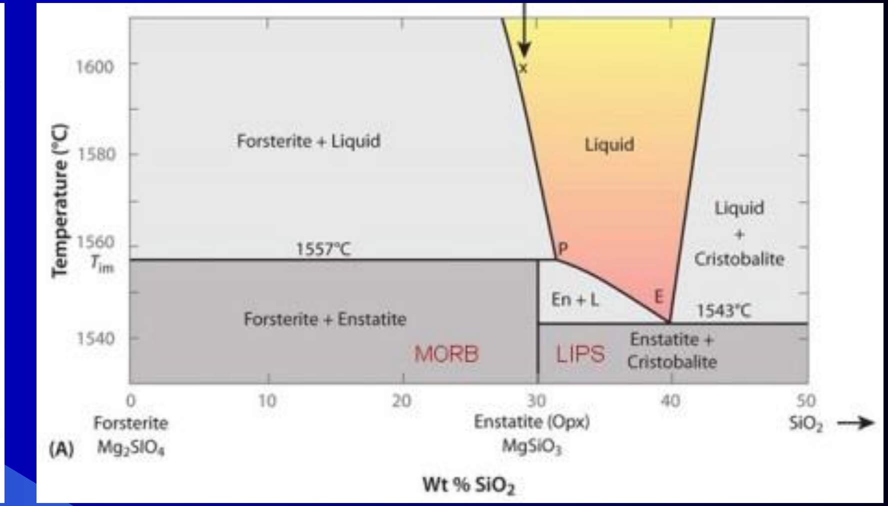
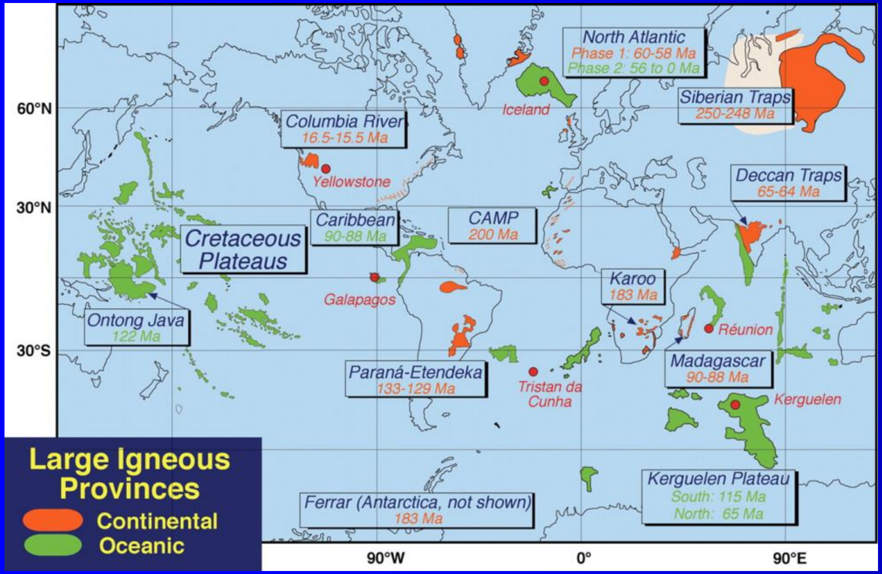
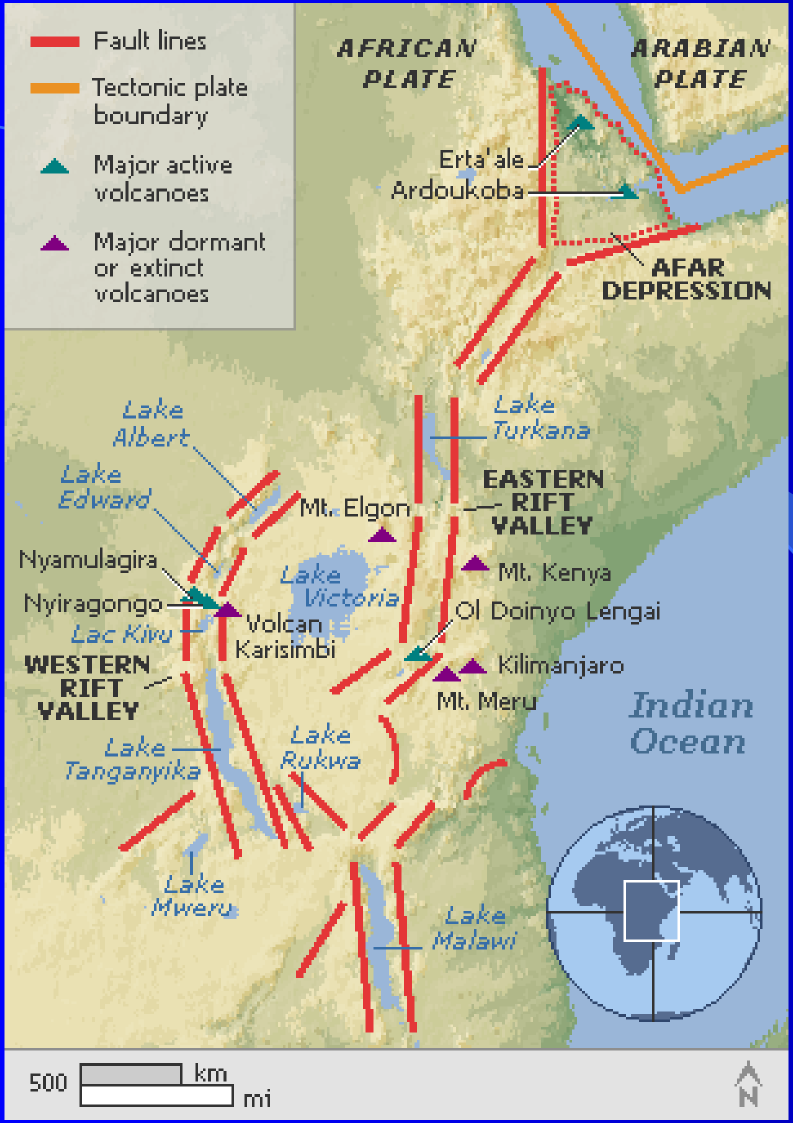




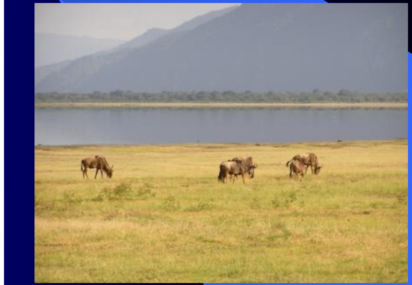
Oceanic LIPs give rise to oceanic plateaus. I wonder what happens when an oceanic plateau tries to go down a subduction zone?

