# Lesson 6 Part II

# Rocks of the earth, cont’d

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What kind of rock makes up the table and the shield volcanoes?

It is basalt. The word is derived from the Latin *basanites* used by Pliny the elder in his Historia Naturalis for the very hard black rock and is ultimately derived from the Greek βάσανος (*basanos*=touchstone)

Basalt is defined as a black to dark grey, aphanitic rock consisting of some 65% of plagioclase (anorthite to labradorite), about 30% or less pyroxene and less than 10% feldspathoids. Its total silica ($SiO_2$) content fluctuates between 45 to 55%.

Basalt is the most widespread volcanic rock in the Solar System. We know it from the earth, Moon, Mars, Mercury and Venus. On earth it covers the ocean floors, makes up almost all the oceanic islands and plateaux, many of the island arcs, and, on the continents, the vast flood basalt provinces plus it occurs commonly in rifts.

A massive basalt sample

Basalt forms by the solidification of basaltic lava at the surface or by the solidification of basaltic magma close to the surface. In both cases, the solidification, i.e. crystallisation, is fast enough to create an aphanitic texture.

Lava is molten rock at the surface. The word lava comes from Italian probably from the Latin root “labes” meaning a “fall” or “slide”. It seems that as a technical term it was first used in 1737 by Francesco Serao to describe the eruption of Vesuvius in 14$^{th}$ May to 4$^{th}$ June 1737.

Magma is molten rock in the earth. It comes from the Greek word μάγμα meaning a thick viscous unguent. Its earliest use seems to have been in the fourth century CE in Rutilius Taurus Aemilianus Palladius’ book on agriculture (*Opus agriculturae* or *De re rustica*).


A basaltic pahoehoe lava flow forming, Hawaii, USA


A solidified pahoehoe lava flow, Kona, Hawaii, USA


Pahoehoe lavas, Piton de la Fournaise, Réunion, Indian Ocean

Pahoehoe is a Hawaiian word. It was introduced into the geological terminology by the great American geologist Clarence Edward Dutton in 1883. Dutton described the pahoehoe lava thus:

"Its general character can be appreciated far better by a drawing or a photograph than by verbal description. Imagine an army of giants bring to a common dumping-ground enormous caldrons of pitch and turning them upside down, allowing the pitch to run out, some running together, some being poured over preceding discharges, and the whole being finally left to solidify. The individuality of each vessel full of pitch might be half preserved, half obliterated. The surface of the whole accumulation would be embossed and rolling, by reason of the multiplicity of the component masses, but each mass by itself would be slightly wrinkled, yet, on the whole, smooth, involving no further impediment to progress over it than the labour of going up and down the smooth-surfaced hummocks."
(Dutton, 1883, p. 95)

A pahoehoe lava field in Hawaii from Dutton 1883.

Pahoehoe lava is also sometimes called “ropy lava” in the literature. This is not very apt, because not all pahoehoe is ropy as we have just seen also in Dutton’s “type” pahoehoe. It is simply “smooth lava”.

Vesicular basalt

The other type of lava is called the "aa type" (also spelled a-a or a'a'), which is also a Hawaiian term and also introduced by Dutton in the same 1883 publication into the geological literature.

An aa type lava flow advancing on a field, Hawaii, USA

An aa-type lava field in Kula, western Turkey

An aa-type lava field in front of the Sandal tephra cone in Kula, western Turkey

The top surface of the same aa-field in Kula, western Turkey


An aa-type lava flow field at Hilea, Hawaii, USA, from Dutton 1883.

Dutton characterises the aa-type flows with the following words in the same paper:

“The second form of the lavas is called by the natives a-a, and its contrast with the pahoehoe is about the greatest imaginable. It consists mainly of clinkers sometimes detached, sometimes partially agglutinated together with a bristling array of sharp, jagged, angular fragments of a compact character projecting up through them. The aspect of one of these aa streams is repellent to the last degree, and may without exaggeration be termed horrible.”

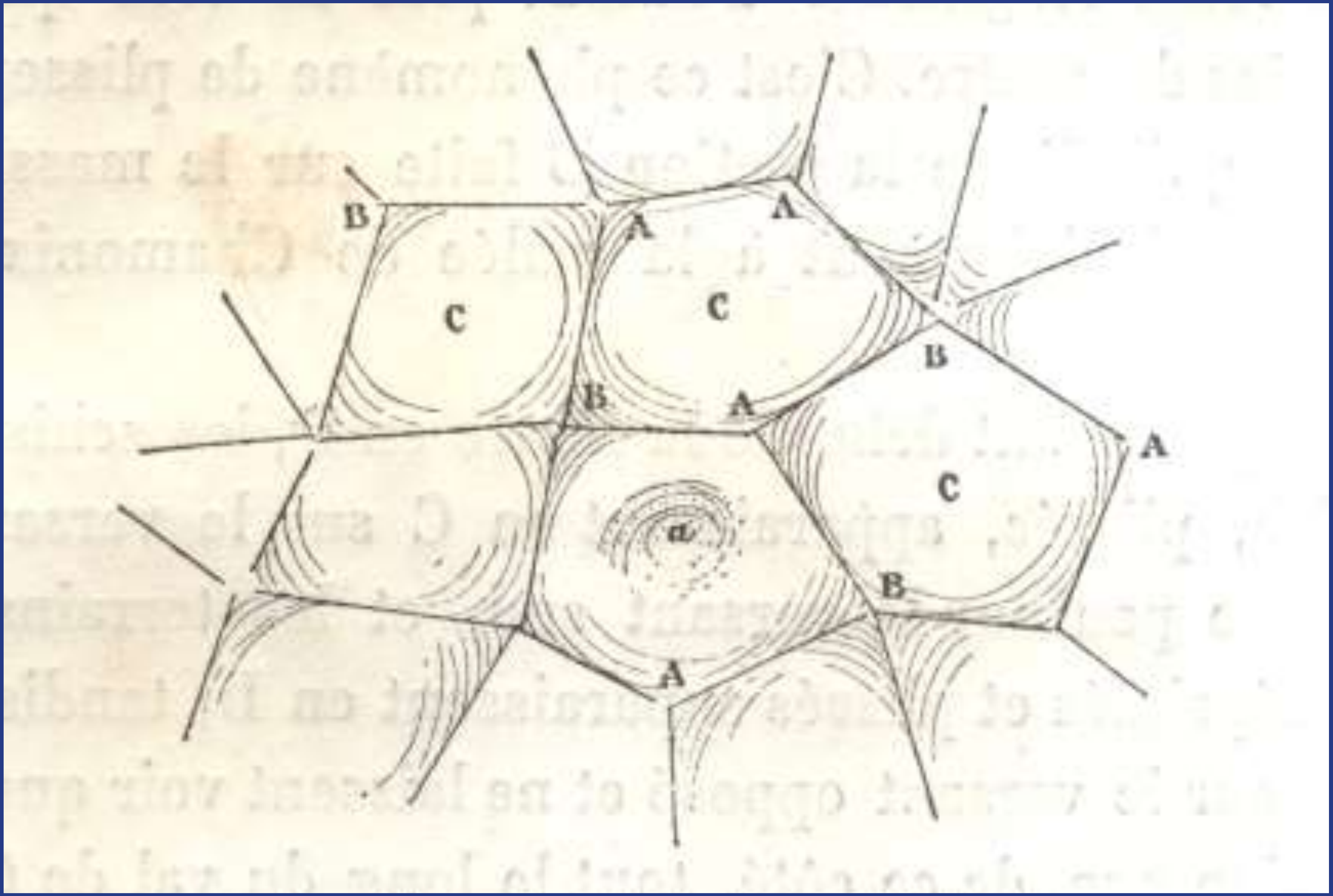
(Dutton, 1883, p. 95)

Columnar basalt

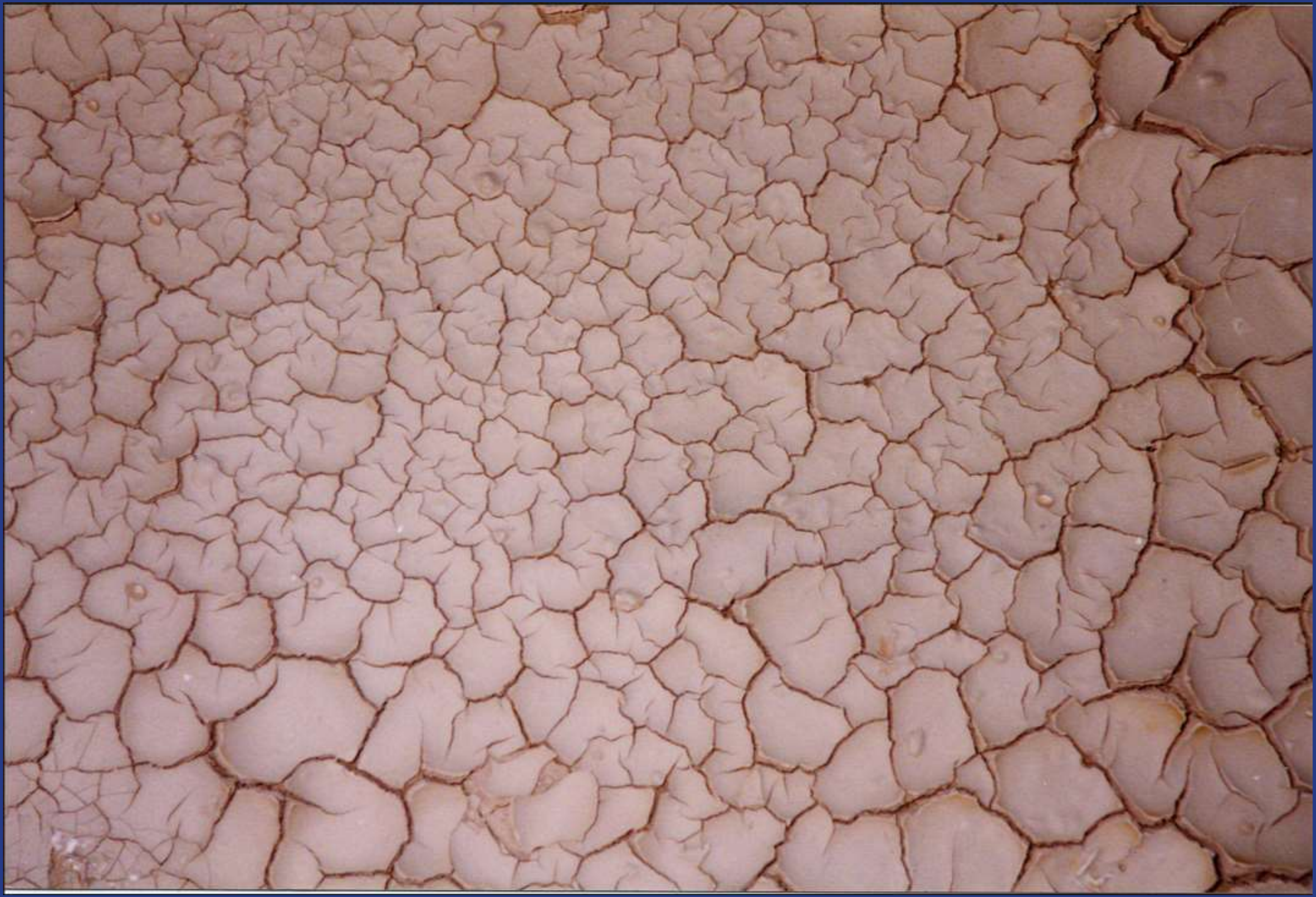
Columnar basalts, Giant's Causeway, Northern Ireland

The famous "organ", Giant's Causeway, Northern Ireland

Columnar cooling cracks in basalts, Giant’s C auseway, Northern Ireland




Contraction cracks or joints in solidifying molten rock.



Most contracting fluids generate similar cracks or contraction joints as we have just seen in basalts creating the columnar basalt exposures: these are mud cracks in a drying mud puddle in Sicily.

Pillow basalt

Pillow and “tooth-paste” basalts at the sea floor

Let us go back to the definition of basalt:

Basalt is defined as a black to dark grey, aphanitic rock consisting of some 65% of plagioclase (anorthite to labradorite), about 30% or less pyroxene and less than 10% feldspathoids. Its total silica ($SiO_2$) content fluctuates between 45 to 55%.

At this stage we need to learn three textural terms used in describing rocks, because one of them, aphanitic, we already had to use when defining basalt.

These terms are:

1. Phaneritic refers to an igneuous texture in which the individual constituent minerals can be seen by the unaided eye. It comes from the Greek φᾰνερός (*faneros*= open to sight, visible)

2. Aphanitic refers to an igneous texture in which the constituent mineral cannot be seen by the unaided eye. To study rocks with aphanitic textures one would need a microscope.

3. Porphyritic refers to an igneous texture in which there are two distinct crystal sizes. One, referred to as the matrix or the groundmass consists of smaller crystals (it may be aphanitic or phaneritic), and the other consists of larger crystal sizes called phenocrysts (always phaneritic). The term porphyritic comes from the Egyptian porphyry allegedly discovered by a Roman legionary in 18 CE Caius Cominius Leugas according to Pliny the elder. It is an andesite of violet colour. The classical quarry was rediscovered in 1823 by Sir Francis Burton and Sir John Gardner Wilkinson, the father of British Egyptology.

Let us go back to our classification on the basis of depth of origin of the igneous rocks and see how the textures correlate with them:

1. Surface igneous rocks (volcanic rocks): generally aphanitic or at best porphyritic. Only ignimbrites (welded tuffs) are in part phaneritic. Volcanic glasses are said to have a glassy texture.

2. Intermediate depth igneous rocks (subvolcanic rocks): can be porphyritic, commonly with aphanitic groundmass and pheocrysts. Often fine grained phaneritic.

3. Deep igneous rocks (plutonic rocks; the name is derived from the Roman god of the subterranean world *Pluto*, equivalent of the Greek *Hades*). Deep igneous rocks are always phaneritic. They can be porphyritic With phaneritic graundmass and also phaneritic phenocrysts.

Phaneritic texture in a granodiorite

Aphanitic texture in basalt: individual crystals cannot be seen by the unaided eye.

Examples of porphyritic textures

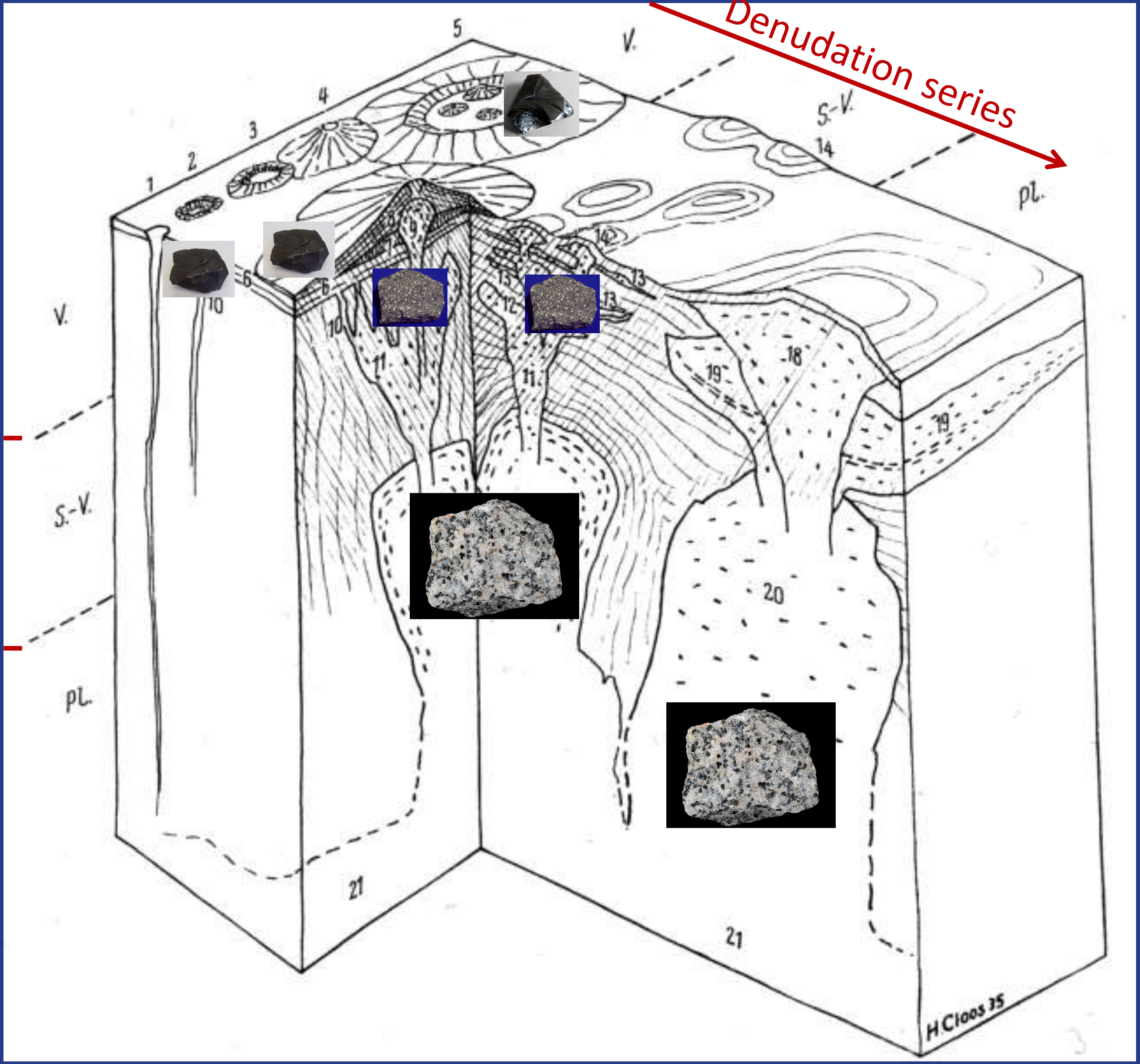
Since volcanic glasses are not crystalline, they have glassy textures (obsidian, pumice)

Obsidian displaying glassy texture.

Volcanic

Sub-volcanic

Plutonic




Distribution of the places of origin of the igneous textures

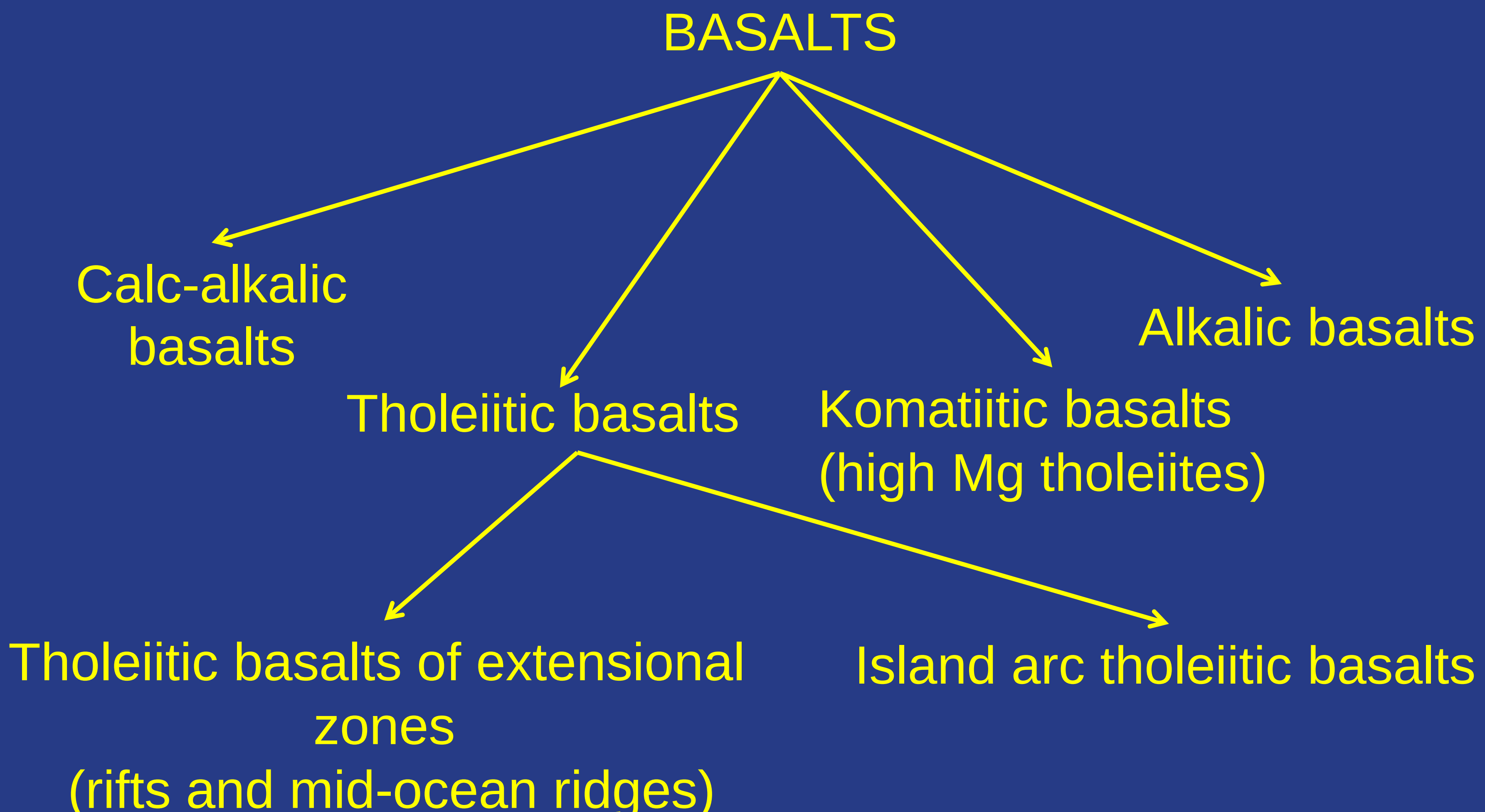
Basalts are now classified according to their chemistry. This is a new development that happened in the latter half of the twentieth century with the great developments in geochemistry made possible by the developments in technology (we can now make chemical analyses of rocks faster and more precise). Before that basalts used to be described according to their petrography using the accessory minerals they might contain.

Let us remember what basalt is:

Basalt is defined as a black to dark grey, aphanitic rock consisting of some 65% of plagioclase (anorthite to labradorite), about 30% or less pyroxene and less than 10% feldspathoids. Its total silica ($SiO_2$) content fluctuates between 45 to 55%. Let us remember that if the silica ($SiO_2$) content is below 45%, the rock is no longer a basalt, but an ultramafic rock!

Here, the main constituents are plagioclases and the pyroxenes. The accessories are the feldspathoids. Initially, the basalts were said to be ……-bearing basalt, such as olivine-bearing basalt, nepheline bearing basalt, leucite-bearing basalt, even hornblende-bearing basalt. This last one was so surprising a find that the hornblende-bearing basalt was given a special name by the famous American petrologist and geochemist Henry Stephens Washigton, "kulaite" from Kula in western Turkey, where Washington did his PhD field work (1895). The name kulaite was coined in 1900. But it is no longer used. Instead, it is suggested that one uses hornblende-bearing alkali or alkaline or alkalic basalt.

Chemically basalts are divided into four: calc-alkalic basalts, tholeiitic basalts, komatiitic basalts and alkalic basalts:



All basalts form by the partial melting of ultramafic rocks (naturally if a basalt is melted completely and let recrystallise at the rate it had originally crystallised, one would still get basalt. But this is rare in nature).

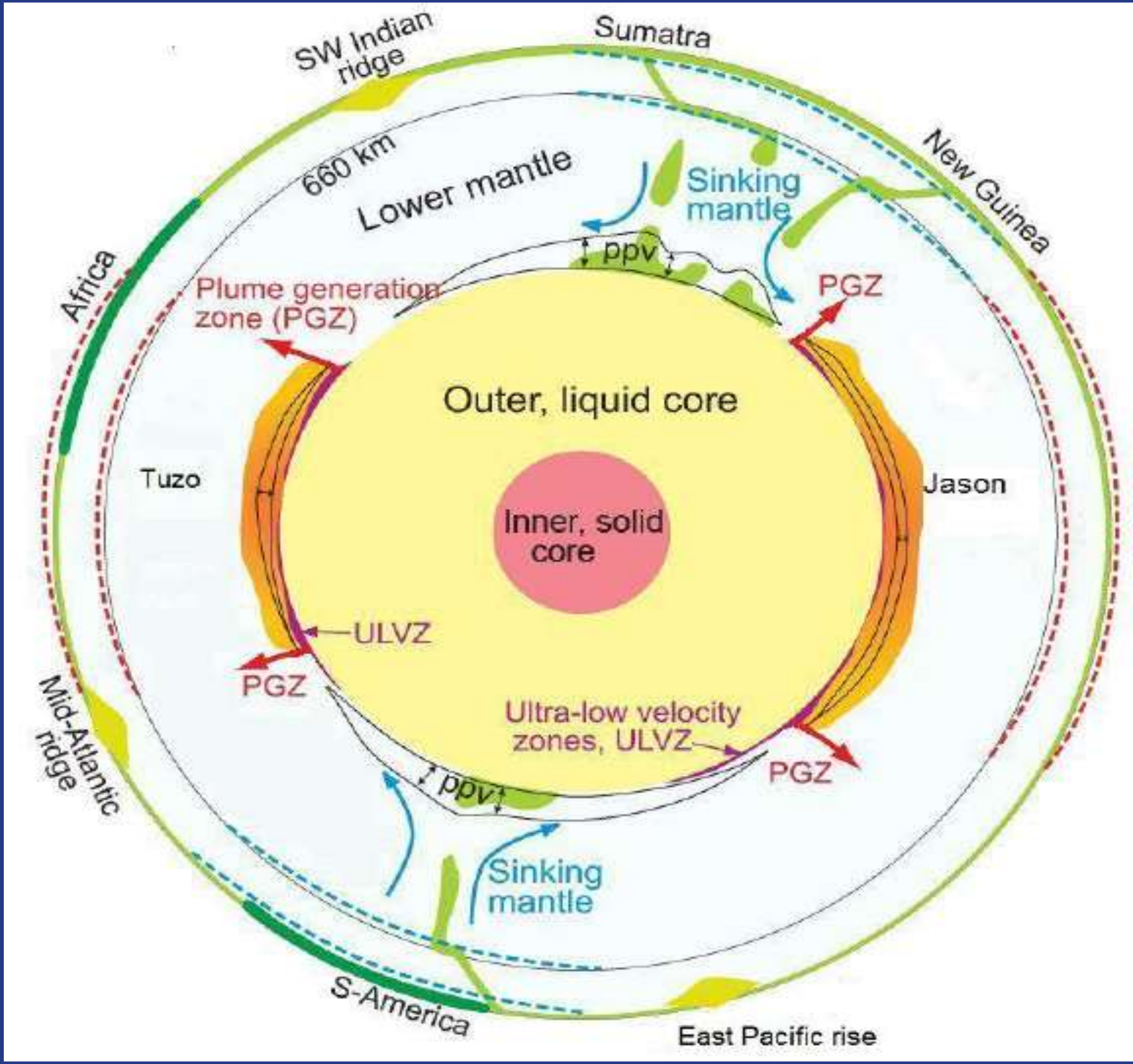
So what are ultramafic rocks?

Ultramafic rocks are the most abundant rocks in the earth as they form the totality of the earth's mantle, i.e., 84% of the earth's volume!

Consequently, basalt is the most widespread volcanic rock on earth and forms in almost all tectonic environments.

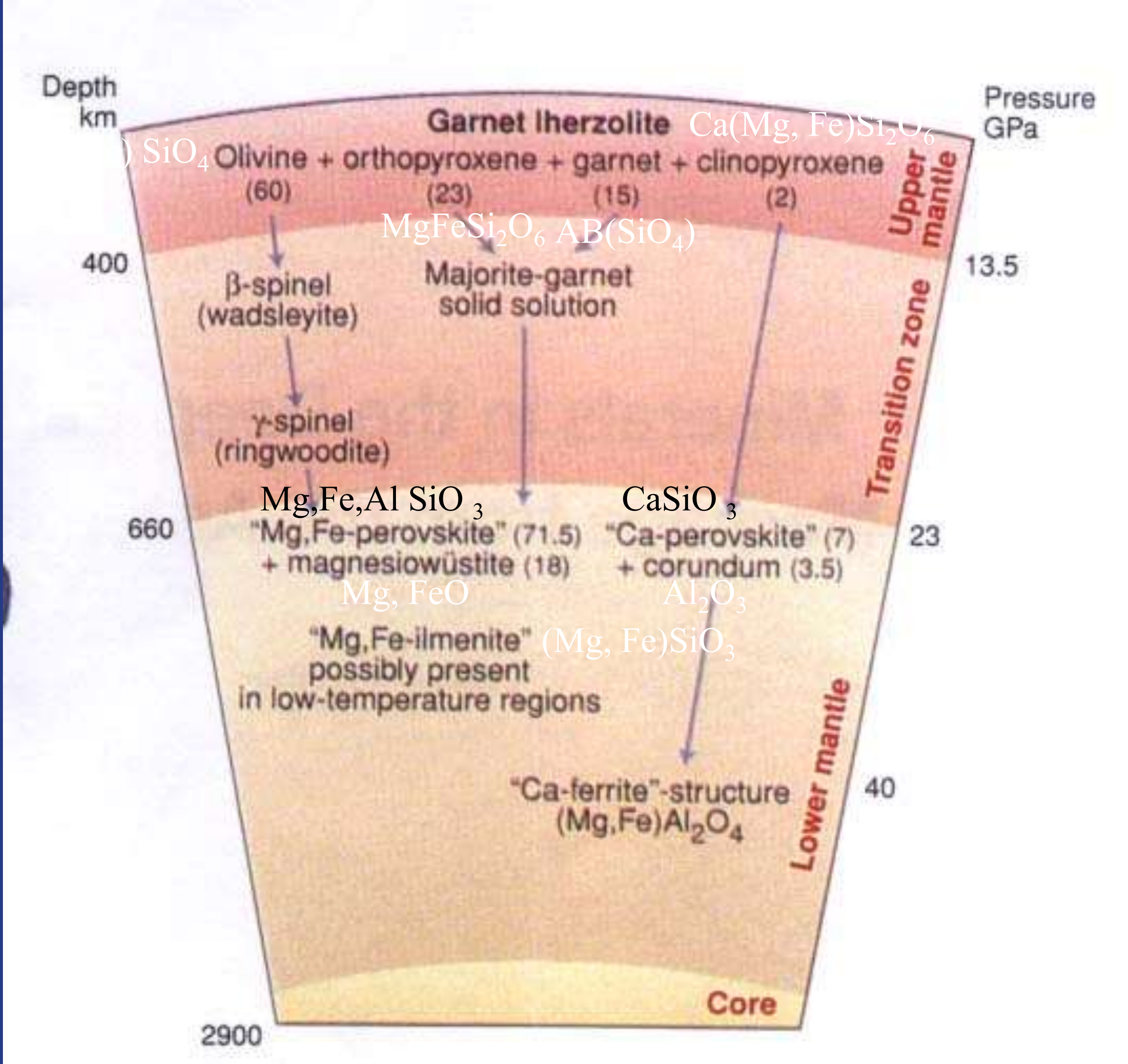
Let us first answer the question: What are ultramafic rocks?

Ultramafic (in the old literature also called ultrabasic) rocks are silicate rocks in which the amount of $SiO_2$ is less than 45% and the rest is made up of ferromagnesian minerals, i.e. minerals containing iron and magnesium.

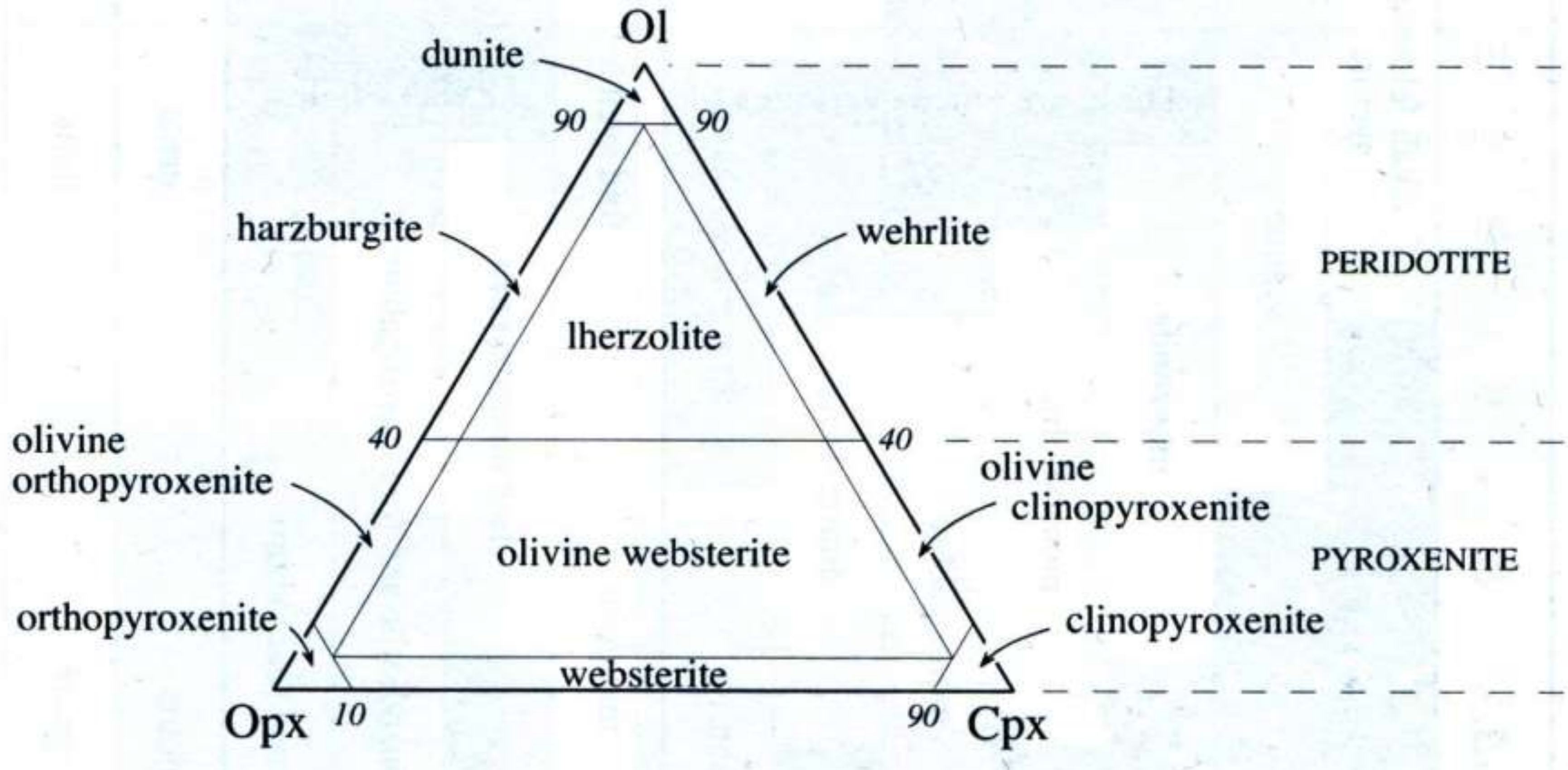



The interior of the earth

(From Kevin Burke written comm.). Everything that is left white consists of ultramafic rocks!