Alkaline Igneous Rocks Associated with Continental Rift Valleys



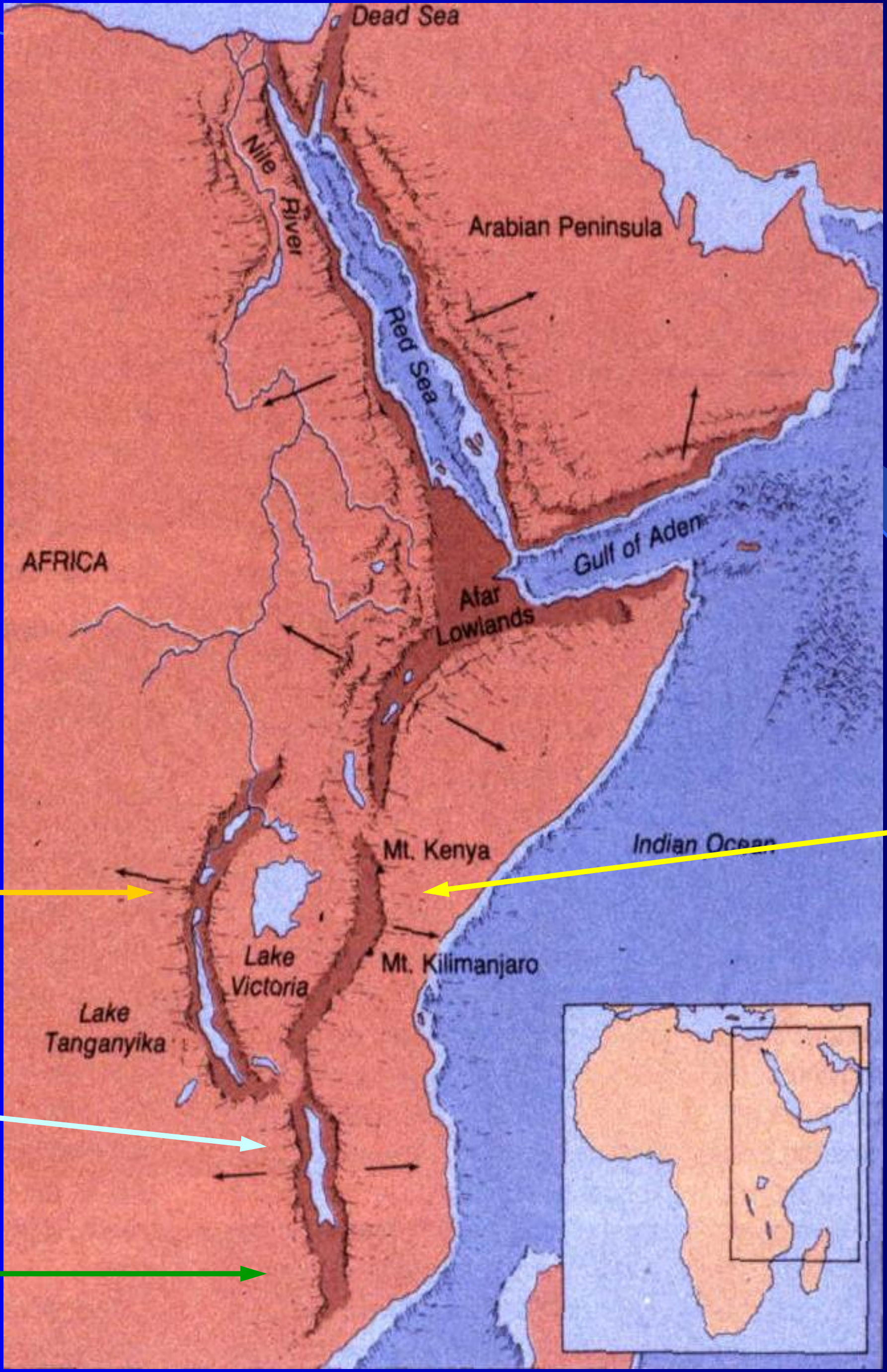
Volcanic	Plutonic
Alkali olivine basalt	Nepheline gabbro
Trachyte	Syenite
Phonolite	Nepheline syenite


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



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)

Current and past locii of alkaline magmatism in East Africa



Western rift

(Potassic)

Eastern rift

(Sodic)

NNAP

CAP

Oldoinyo Lengai

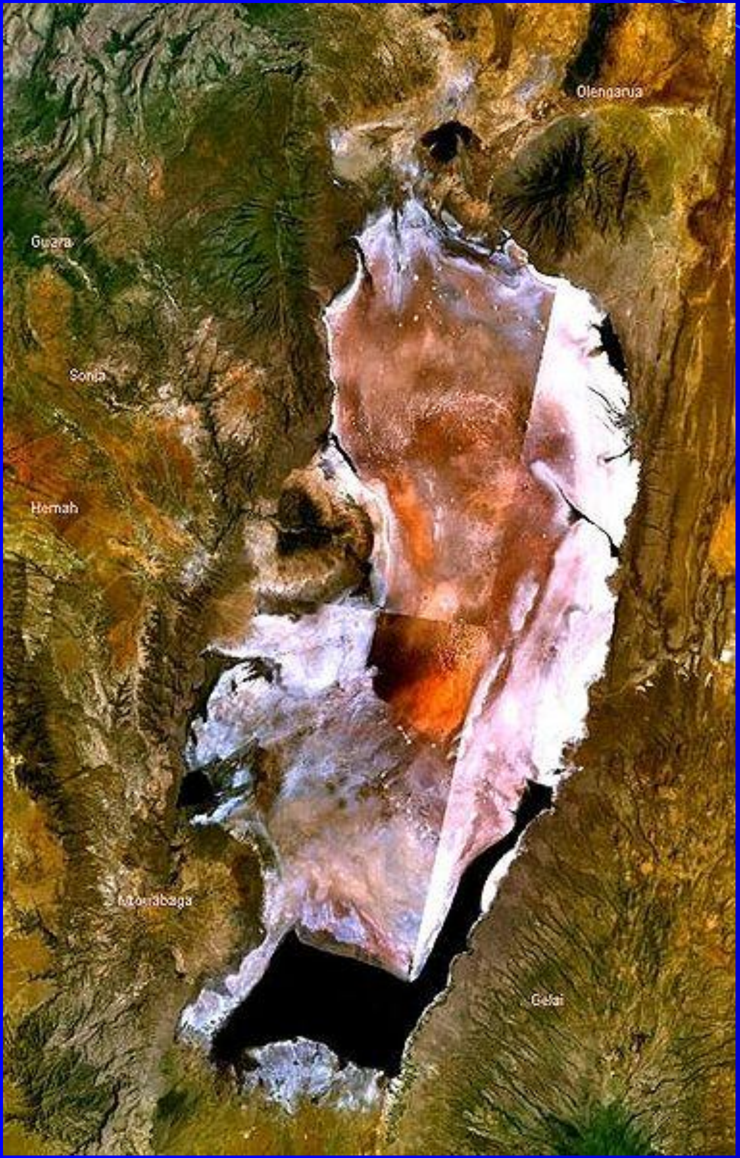
The only active carbonatite (natrocarbonatite) volcano on Earth