Proposed mantle mineralogy using the meteorite data (Stöffler, 1997)




Classification of ultramafic rocks according to their olivine and pyroxene contents. Opx is orthopyroxene, cpx is clinopyroxene.

# PERIDOTITES

The term peridotite was first introduced by the great French geologist Louis Cordier in 1842 to designate an olivine-rich basalt. Later, in 1877, the great German petrographer Harry Rosenbusch redefined it as a rock consisting mainly of olivine. In peridotites feldspars are absent and spinellids are the main accessory minerals.

The name comes from the French term for nesosilicates: *péridot*

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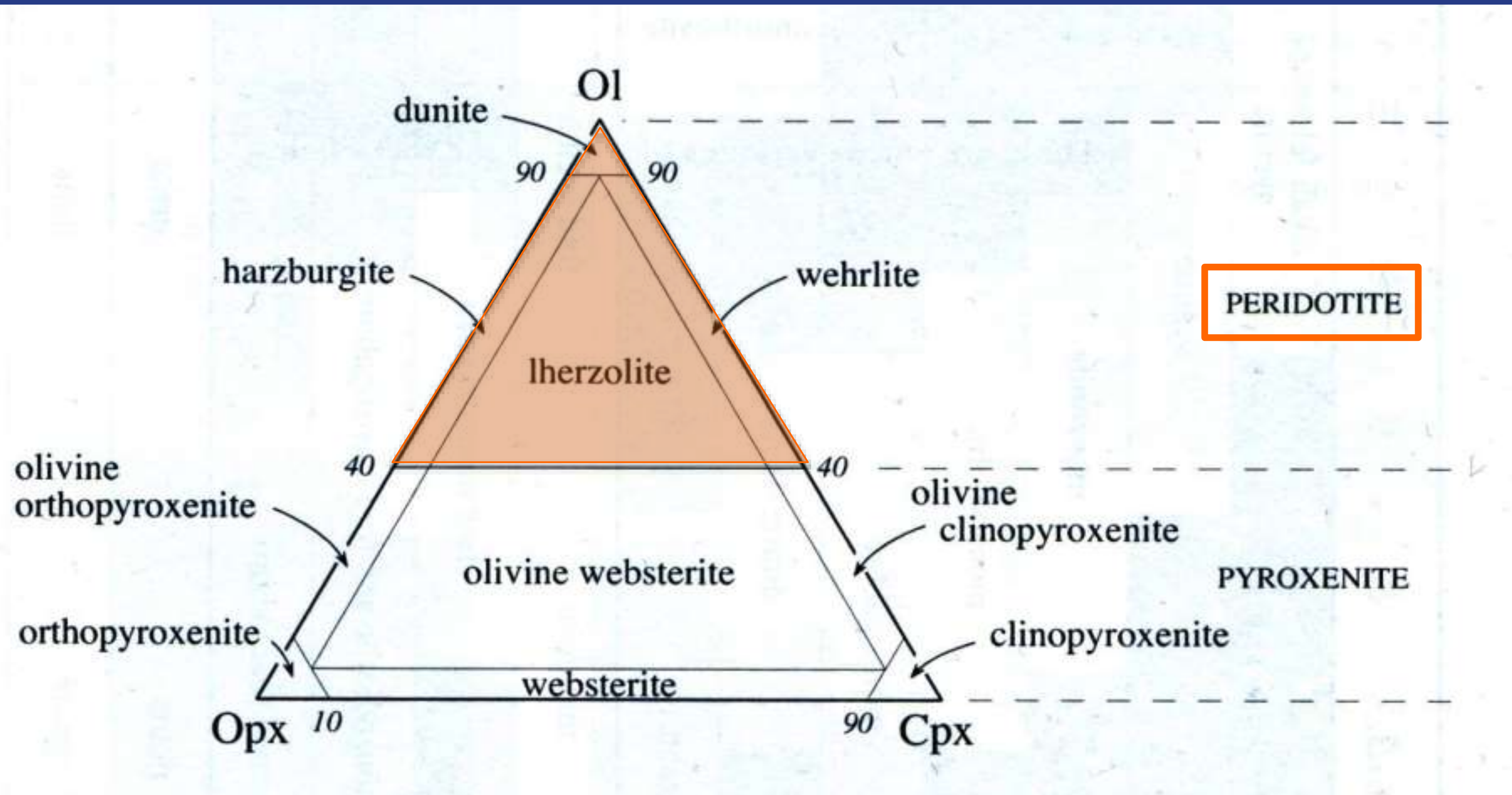
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olivine
orthopyroxenite
olivine
clinopyroxenite
olivine websterite
PYROXENITE
orthopyroxenite
clinopyroxenite
websterite
Opx
10
90
Cpx

# PERIDOTITES

Dunite

Lherzolite

Harzburgite

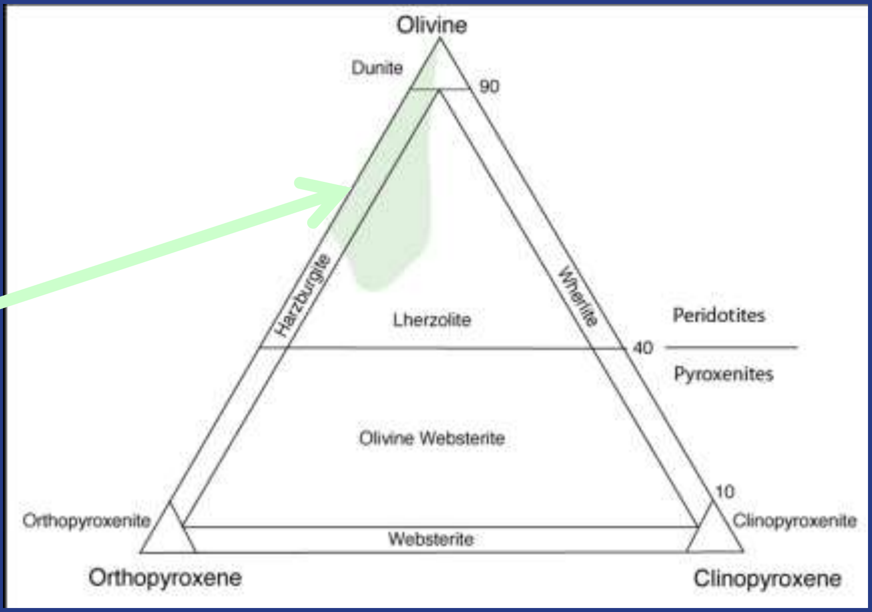
Wehrlite

Dunite: A phaneritic plutonic rock consisting of more than 90 % olivine (usually forsterite) with less than 10% of other ferromagnesian minerals such as pyroxenes, chromite, magnetite and pyrope. The rock was named by the German-Austrian geologist Ferdinand von Hochstetter in 1864 after the Dun Mountain in New Zealand. It is rarely also called olivinite, but please DO NOT USE this word as it might get confused with the rare mineral name olivenite.

An unweathered sample of dunite

Lherzolite: A phaneritic ultramafic igneous rock consisting of 40 to 90% olivine together with orthopyroxene (commonly enstatite or bronzite) and chromium rich clinopyroxene (chrome diopside or just diopside or diallage) with much lesser amouts of aluminium spinel and garnet. Calcium plagioclase can occur in lherzolites if they crystallised at 20 to 30 km depth, i.e., below rifts and thin pieces of the continental crust. When the depth is greater the aluminium phase is spinel and, when in excess of 90 km depth, it is pyrope garnet. Garnet lherzolites make up by far the largest part of the upper mantle down to about 300 km depth (maximum depth of cratonic keels).

The name is derived from the pond of Lers (or Lhers or l'Hers) in the French part of the Pyrenees and first introduced by the French naturalist Jean-Claude Delamétherie in 1795. The rock was first described in detail by Alexis Damour in the nineteenth century.




Most of the peridotites in the uppermost mantle

Spinel lherzolite from Mt. Leura, Victoria, South Australia

Harzburgite: Harzburgite is a phaneritic plutonic rock consisting of 40 to 90% olivine and 60 to 11% orthopyroxene (mainly hypersthene). The enstatite-bearing variety is called saxonite. Chromium spinel forms a main accessory mineral. There are also garnet-bearing harzburgites that are far less common and generally are encountered in kimberlite pipes.

Harzburgite is commonly a product of partial melting and extraction of clinopyronexes from the lherzolites. The thus extracted partial melts ascend to the surface and erupt as basalts or solidify in subvolcanic bodies in the form of dolerite (or diabase in American terminology).

Harzburgite was named after the locality near the Harzburg (or the Grosse Harzburg) in the northwestern edge of the Harz Mountains, Germany, by Harry Rosenbusch in 1887).

Harzburgite from Madagascar

Harzburgite from the Stillwater layered intrusion, Montana, USA (photo by Michael P. Klimetz)

Wehrlite: Wehrlite is a phaneritic plutonic rock consisiting of 40-90% olivine and 60 to 10% clinopyroxene although some little orthopyroxene may still be present. As accessories it may have ilmenite, chromite, magnetite and some aluminium phase that may be a spinel, plagioclase or garnet. Wehrlite usually occurs in cumulate phases in layered intrusions and ophiolites, as xenoliths and also has been reported from some meteorites. Wehrlite was named after the chemist Alois Wehrle by the German mineralogist Wolfgang Franz von Kobell in 1838.

Wehrlite from Norway: green: diopside, orange: olivine, pink: garnet.

How to partially melt lherzolites to make basalt?

There are three ways to melt a rock:

1. Raise the temperature

2. Drop the pressure (decompression melting)

3. Increase volatiles (usually water) in the rock (hydrous melting)

All of these things usually happen at tectonically active zones, i.e. either at plate boundaries or atop mantle plumes.

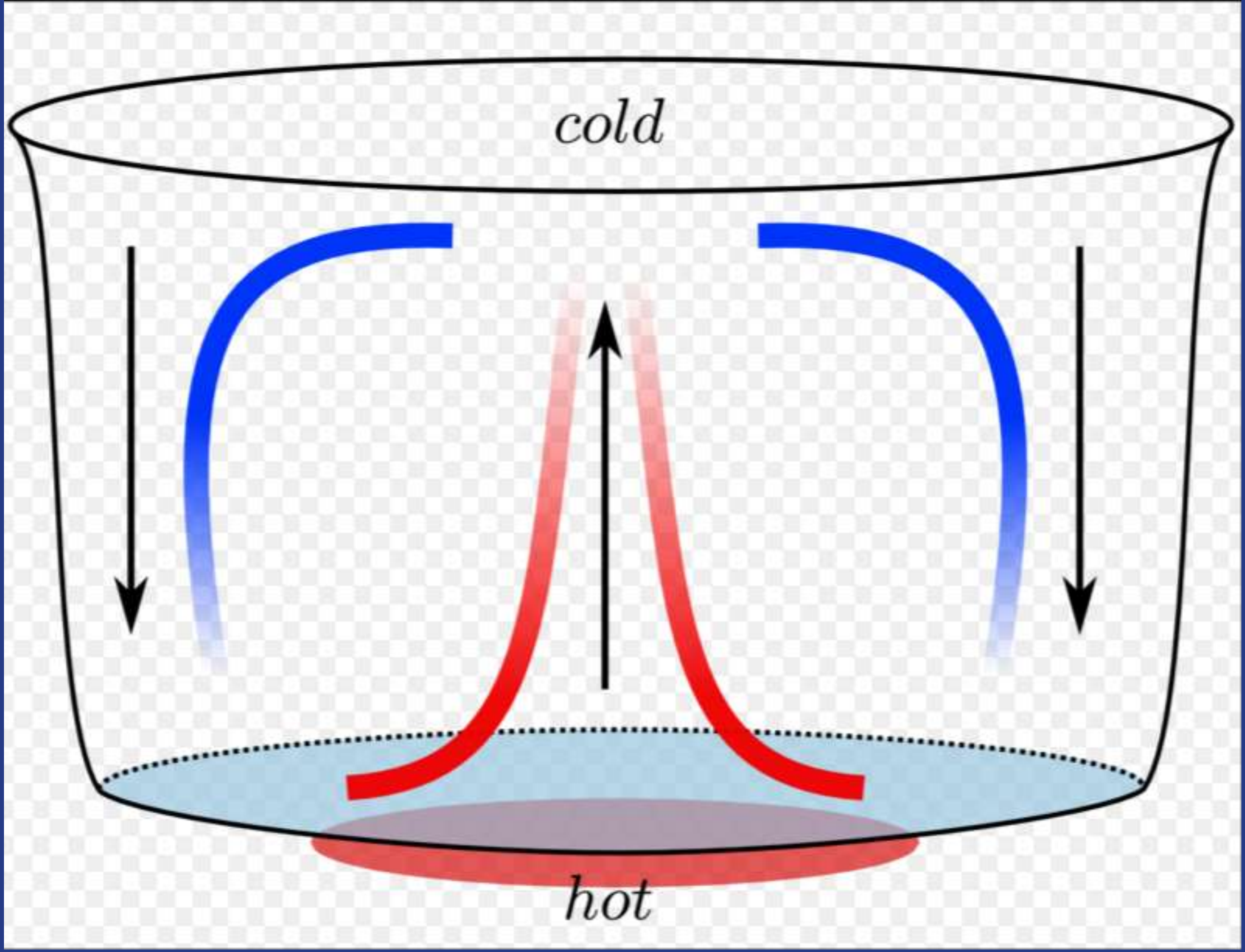
For active volcanism to exist, there must be active tectonism.

Tectonism is the deformation of the earth’s lithosphere.

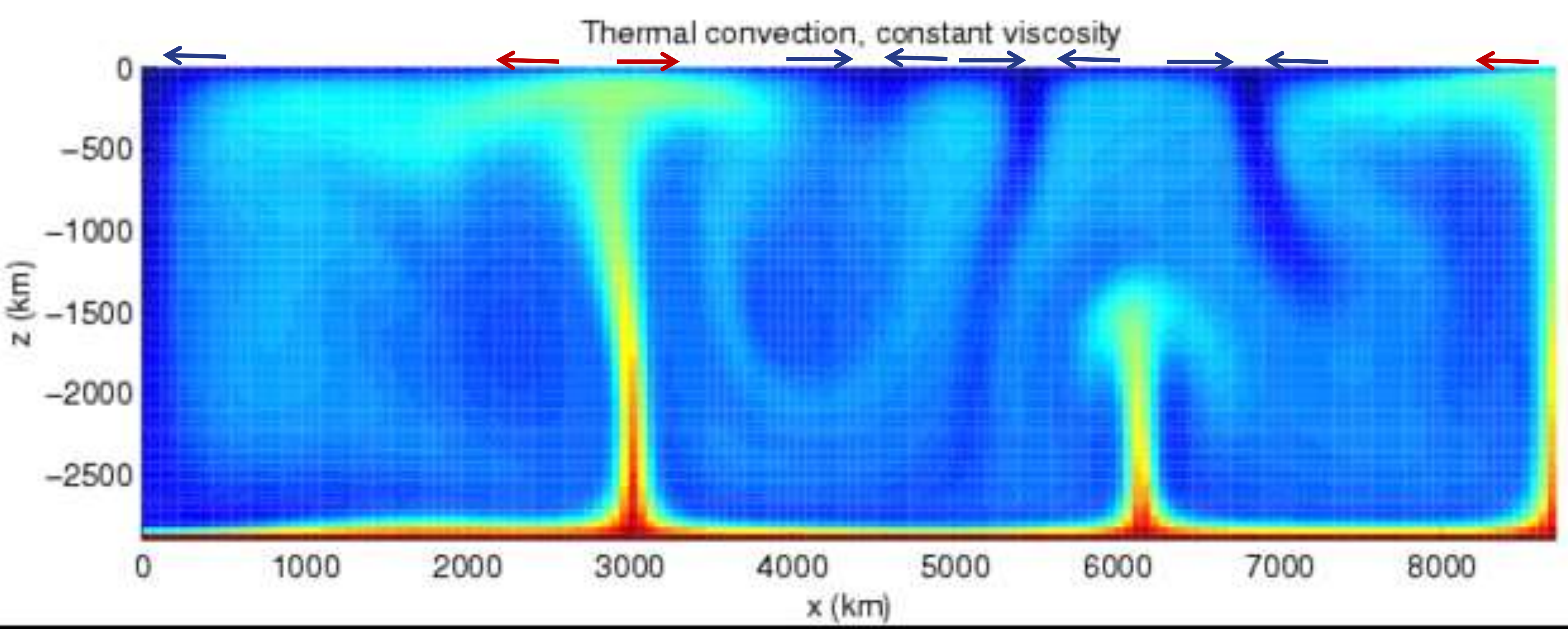
Tectonism makes mountains, rift valleys, oceans, big strike-slip faults etc.

There is tectonism on earth, because the earth is losing heat. Heat is lost through three mechanisms:

1. Radiation
2. Conduction
3. Convection
4. Of these, the most efficient in non-incandescent bodies is convection

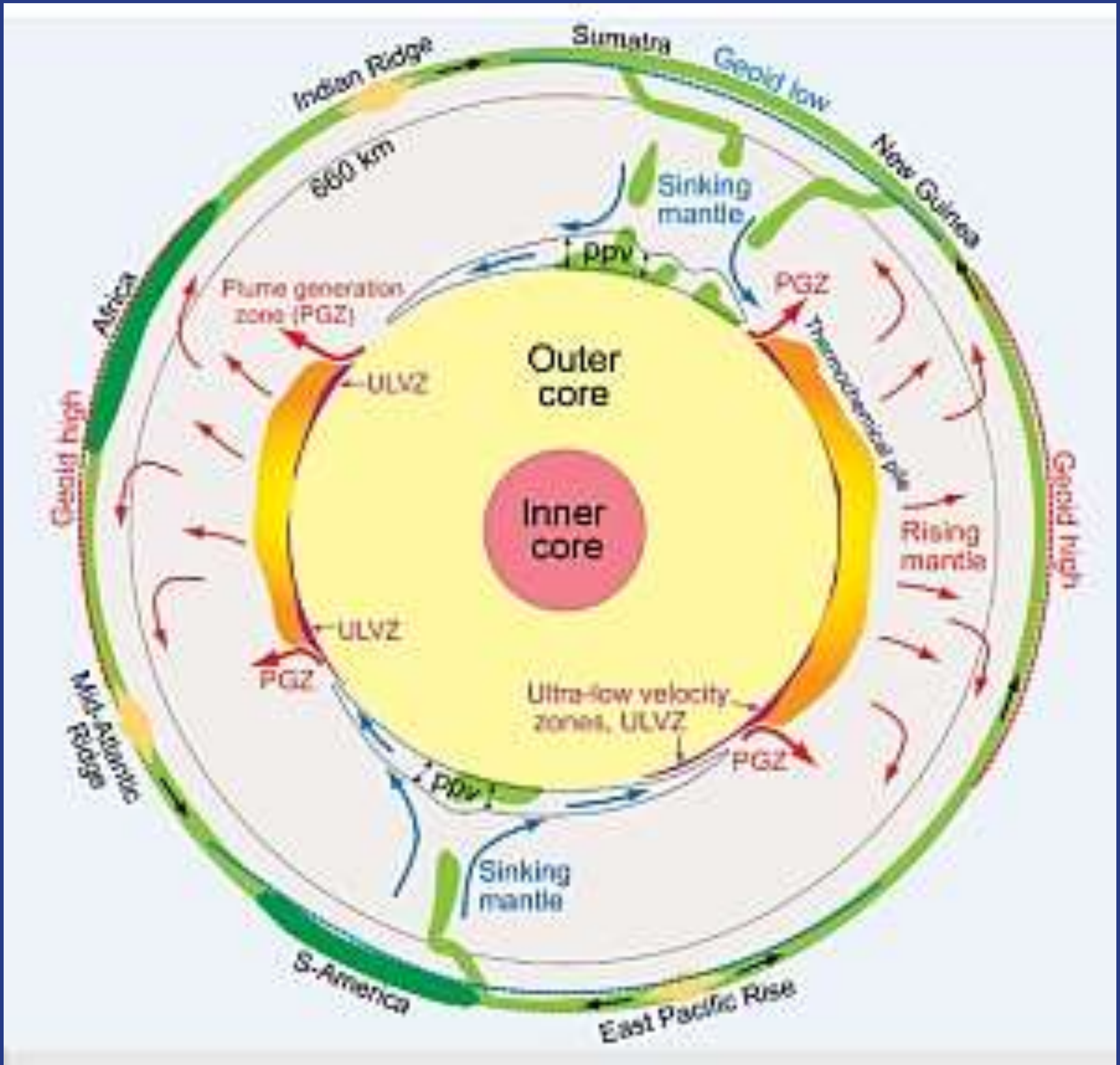



Convection in a cup of water heated from below

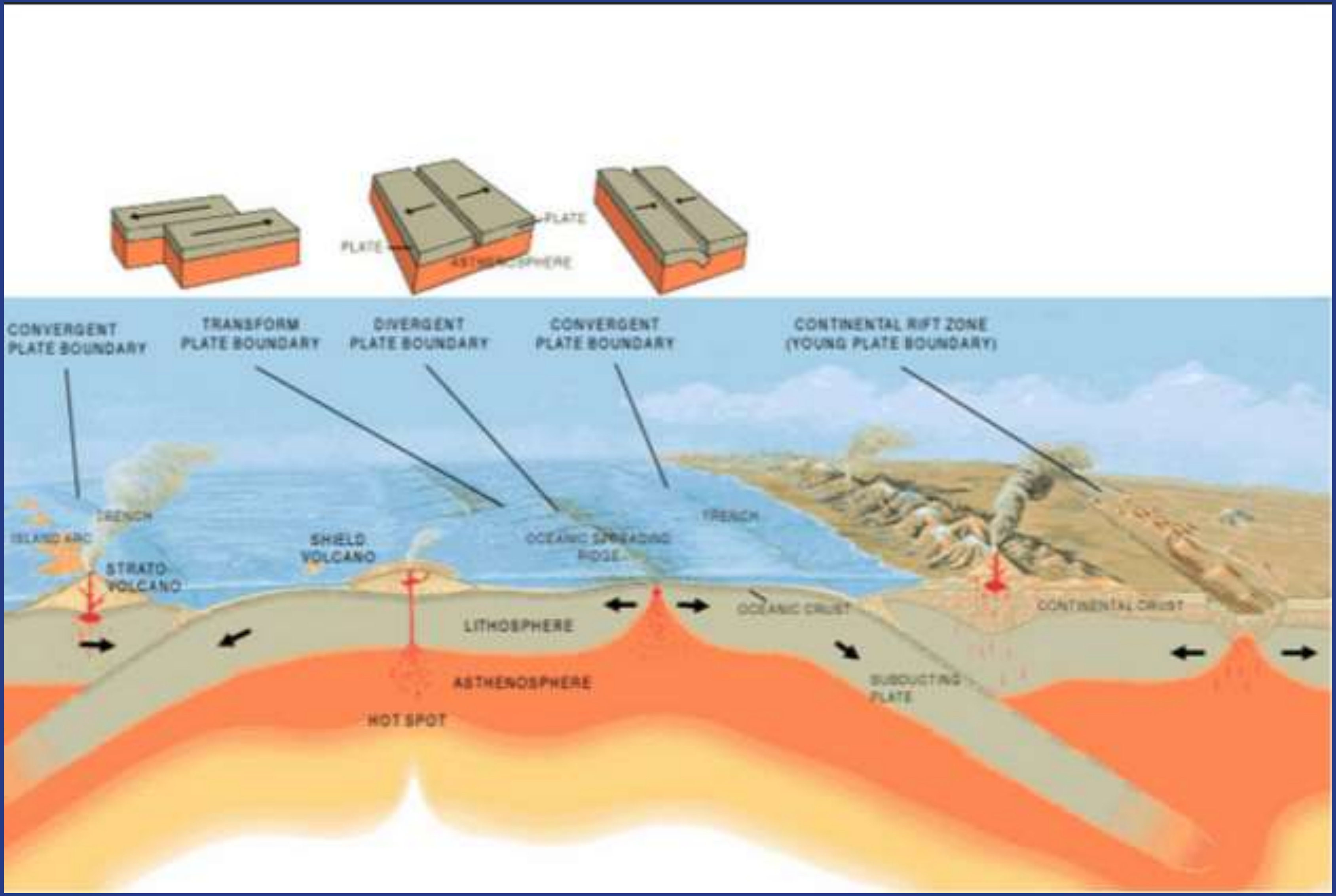



A model of convection in the earth

One consequence of convection in earth is the presence of zones of divergence and zones of convergence on its surface.

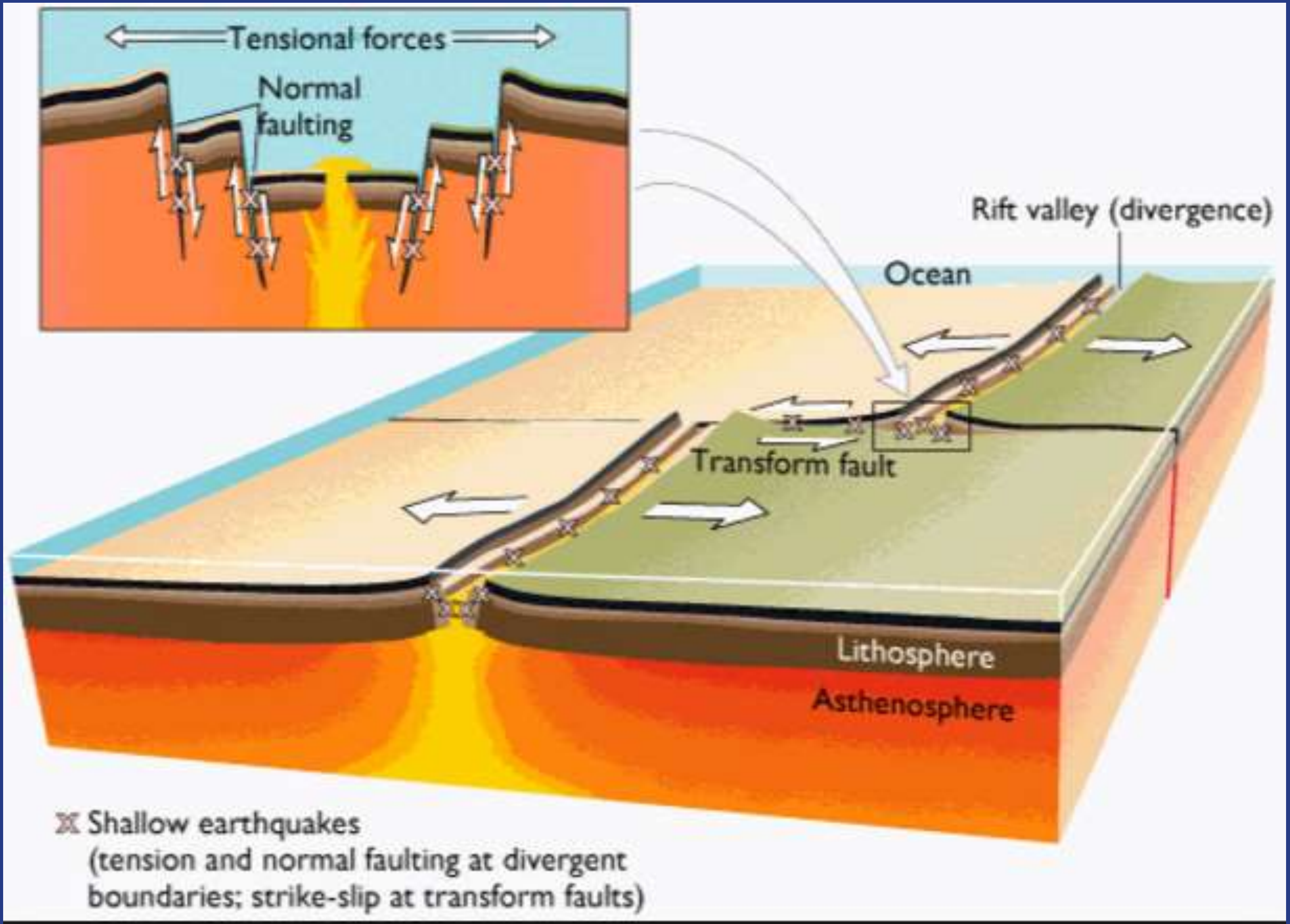



A very simplified diagram showing convection on earth

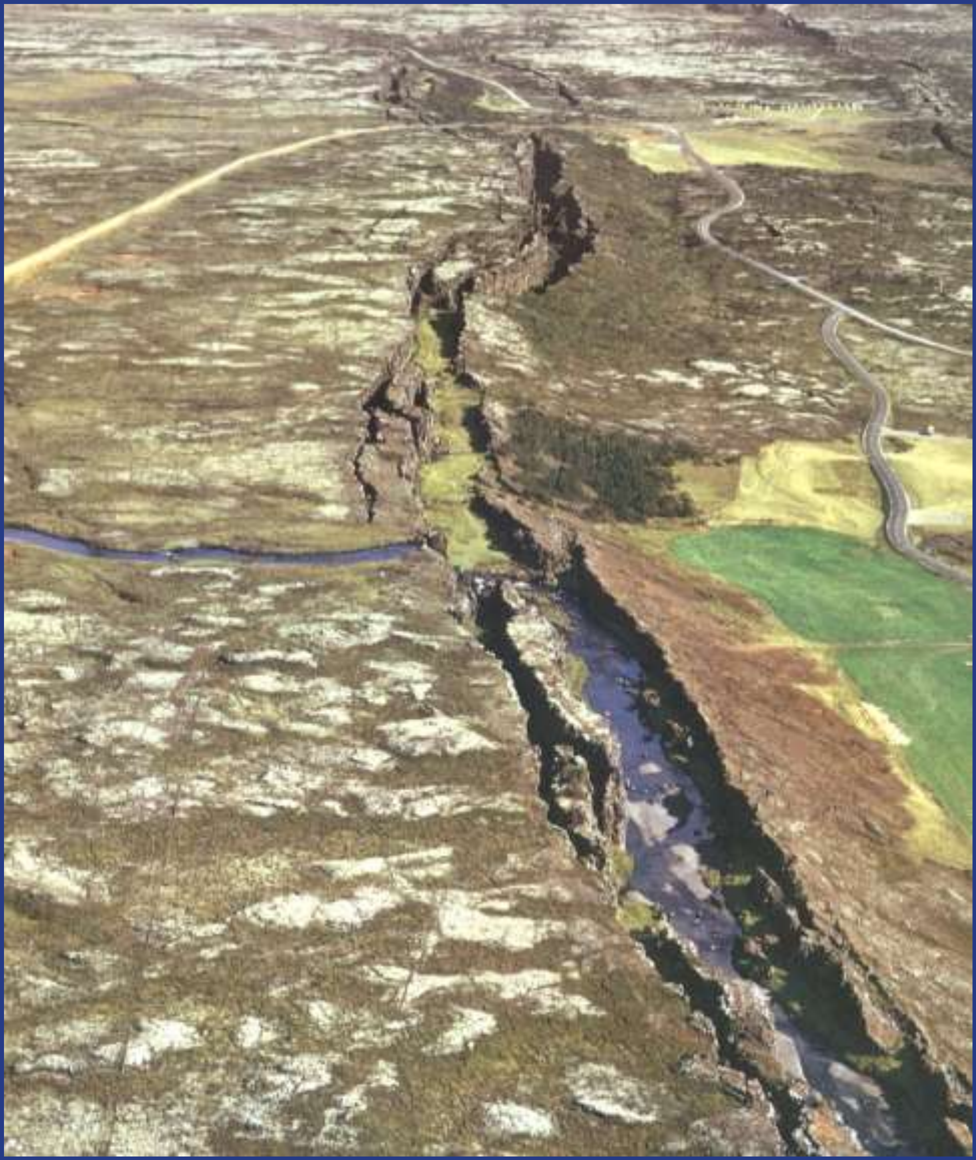



Zones of divergence and zones of convergence on earth. We here concentrate on zones of divergence in the oceans, where tholeiitic basalts are made by partially melting lherzolite through decompression melting.

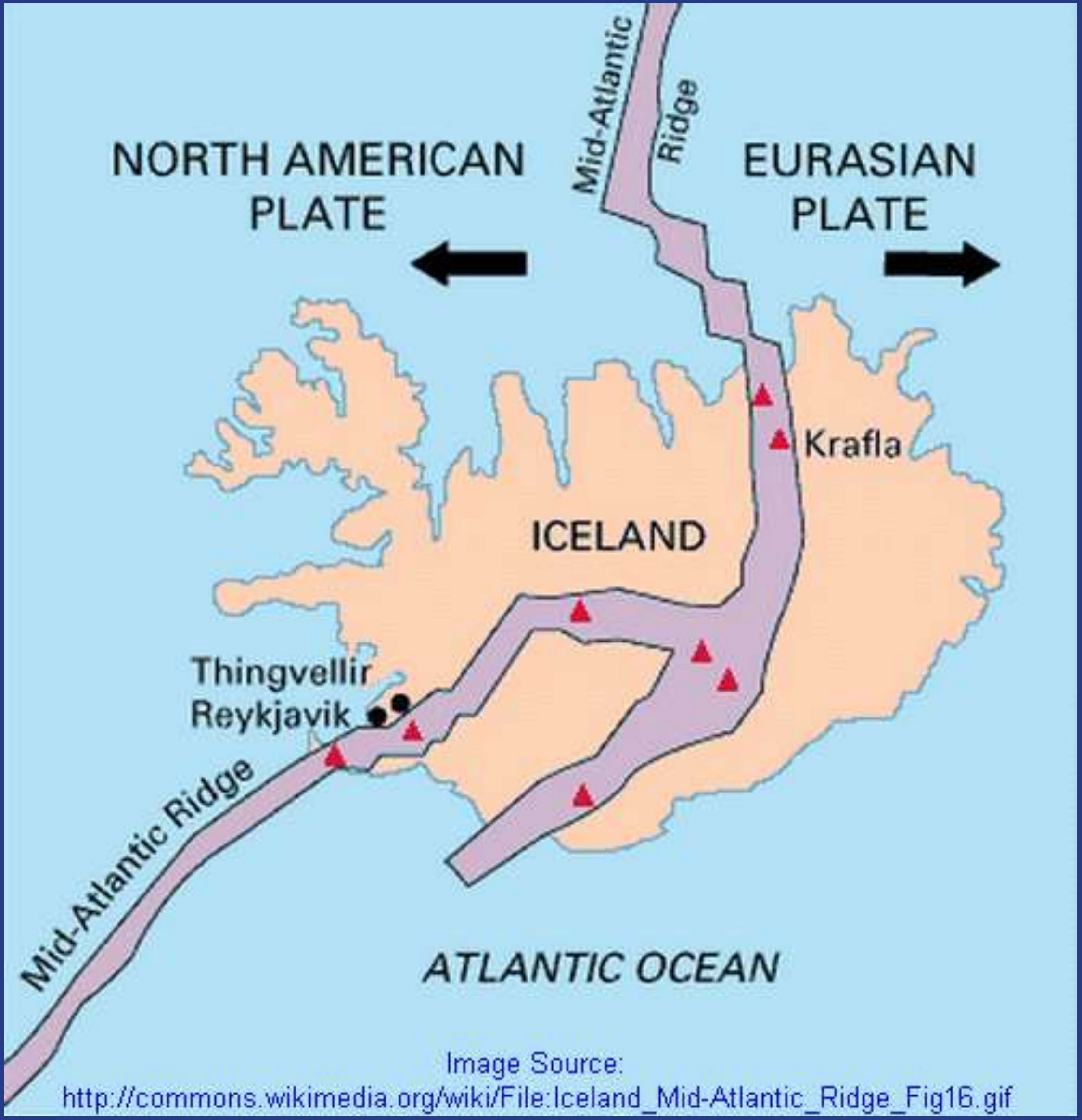
The mid-ocean ridge system of the earth (in deep blue) today



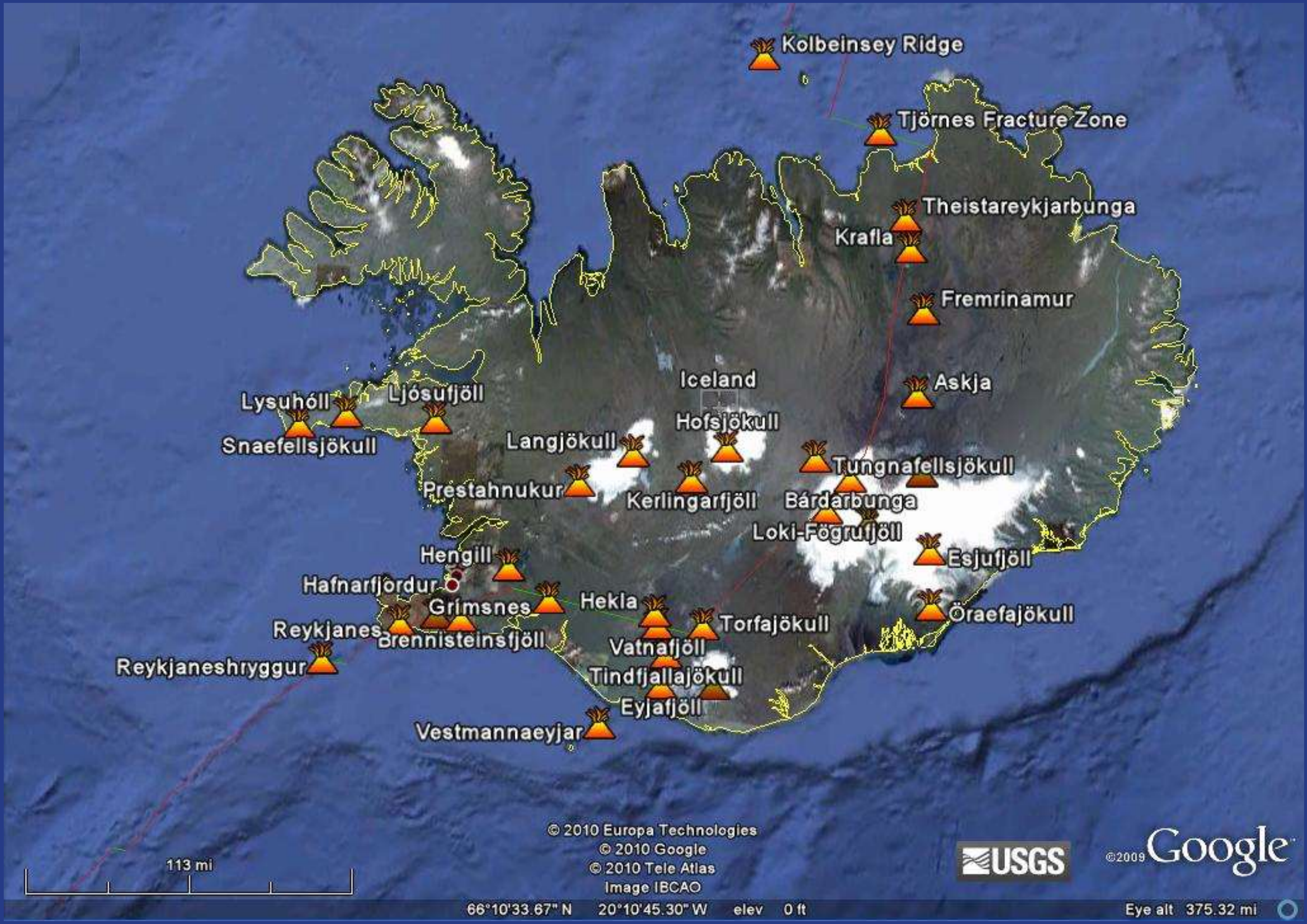

Very schematic diagrams showing how mid-ocean ridges function



The Mid-Atlantic Ridge in Iceland

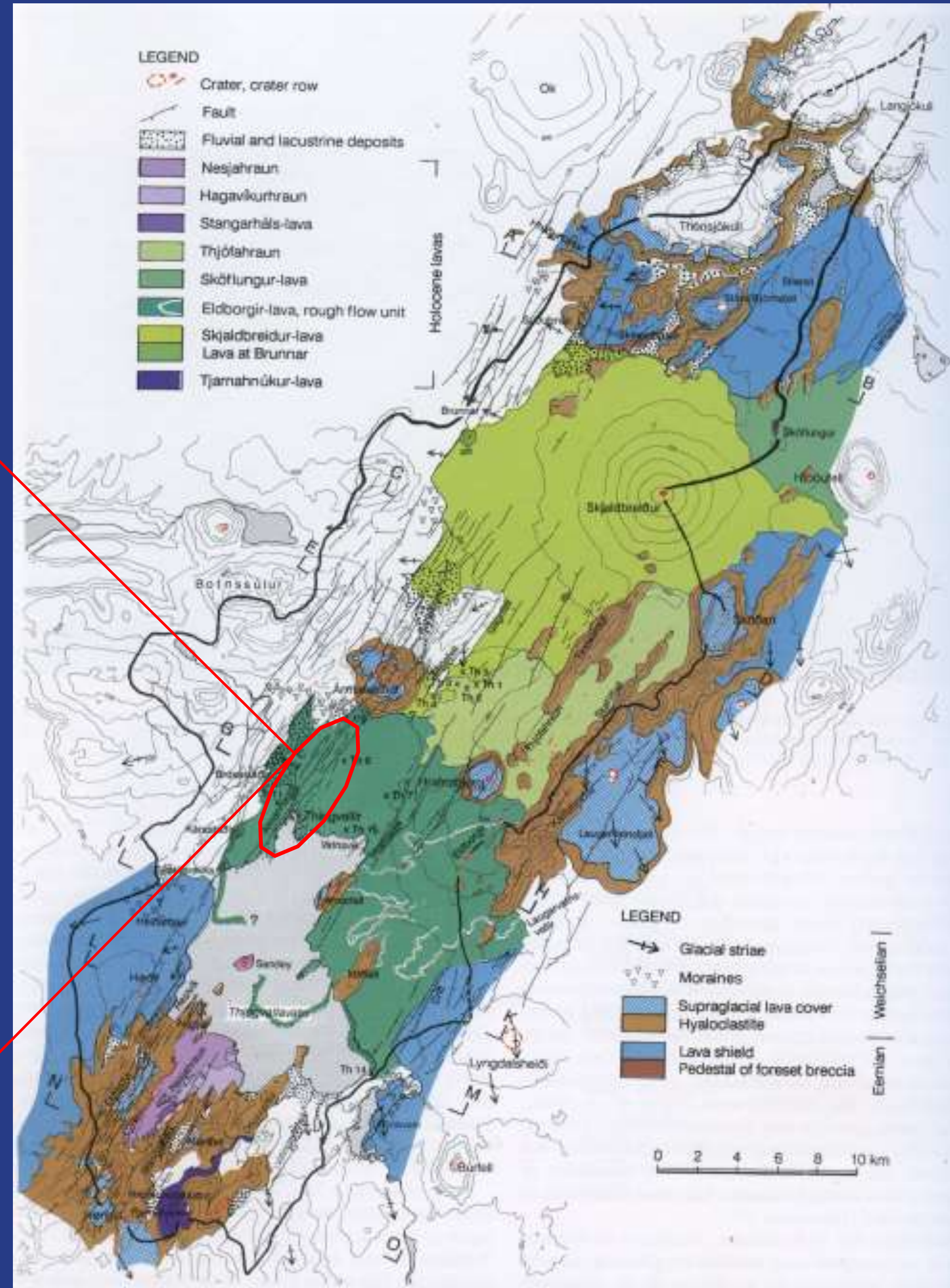



The Icelandic rift valleys form a part of the Atlantic mid-oceanic spreading centre

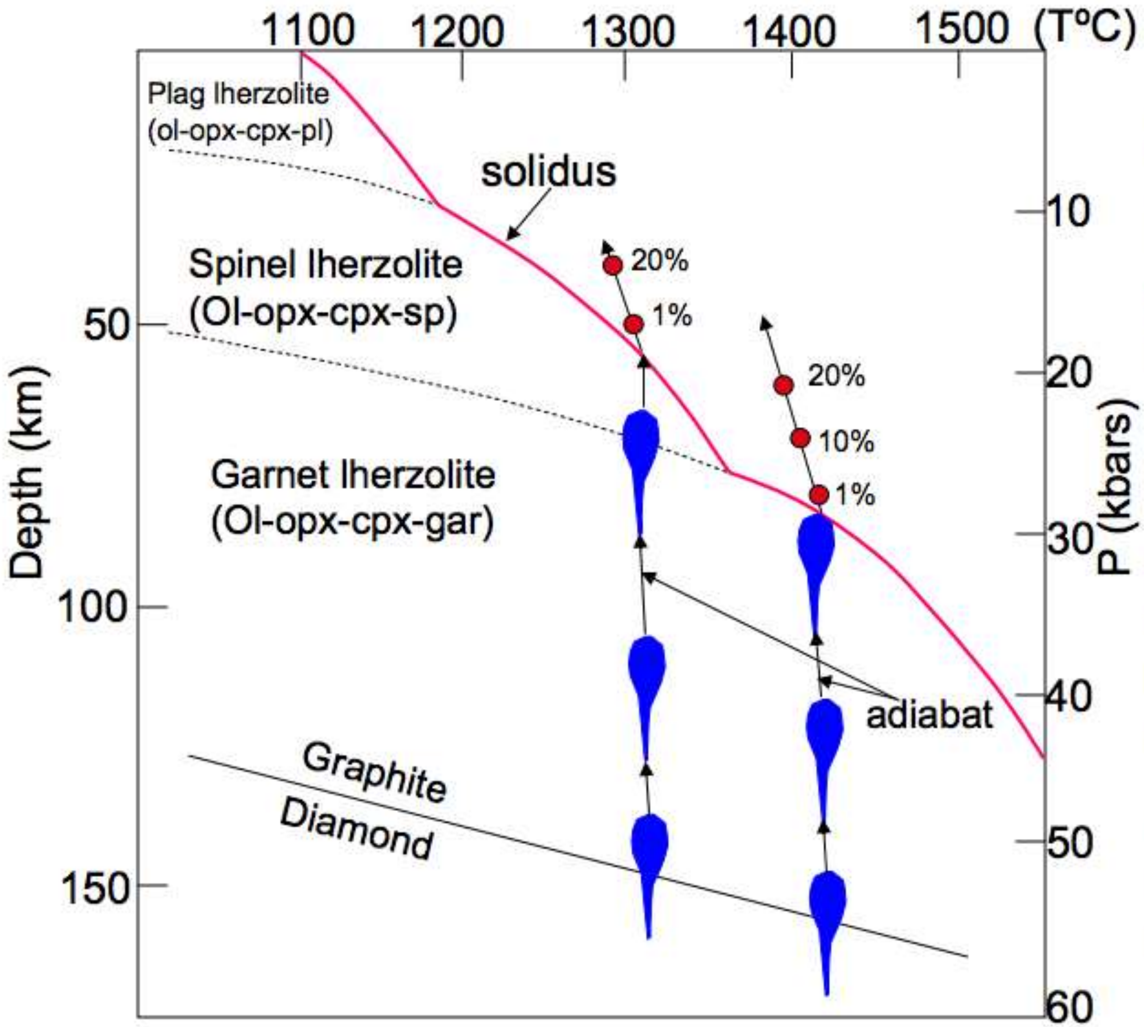



Volcanoes on Iceland plotted on a space imagery mosaic by the USGS

# The Allmannagjá
(view to the S)



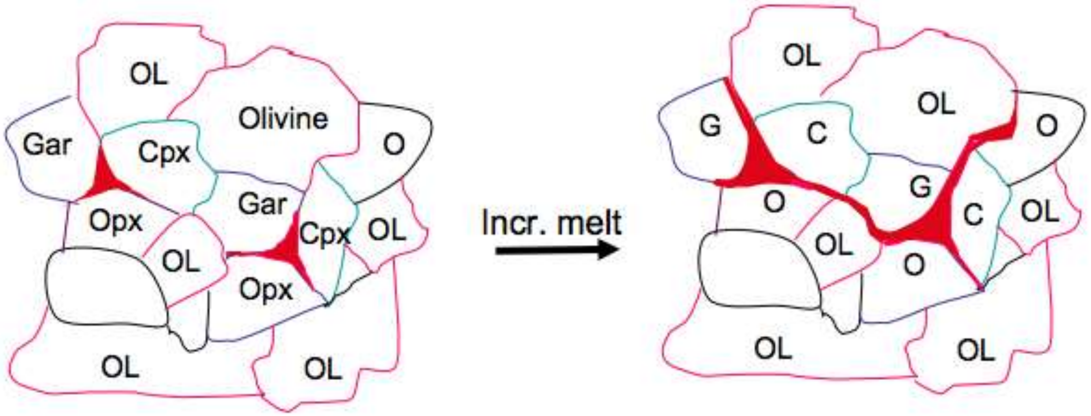
# Partial melting of mantle peridotite




**Melting** begins when upwelling mantle intersects the peridotite solidus. With decreasing pressure above the solidus, extent of melting increases. The amount of melting is limited by the heat available since the heat of fusion is large. Extent of melting can vary from ~1% to ~20%. The T, P and % melting determine the composition of the basaltic magma produced.

From http://courses.washington.edu/ess439/ESS%20439%20Lecture%204%20slides.pdf

# How does melting occur in the mantle?




Melting of garnet lherzolite begins at **cpx-cpx-garnet** triple junctions in response to a reduction in pressure. Olivine is not involved in melting at early stages.

As the extent of melting increases, melt migrates along grain boundaries forming an inter-connected network that allows the melt to segregate from the unmelted crystal residue.

**Composition of melt** depends on the P and T (which controls the extent of melting) and the phases involved in the melting. Suppose that ~1/3 (opx) + ~1/3 (cpx) + ~1/3 (garnet) were melting. Opx and cpx contain ~54% $SiO_2$ and garnet contains ~ 42% $SiO_2$. The melt would contain [1/3(54) +1/3(54) + 1/3(42)]% $SiO_2$, i.e., ~ 50% $SiO_2$. In other words, magmas formed by mantle melting will contain ~50% $SiO_2$ **(basalt)**.

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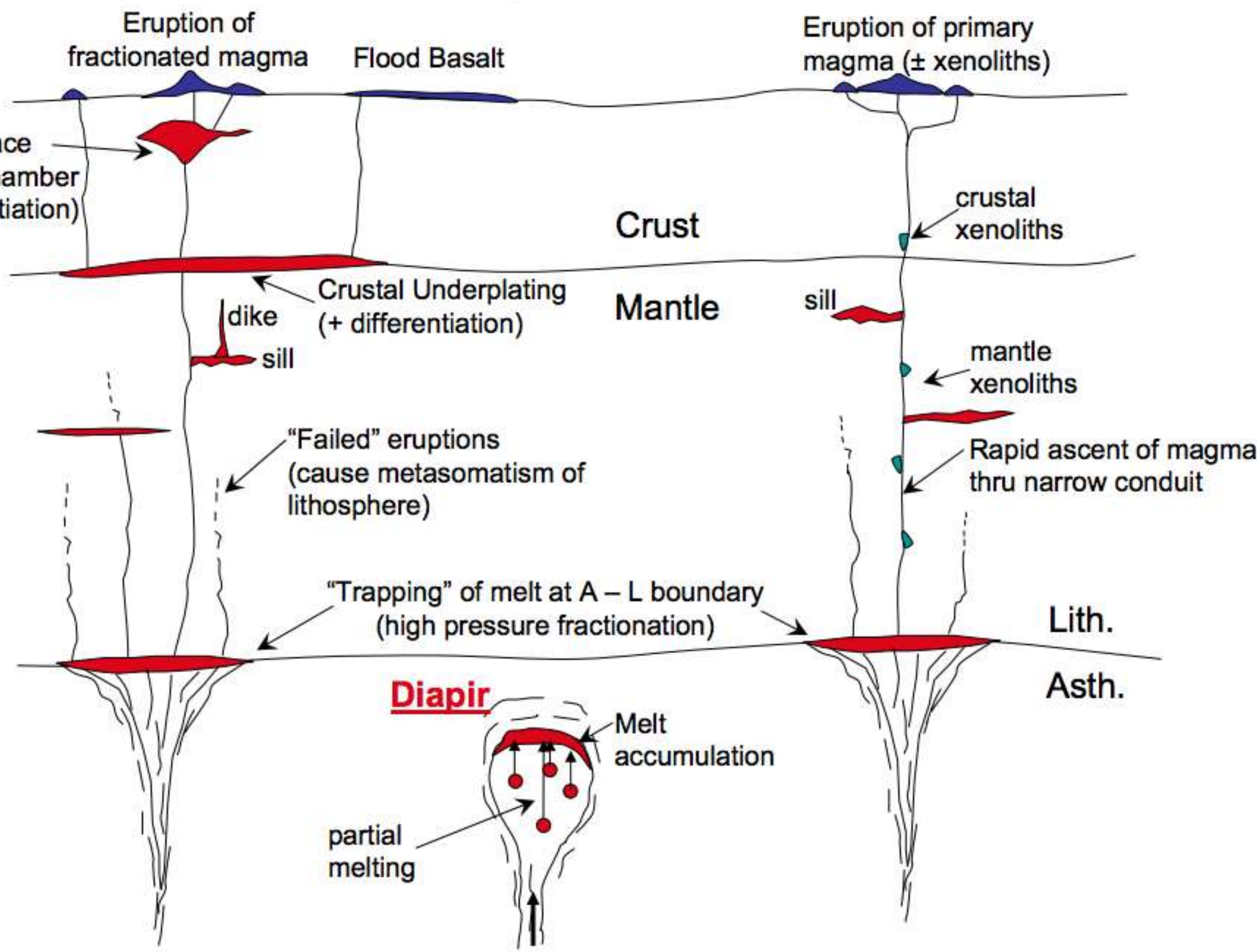
# Schematic view of some processes in basalt formation

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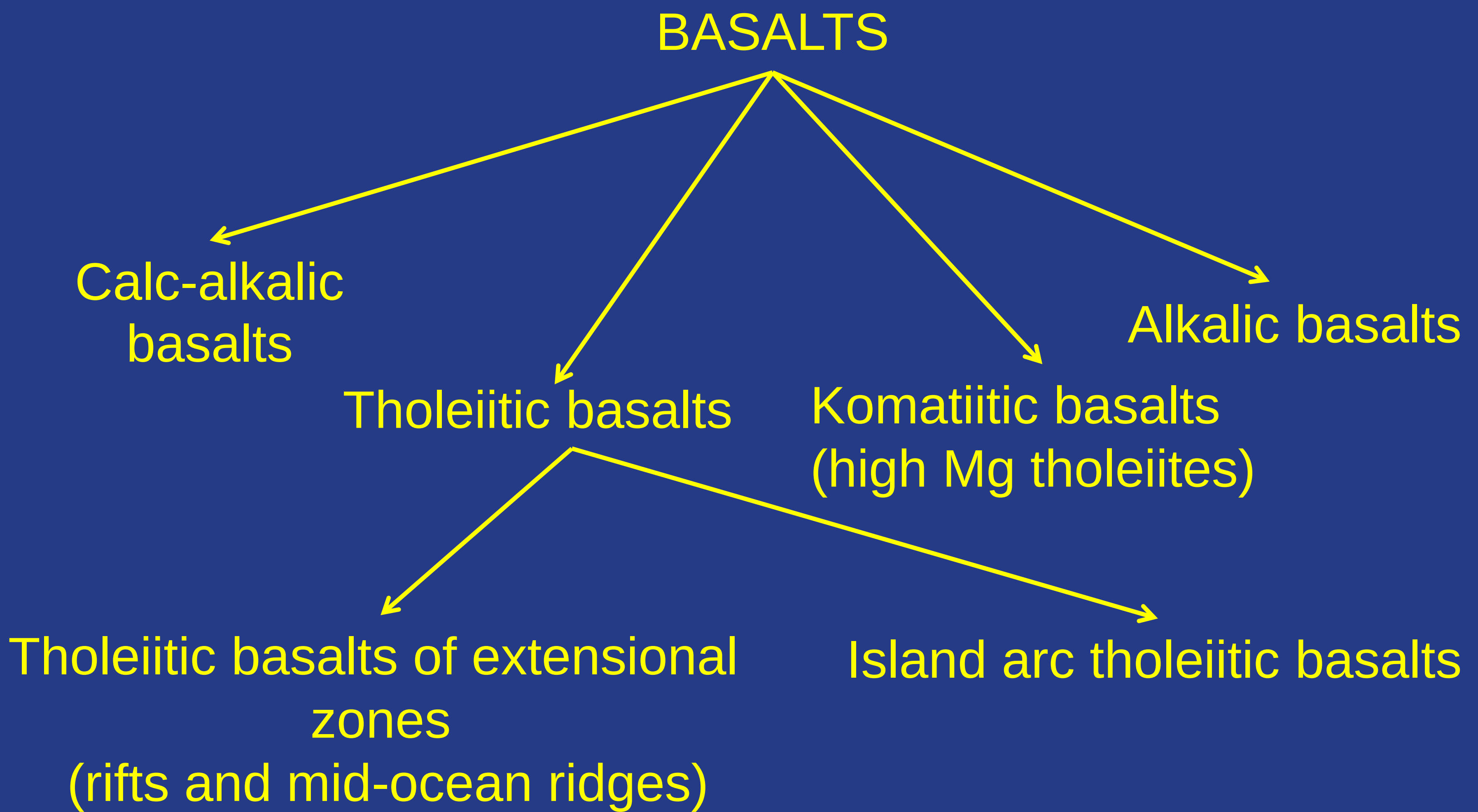
Let us now look at the kinds of basalts we mentioned earlier:

Chemically basalts are divided into three: calc-alkalic basalts, tholeiitic basalts, komatiitic basalts and alkalic basalts:



We can rephrase the earlier diagram by saying that basalts are divided into two main classes:

1. Sub-alkalic basalts (calc-aalkalic, tholeiitic and high Mg-tholeiitic basalts)

and

2. Alkalic basalts.

The subalkalic basalts are divided into two: tholeiitic and calc-alkalic magmas. Tholeiites are those that are formed from reduced magmas. As a reduced magma begins crystallising Mg-rich and Fe-poor minerals (forsterite, Mg-pyroxenes), the Fe in the remaining melt begins to increase. Finally as all Mg is used up, the magma begins precipitating alkalis, but by that time it has already almost completely solidified creating a tholeiitic basalt.

By contrast, the calc-alkalic magmas are oxidised. They can oxidise iron and precipitate magnetite and the magma never has a chance to get enriched in iron.

The question now becomes: what can oxidise a magma?

What is oxidation?

Oxidation is loss of electons or an increase in oxidation state by a molecule or an atom.

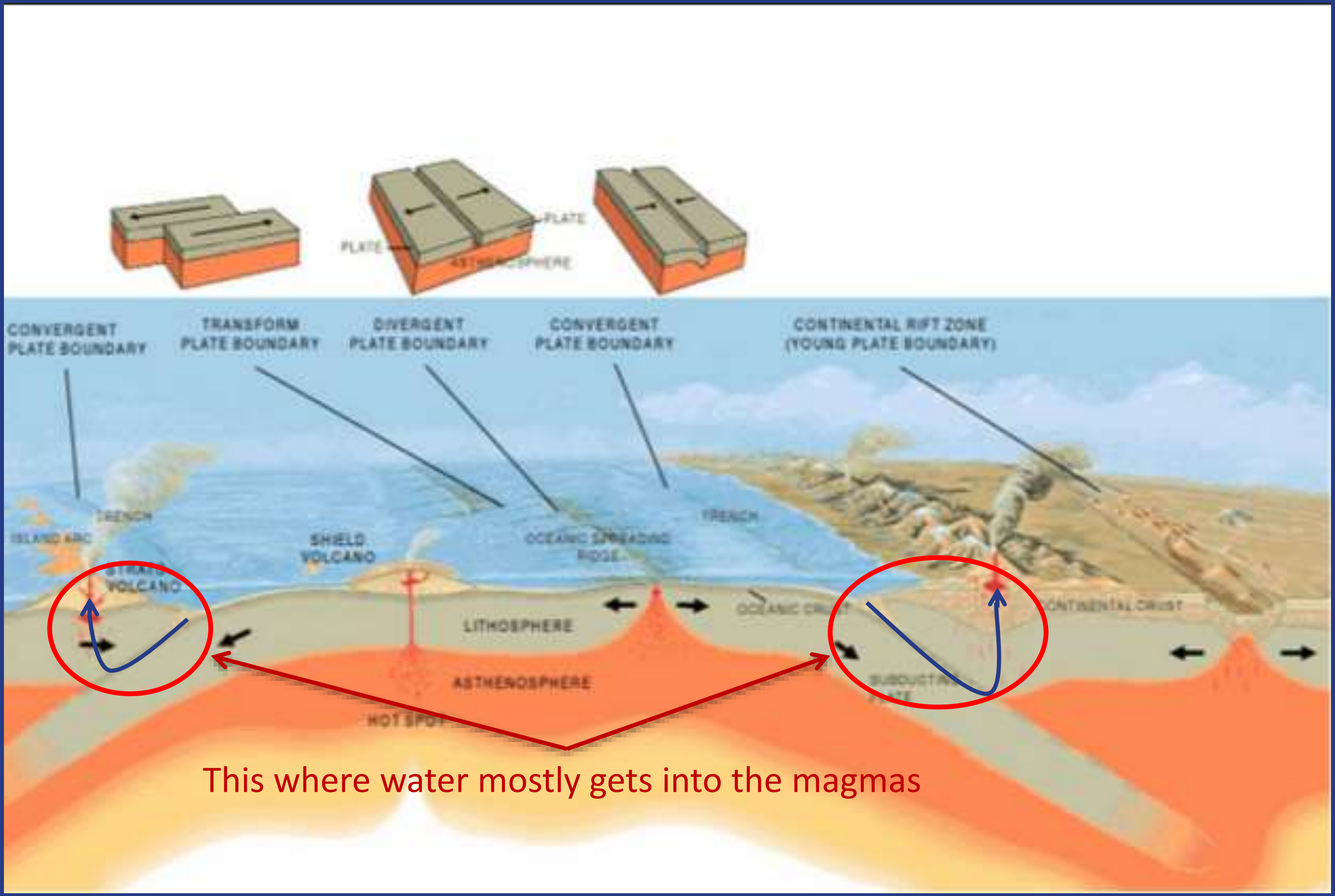
Reduction is gain of electrons or a decrease in oxidation state of an atom or a molecule.

Therefore oxidising agents steal electrons from other atoms and molecules and oxidise them, while reducing themselves.

Oxidising agents are known as oxidants or oxidisers. The oxidants are elements or molecules with high oxidation states:

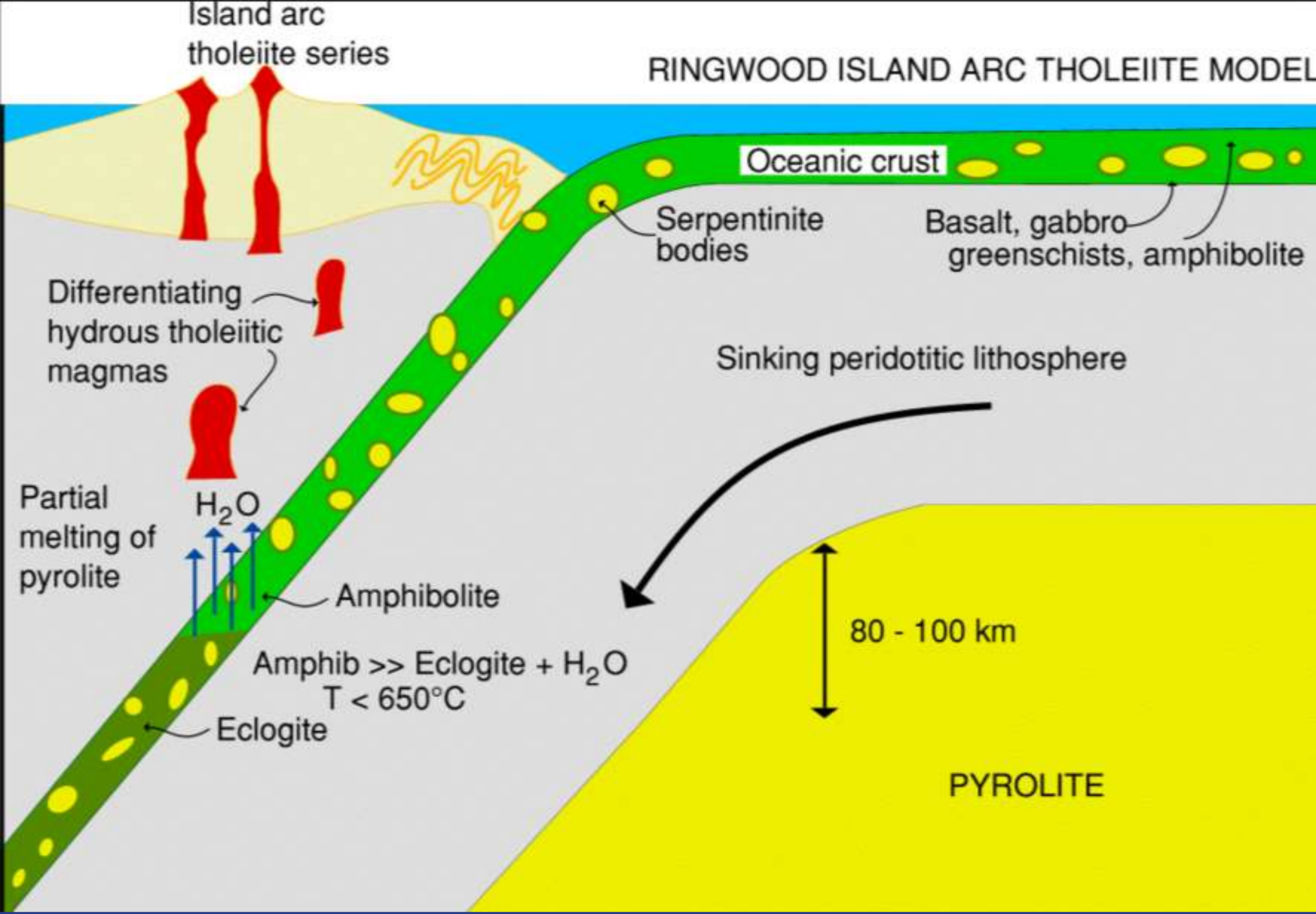
$H_2O_2$, $MnO_4^-$, $CrO_3$, $Cr_2O_7^{2-}$, $OsO_4$, $O_2$, $F_2$, $Cl_2$, $Br_2$

# The most abundant oxidising substance for magmas is water! So how does water get into magmas?

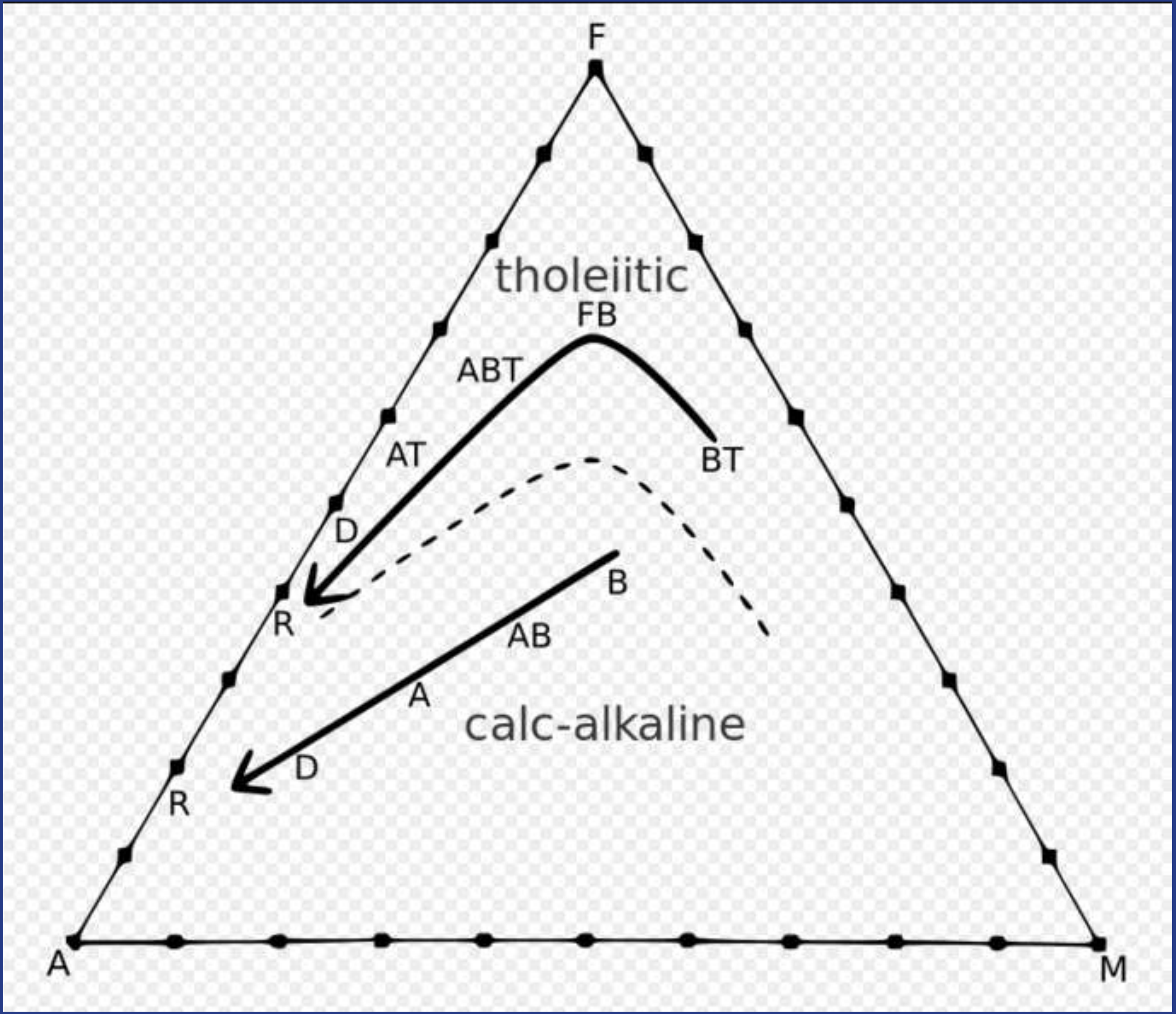


Water is a key ingredient in the generation of magmas in subduction zones. This review focuses on the role of water in the generation of magmas in the mantle wedge, the factors that allow melting to occur, and the plate tectonic variables controlling the location of arc volcanoes worldwide. Water also influences chemical differentiation that occurs when magmas cool and crystallize in Earth's continental crust. The source of $H_2O$ for arc magma generation is hydrous minerals that are carried into Earth by the subducting slab. These minerals dehydrate, releasing their bound $H_2O$ into overlying hotter, shallower mantle where melting begins and continues as buoyant hydrous magmas ascend and encounter increasingly hotter surroundings. This process is controlled by plate tectonic variables that ultimately influence the location of the active volcanic arc above subduction zones. Water also modifies the thermodynamic properties of melts, leading to the unique chemical composition of arc volcanic rocks and Earth's continental crust.