Gregoryite - $(Na_{2,}K_{2,}Ca)CO_3$

Nyerereite - $Na_2Ca(CO_3)_2$


lava flow
fresh lava
summit
500m
N

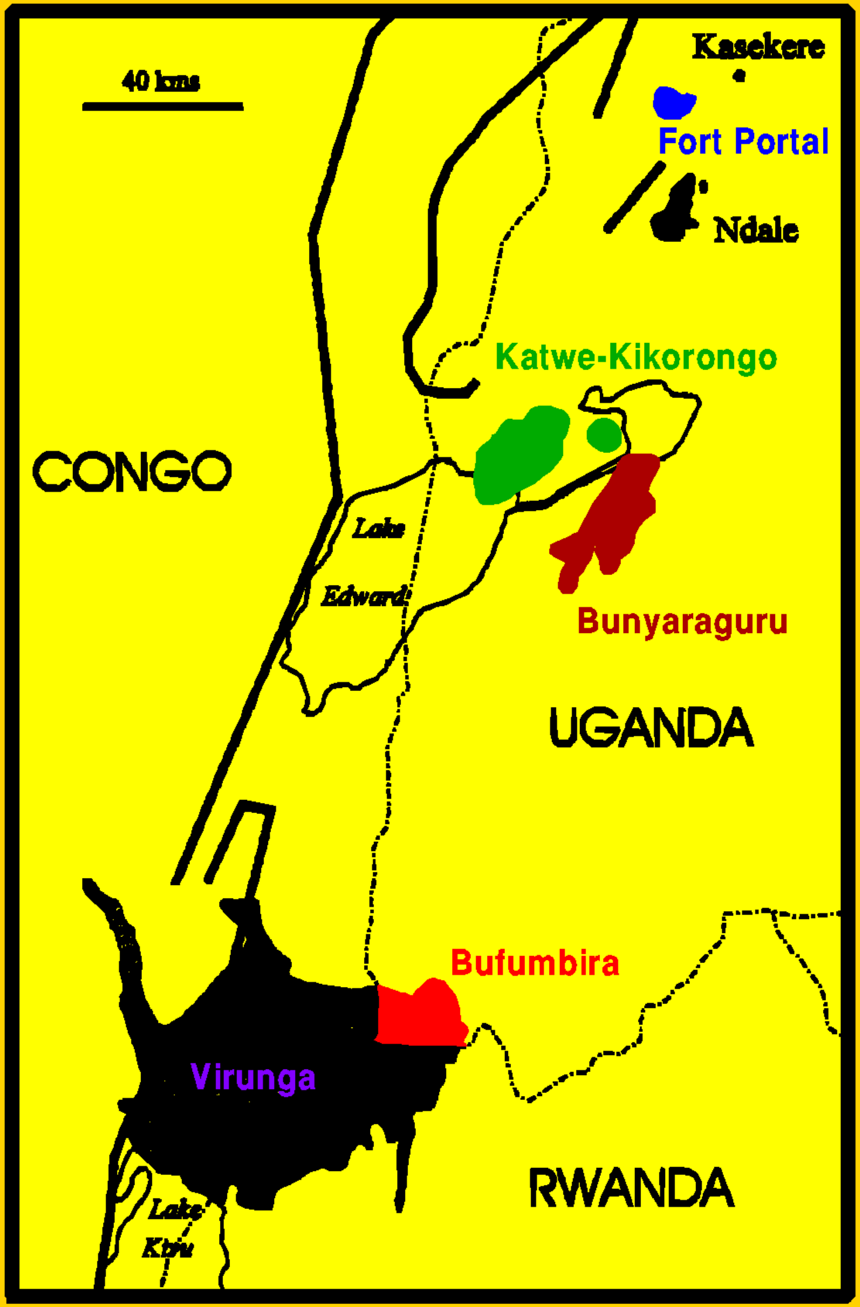
Lake Natron




©wildencounters.net

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

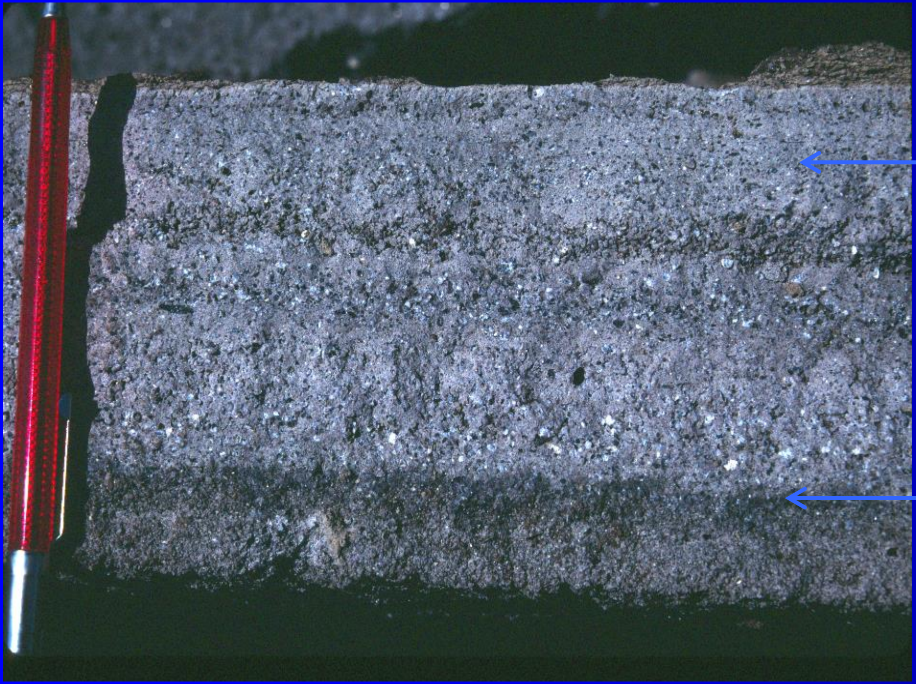
Fort Portal

Tuff cone

Tuff cone and crater lake

Fort Portal

Quarry - “flaggy”
tuff



Lapilli-tuff

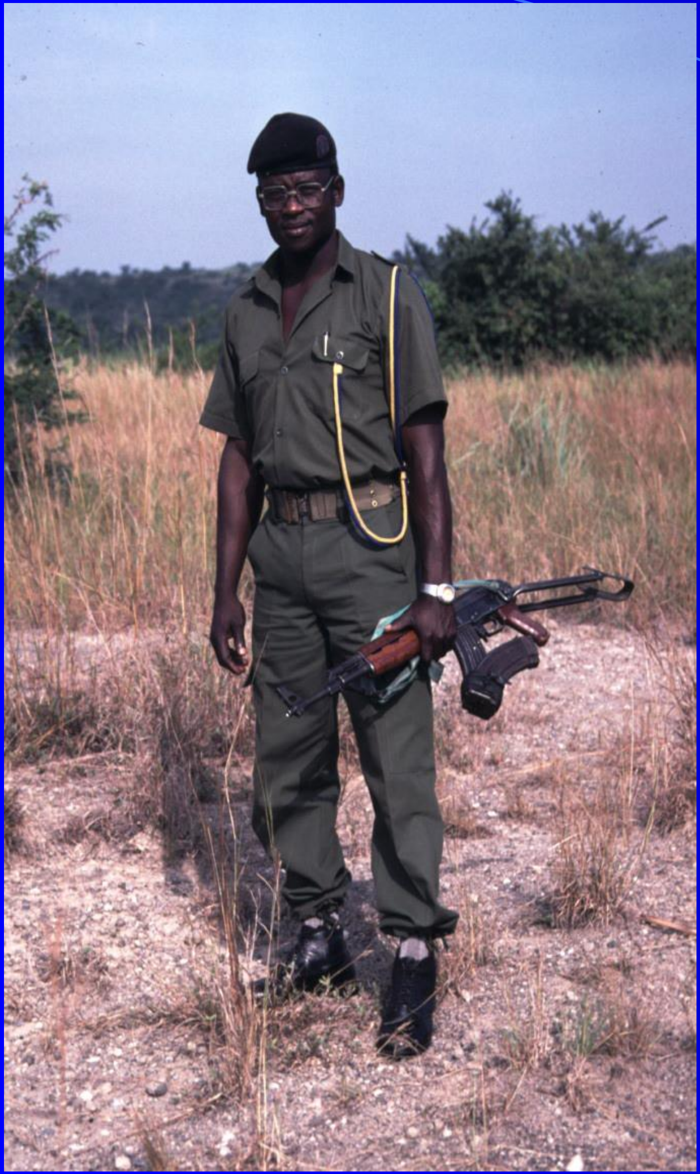
Ash-tuff

Blister in the Fort Portal ash flows

Ripple marks on surface of ash flow

Katwe-Kikorongo

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



Katwe-Kikorongo

Crater lake

Crater

Rim is composed of tuffs and agglomerates

Katwe-Kikorongo

Subaqueous tuffs

Bufumbira

Mgahinga and Sabinio volcanoes

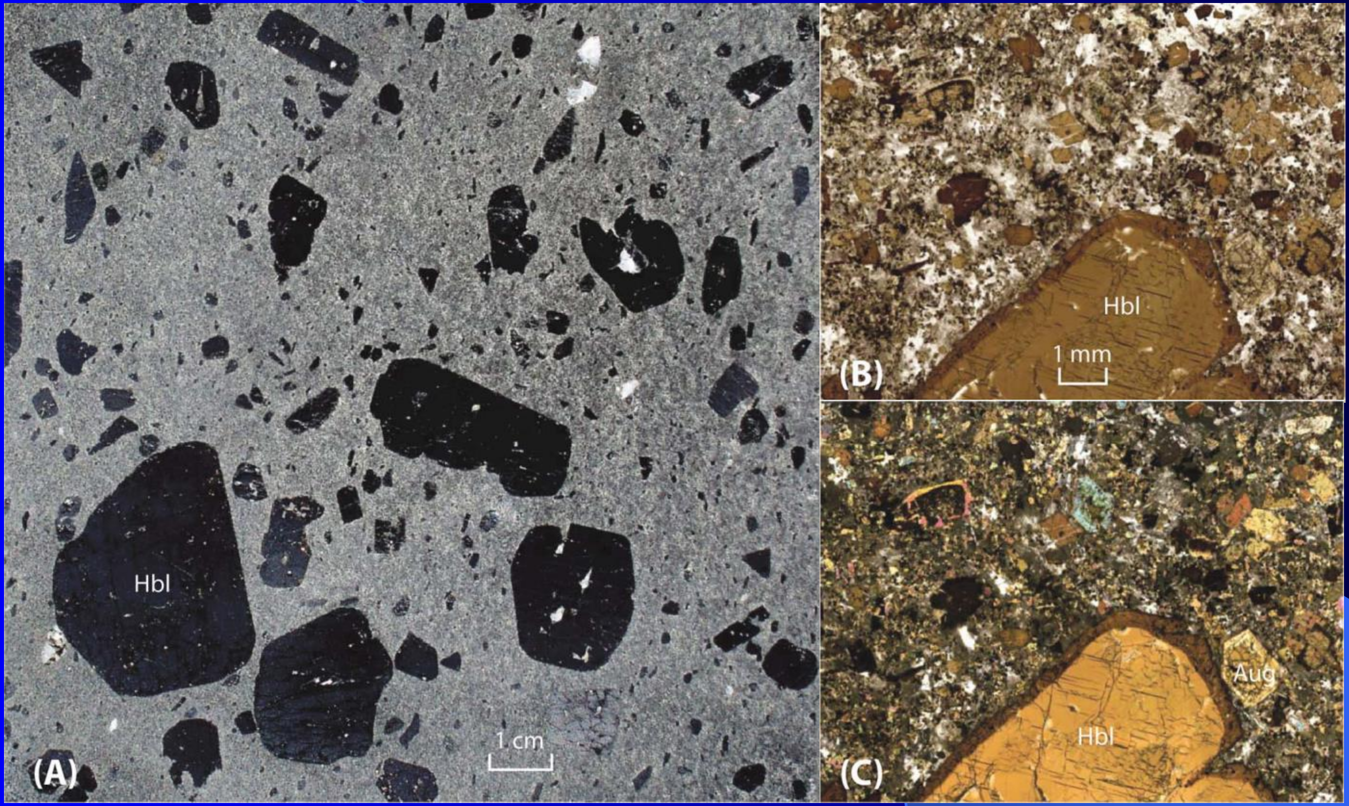
Trachyte plug

Bufumbira

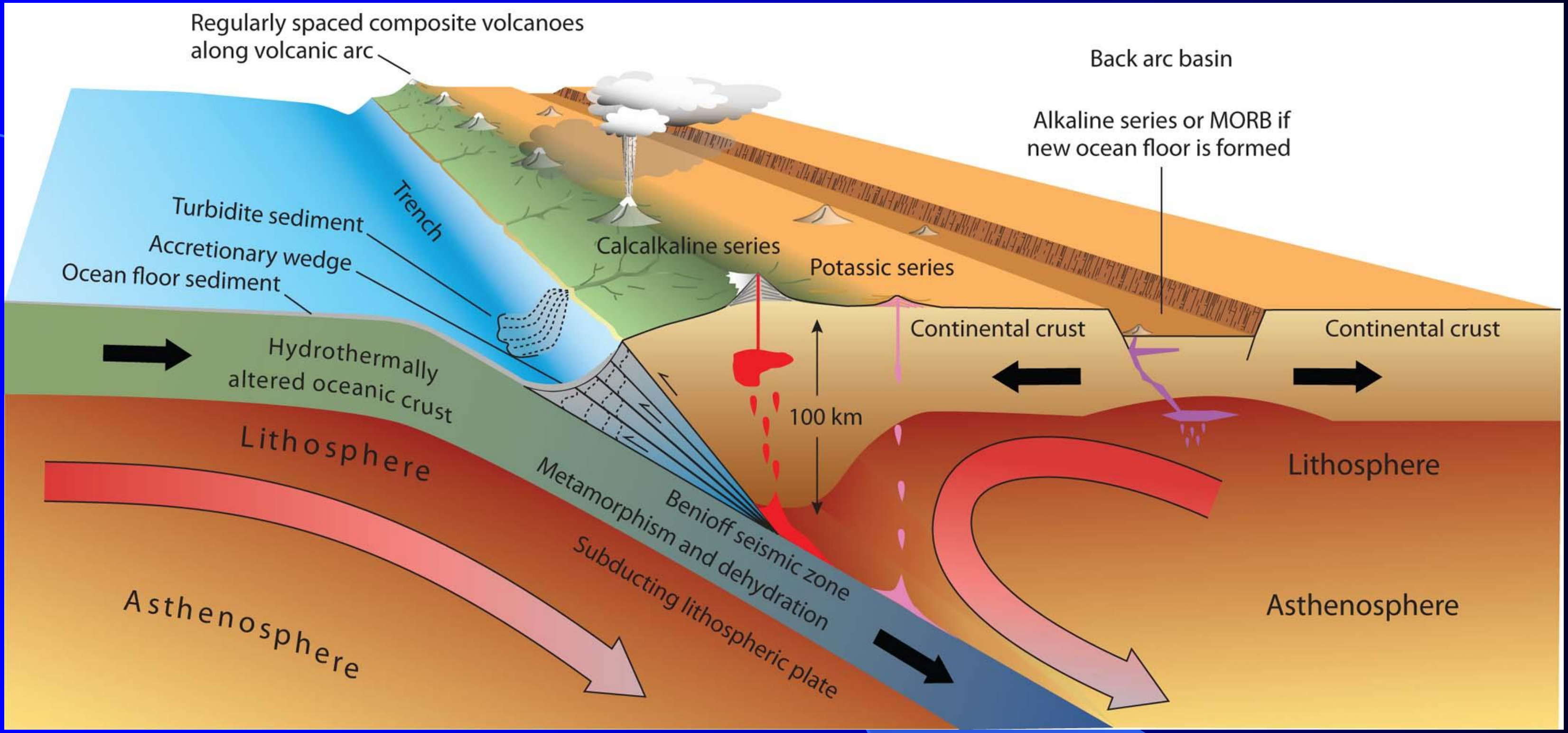
Lapilli tephra

Leucite basalt

Lamprophyre - any of a group of dark gray to black intrusive igneous rocks that generally occur as dikes. They are characterized by a porphyritic texture in which large phenocrysts of dark, iron-magnesium silicate minerals (biotite, hornblende, augite, olivine) are enclosed in a fine-grained to dense groundmass. Feldspars do not occur as phenocrysts. The groundmass is comprised of the iron-magnesium silicate minerals plus K-feldspar, plagioclase, or feldspathoid.