Grove, T. L. et al., 2012, *Annual Review of Earth and Planetary Sciences,* v. 40, pp. 413-439




Ted Ringwood’s model of making island arc tholeiites




The evolution of tholeiitic and calc-alkalic magmas

In 1970 the Czech geochemist Petar Jakeš and the American geochemist James B. Gill pointed out that many of the island arc basalts could not properly be called calc-alkalic, because they have lower silica mode, more iron enrichment, higher $Na_2O/K_2O$ ratios, less K and associated trace elements K/Rb ~ 1000, Th/U~1-2 and chondritic REE patterns with la/Yb=1-2.

Although sharing some tholeiitic features, they differ from normal tholeiitic series by having a higher percentage of intermediate and acid members and too little normative olivine, for example, to have been in equilibrium with peridotite. In such distinctive features as REE, Th, and U contents and La/Yb, Th/U, and K/Rb ratios, they are more like mid-ocean ridge tholeiites than any other terrestrial rocks, but they differ from them in silica mode, alkali content and isotopic composition, and MgO, FeO, Ni, and Cr contents.

Some of the spatial, temporal, and chemical characteristics of such island arc tholeiites may be explained by mixing of the partial melting products of resorbed lithosphere and overlying upper mantle.

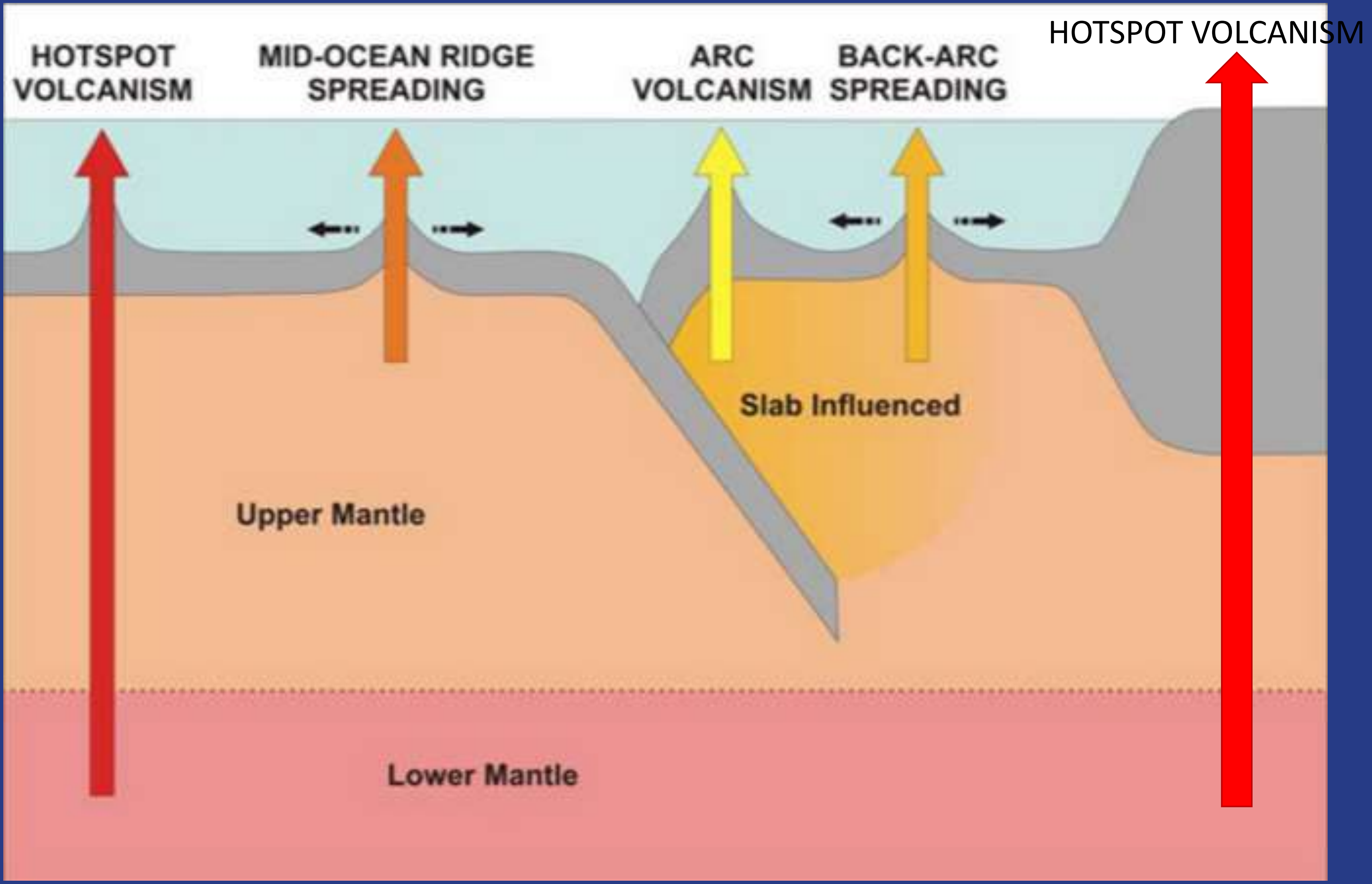
From: Jakeš, P. and Gill, J., 1970, Rare earth elements and the island arc tholeiitic series: *Earth and Planetary Science Letters*, v. 9, pp. 17-28.

The formation of alkalic basalts: For similar $SiO_2$ content, the alkalic basalts have more Na and K oxides in them and often have nepheline in their groundmass. Why is the difference? This is a function of the amount of partial melting and depth of partial melting. Remember that both Na and K have fairly large ions and would like to get into the liquid as soon as they can. So, the smallest amount of melting will get them out into the melt first.

So if one has 25% partial melting in lherzolite at depths shallower than 30 km, one would generate tholeiitic basalt. If the same amount of partial melting occurs at depths greater than 30 km one would get alkalic basalt.

If one has 30% melting at 60 km depth, one would get tholeiitic basalt. If one has 20% partial melting at 60 km depth, one would get alkalic basalt.

High Mg tholeiites (i.e., the so-called komateiitic basalts require very much larger amounts of partial melting at high temperatures.




Sites of basalt origin on planet earth.

Definition of hotspot in geology:

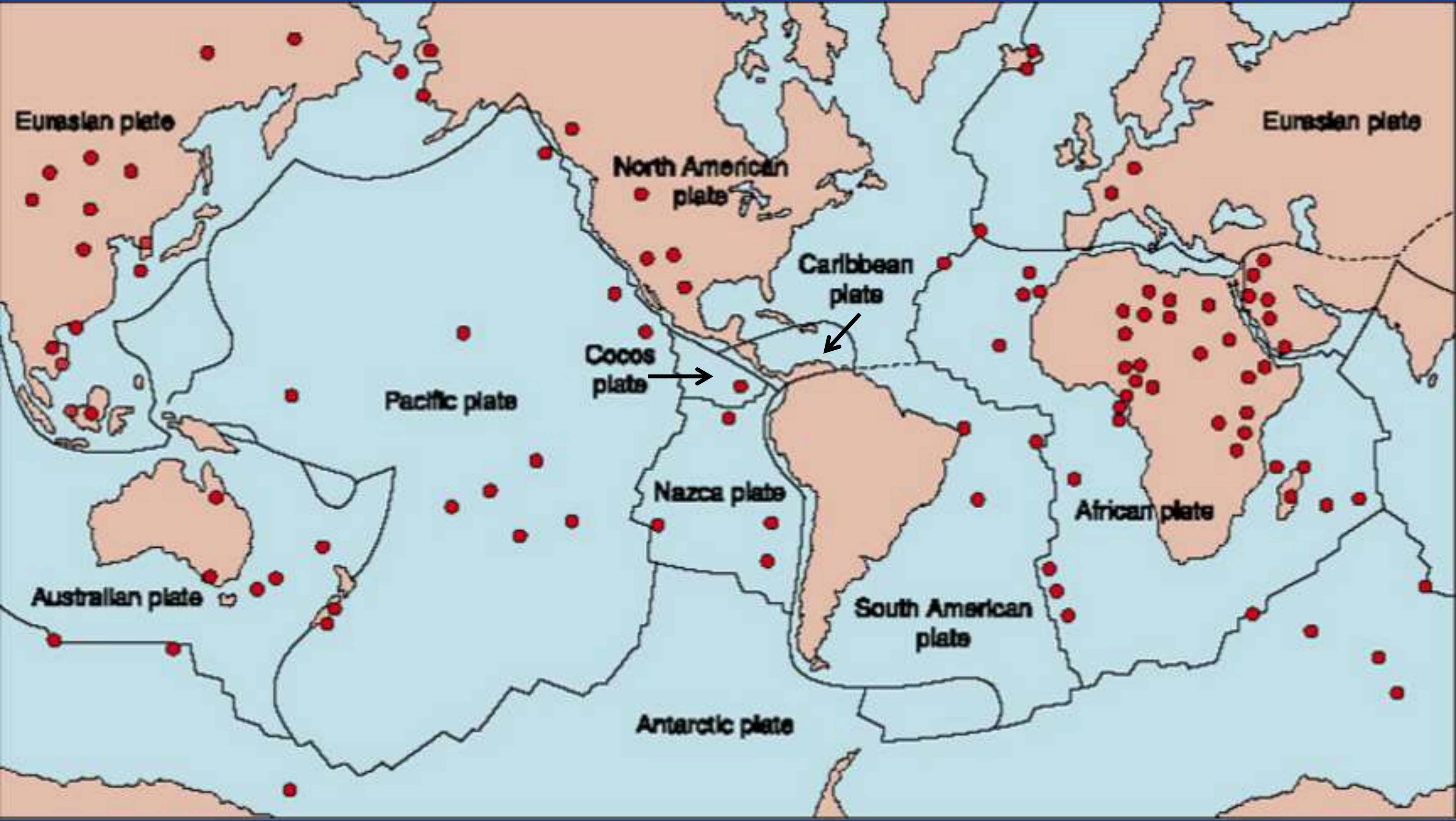
Hotspot is a region of volcanism that cannot be explained by normal plate boundary processes. Hotspots may occur in plate interiors (e.g., Hawaii) or along plate boundaries (e.g., Iceland).

Hotspots are usually results of mantle plume activity.

Definition of a mantle plume:

Mantle plume is a rising column of mantle that is about 300°C hotter than its surroundings.

Mantle plumes may be of shallow origin (~600 km) or deep origin (2900 km, i.e. at the core/mantle boundary)




Major hotspots on earth

We have so far considered mainly basaltic volcanoes. We now go onto volcanoes that erupt not only basalts, but also other rock types.

We start with the simplest: the ash cones.

Effusive

Explosive

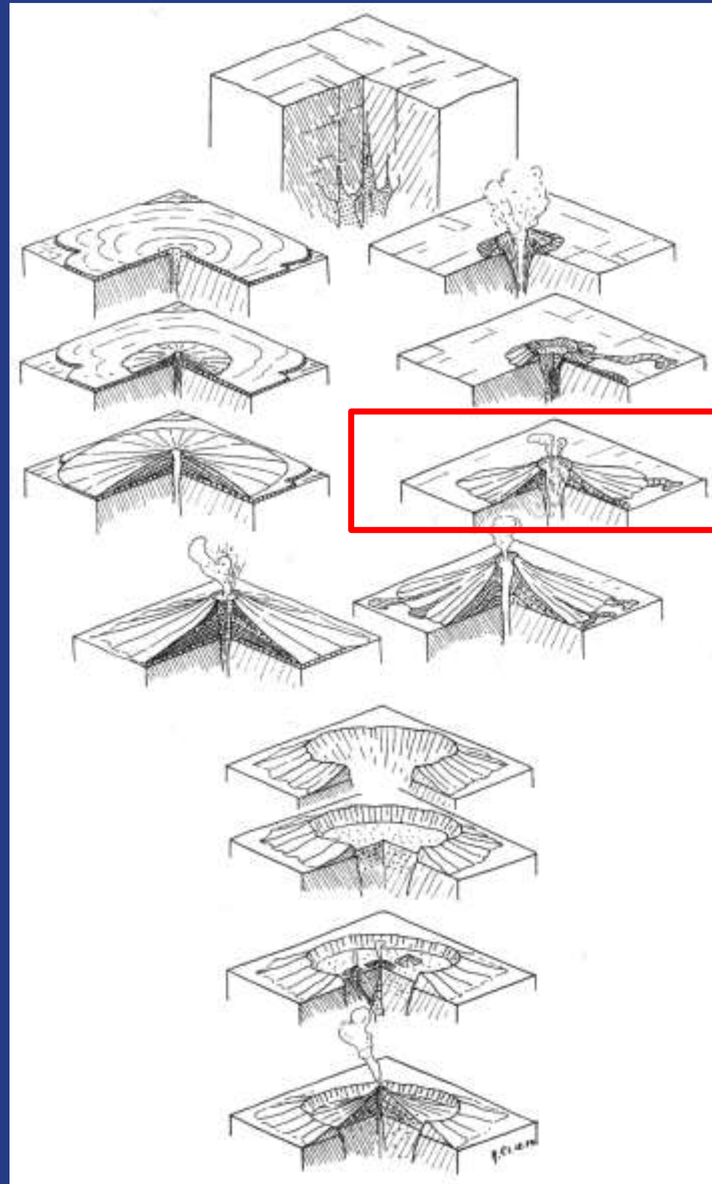


Table volcanoes

Table-shield volcanoes

Shield volcanoes

Mixed volcanoes

Maars

Maar w/ lava flow

Ash volcanoes

Mixed volcanoes

Caldera

Filled caldera

Second generation volcanoes

Vesuv-Stage

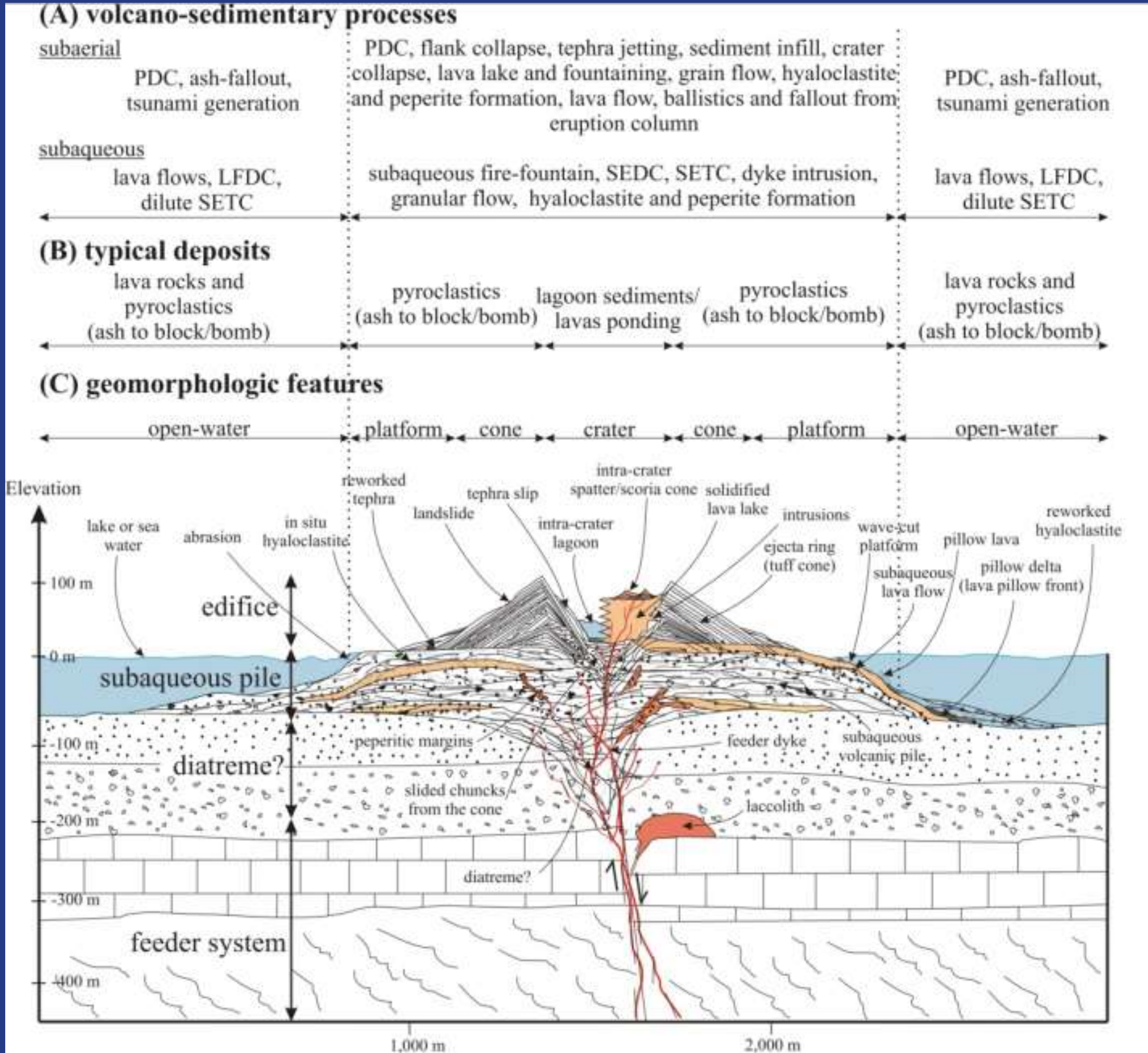
From H. Cloos 1936 *Einführung in die Geologie*

Ash volcanoes are usually monogenetic volcanic structures consisting of volcanic ash deposits and are divided into two types: ash cones and ash rings.

Koko crater, an extinct tuff cone on the island of Oahu, Hawaii, USA.

Fort Rock, a partially eroded tuff ring in Oregon, USA.

Fort Rock seen from the ground. Notice the layered structure of its wall!




Cross-section of a tuff cone.

Since volcanic ash or tuff builds the ash cones (or tuff cones), what is volcanic ash?

Volcanic ash is commonly defined to be solid particles, smaller than 2 mm diameter (i.e. sand to shale size), thrown out by volcanoes. Ash (or tuff) is produced by phraetomagmatic explosions and degasification resulting from depressurisation of rising magma in a volcanic chimney.


Volcanic ash from the Merapi (left) and the Kelud (right) volcanoes, Java, Indonesia.

Volcanic ash  can be extremely hazardous in a variety of ways. If expelled in large quantities into the upper atmosphere it affects the climate: In April 1815 Mt. Tambora in eastern Java, Indonesia, erupted 150 cubic kilometres of tephra into the air, blocked sunlight and caused a global decrease of average temperatures by some 3 °C. The result was that 1816 was a year without summer, resulting in widespread crop failure in Europe and North America, famine and disease.

If volcanic ash enters aircraft engines it can solidify on their moving parts and stall them.

It can disrupt functioning machinery in power supply plants, water supply plants, sewage treatment plants, communication facilities of many sorts. When mixed with water it turns into a cement-like substance and causes houses to collapse under its weight and in lungs it essentially stops the functioning of lungs causing suffocation.

Even cool ash can cause all sorts of skin, eye, note and mouth inflammation.


For others it has been less entertaining: a suffocating man in Pompeii in the ash cloud of the Vesuvius during the 79 CE eruption (some became flash-heated!)

For some, volcanic ash is unimportant!

Volcanic ash cloud rising from Mt. Redoubt in Alaska, USA.

Volcanic ash may be of any igneous rock composition. The principal ones are the following:

Ultramafic tuffs: these are of extreme rarity in the present-day world and are encountered only in diatremes that come from the bottom of the lithosphere and bring up diamonds (kimberlite pipes). They have less than 45% silica and consist of more than 90% ferromagnesian minerals with essentially no water (olivines and pyroxenes with rare phlogopite). They were probably more common in the Archaean (>2500 million years ago) when ultramafic surface volcanism was possible.

Basaltic tuffs: these are very common and occur wherever there are basaltic volcanoes: along the mid-oceanic spreading centres (Iceland, Afar, Azores, etc.), big basaltic palteaux (e.g. Columbia in the northwestern USA), oceanic islands (e.g., Hawaii), continental basaltic cones (e.g. East Africa, Kula in western Turkey). They can be abundant enough to seriously affect the atmosphere by blocking the Sun light for long periods of time, as, for example, during the 1783 Laki eruptions in Iceland, when 130 craters began erupting at once along a long fissure. Basaltic tuffs are usually black, greenish black or brick red (when oxidised). When weathered, they generate calcite, chlorite, serpentine. If the lavas are undersaturated with respect to silica and contain feldspathoids such as leucite or nepheline, the weathered basaltic tuffs are often rich in zeolites, such as analcime (actually a feldspathoid!!), prehnite, natrolite, scolecite, chabazite, heulandite, etc.

Basaltic tuff layers, Galapagos Islands, Ecuador

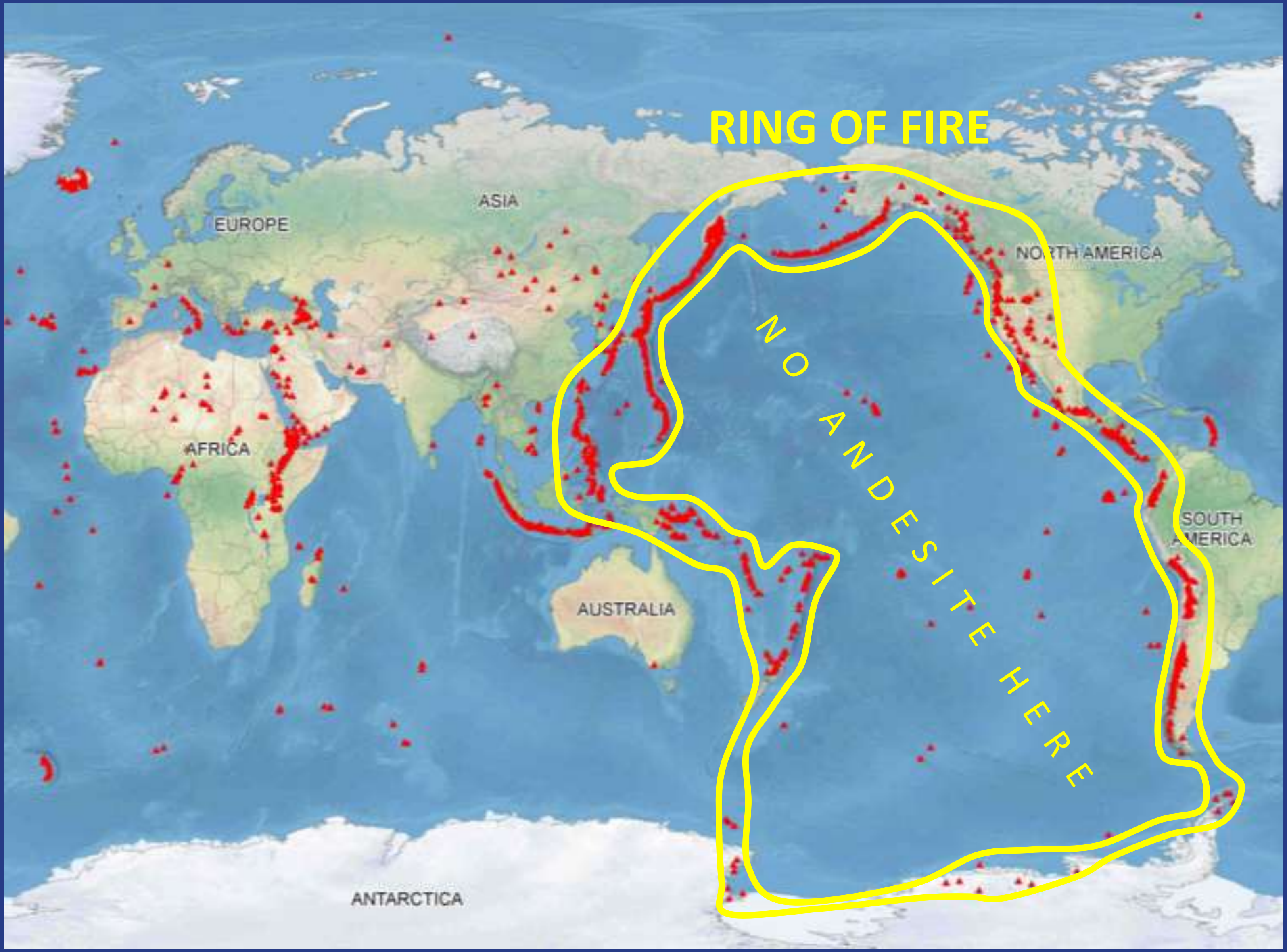
Red basaltic tuff layers in the Monaro volcanic Province in New South Wales, Australia.

Giant head statues, the moai,  from the Easter Island, Chile, made up of basaltic tuffs.

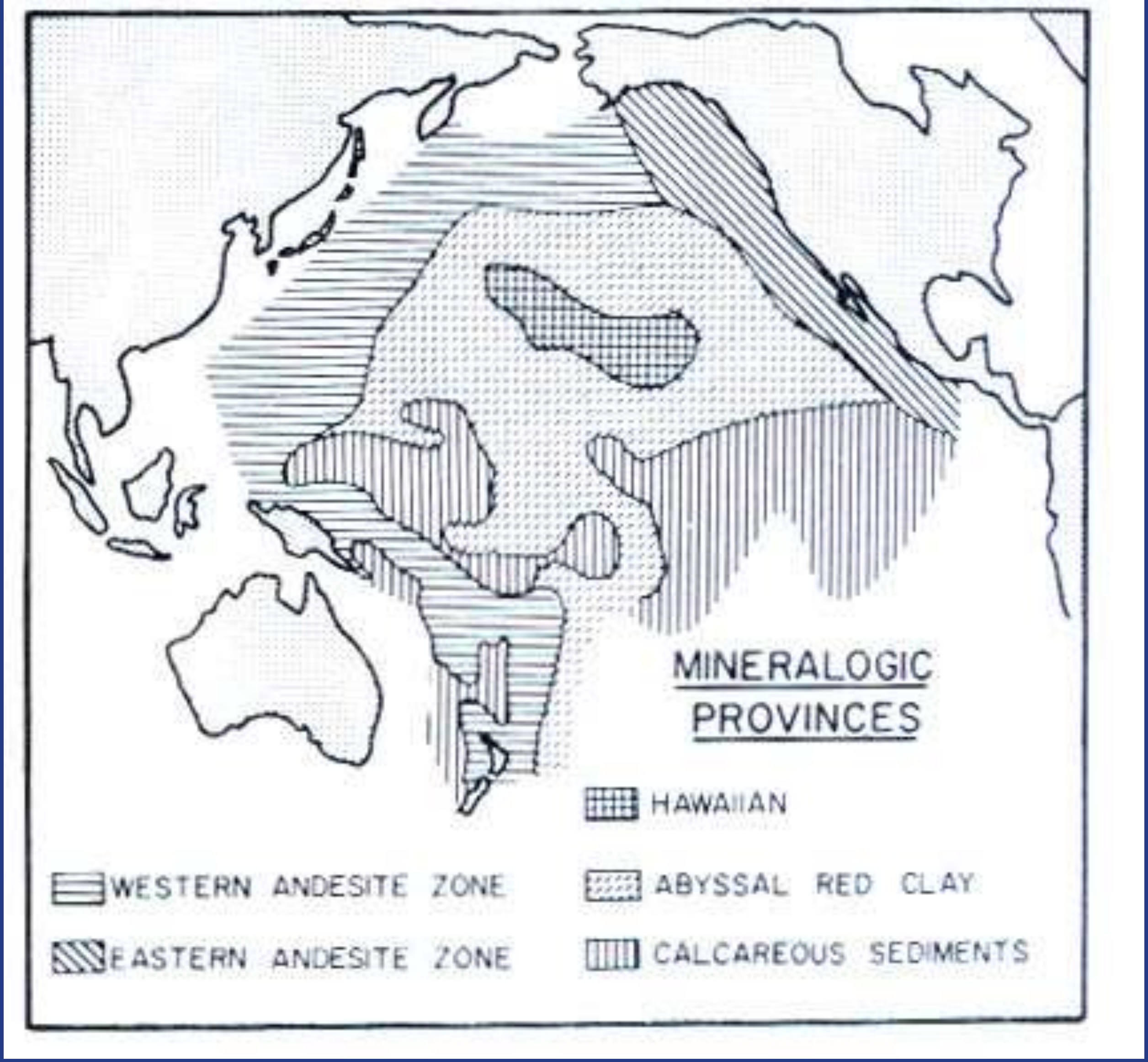
The Rano Raraku ash cone on the Easter Island from which basaltic tuff was obtained to carve the giant moai.

Andesitic tuff: An extremely common volcanic tuff kind consisting of andesitic material. When weathered, their cavities get occupied by calcite, chlorite, quartz, epidote, and chalcedony. Andesitic tuffs are common along subduction-zone magmatic belts (such as the “Ring of Fire” around the Pacific Ocean).

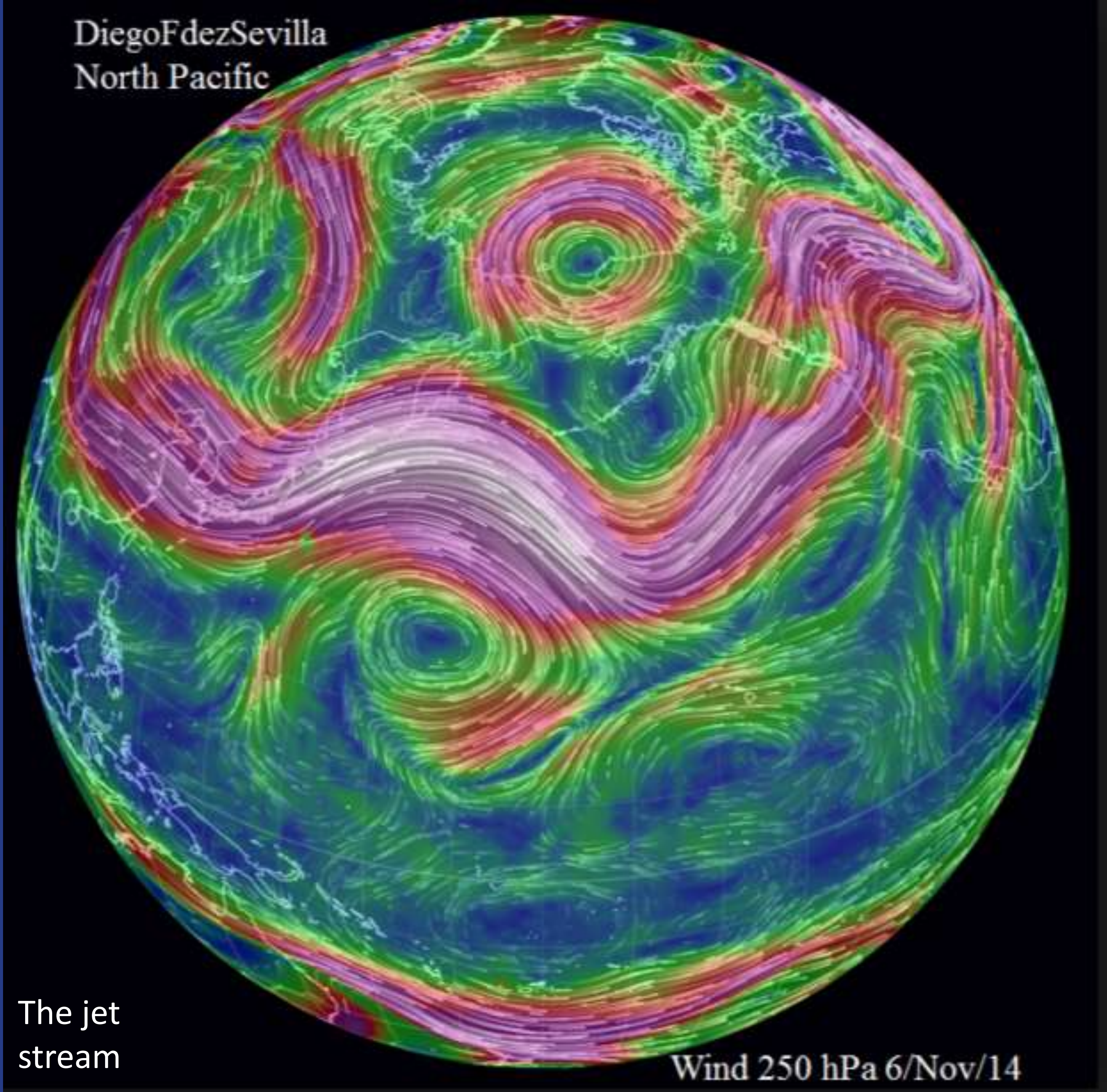
This is a hornblende-bearing andesitic tuff.



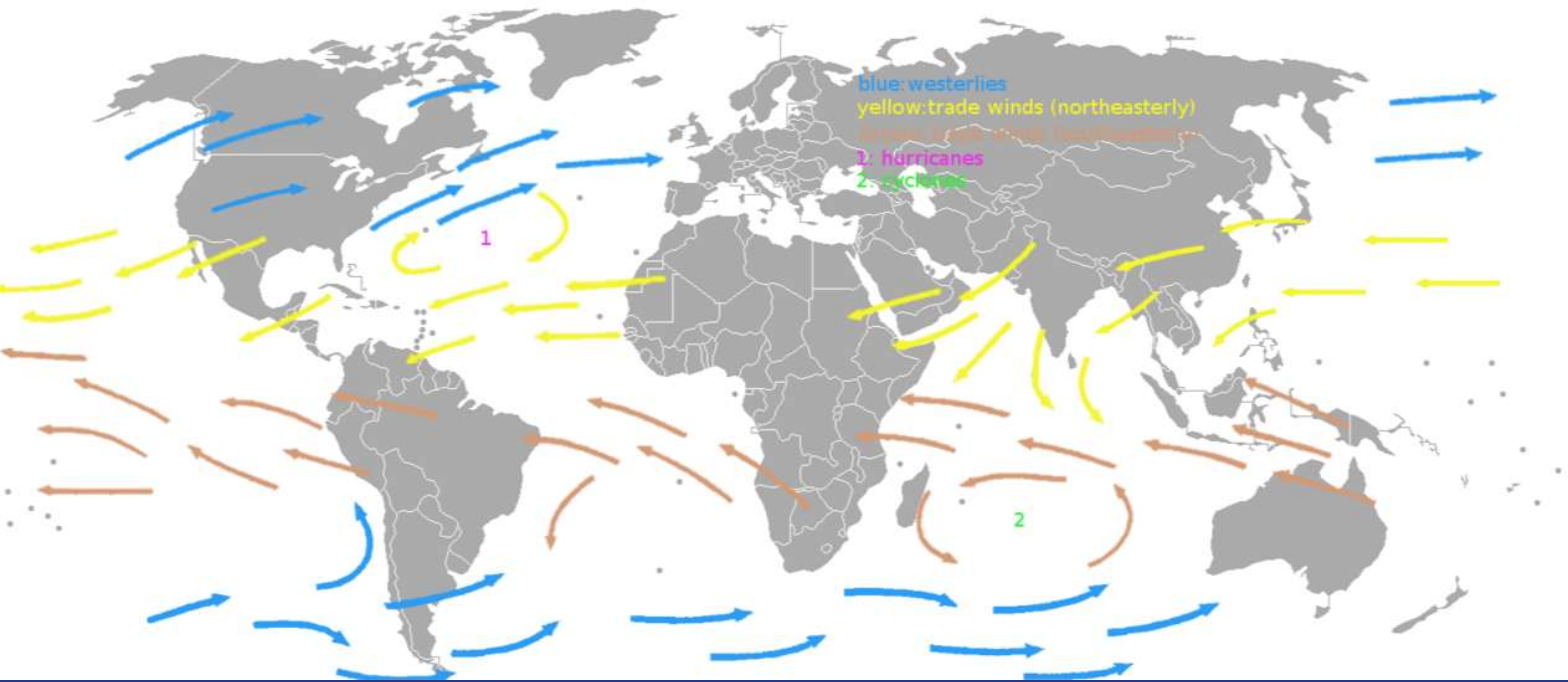

Notice the great abundance of volcanoes around the Pacific Ocean. Those in the west, along the American Cordillera are mostly andesitic and some rhyolitic. Those along the Asian marign are andesitic with some basaltic. The ones along Antarctic margins are mostly alkalic basalts.




Major sediment provenance regions in the Pacific Ocean (from Lisitzin, 1972)




The jet stream



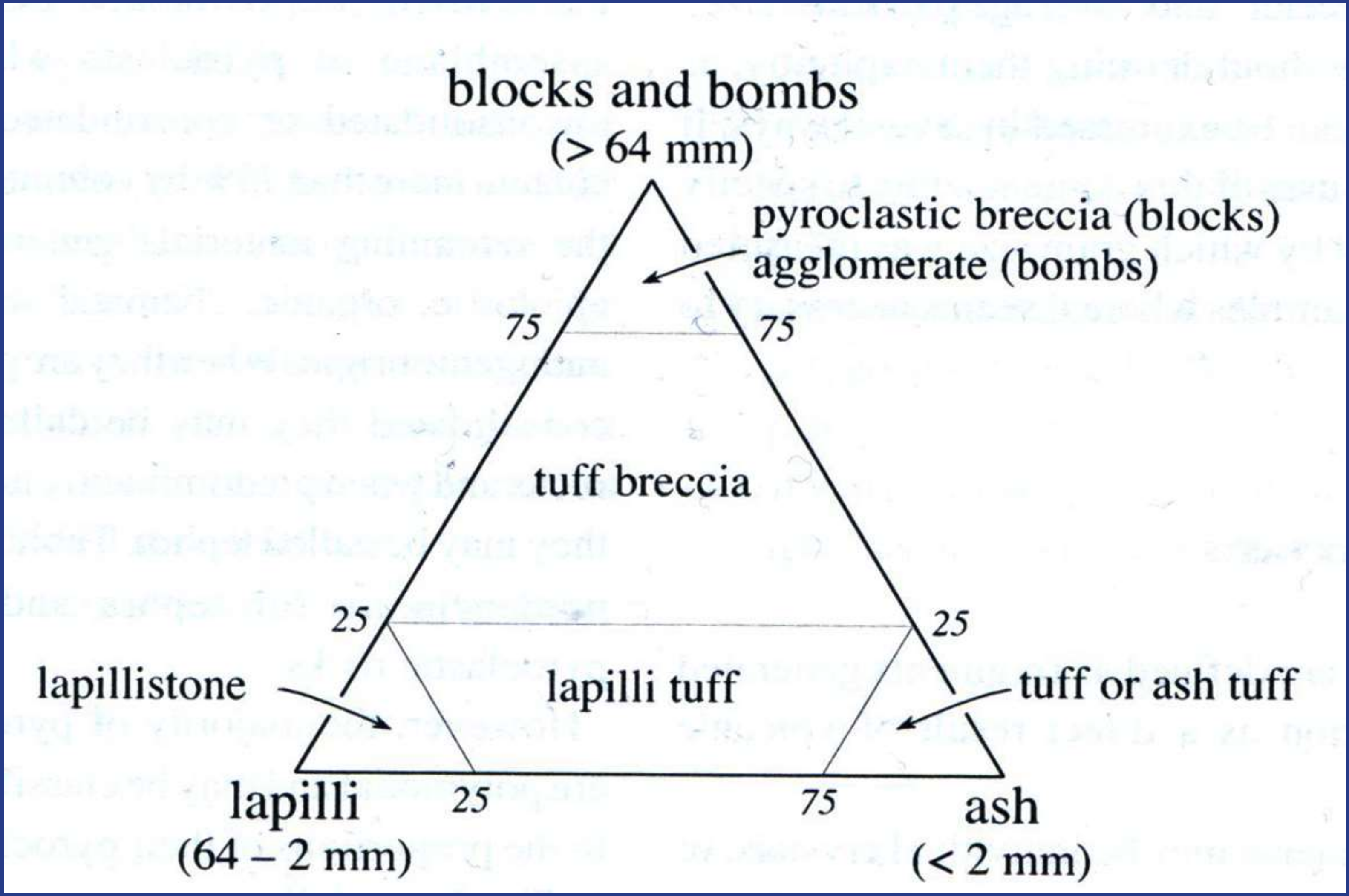

# Distribution of trade winds

Trachyte tuff: Trachyte tuffs are transitional between saturated and oversaturated volcanic rocks and contain no quartz, but they do contain feldspars with compositions ranging from anorthoclase to sanidine. In places they may have oligoclase and contain augite, hornblende and biotite. Upon weathering they turn into kaolinite with some secondary quartz.

Weathered trachytic tuff, Campania, Italy

Rhyolitic tuffs: The rhyolitic tuffs contain mainly potassium feldspars, muscovite and quartz and tiny fragments of pumice and volcanic glass (obsidian). In areas of large caldera collapses, they occupy vast areas as in the western parts of the USA and Northern New Zealand. Smaller blankets exist elsewehere such as Iceland, Hungary, Italy, the Andes.

Rhyolite tuff breccia




Tephra classification according to Fisher (1966) recommended by Le Maitre et al. (2002) showing the relations of volcanic ash (tuff) to other tephra sizes

So far I have used the to terms ash and tuff interchangeably.  Yet there is a difference in their strict meanings:

Ash is simply material that is less that 2 mm in diameter. It can be further subdivided into coarse ash 2 mm to 1/16 mm and fine ash less than 1/16 mm. Tuff is defined as a pyroclastic rock in which the ash component is more than 75%. However, the usage of tuff and ash in the literature is interchangeable and does not follow the recommended lines, because most tuff or ash descriptions are field descriptions made quickly at outcrop.

The term tuff has been enlarged in its meaning and given three qualifiers:

1. Tuff breccia: A pyroclastic rock, in which bombs and/or blocks range in amount from 25 to 75%

2. Lapilli tuff: A pyroclastic rock in which bombs and other blocks are less than 25 %

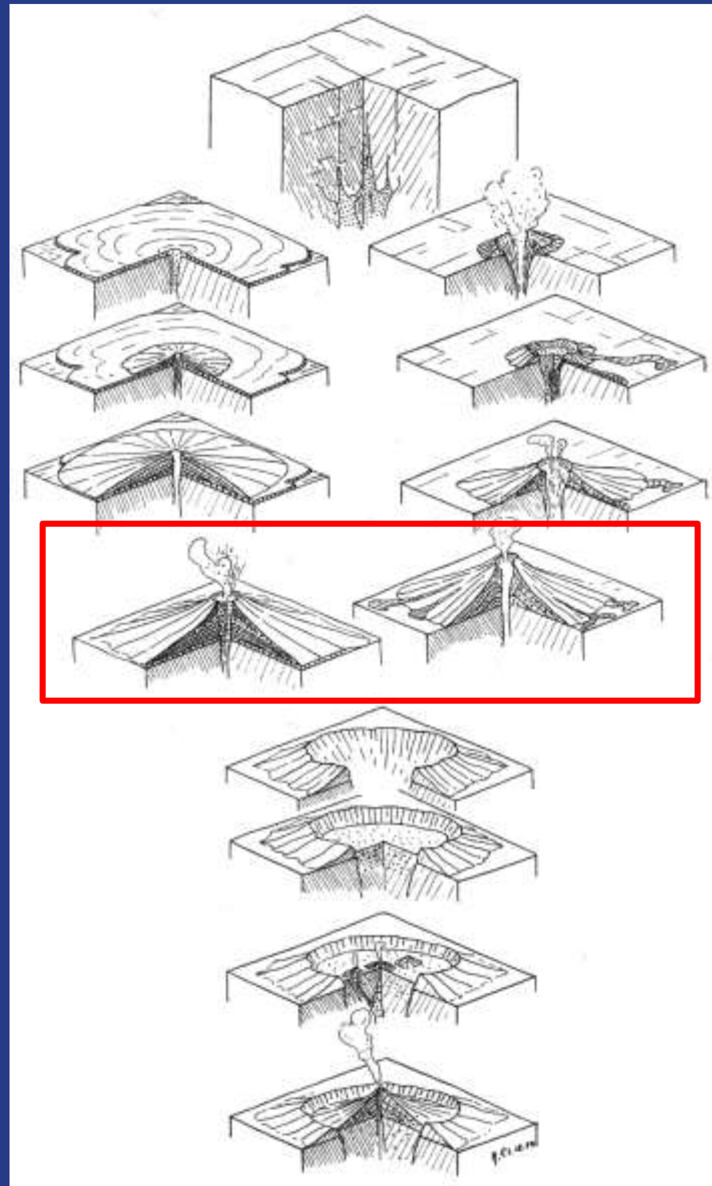
3. Tuff or ash tuff: a pyroclastic rock in which the ash component is more than 75%

A fourth term that is recommended is lappillistone defined as a rock in which the amount of lapilli is more than 75%.

However, these terms are hardly ever used in the literature. As I said above, ash and tuff are the two terms that are in use and tuff is simply ash that may have larger size classes in it, but it is ash-based. This is what you need to know.

Cross-section of a tephra cone in Kula, western Turkey. Note the alternating lapilli and bomb and block layers.

Effusive | Explosive



Effusive:

- Table volcanoes
- Table-shield volcanoes
- Shield volcanoes
- Mixed volcanoes

Explosive:

- Maars
- Maar w/ lava flow
- Ash volcanoes
- Mixed volcanoes
- Caldera
- Filled caldera
- Second generation volcanoes
- Vesuv-Stage

From H. Cloos 1936 *Einführung in die Geologie*

After the ash volcanoes or perhaps better tuff volcanoes we come to another class that builds the classical volcano type: the stratovolcanoes. These are the volcanoes that Hans Cloos calls the “mixed volcanoes” because they are made up of alternating layers of lavas and pyroclastic material. These alternating layers are what gives this type of volcano its most common name: stratovolcano, meaning layered volcano.

Rittmann pointed out that there are really no perfect stratovolcanoes in the world containing half lavas and half pyroclastic materials. He said they are either mainly pyroclastic-built cones or lava-built cones.

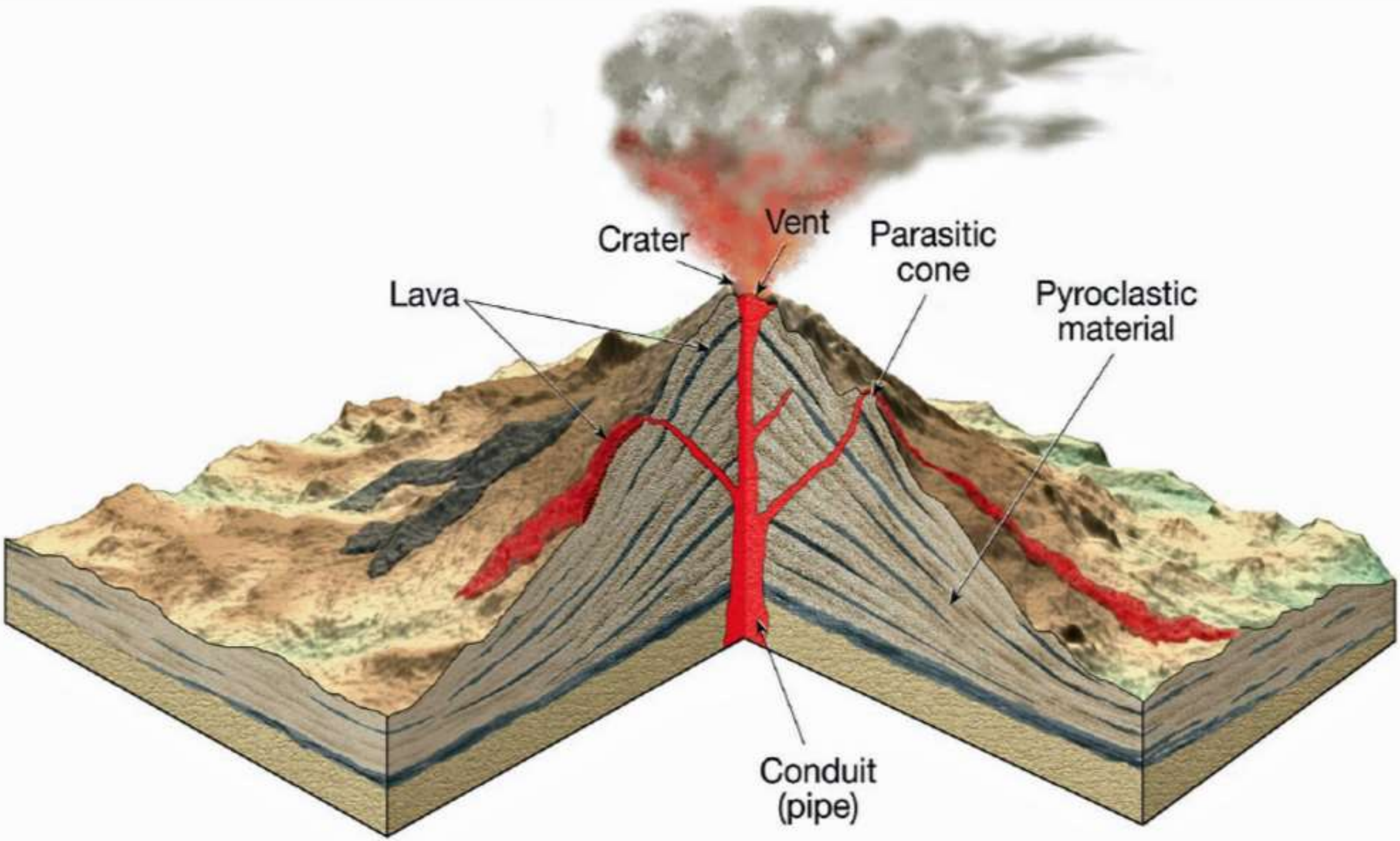
Let us remember that until about the seventies of the twentieth century, volcanic edifices created by eruptions were classified as:

1. Hawaiian shield volcanoes

2. Strombolian stratovolcanoes

3. Vulcano-type stratovolcanoes

1. Vesuvian or Peléan type stratovolcanoes +calderas produced by Plinian eruptions.



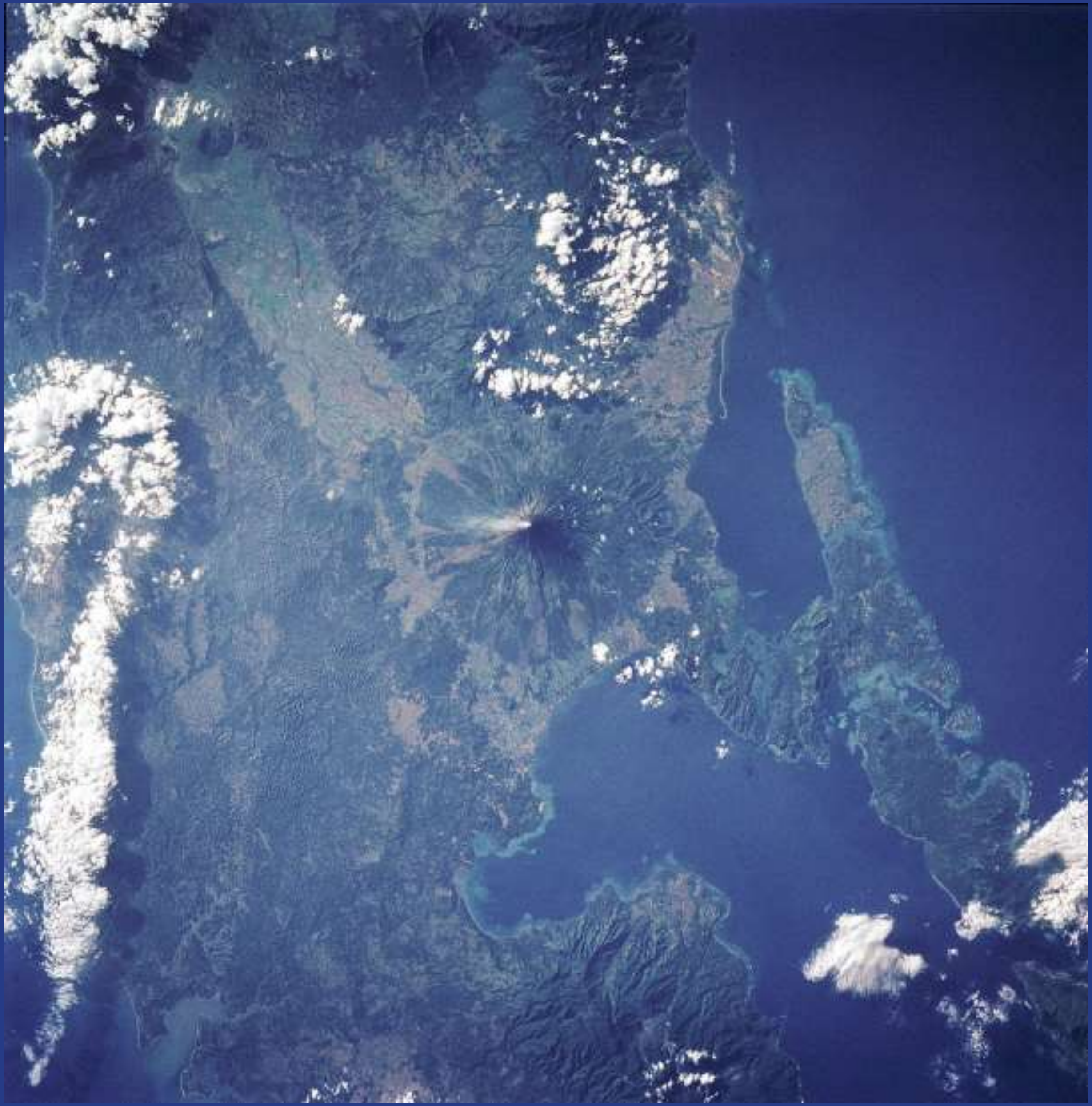

Block diagram of an idealised stratovolcano.

Mt. Mayon, Philippines. Perhaps the most symmetric, perfect stratovolcano on earth.

Another view of Mayon

Mayon erupting

A close-up view of the Mayon lavas



Mayon seen from space. Notice the almost perfectly circular base.

Another famous stratovolcano: the Fuji–San in Japan, near Tokyo.

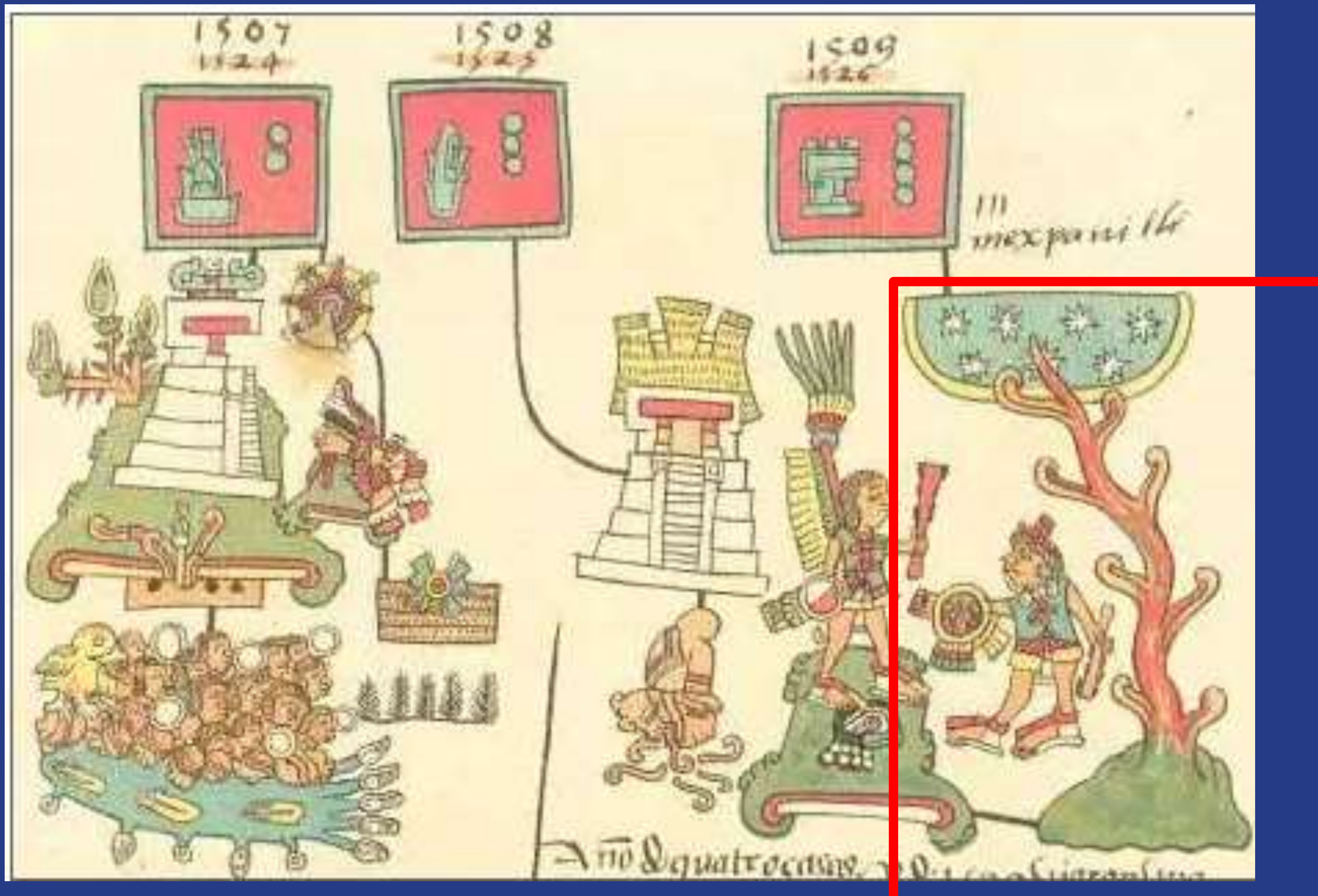
Fuji-San stratovolcano from the ground

Fuji-San in a traditional Japanese painting

The stratovolcano of Cotopaxi, northern Andes, Ecuador

Chimborazo, northern Andes, Ecuador. Before the Himalayas were measured, Chimborazo was believed to be the highest peak in the word. It is 6268 m high and the highest peak near the

Izalco stratovolcano, El Salvador, Central America




An Aztec depiction of an erupting stratovolcano in Mexico in 1509, 10 years before the arrival of Hernán Cortés in 1519

Popocatapétl (meaning “smoking mountain” in Nahuatl language), the most active stratovolcano in Mexico.

The highest mountain in Mexico (5636 m): the stratovolcano of Pico de Orizaba or Citlaltépetl (meaning “star mountain” in Nahuatl)


The famous 1915 eruption of the Lassen Peak, the southernmost stratovolcano of the Cascade Range in the western USA.

Lassen Peak or Mt. Lassen stratovolcano today

Mt. Rainier, the highest volcano along the Cascade Range, northwestern United States, is 4394 m high. Its last eruptions occurred some 1000 years ago, although the cone is some half a million years old with oldest eruptions exceeding 800,000 years in age.


The Aleutian island arc and its relation to the Kamchatka-Kurile arc


The Aleutian island arc is extremely active volcanically

The Shishaldin stratovolcano, Aleutian islands, Alaska, USA

Mt. Sinabung stratovolcano, Indonesia, in eruption

Mt. Sinabung eruption at night

Kuh-e Taftan (i.e. Taftan Mountain), a stratovolcano in Balochistan, southern Iran


Kuh-e Bazman (i.e. Bazman Mountain), a stratovolcano in Balochistan, southern Iran

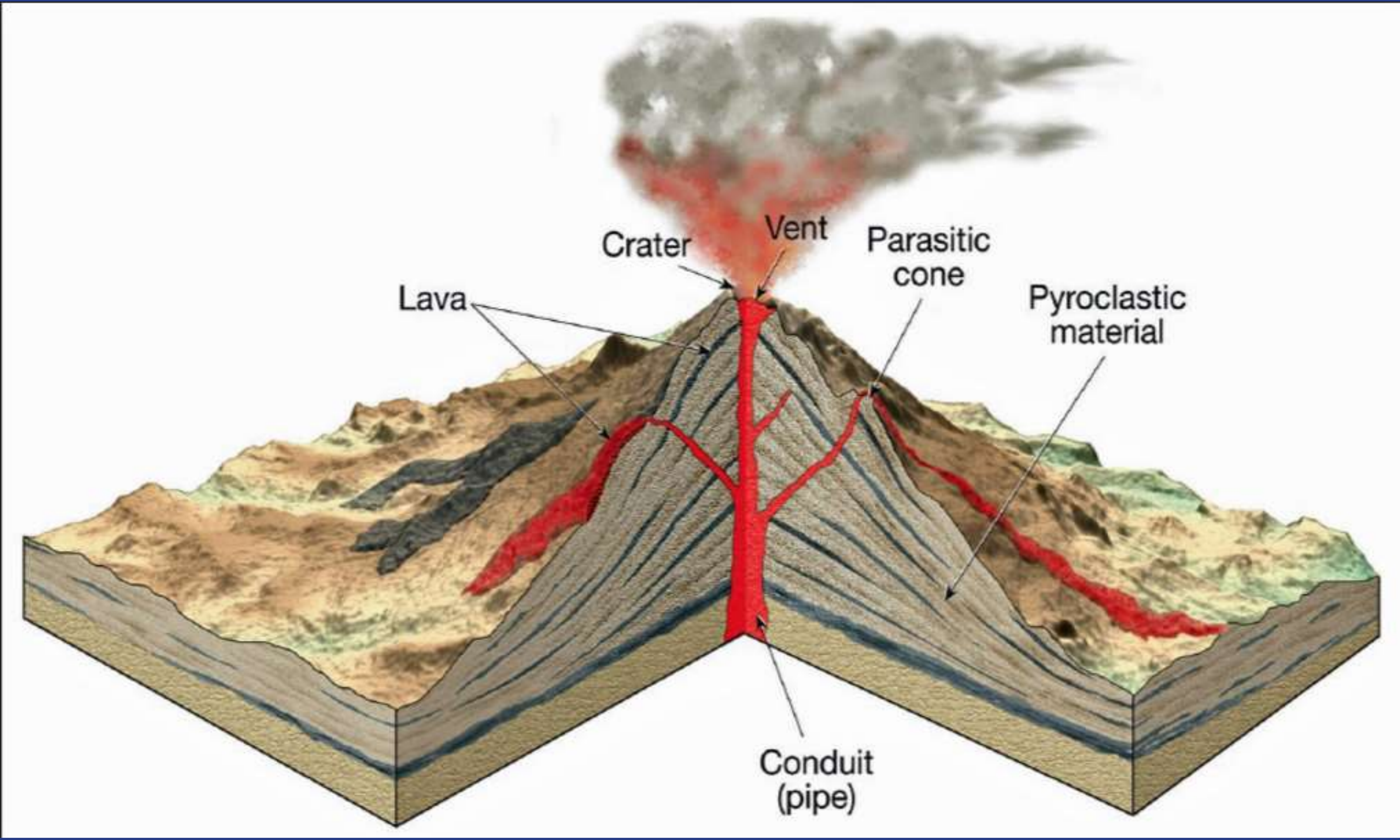
Kuh-e Bazman from space. Note the radial drainage

The Damavand Stratovolcano, Alburs Mountains, northern Iran

Elbrus Stratovolcano, the Greater Caucasus, Russian Federation

Mt. Ağrı stratovolcano, eastern Turkey

Erciyes Stratovolcano (Mt. Argaeus of the classical authors) , Kayseri, central Turkey (photo by A. M. C. Şengör, 1972)




Let us go back to the idealised stratovolcano.

Stratovolcanoes erupt both lava and tephra. That there is a regular lava/tephra alternation in any stratovolcano is not something widely observed. The lava/tephra successions and their relative amounts in any one cone is entirely irregular.

Stratovolcanoes erupt all sorts of lavas: from basalts through andesites and trachytes to rhyolites although most stratovolcanoes are known as andesitic volcanoes.

Since we have looked at basalts, let us look at the other kinds of rocks stratovolcanoes erupt, andesite being the most common.

Andesite: An intermediate igneous rock with aphanitic to porphyritic texture, usually blakish grey grey to spotted grey coloured, the silica content of which ranges from 57% to 63%. Andesite consists usually of plagioclase (commonly zoned from labradorite to oligoclase) pyroxene, hornblende and/or biotite. Magnetite, zircon, apatite and ilmenite may be present as accessory minerals and also minor amounts of alkali feldspar.

## An important note on the history of the term andesite:

Harry Rosenbusch (1836-1914) (1898, p. 288, footnote 1) pointed out, that the term andesite was first introduced by Leopold von Buch (1836, p. 190, [1885], p. 308; von Buch had read his paper before the Academy of Sciences in Berlin on 26th March 1835: see von Humboldt, 1858, p. 633), in order to separate the albite-containing varieties of the trachyte family of his time from the sanidine-containing ones. Von Buch himself never used the term again (von Humboldt, 1858, p. 636) and later the term was dropped in favour of trachyte alone, because the definition, von Humboldt wrote, should have specified not albite with hornblende, but oligoclase with augite. In 1861 Justus Roth reintroduced it for the younger volcanic rocks, in which oligoclase-amphibole or oligoclase-augite were dominant (Roth, 1861, p. XLV, footnote 1) in order not to stretch the meaning of trachyte too far. However, as is common in geology, the term trachyte continued long after Roth's redefinition of andesite to be used for rocks which we today would call andesite and even rhyolite. In some cases, the reverse happened too: Tyrell (1921) pointed out, for example, that Daly's (1914) computations of the average composition of andesite were such that they would even include rocks called trachyte today! Von Humboldt's (1858) long and detailed endnote 85 on his pp. 633-636 gives an excellent summary of the fortunes of the term andesite until 1858, just three years before Roth finally resurrected it.