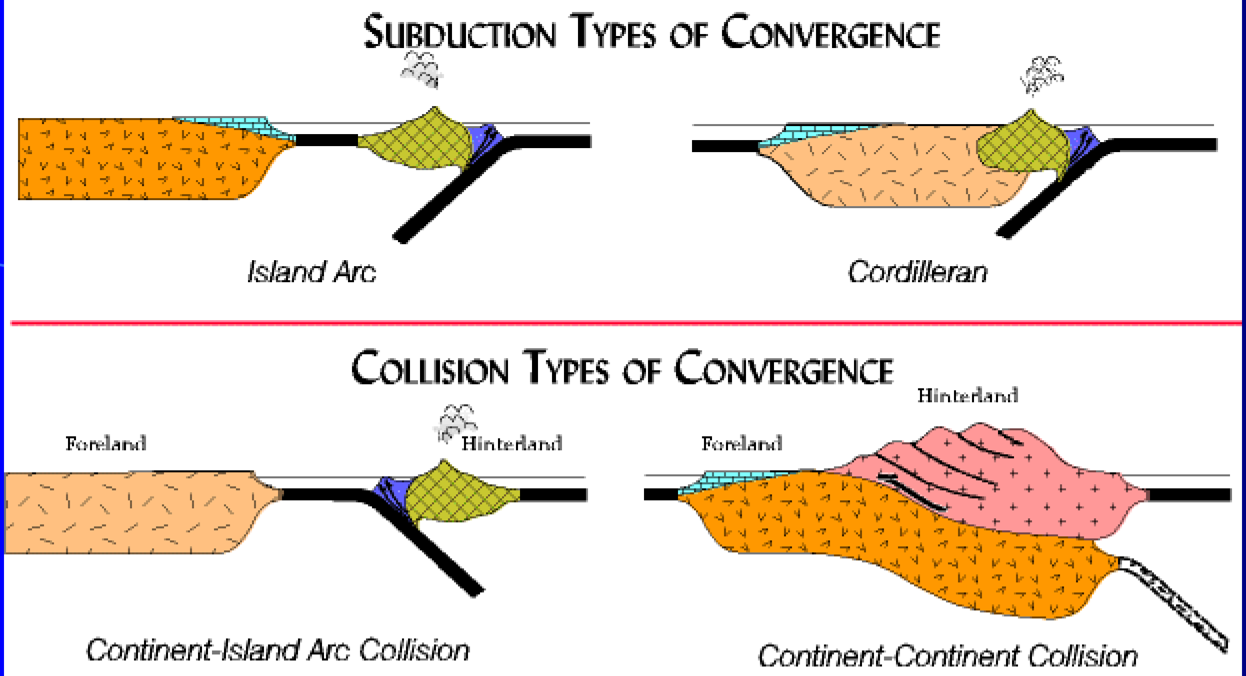


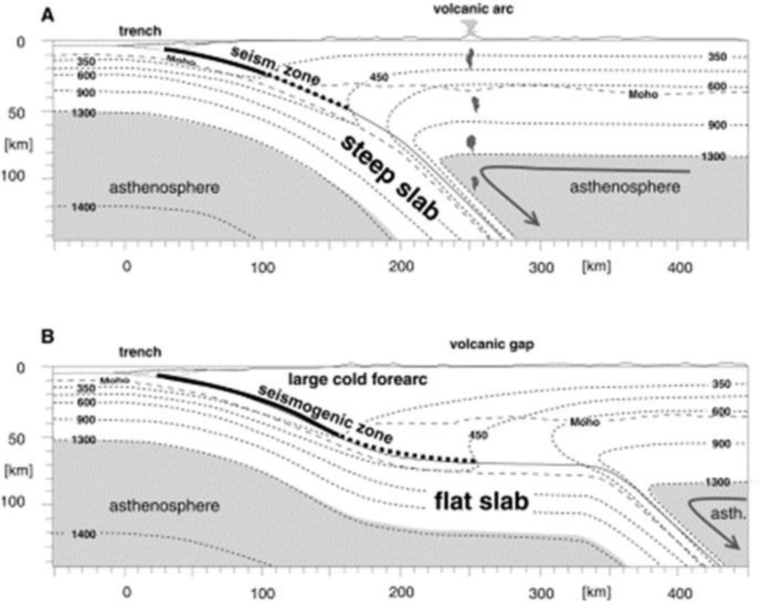
The Subduction Zone Factory



Calcalkaline vs tholeiitic

Volcanic	Plutonic
High-alumina basalt (Al_2O_3 > 16.0%)	Gabbro
Andesite	Diorite
Dacite	Granodiorite
Rhyolite	Granite


SUBDUCTION TYPES OF CONVERGENCE
Island Arc
Cordilleran
COLLISION TYPES OF CONVERGENCE
Foreland
Hinterland
Foreland
Hinterland
Continent-Island Arc Collision
Continent-Continent Collision


A
trench
volcanic arc
seism. zone
Moho
steep slab
asthenosphere
asthenosphere
350
600
900
1300
1400
450
0
50
[km]
100
0
100
200
300
[km]
400
B
trench
volcanic gap
large cold forearc
seismogenic zone
Moho
flat slab
asthenosphere
asth.
350
600
900
1300
1400
450
0
50
[km]
100
0
100
200
300
[km]
400

INTERNATIONAL CHRONOSTRATIGRAPHIC CHART

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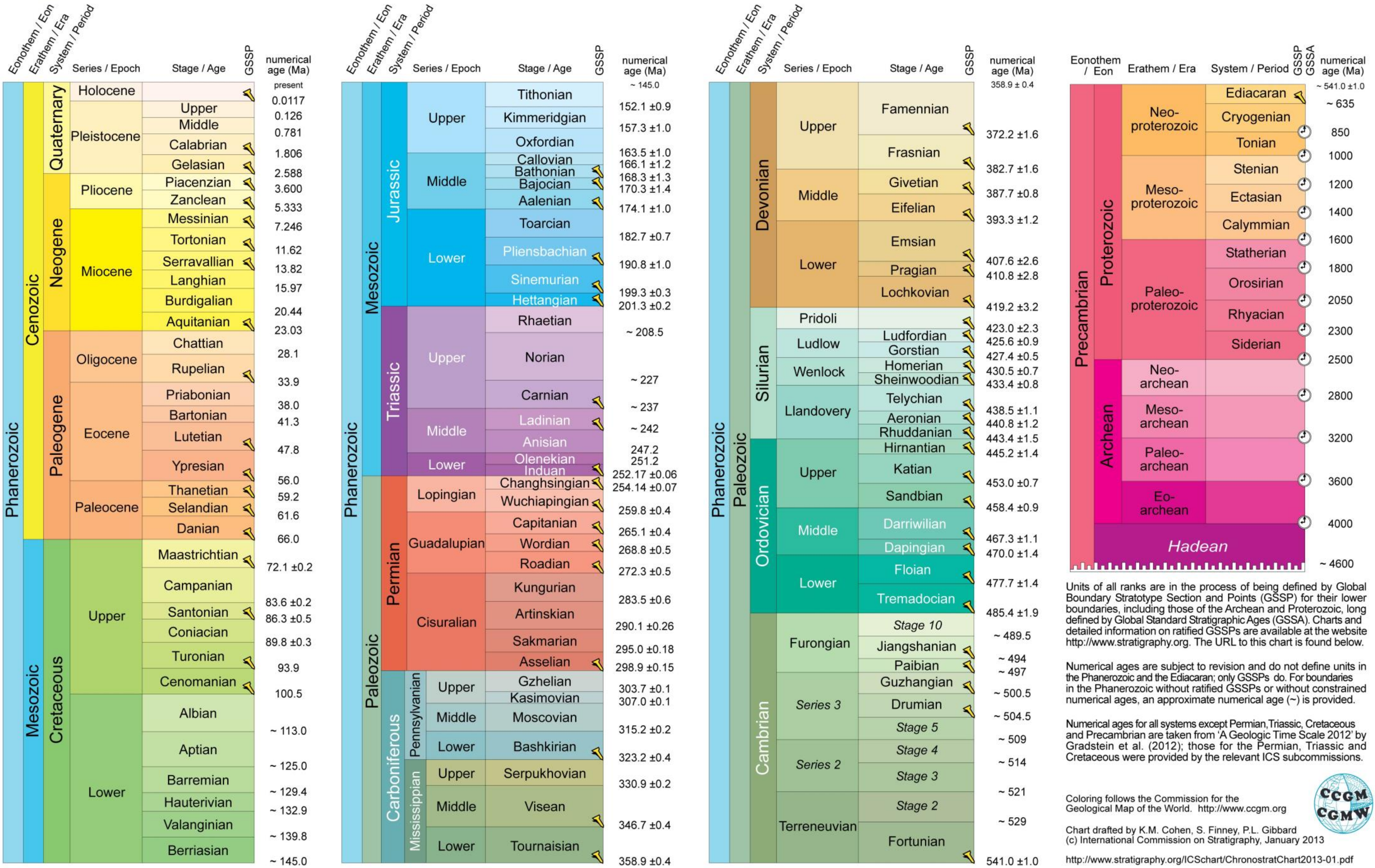
International Commission on Stratigraphy

v 2013/01



Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	GSSP	numerical age (Ma)
						present
Phanerozoic	Cenozoic	Quaternary	Holocene		✓	0.0117
			Pleistocene	Upper		0.126
				Middle		0.781
				Calabrian	✓	1.806
				Gelasian	✓	2.588
		Neogene	Pliocene	Piacenzian	✓	3.600
				Zanclean	✓	5.333
			Miocene	Messinian	✓	7.246
				Tortonian	✓	11.62
				Serravallian	✓	13.82
				Langhian		15.97
				Burdigalian		20.44
				Aquitanian	✓	23.03
		Paleogene	Oligocene	Chattian		28.1
				Rupelian	✓	33.9
			Eocene	Priabonian		38.0
				Bartonian		41.3
				Lutetian	✓	47.8
				Ypresian	✓	56.0
			Paleocene	Thanetian	✓	59.2
				Selandian	✓	61.6
				Danian	✓	66.0
	Mesozoic	Cretaceous	Upper	Maastrichtian	✓	72.1 ±0.2
				Campanian		83.6 ±0.2
				Santonian	✓	86.3 ±0.5
				Coniacian		89.8 ±0.3
				Turonian	✓	93.9
				Cenomanian	✓	100.5
			Lower	Albian		~ 113.0
				Aptian		~ 125.0
				Barremian		~ 129.4
				Hauterivian		~ 132.9
				Valanginian		~ 139.8
				Berriasian		~ 145.0

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	GSSP	numerical age (Ma)
						~ 145.0
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian		152.1 ±0.9
				Kimmeridgian		157.3 ±1.0
				Oxfordian		163.5 ±1.0
			Middle	Callovian		166.1 ±1.2
				Bathonian	✓	168.3 ±1.3
				Bajocian	✓	170.3 ±1.4
				Aalenian	✓	174.1 ±1.0
			Lower	Toarcian		182.7 ±0.7
				Pliensbachian	✓	190.8 ±1.0
				Sinemurian	✓	199.3 ±0.3
				Hettangian	✓	201.3 ±0.2
		Triassic	Upper	Rhaetian		~ 208.5
				Norian		~ 227
				Carnian	✓	~ 237
			Middle	Ladinian	✓	~ 242
				Anisian		247.2
			Lower	Olenekian		251.2
				Induan	✓	252.17 ±0.06
	Paleozoic	Permian	Lopingian	Changhsingian	✓	254.14 ±0.07
				Wuchiapingian	✓	259.8 ±0.4
			Guadalupian	Capitanian	✓	265.1 ±0.4
				Wordian	✓	268.8 ±0.5
				Roadian	✓	272.3 ±0.5
			Cisuralian	Kungurian		283.5 ±0.6
				Artinskian		290.1 ±0.26
				Sakmarian		295.0 ±0.18
				Asselian	✓	298.9 ±0.15
		Carboniferous Pennsylvanian	Upper	Gzhelian		303.7 ±0.1
				Kasimovian		307.0 ±0.1
			Middle	Moscovian		315.2 ±0.2
			Lower	Bashkirian	✓	323.2 ±0.4
		Mississippian	Upper	Serpukhovian		330.9 ±0.2
			Middle	Visean	✓	346.7 ±0.4
			Lower	Tournaisian	✓	358.9 ±0.4

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	GSSP	numerical age (Ma)
						358.9 ± 0.4
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	✓	372.2 ±1.6
				Frasnian	✓	382.7 ±1.6
			Middle	Givetian	✓	387.7 ±0.8
				Eifelian	✓	393.3 ±1.2
			Lower	Emsian	✓	407.6 ±2.6
				Pragian	✓	410.8 ±2.8
				Lochkovian	✓	419.2 ±3.2
		Silurian	Pridoli		✓	423.0 ±2.3
			Ludlow	Ludfordian	✓	425.6 ±0.9
				Gorstian	✓	427.4 ±0.5
			Wenlock	Homerian	✓	430.5 ±0.7
				Sheinwoodian	✓	433.4 ±0.8
			Llandovery	Telychian	✓	438.5 ±1.1
				Aeronian	✓	440.8 ±1.2
				Rhuddanian	✓	443.4 ±1.5
		Ordovician	Upper	Hirnantian	✓	445.2 ±1.4
				Katian	✓	453.0 ±0.7
				Sandbian	✓	458.4 ±0.9
			Middle	Darriwilian	✓	467.3 ±1.1
				Dapingian	✓	470.0 ±1.4
			Lower	Floian	✓	477.7 ±1.4
				Tremadocian	✓	485.4 ±1.9
		Cambrian	Furongian	*Stage 10*		~ 489.5
				Jiangshanian	✓	~ 494
				Paibian	✓	~ 497
			Series 3	Guzhangian	✓	~ 500.5
				Drumian	✓	~ 504.5
				Stage 5		~ 509
			Series 2	*Stage 4*		~ 514
				Stage 3		~ 521
			Terreneuvian	*Stage 2*		~ 529
				Fortunian	✓	541.0 ±1.0

Eonothem / Eon		Erathem / Era	System / Period	GSSP GSSA	numerical age (Ma)
					~ 541.0 ±1.0
Precambrian	Proterozoic	Neoproterozoic	Ediacaran	✓	~ 635
			Cryogenian	◷	850
			Tonian	◷	1000
		Mesoproterozoic	Stenian	◷	1200
			Ectasian	◷	1400
			Calymmian	◷	1600
		Paleoproterozoic	Statherian	◷	1800
			Orosirian	◷	2050
			Rhyacian	◷	2300
			Siderian	◷	2500
	Archean	Neoarchean		◷	2800
		Mesoarchean		◷	3200
		Paleoarchean		◷	3600
		Eoarchean		◷	4000
	Hadean				~ 4600

Units of all ranks are in the process of being defined by Global Boundary Stratotype Section and Points (GSSP) for their lower boundaries, including those of the Archean and Proterozoic, long defined by Global Standard Stratigraphic Ages (GSSA). Charts and detailed information on ratified GSSPs are available at the website http://www.stratigraphy.org. The URL to this chart is found below.

Numerical ages are subject to revision and do not define units in the Phanerozoic and the Ediacaran; only GSSPs do. For boundaries in the Phanerozoic without ratified GSSPs or without constrained numerical ages, an approximate numerical age (~) is provided.

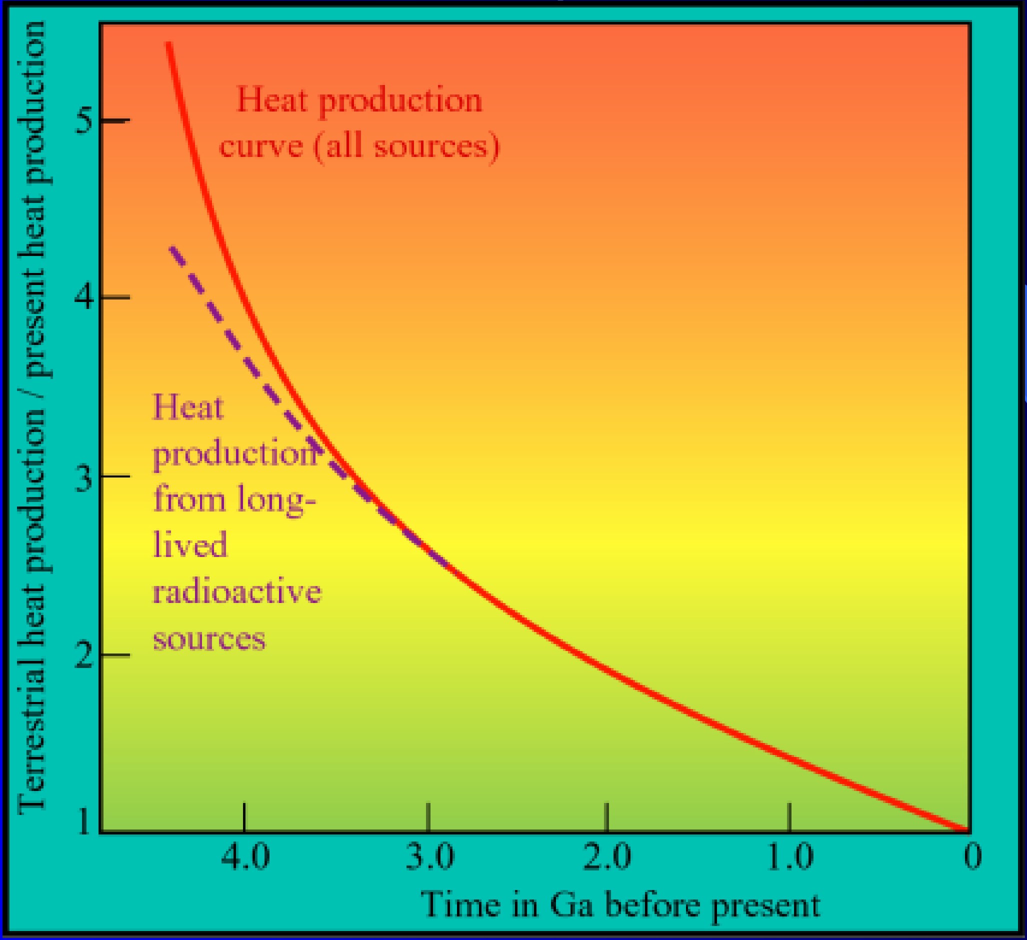
Numerical ages for all systems except Permian, Triassic, Cretaceous and Precambrian are taken from 'A Geologic Time Scale 2012' by Gradstein et al. (2012); those for the Permian, Triassic and Cretaceous were provided by the relevant ICS subcommissions.