Andesites erupt at temperatures ranging from 1100°C to 900°C.

They form through three mechanisms:

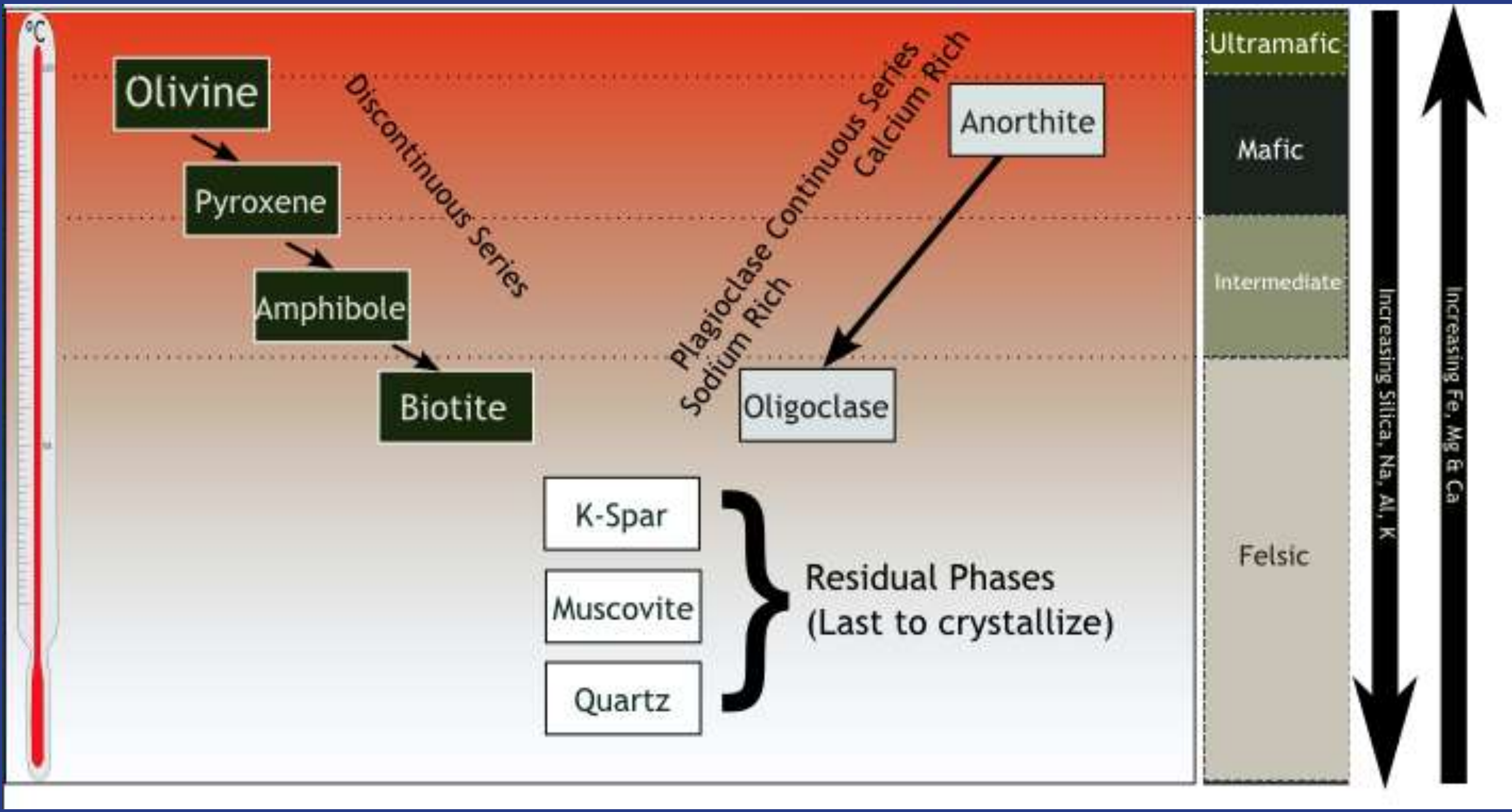
1. Fractional crystallisation

2. Melting of the continental crust

3. Mixing of basaltic and rhyolitic magmas.

The last two mechanisms occur in areas of thick continental crust (e.g., Tibet, Altiplano in the Andes, eastern Turkey) or in continental crust in areas where the geothermal gradient is very steep (e.g. in rift zones).

But let us first concentrate on fractional crystallisation, an extremely important mechanism to create almost all compositions of magma! The idea was first introduced by the great Canadian petrologist Norman Levi Bowen in 1928.




Let us begin with an ultramafic magma, say, of lherzolite composition. We let it cool. The first crystals that form out of it as the temperature drops will be olivine, as the temperature cools past the olivine liquidus.

At this point we need to learn two new terms: solidus and liquidus

Solidus: Temperature at which the first droplet of liquid is produced out of a solid (beginning of melting)

Liquidus:Temperature at which the first crystal forms out of a liquid (beginning of crystallisation)

In the magma if the olivine is not taken out of the magma after it forms (for example by settling into or onto the magma chamber walls), it reacts with the residual magma and turn into a pyroxene. Then if pyroxene is left as the temperature continues dropping it turns into an amphibole and so on. That is why Bowen called the olivine to biotite branch of the reaction series, the “discontinuous series” and the plagioclase branch the “continuous series”.

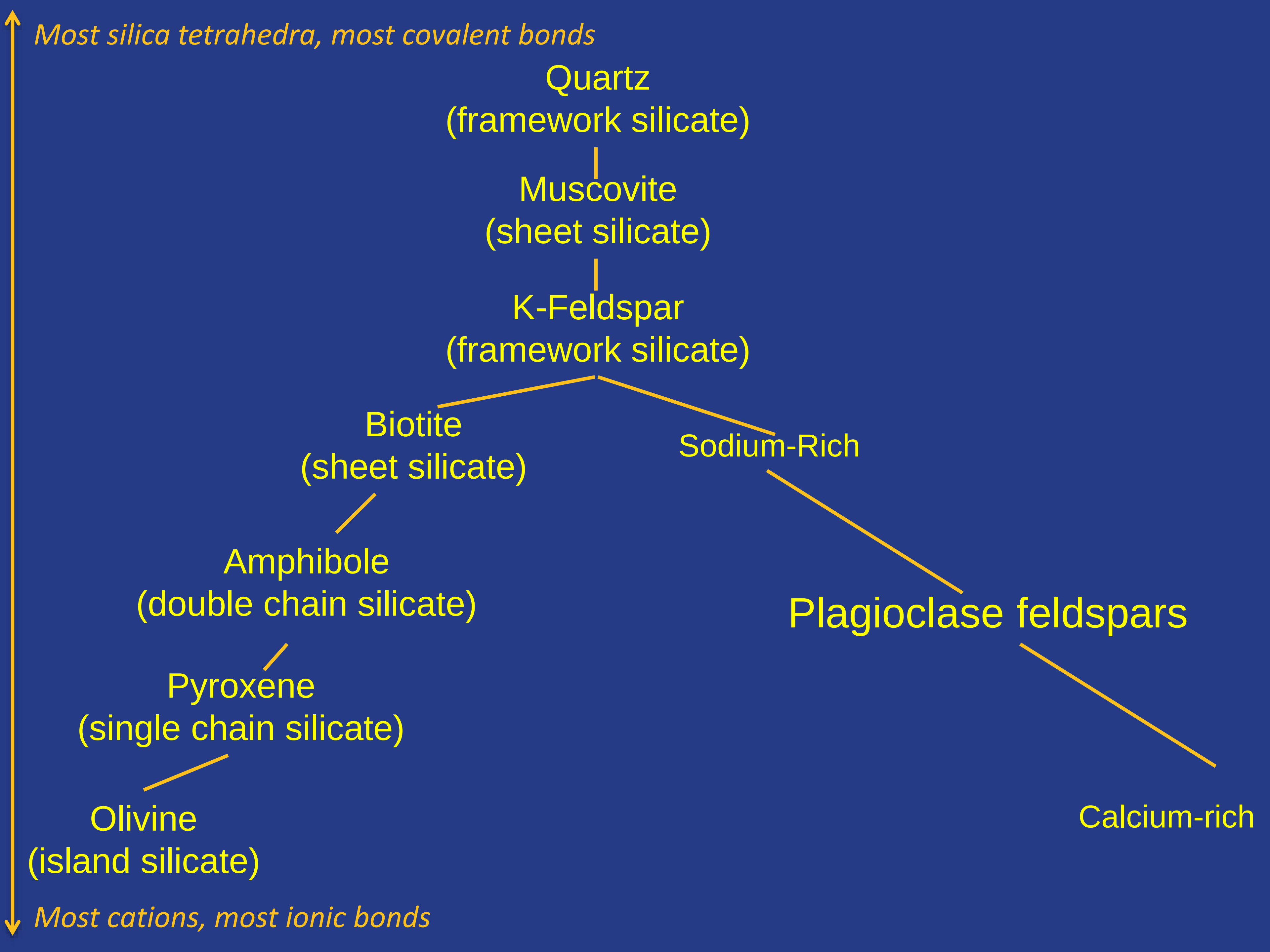
Once all the ferromagnesian minerals and the plagioclase feldspars form, the remaingng magma makes K-feldspars, muscovite and finally quartz!

This process is called fractional crystallisation, because at each step a fraction of the magma crystallises and makes a certain type of rock. One can see that through fractional crystallisation one can generate even a granite from an ultramafic magma.

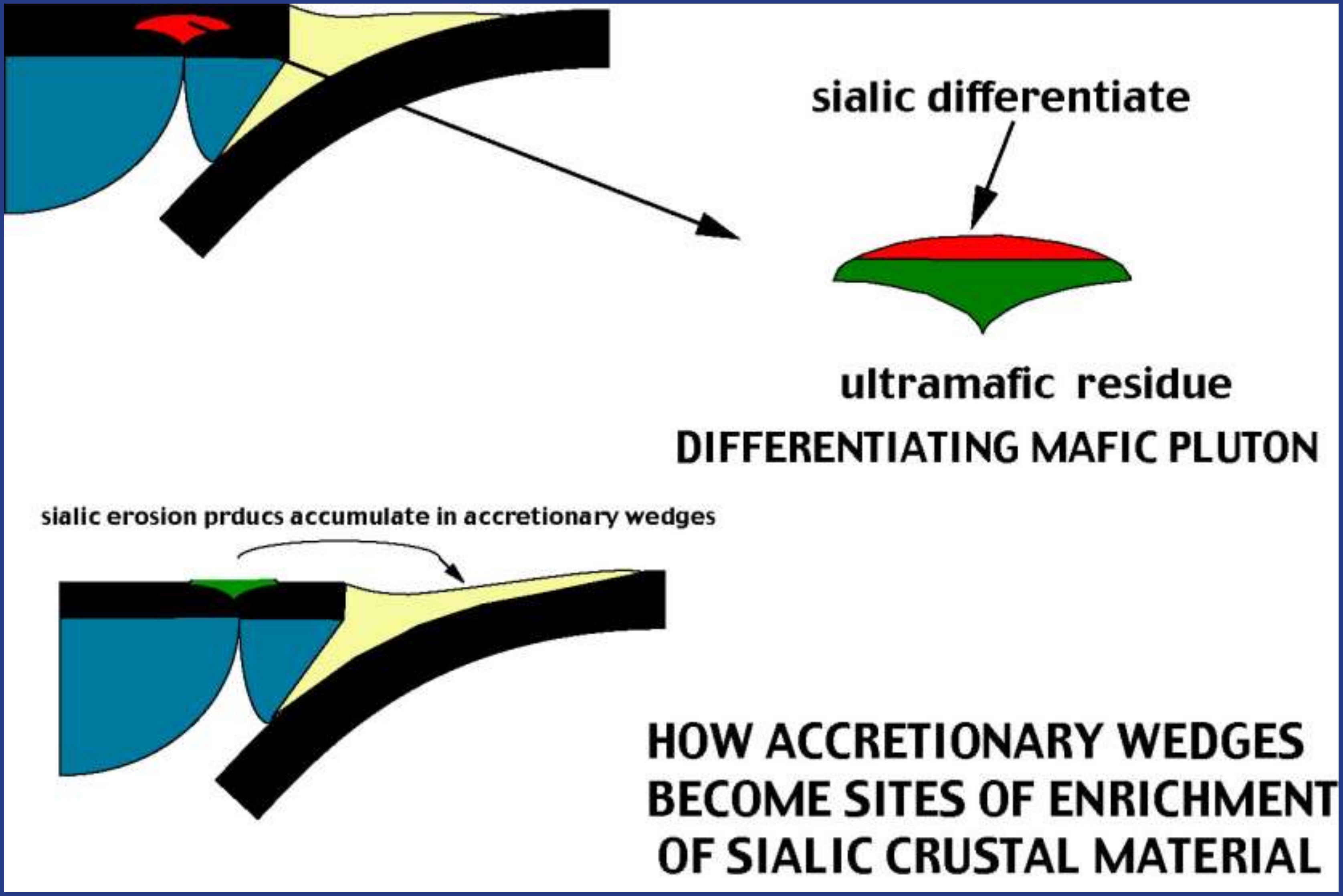
Yet nature is not so simple: few magma chambers are big enough to have enough magma to crystallise even granite; few magma chambers are ever left alone long enough to complete Bowen's process: they may be rapidly uplifted and freeze before they have had a chance to complete the sequence. New magma may get injected into them before the fractional crystallisation is complete. Nevertheless Bowen's reaction series is a helpful way to visualise how a mainly ultramafic planet (let us remember that 84% of the earth is made up of mantle, which entirely consists of ultramafic rocks) ended up generating continental crust, which is mainly of andesitic composition.

The American geochemist Samuel Stephen Goldich noticed in a paper published in 1938 that minerals' resistance to chemical weathering is the inverse of the Bowen's reaction series. Goldich noticed that minerals crystallized at lower temperatures (and pressures) were more resistant to weathering than those crystallized at high temperatures (and pressures). In other words the last minerals to crystallize from a melt were the most resistant to weathering, such as quartz or K-feldspar, or muscovite. This seemed natural as the minerals that crystallised from the melt crystallised at the lowest temperatures and pressures, i.e., under conditions closest to the surface conditions where weathering takes place.

The weathering sequence is now known as Goldich's Stability Series .


Most silica tetrahedra, most covalent bonds
Quartz
(framework silicate)
Muscovite
(sheet silicate)
K-Feldspar
(framework silicate)
Biotite
(sheet silicate)
Sodium-Rich
Amphibole
(double chain silicate)
Plagioclase feldspars
Pyroxene
(single chain silicate)
Olivine
(island silicate)
Calcium-rich
Most cations, most ionic bonds

How do we combine the three mechanisms of andesite genesis to progressively enrich the continental crust in $SiO_2$?



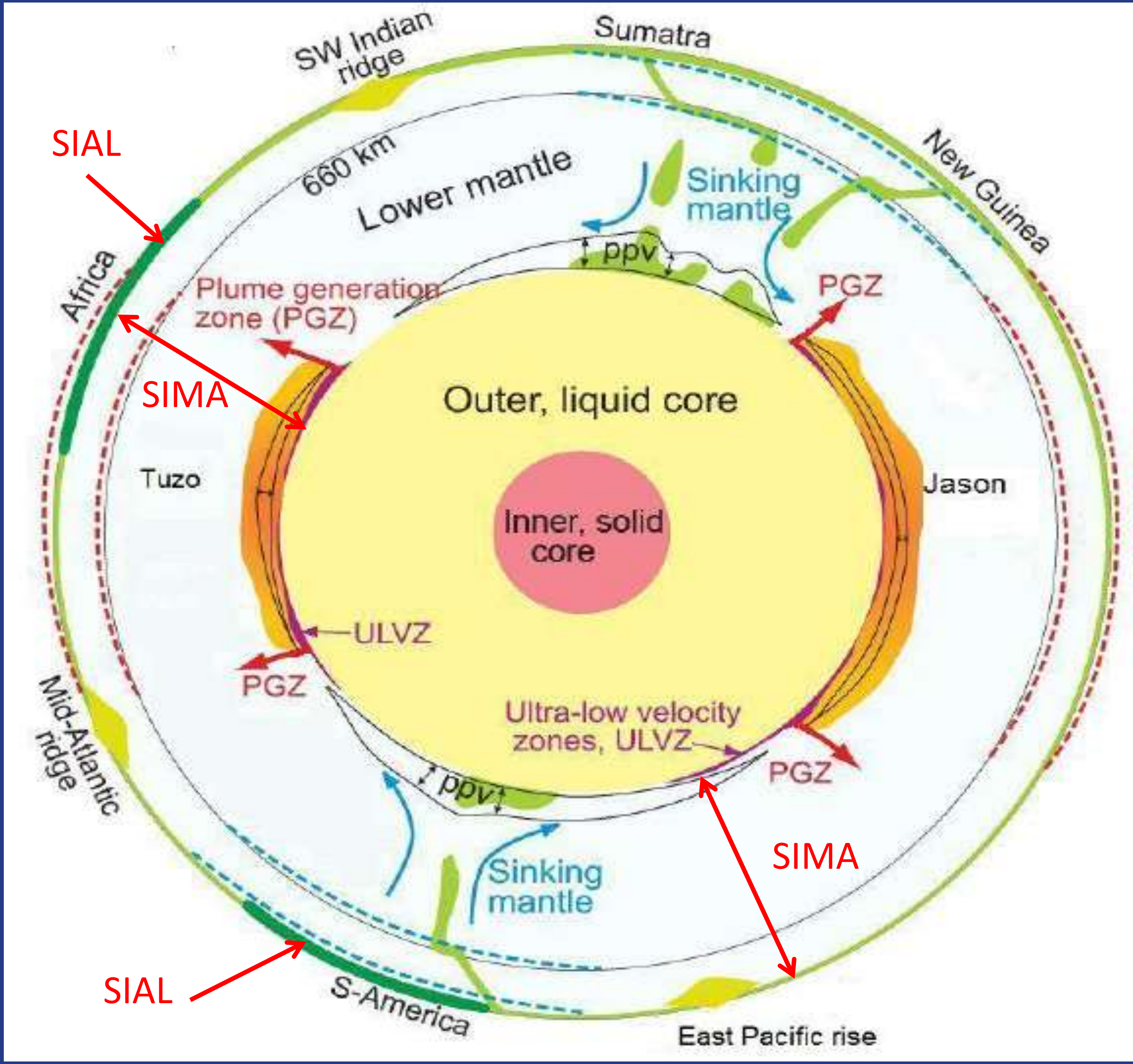
Here again we encounter two new terms: sialic and simatic. Or simply sial and sima.

These terms were introduced by the Austrian geologist Eduard Suess (1831-1914), the greatest geologist who ever lived, and the man who inaugurated modern geology.

Sial is made up of the first syllables of silicon and aluminium and designates the silicon and aluminium rich part of the earth’s rocky rind. Suess had originally called it sal, which was later changed to sial.

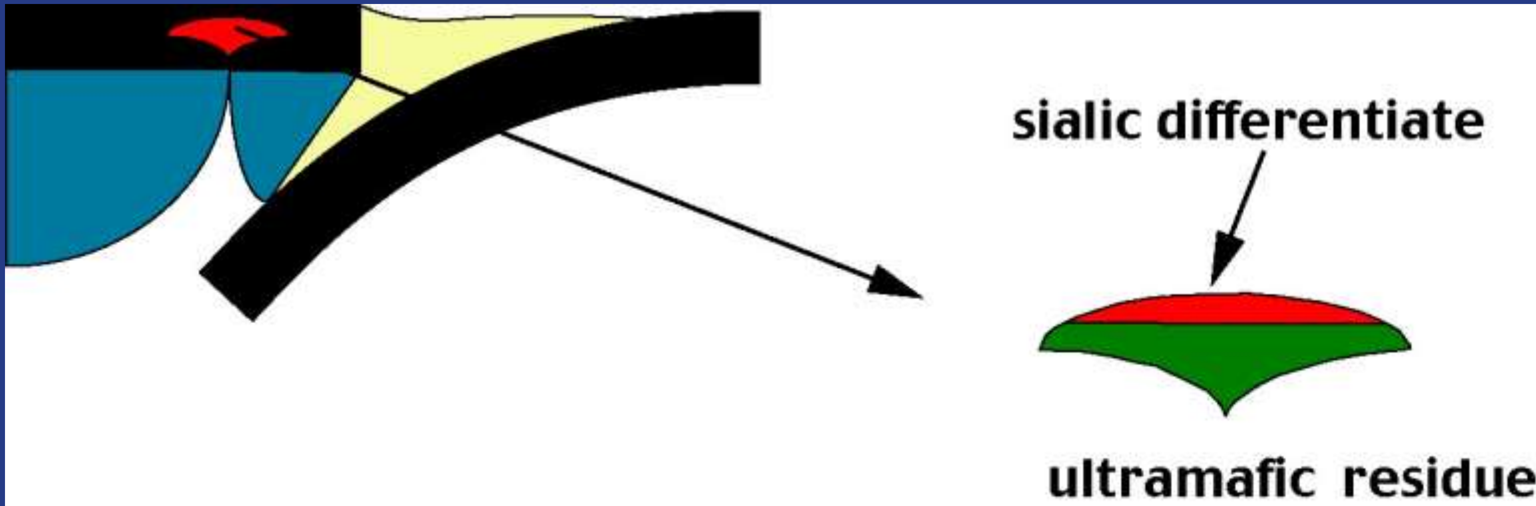
Sima is made up of the first syllables of silicon and magnesium and designates the silicon and magnesium rich part of the earth’s rocky rind.

Today sial corresponds to the continental crust and sima corresponds to the oceanic crust and the entire mantle.

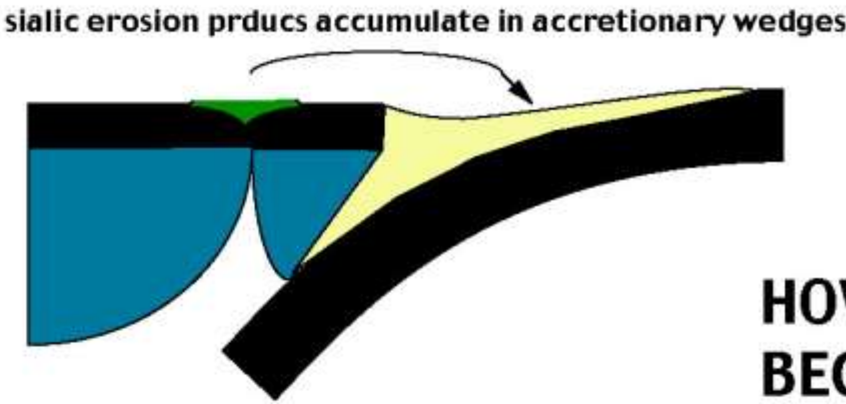



The interior of the earth

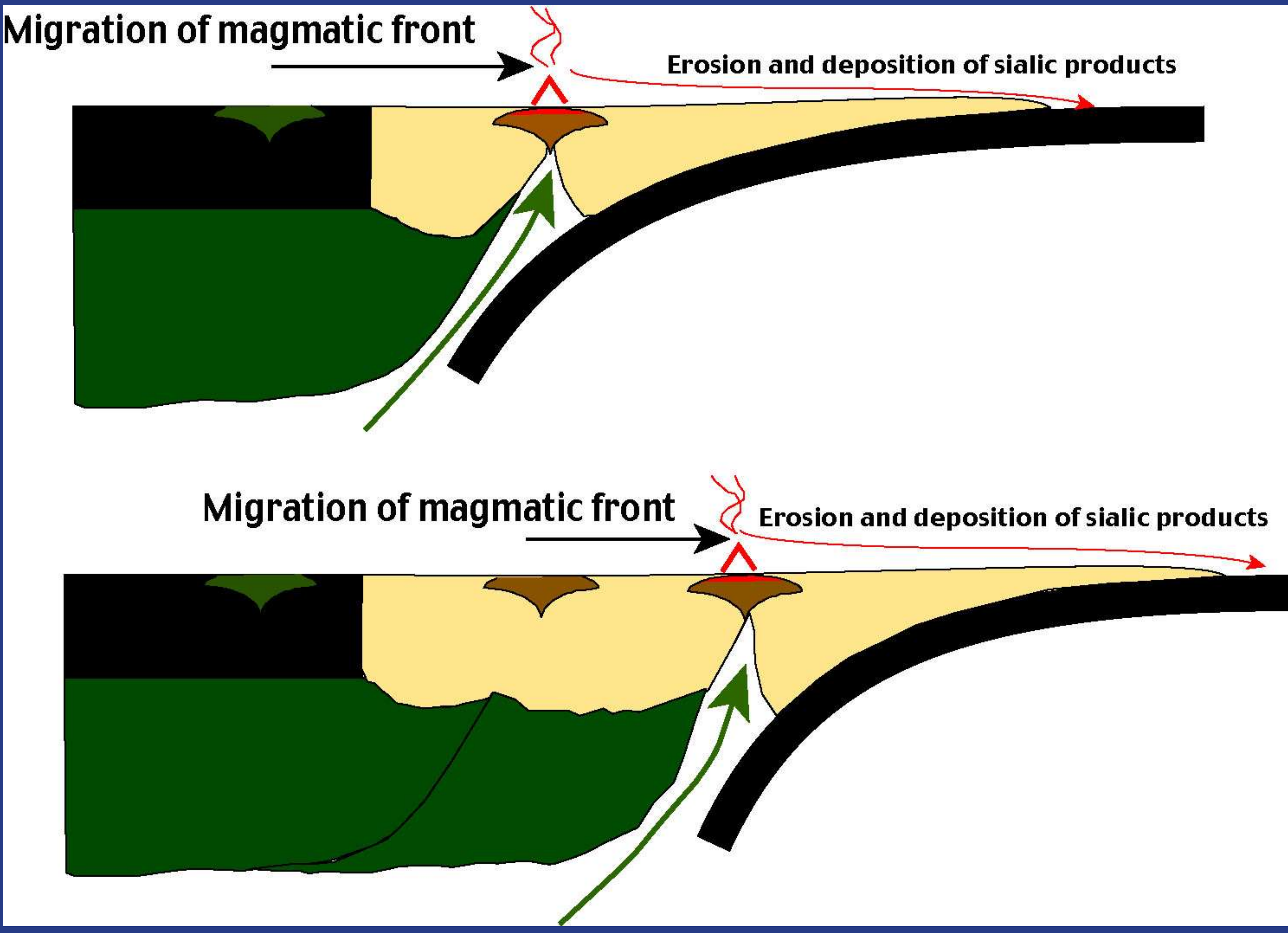
(From Kevin Burke written comm.). Everything that is left white consists of ultramafic rocks!




## DIFFERENTIATING MAFIC PLUTON



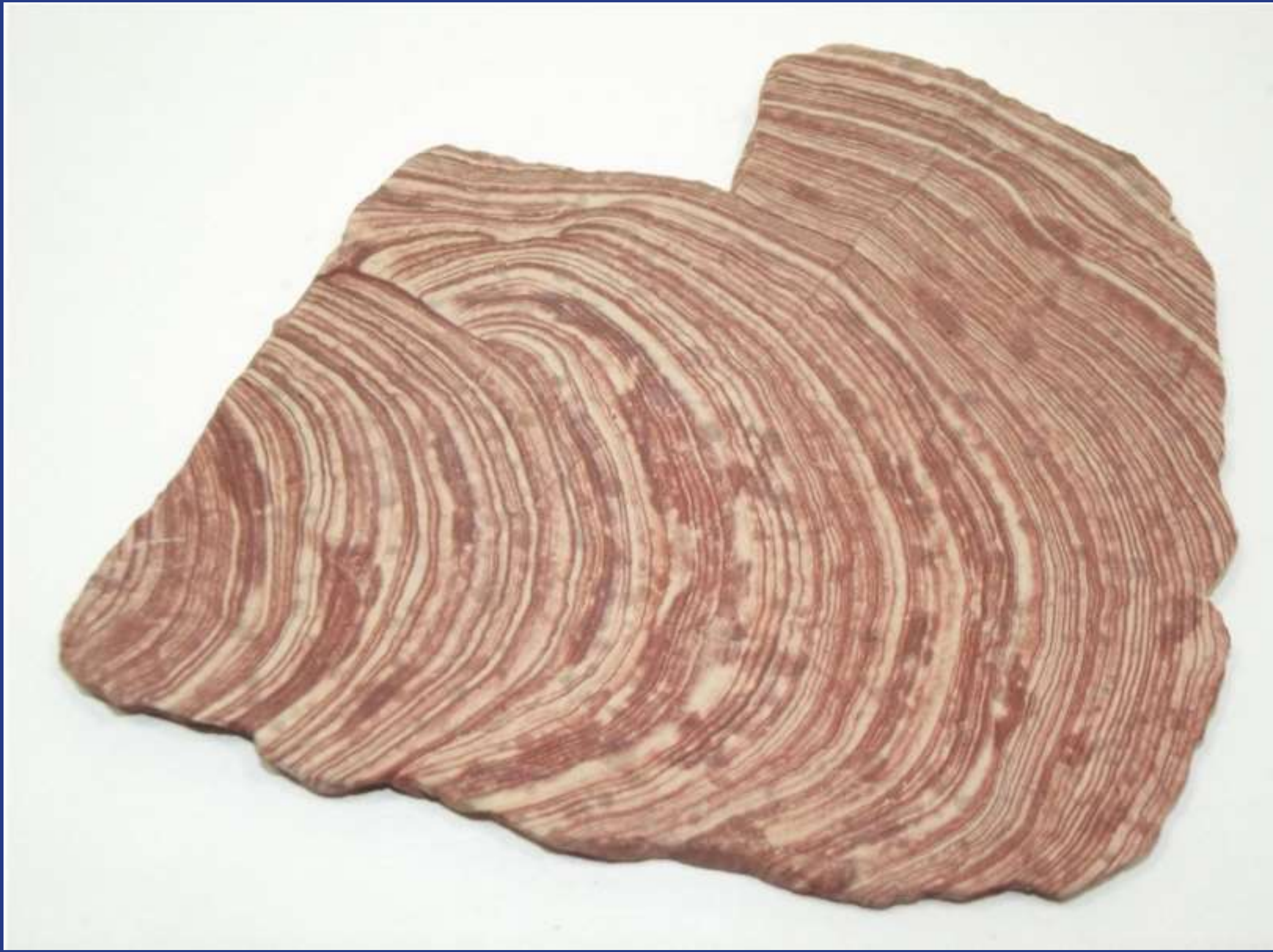

## HOW ACCRETIONARY WEDGES BECOME SITES OF ENRICHMENT OF SIALIC CRUSTAL MATERIAL


Migration of magmatic front
Erosion and deposition of sialic products
Migration of magmatic front
Erosion and deposition of sialic products

If fractional crystallisation or continental melting goes very far, they may generate rhyolites, rocks whose $SiO_2$ content is more than 63%, typically more than 69%.

Rhyolites are igneous rocks with about 60% potassium feldspar (usually sanidine) and some plagioclase (usually in a ration of 2:1), 30% quartz and 10% muscovite. Biotite and hornblende may be also present as accessory minerals. The texture can be anywhere from glassy to porphyritic. In welded tuffs, rhyolites may even become phaneritic in texture.

Rhyolite from New Zealand showing flow structures.

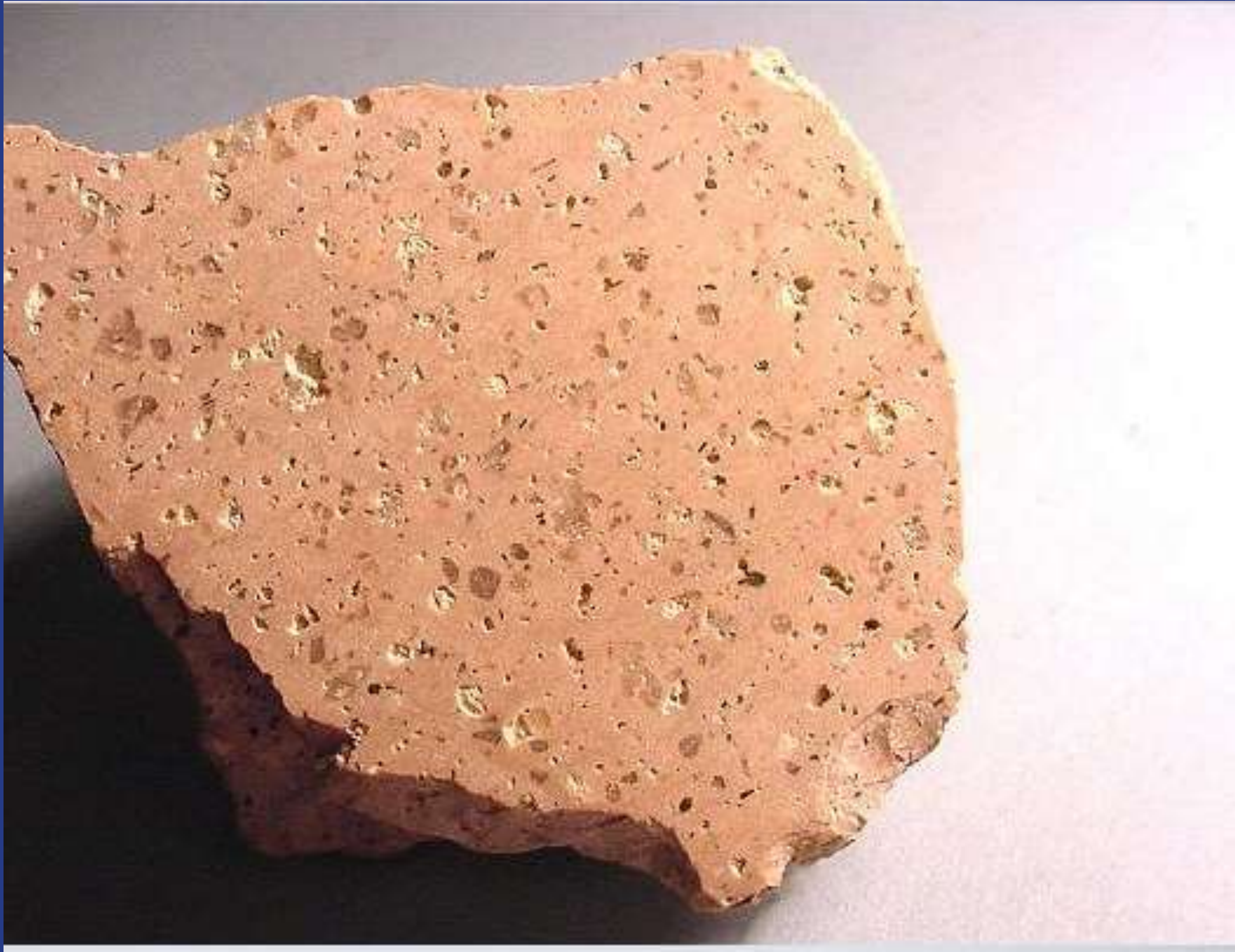


Rhyolite showing beautiful pahoehoe-type flow structures

Rhyolite

Rhyolite porphyry

Rhyolite showing flow banding: Kozushima, Japan



Rhyolite, cut surface. Note the porphyritic texture.

Among the lavas erupted by stratovolcanoes are also saturated volcanic rocks such as trachytes and alkalic volcanic rocks such as phonolites and carbonatites.

Trachyte is essentially a sanidine rock with some plagioclase; quartz or feldspathoids may be also present. Its teexture may be aphanitic or porphyritic.

Porphyritic trachyte from New Zealand


Trachyte from Santa Helena Island, Atlantic Ocean, collected by Charles Darwin.

Phonolite: This is an intermediate composition volcanic rock with usually an aphanitic or porphyritic texture consisting essentially of sanidine or anorthoclase, aegirine, augite and feldspathoids.

Phonolite showing flow texture

Another hand sample of a phonolite

Carbonatite: Carbonatite is an aphanitic to porphyritic volcanic rock in which the amount of primary carbonate minerals exceed 50%. Most carbonatite are assumed to be subvolcanic because carbonatite lavas react with the atmosphere and are dissolved. Only one carbonatite volcano is known to have erupted in historical times: it is the Ol Doinyo Lengai in Tanzania.

Carbonatite

Carbonatite eruption on Ol Doinyo Lengai. The lavas look black because their temperature is about 500°C.

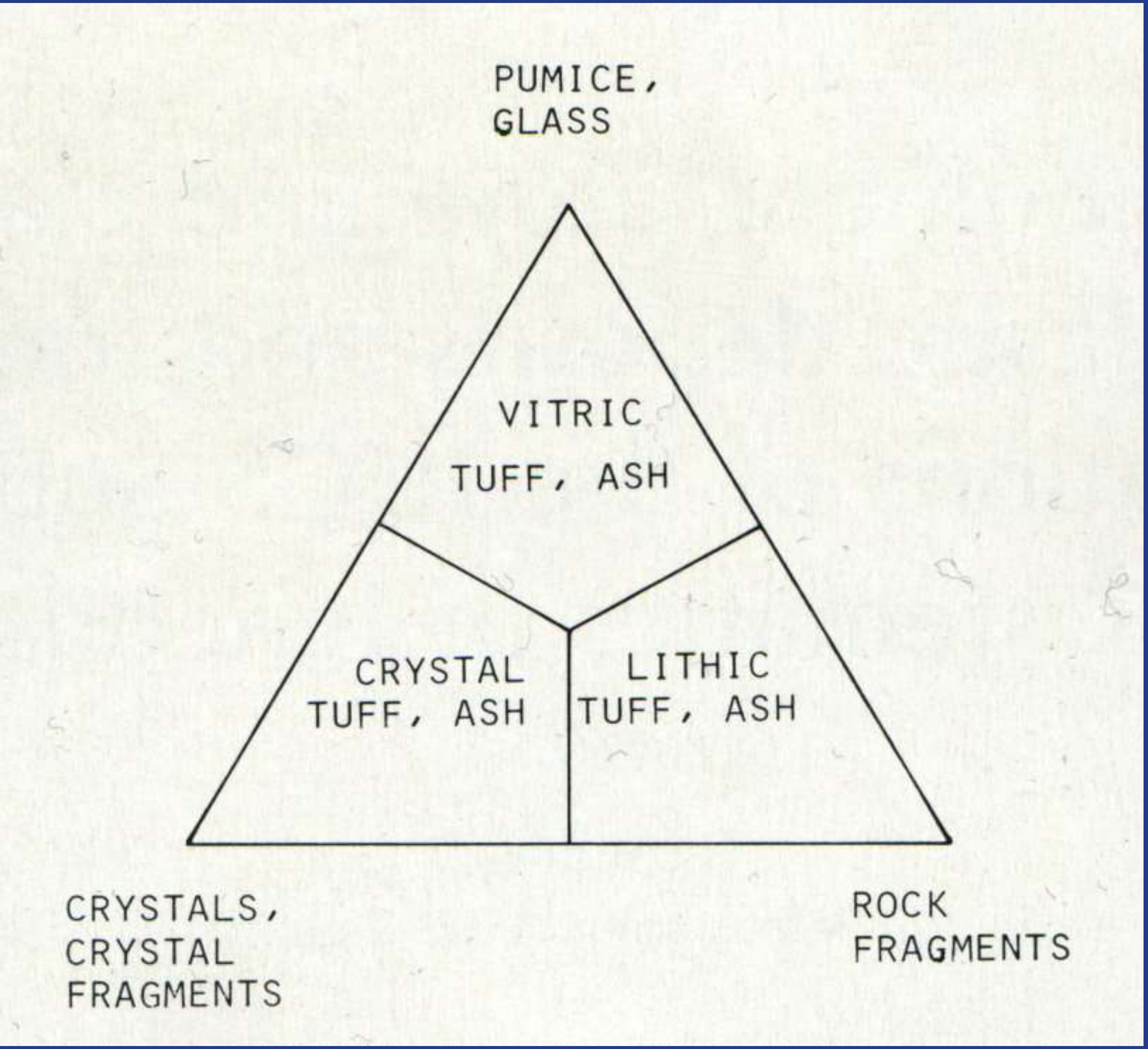
So far we have looked at the rocks erupted as lava from stratovolcanoes.

The other component they erupt is tephra. Tephra gives rise to what is called pyroclastic deposits. Pyroclastic deposits generally alternate with lavas in the main body of a stratovolcano, but let us remember Rittmann's point: most stratovolcanoes are either dominated by tephra or by lavas. A fifty-fifty stratovolcano is a rare occurrence.

So what is a pyroclast and what is a pyroclastic deposit?

The term pyroclast is another way of saying tephra. It comes from the Greek πῦρός (*püros*= fire) and κλάσις (*klasis*= a breaking).

There is great variation among geologists in using the terms pyroclast and pyroclastic.




Subdivision of tuffs and ashes according to their fragmental composition (Schmid, 1981)

In this diagram we encounter two new terms:

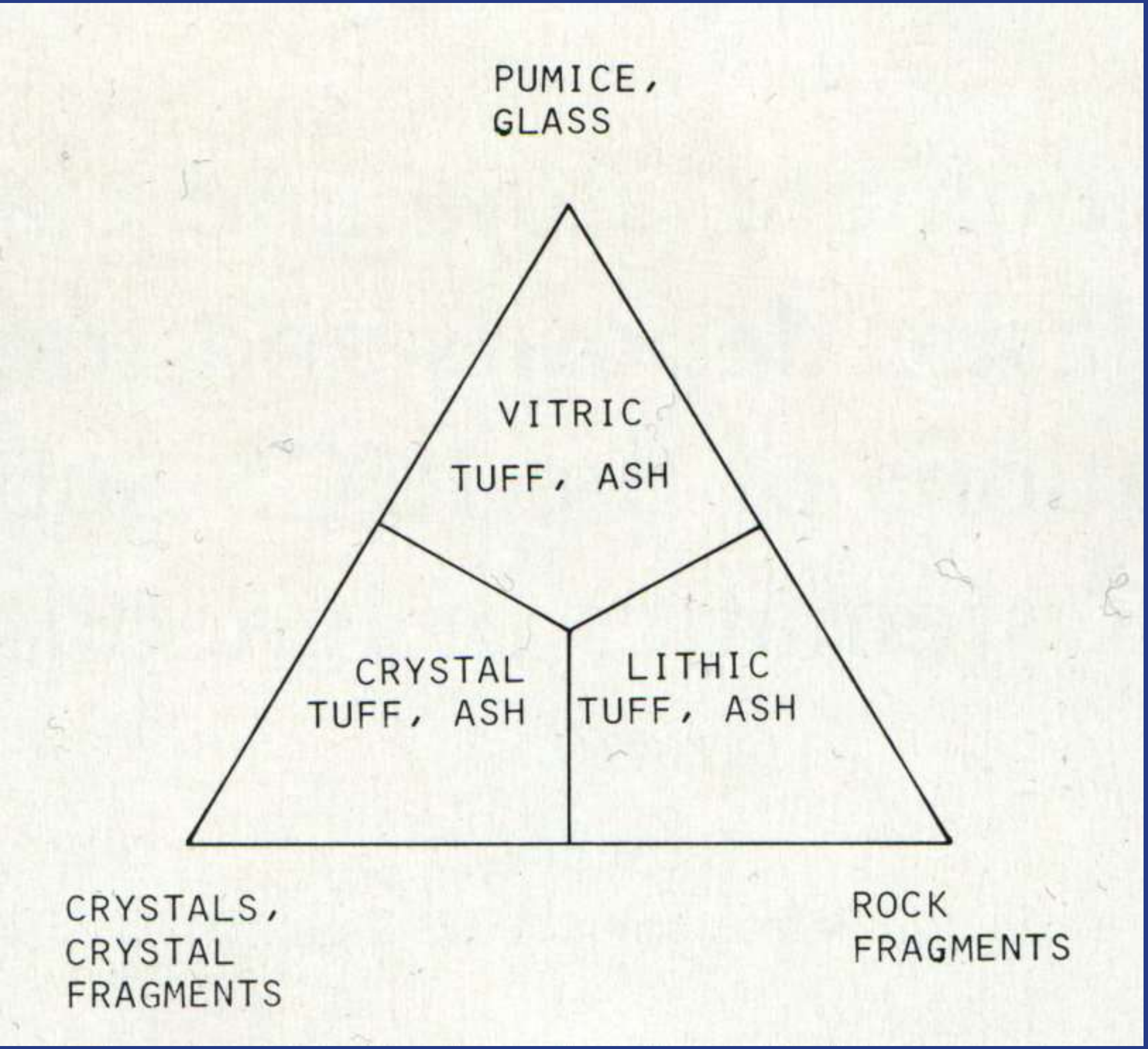
vitric

and

lithic

Vitric simply means glassy. It comes from the Latin word *vitrium* (= glass).

Lithic means stony, stone-like. It comes from the Greek λίθος (*lithos*= a stone)




Subdivision of pyroclasts according to their fragmental composition with no size implication (Schmid, 1981)

TABLE 1. GRANULOMETRIC CLASSIFICATION OF PYROCLASTS AND OF UNIMODAL, WELL-SORTED PYROCLASTIC DEPOSITS

| Clast size (mm) | Pyroclast | Pyroclastic deposit | |
|---|---|---|---|
| | | Mainly unconsolidated: tephra | Mainly consolidated: pyroclastic rock |
| 64 mm | Bomb, block | Agglomerate, bed of blocks or bomb, block tephra | Agglomerate, pyroclastic breccia |
| 2 mm | Lapillus | Layer, bed of lapilli or lapilli tephra | Lapilli tuff |
| 1/16 mm | Coarse ash grain | Coarse ash | Coarse (ash) tuff |
| | Fine ash grain (dust grain) | Fine ash (dust) | Fine (ash) tuff (dust tuff) |

Classification of pyroclasts according to size and the deposits they give rise to (from Schmid, 1981)

Volcanic bombs from the Nemrud and the Tendürek volcanoes, eastern Turkey

Lapilli from the Nemrud volcano, eastern Turkey


Volcanic ash from the Merapi (left) and the Kelud (right) volcanoes, Java, Indonesia.


Agglomerate deposits, latest Cretaceous (65 ma), northern entrance to the Bosphorus, İstanbul, Turkey


2009/06/06 12:52


The Asian Symplegades (clashing rocks): Bay of Kabakos, northern Bosphorus, İstanbul, Turkey


Alternating agglomerate and ash layers of latest Cretaceous age (65 ma), Anadolu Feneri, İstanbul, Turkey


Alternating ash and agglomerate layers, near Poyrazköy, north of the Bosphorus, İstanbul, TURKEY


Andesite (with columnar jointing) and agglomerate of late Cretaceous age (65 ma):
Gulf of Kabakos, northern Bosphorus, İstanbul, Turkey


Columnar andesite-agglomerate contact: Bay of Kabakos, north of the Bosphorus, İstanbul, Turkey


Agglomerate/andesite contact. The andesite here is probably a dyke and not a flow, because of its cross-cutting relationship. But this still needs mapping.


A cross-section across a typical stratovolcano. Tops of layers have been eroded away. Near Rumeli Feneri, north of the Bosphorus, İstanbul, TURKEY


North-northwest-dipping agglomerates of the Bosphorus volcano. Around Poyrazköy.


Lower Miocene ( about 20 ma) agglomerates west of Assos.

Tuff layers, Nemrud Stratovolcano, eastern Turkey

A “bread-crust” bomb in the tuff deposits of
the Nemrud volcano, eastern Turkey

Recent agglomerates in the caldera of the Nemrud volcano, eastern Turkey.

How do pyroclastic deposits form?

There are two ways:

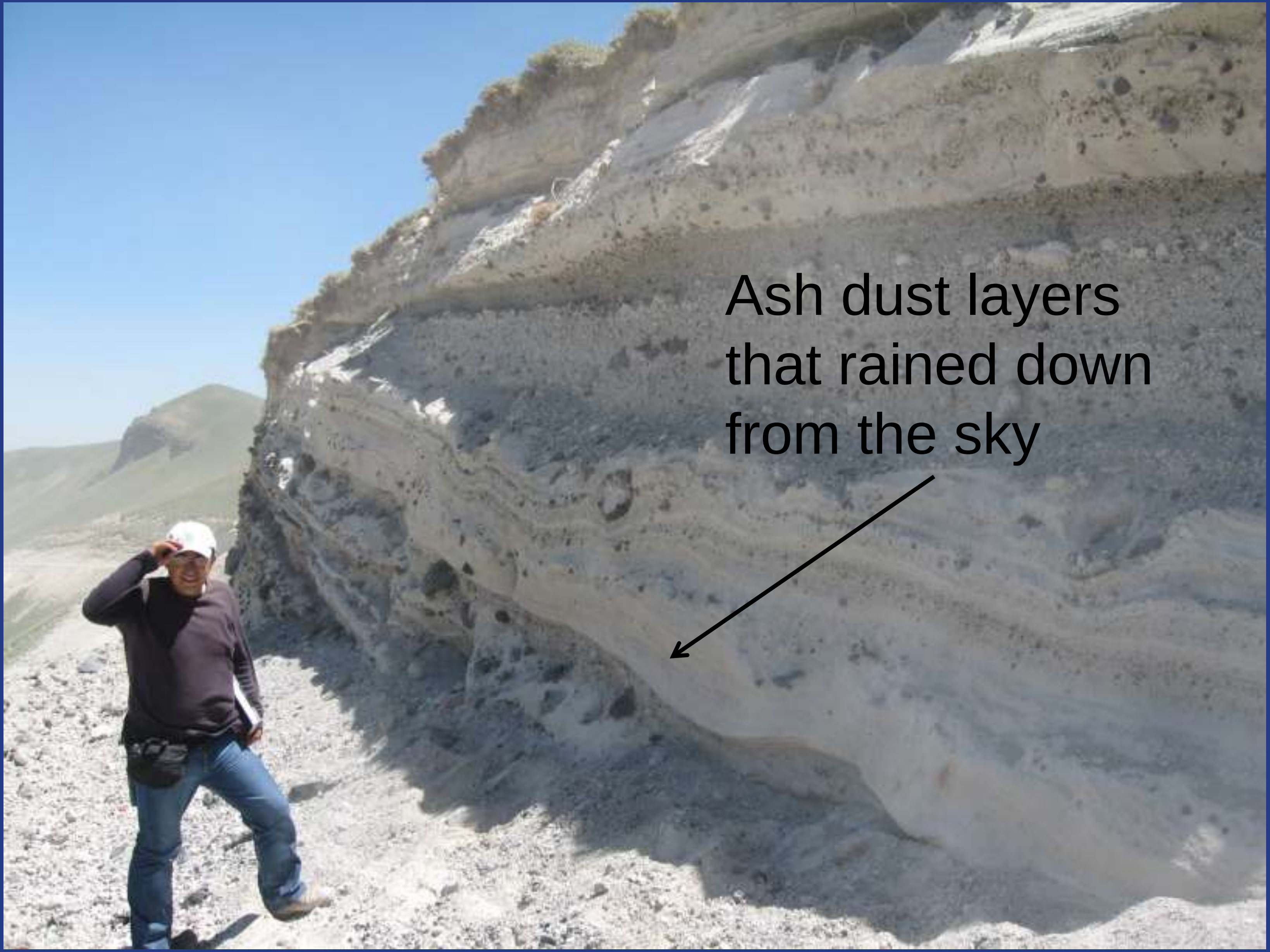
1. By falling out of the sky (settling)
2. By flowing
3. Flowing can be divided into two:
   a. Flow in gaseous form
   b. Flow in liquid form

# Falling out of the sky

Krakatoa, Indonesia: Tuff “rain” on the right.

Krakatoa: ash falling out of the sky

Krakatoa: ash fall



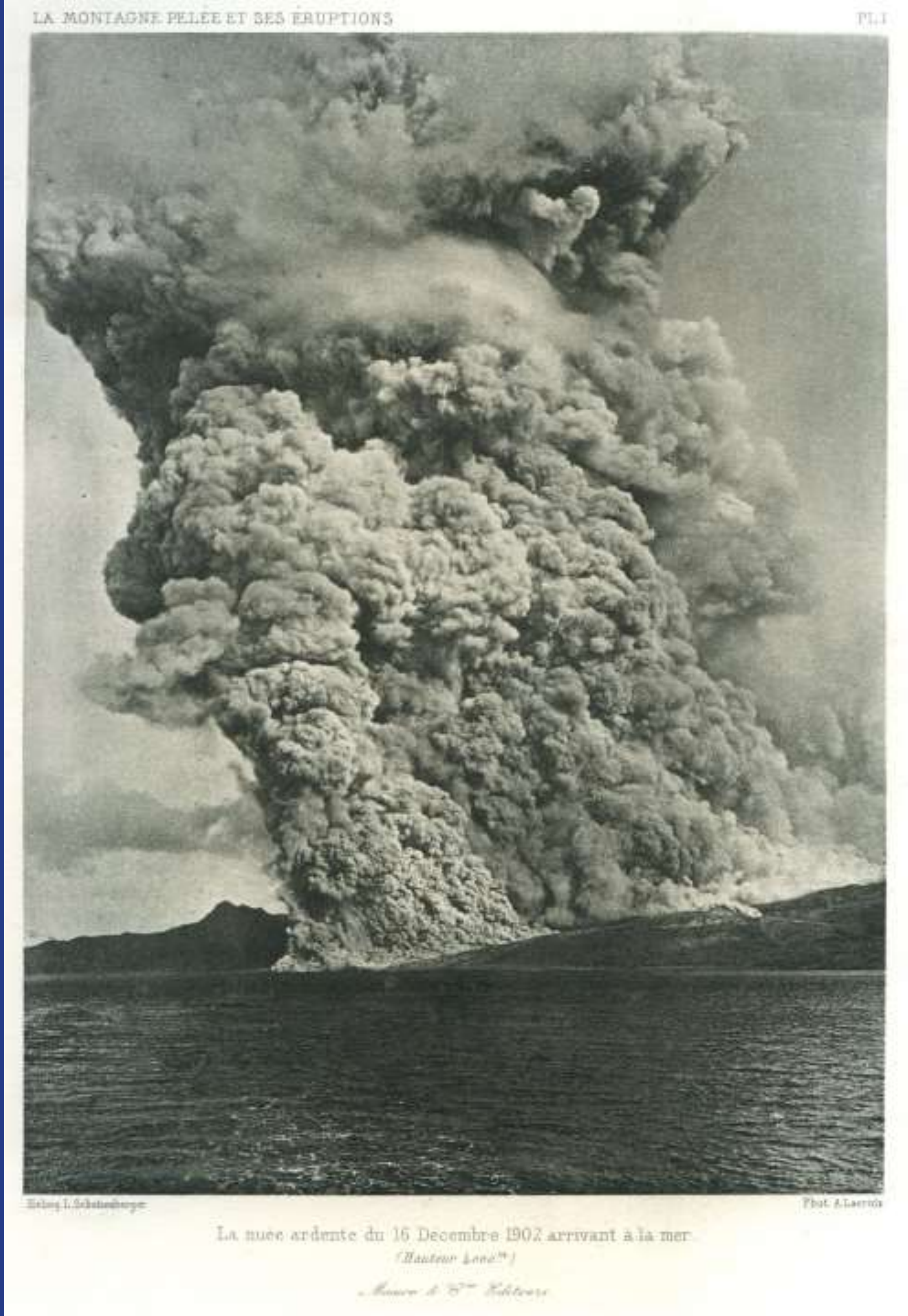

Ash fall tuffs on the Nemrud volcano, Turkey

Depositing pyroclastics by flow:

1. In gaseous medium:

Hot ash builds glowing ash clouds (*nuée ardente*) that descend down the slopes of stratovolcanoes with great speed.

*Nuée ardente* descending down the flank of Mayon, Philippines.

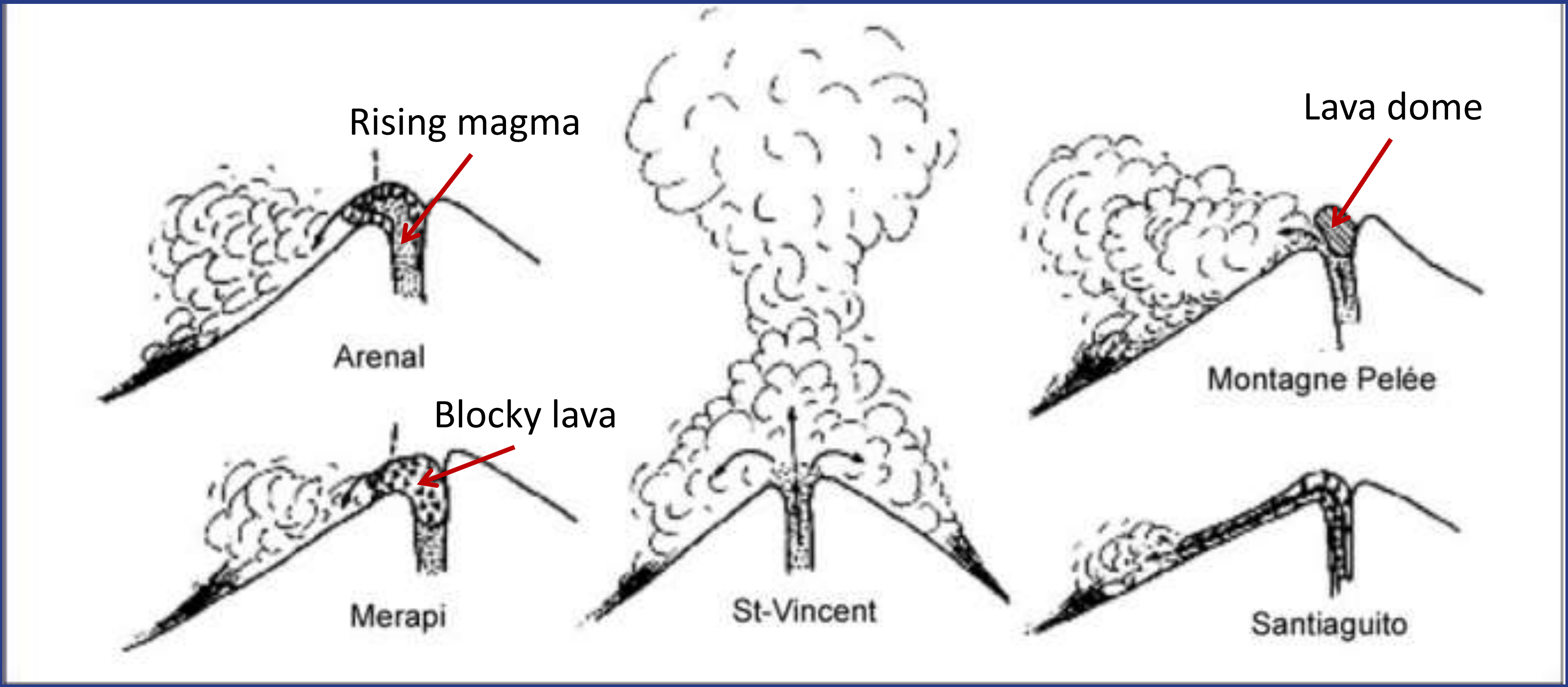



The term *nuée ardente* was introduced into geological terminology by the great French petrographer Albert Lacroix in his 1904 book describing the catastrophic eruption of Mt. Pelée on the island of Martinique in the Caribbean in 1902.

This picture showing the *nuée ardente* of 16$^{th}$ December 1902 form the frontispiece of that famous book.

The *nuée ardente* descends along the slope of the volcano of Mount St.Helens, USA on 7th August 1980

*Nuée ardente* coming down the volcano of la Soufriere on the island of Monserrat, the Caribbean.




Various ways of making *nuée ardente*

The destruction of Pompeii and Herculaneum by the British painter John Martin. Notice the raining ash.

The *nuée ardente* may move with a speed of some 700 km/hour and may reach temperatures of some 1000ºC. They are among the most destructive of a volcano's effects.

When the *nuée ardente* settles, it can create what is known as welded tuffs or ignimbrites, because its temperature is usually higher than the melting temperatures of andesite or granite. As the incandescent ash settles, the asp particles fuse together to create a tough rock, often with a phaneritic texture, forming the welded tuff or ignimbrite.


Ignimbrite from Dalarna, Sweden

Rhyolitic ignimbrite showing porphyritic texture

Ignimbrite and porphyritic granite from the Trans-Himalaya, Tibet, People’s Republic of China

“Rheomorphic” ignimbrite from Gran Canaria, Canary Islands, Spain.

Rheomorphic means that the ignimbrite flowed after settling and led to internal deformation, i.e., formed by flow.

Ignimbrite sheet, Alaska

Aside from natural events, a very tragic example of a pyroclastic flow is what happened on the 11th of September, 2001. Huge amounts of rubble were brought up into the air as the Twin Towers collapsed, the rubble-laden air was heavier than the surrounding air, and it propagated down the streets of New York very rapidly. Some people died as a result of asphyxiation many blocks away, because people's lungs can't cope with very many particles in the air they breathe. From the point of view of fluid mechanics, the questions that were of interest were how quickly the concentration of particulates would decrease, and also how far would the flow travel. It didn't go all the way to Upper Manhattan, but it did go quite a way.

When the twin towers collapsed after the 11th September 2001 attack on the World Trade Centre in New York City, the dust created by the collapse of the buildings behaved just like a *nuée ardente*, except that it was not hot. Many people died of asphixiation.

What happens when a pyroclastic flow comes to sea?

*Nuée ardente* coming to sea in the la Soufriere volcano, Caribbean Sea.

*Nuée ardente* coming to sea in the Japanese island of Oyama.

# Pyroclastic Flows Entering Water

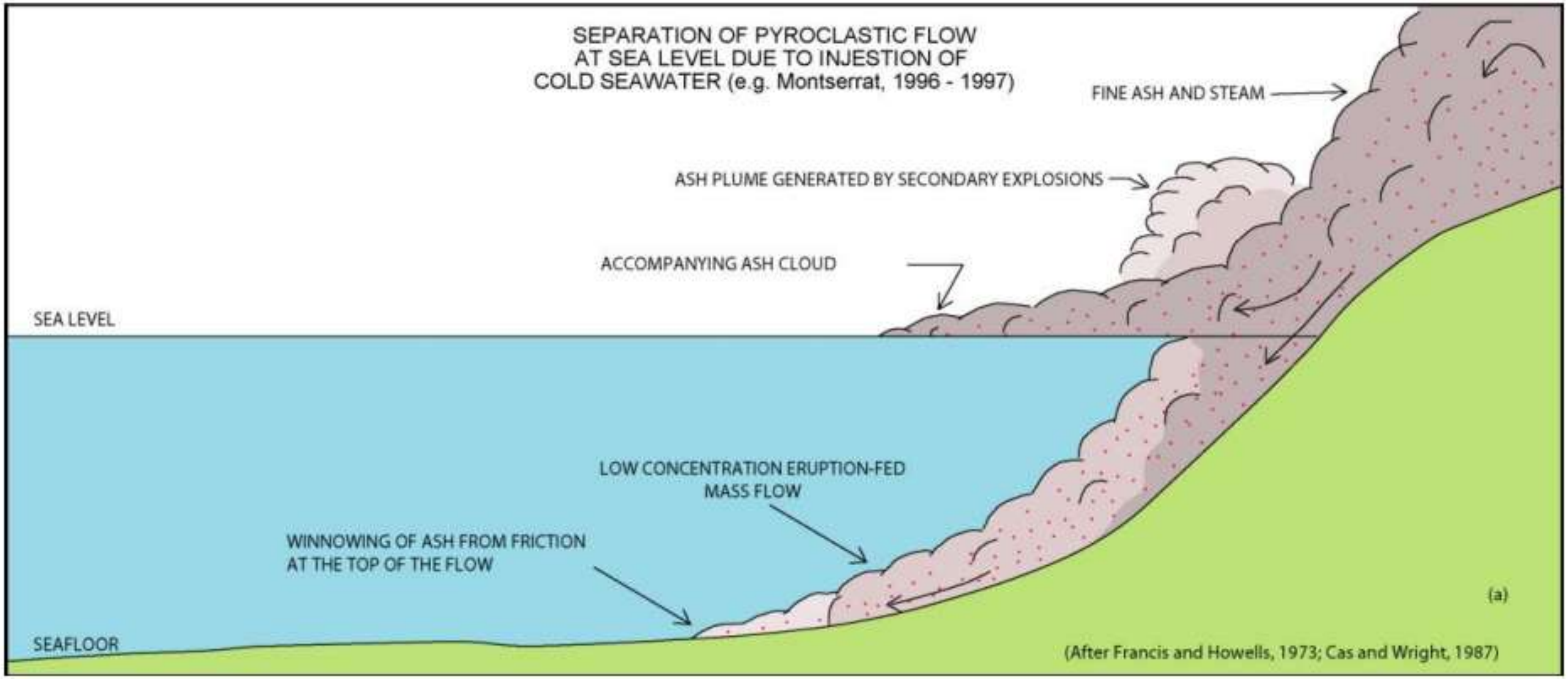



Figure 5. Behavior of subaerial pyroclastic flows entering the sea. Pyroclastic flow may a) continue to move laterally over the e pyroclastic flow may enter the sea and continue to flow underwater; and c) the pyroclastic flow may react explosively with seawater and produce widespread steam-generated ash eruptions.

From:
http://www.d.umn.edu/~rmorton/ronshome/Volcanology/Subaqueous%20Pyroclastic%20

# Montserrat (1995-present)

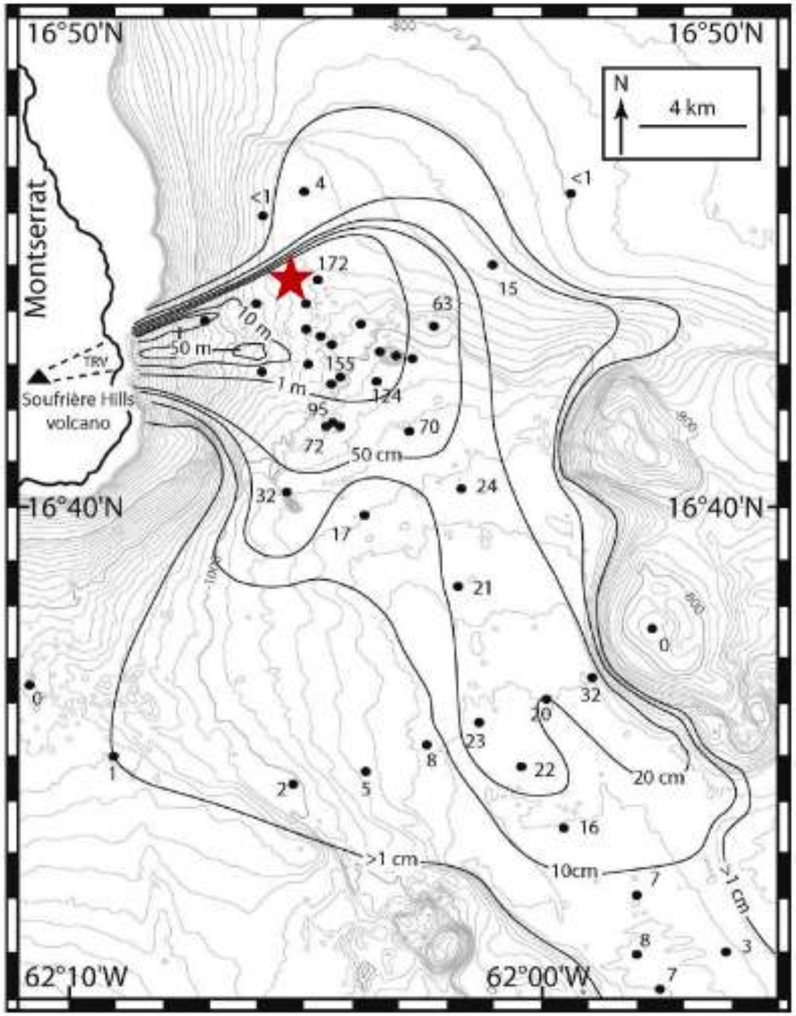



Figure 3. Isopach map showing the cumulative thickness within the 1995–2003 Soufrière Hills deposits within the Tar River valley (TRV) submarine pyroclastic fan. Contours are as marked in meters and centimeters. The core thickness measurements are given in centimeters.