Coloring follows the Commission for the Geological Map of the World. http://www.ccgm.org

Chart drafted by K.M. Cohen, S. Finney, P.L. Gibbard

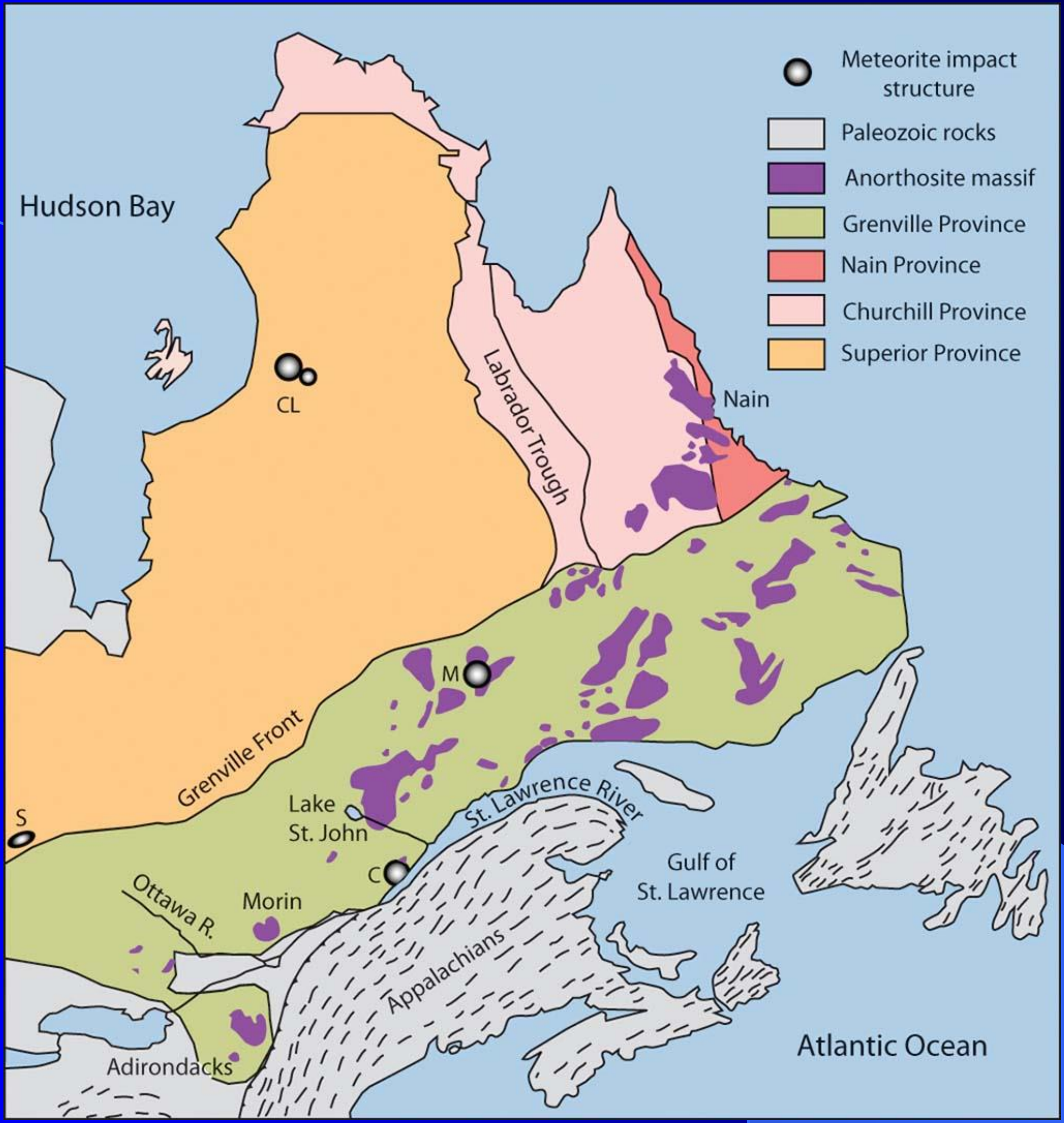
http://www.stratigraphy.org/ICSchart/ChronostratChart2013-01.pdf

Earth’s heat production



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

Proterozoic Massif-type Anorthosites



Bimodal Archean Terranes

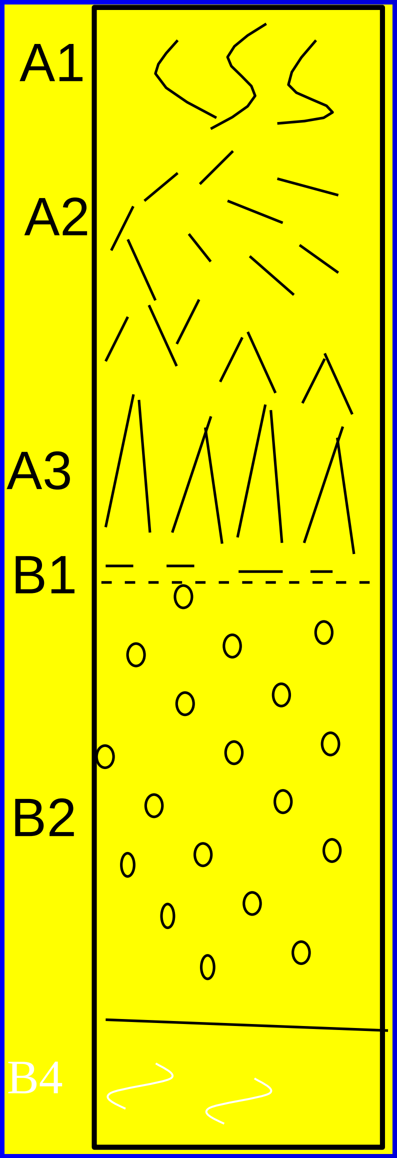
Greenstone belts (commonly dominated by greenschist facies amphibolites)

- Mafic and ultramafic Mg-rich (= komatiites) lavas
  - Some intermediate lavas (andesites)
- Detrital sediments
  - Some chemical sediments (BIFs) or biogenic formations (stromatolites)

Gneissic « basement » or plutons (TTGs - Tonalites, Trondhejmites and Granodiorites

The original komatiites in Komatii formation (~1.5 km from type locality). South Africa

Subdivision of komatiite flows (Arndt et al. 1977)



Polysutured top

Random spinifex

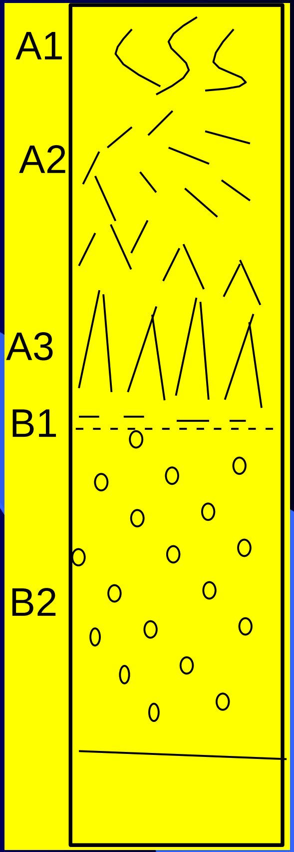
Orientated spinifex

parallel blades of spinifex

solid subhedral olivine

Basal chill, polysutured

Chilled/brecciated top



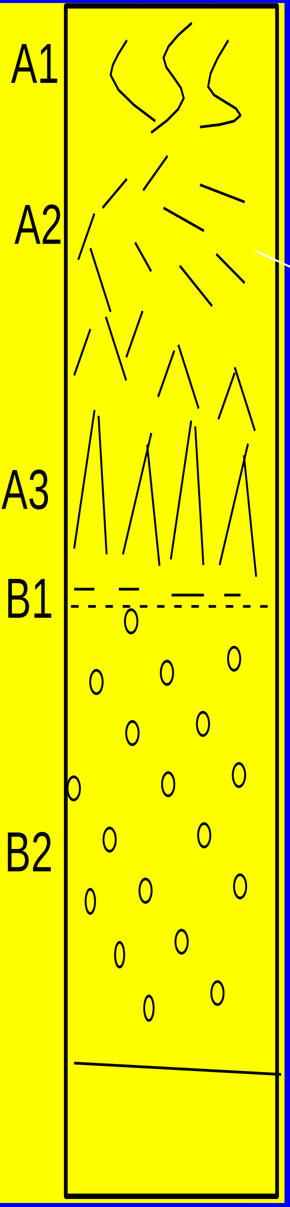
Subaquatic emplacement

Spinifex textured layer(s)

- Random spinifex
- Orientated spinifex
- Plate spinifex

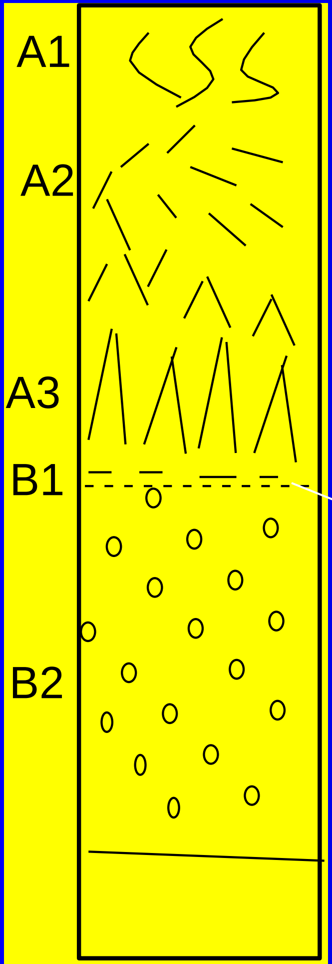
Spinifex grass, Western Australia (Barnes 1990)

Random spinifex

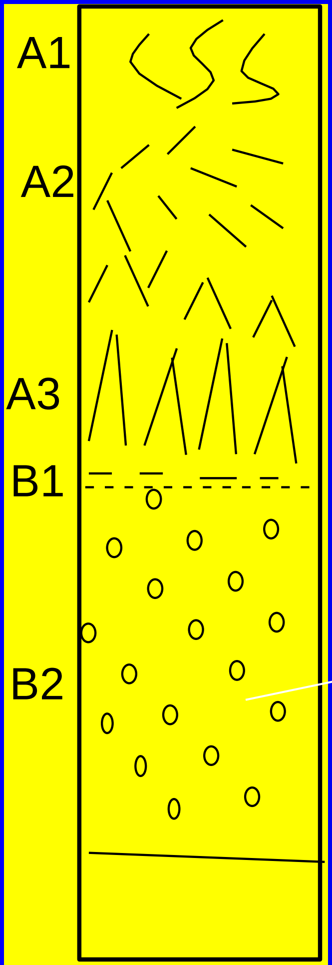


Orientated spinifex

Plate spinifex



Polyhedral olivine



What are the implications of komatiites?

- Probably formed in hot-spot like situations (difficult to arrive at > 1600°)
- Even though, this is hotter than modern hotspots
- At least some parts of the Earth were very hot
- At least part of the GSB formed from hotspots (intraplate situation)

TTGs

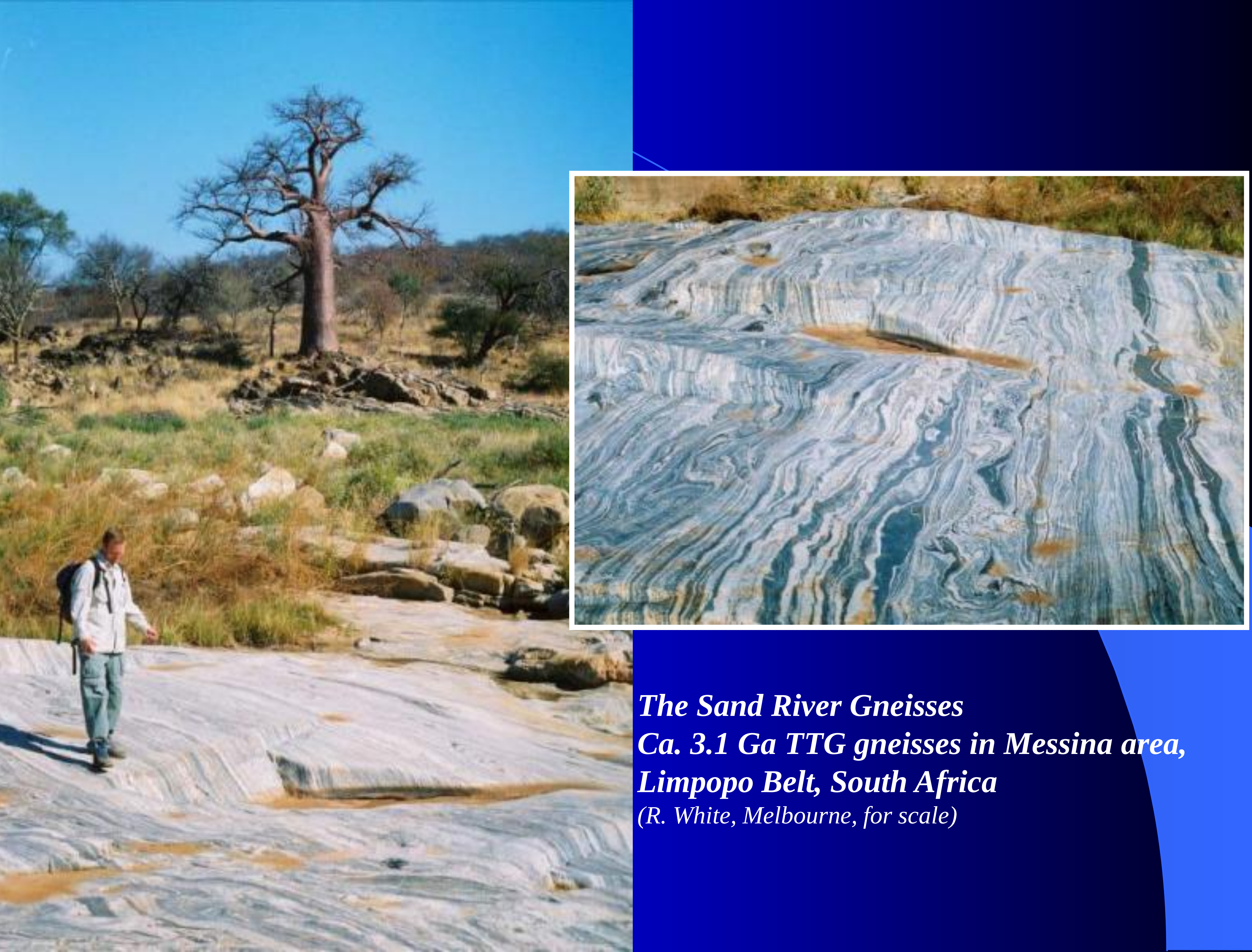
- Archaean TTG (Tonalite, Trondhjemites and Granodiorites)
- ≈ grey gneisses *(although in details, some TTGs are not grey gneisses and some grey gneisses are not TTG…)*

Commonly complex, migmatitic, polydeformed orthogneisses

Gneiss d'Amitsôq (Groenland) : 3.82 Ga

Gneiss de Kivijärvi (Finlande) : 2.86 Ga

Gneiss Péninsulaires d'Inde : 3.20 Ga



The Sand River Gneisses
Ca. 3.1 Ga TTG gneisses in Messina area,
Limpopo Belt, South Africa
(R. White, Melbourne, for scale)

And there’s so much more in the Precambrian

Formation of the crust

Sanukitoids

Take a graduate course in igneous petrology to learn more.