(Trofimovs et al., 2006)

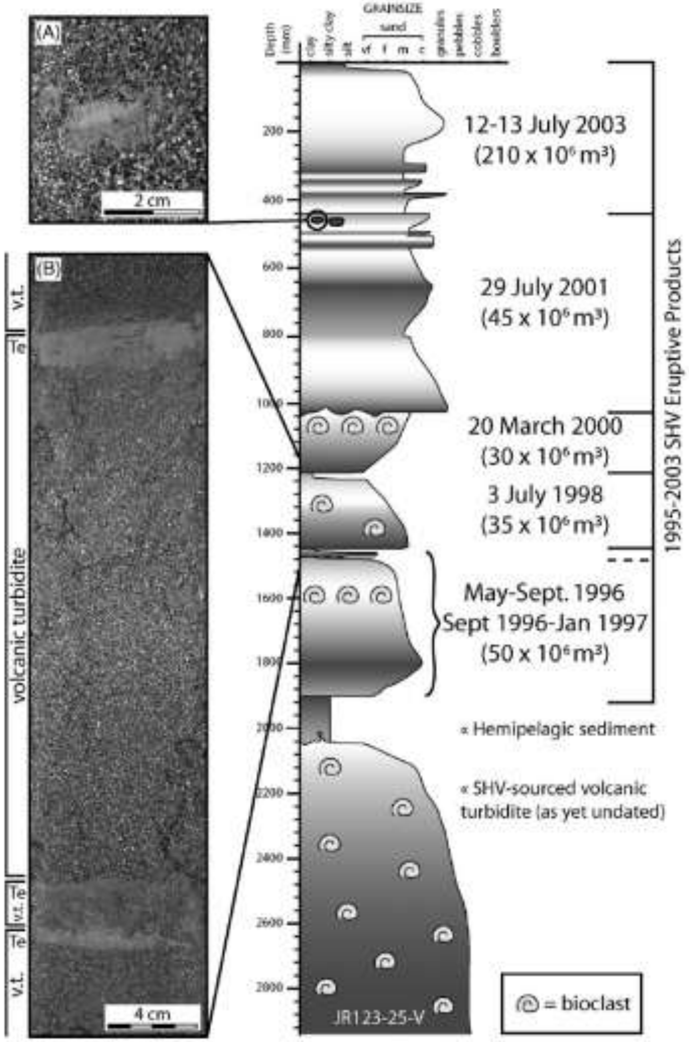
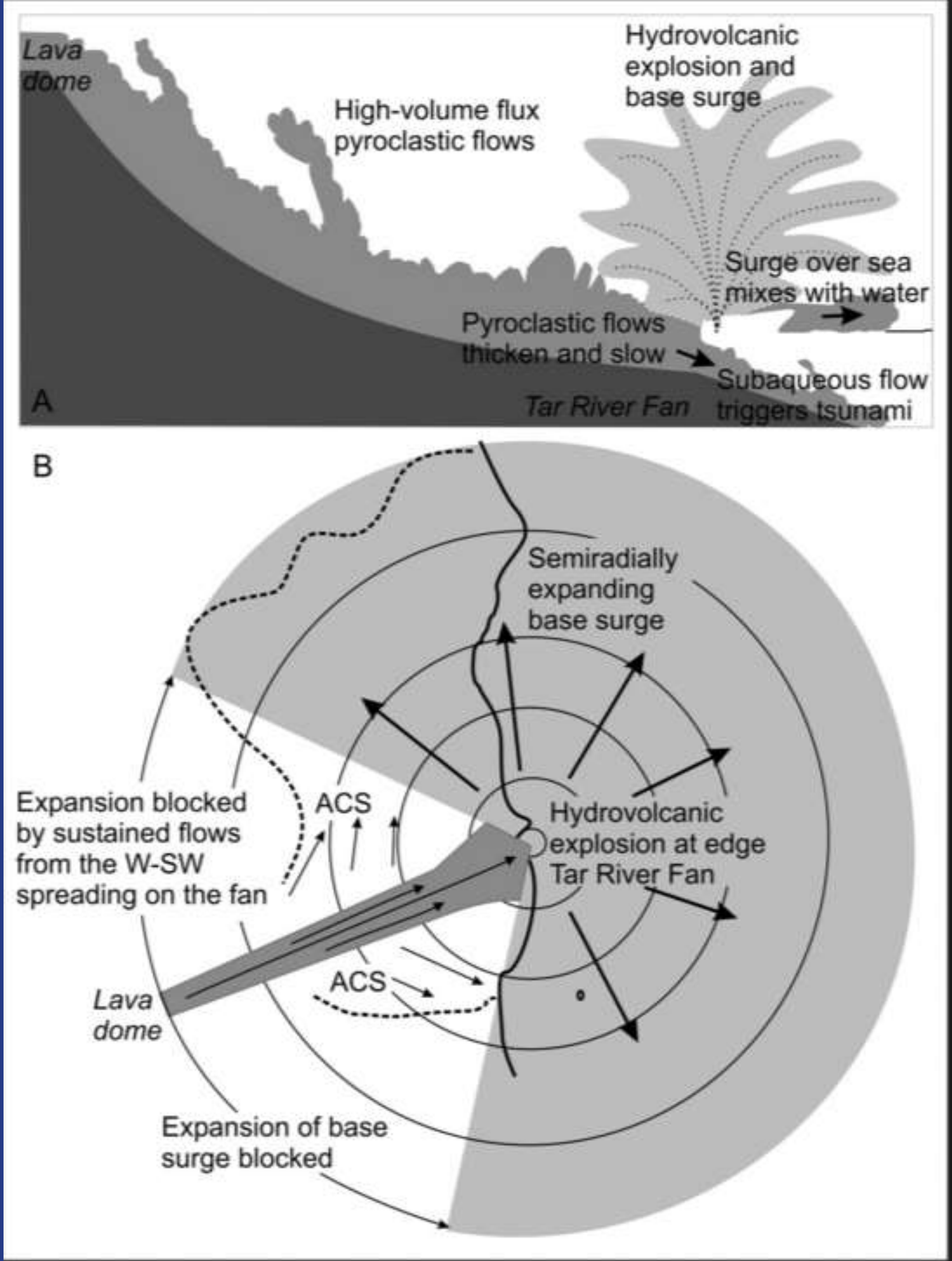



Figure 4. Stratigraphic log and photographs from the marine sediments taken from Vibrocore sample JR123–25-V (16°44′47″N, 62°05′12″W). Six volcanic turbidite units were identified as originating from the 1995–2003 Soufrière Hills volcano (SHV) eruption. (A) Centimeter-scale mud intraclast at the top of a volcanic turbidite unit (450 mm depth). (B) Series of stacked volcanic turbidite units separated by fine-ash Te layers (1190–1450 mm depth); v.t.—volcanic turbidite; vf—very fine; f—fine; m—medium; c—coarse.



Lava dome
High-volume flux pyroclastic flows
Hydrovolcanic explosion and base surge
Surge over sea mixes with water
Pyroclastic flows thicken and slow
Subaqueous flow triggers tsunami
Tar River Fan
A
B
Semiradially expanding base surge
Expansion blocked by sustained flows from the W-SW spreading on the fan
ACS
Hydrovolcanic explosion at edge Tar River Fan
ACS
Lava dome
Expansion of base surge blocked

Depositing pyroclastics by flow: 2. In liquid medium:

Lahars: are volcanic mudflows or debris flows. The term Lahar is of Javanese origin.

Definition of debris (from the French *débris*=pieces of something that is broken; remains of something that is destroyed): scattered pieces of rubbish, dump, or clastic material.

Lahars form by mixing tephra with water:

1. When eruptions melt an existing ice field or even a glacier.

2. When eruption destroys a crater lake

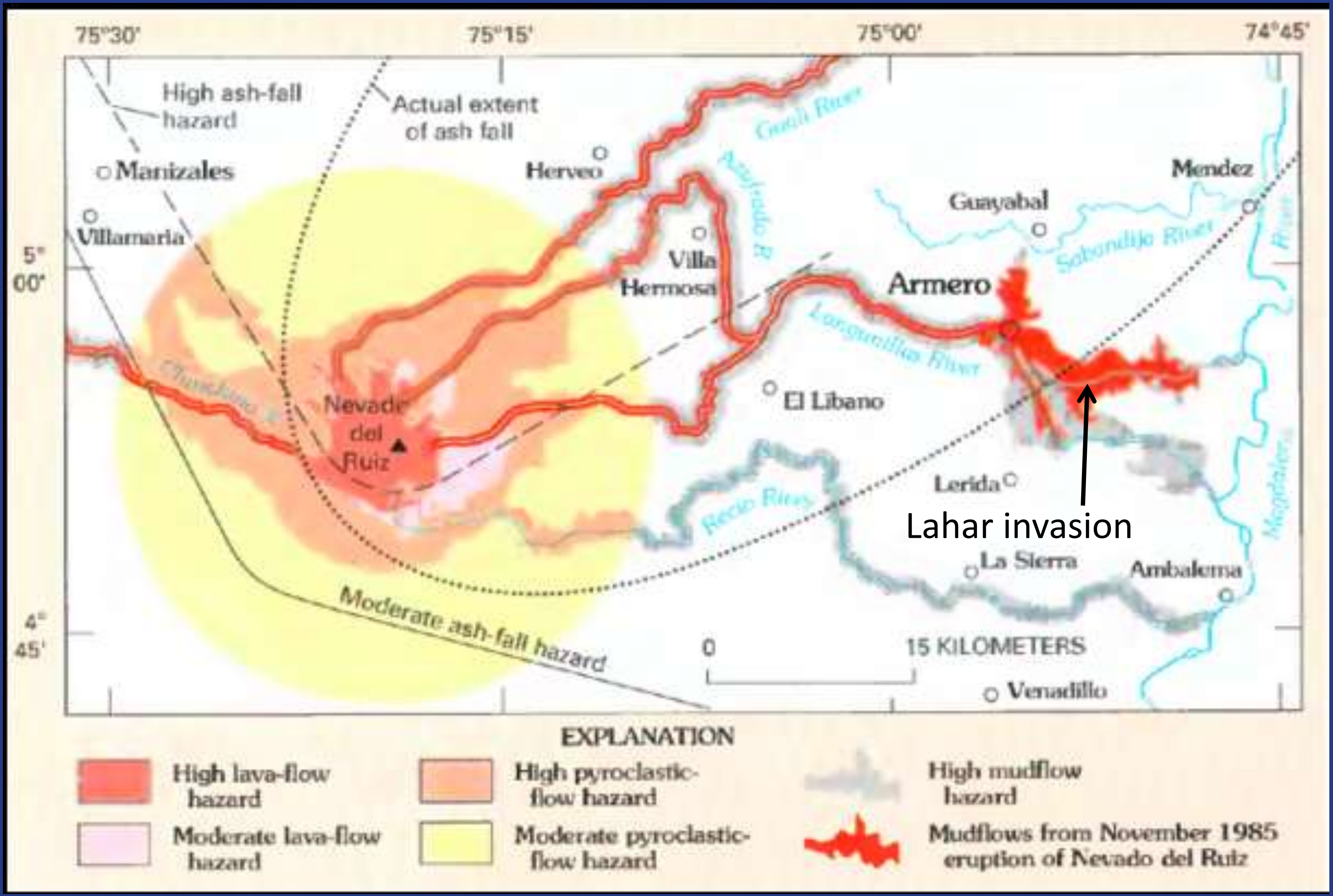
3. When eruption is accompanied by heavy rain.

4. When erupion causes landslides in moist soil.

5. Lahars usually have the consistency of wet concrete and flow like it. When flowing in rain, their viscosity decreases and they gain speed.


A lahar coming down the stratovolcano of Nevado del Ruiz in Colombia in 1985 buried the town of Armero in 5 m of mud and killed 23,000 people.


Erosion scar of the Lahar coming down Nevado del Ruiz during the 1985 eruption.




Hazard map of Nevado del Ruiz in Colombia

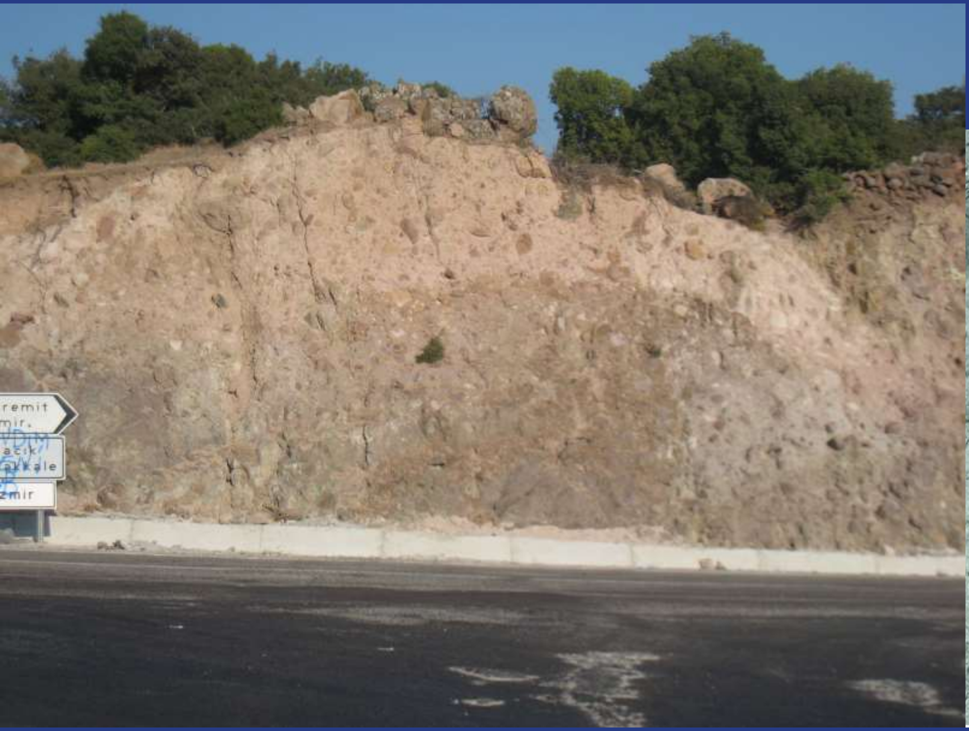
Another view of the Nevado del Ruiz lahar invasion
in the town of Armero, Columbia

The summit crater of Nevado del Ruiz before the catastrophic December eruption. Notice the snow! That is blueprint for disaster.

A part of the town of Armero after the Lahar invasion

Deposits and associated lahars from the September 1995 eruption of Mt. Ruapehu. Lahar down Whangaehu Glacier is from a syn-eruptive event created by explosive ejection of crater lake water. Photo courtesy of Lloyd Homer, GNS Science.

A lahar deposit in Chile. How do you think agglomerates originate?

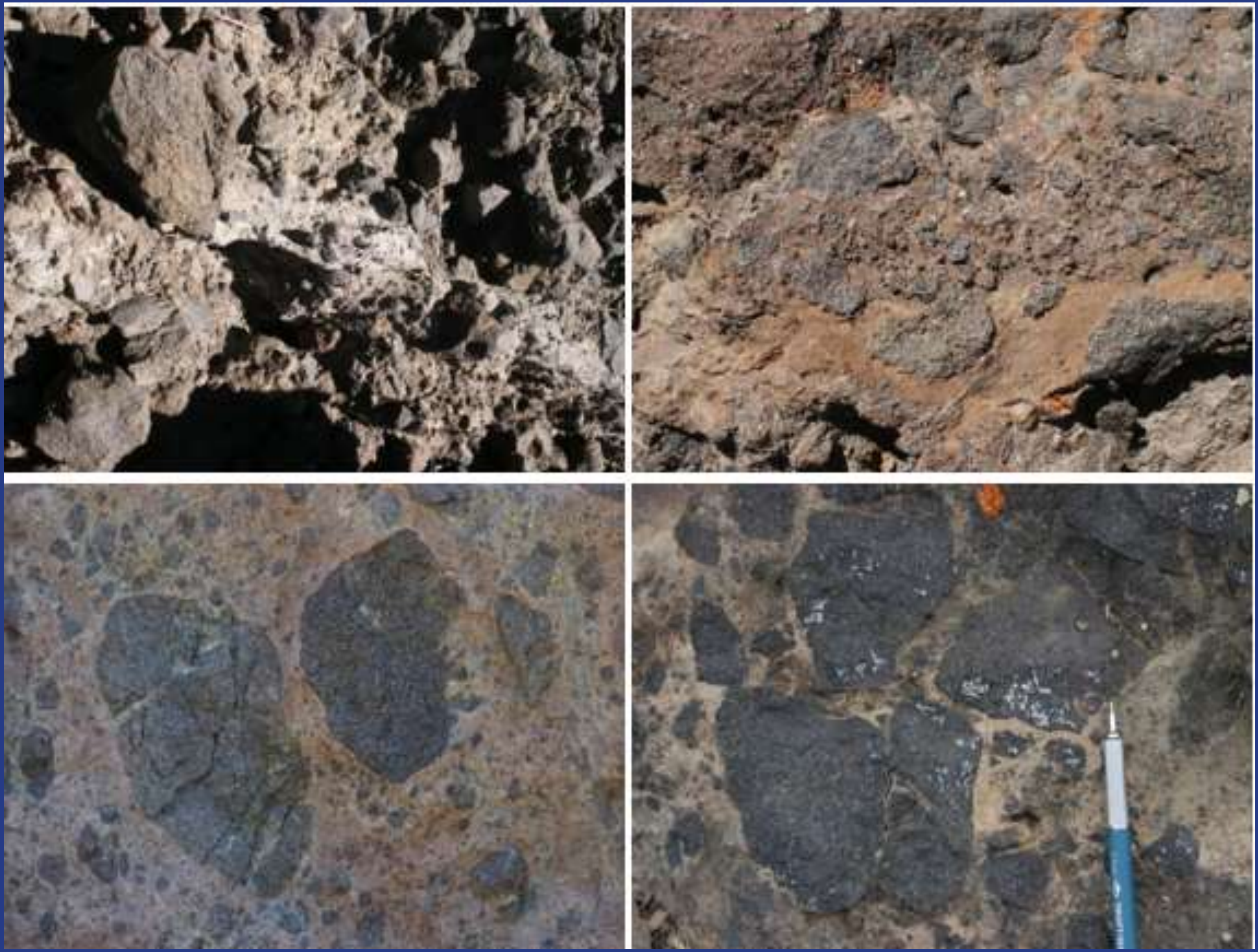


Agglomerates, west of Assos, western Turkey

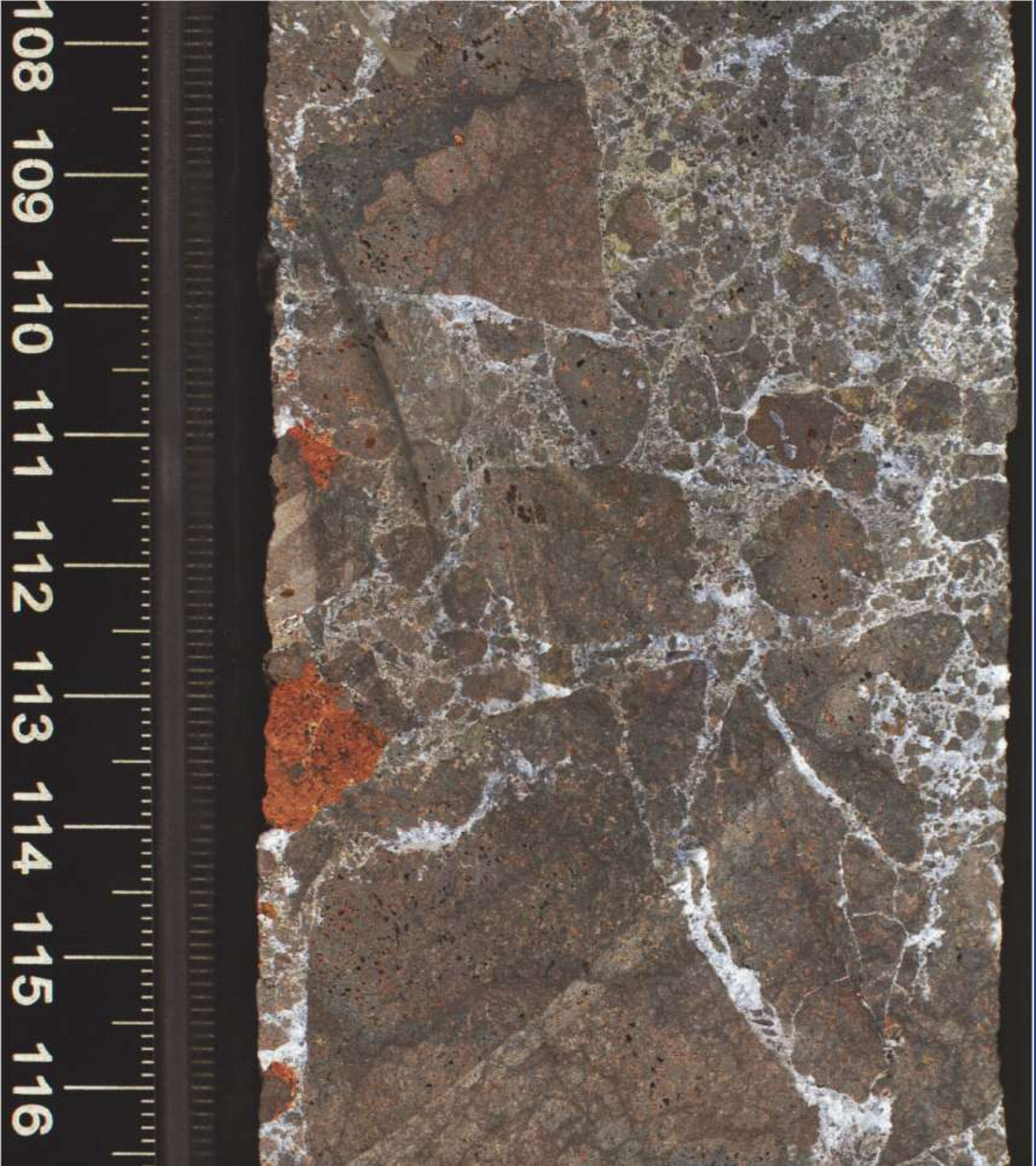
Lahar deposit, Chile


Ruapehu lahar, New Zealand. Notice the components: Ash, water and ice!

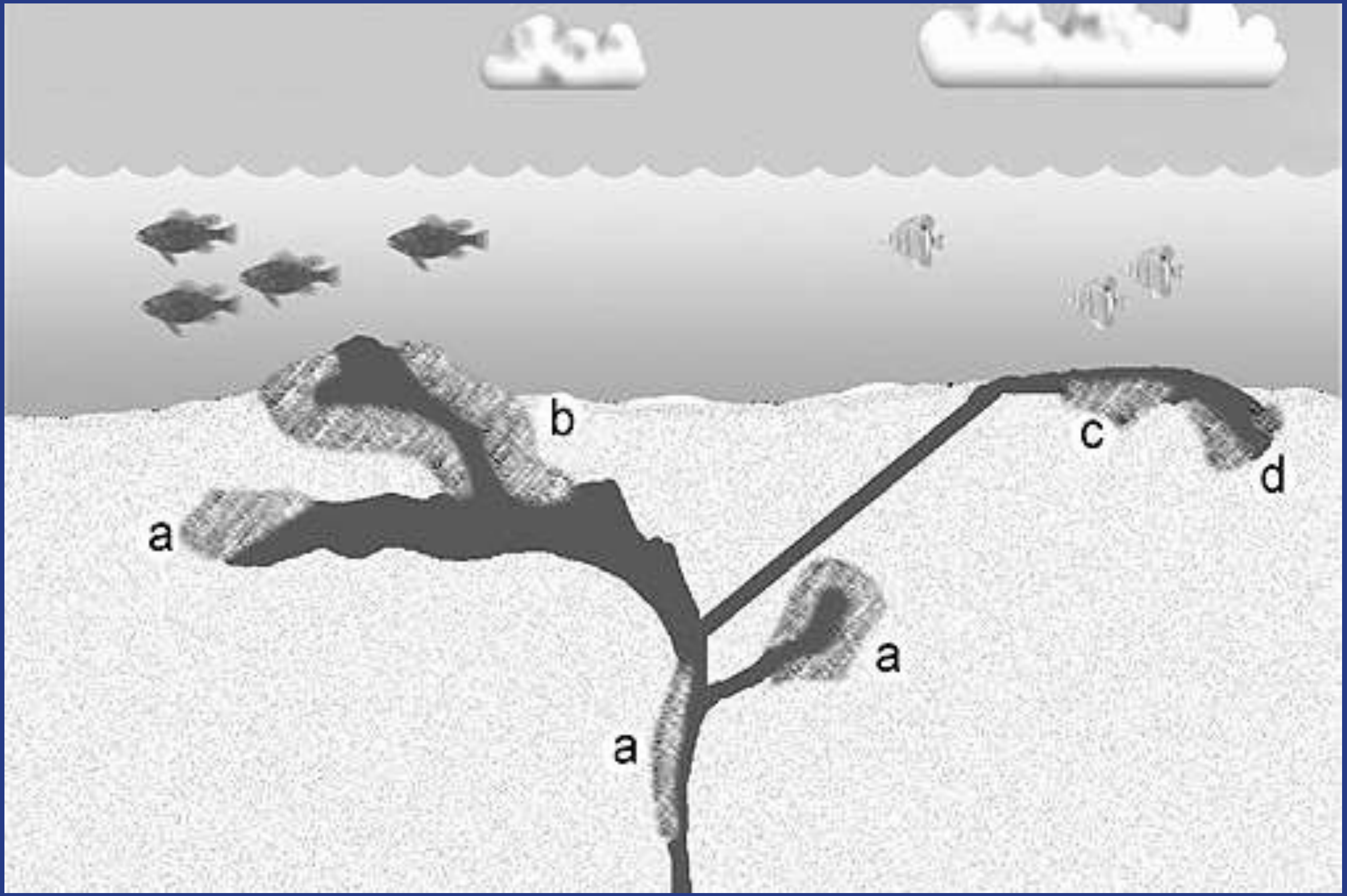
A final term that we want to learn in pyroclastic terminology is peperite. The term was introduced in 1827 by the English geologist and economist George Poulette Scrope when describing the volcanoes in Limagne, in Central France. Scrope applied it to pyroclastics with a texture resembling salt-and-pepper. He thought the texture was created when unconsolidated sediments come into contact with hot lava. Later it was thought that it was shallow intrusions into unconsolidated sediment that generated peperites. It is now generally thought that very shallow magma coming into unconsolidated sediment causes explosions and creates peperites.



Peperites, Mehrten Formation of Miocene age, California, USA

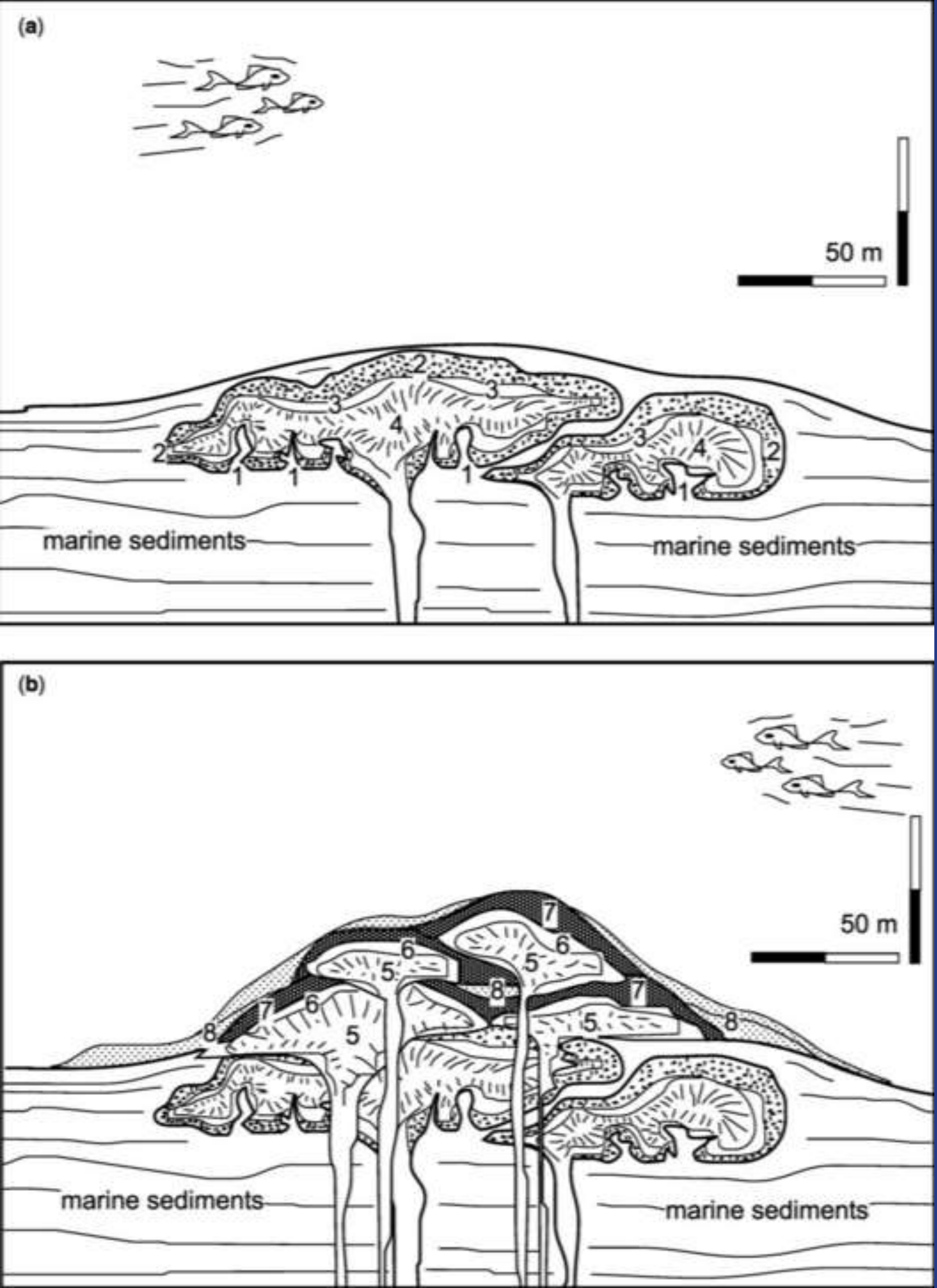



Typical peperite, from the Louisville mantle plume track in the Pacific Ocean recovered during the IODP leg 330.




Environments of peperite formation:
a: margins of dykes and other subvolcanic intrusive bodies
b: margins of partly emergent intrusions
c: bases of lava flows
d: around “invasive” lava flows.

From White, J.D.L., McPhie, J. and Skilling, I., 2000, Peperite: a useful genetic term, *Bulletin of Volcanology* v. **62,** pp.65–66.



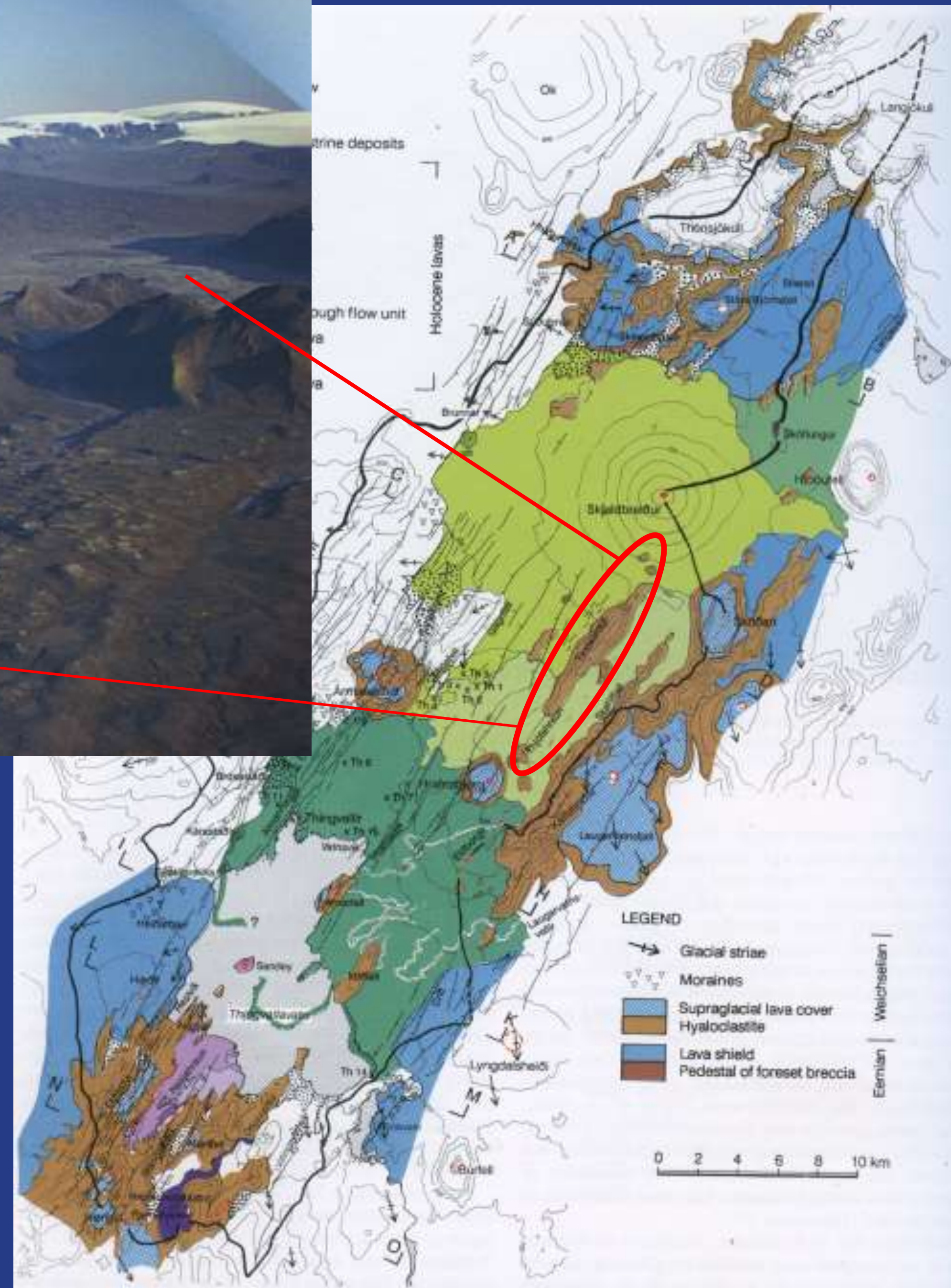

Peperites (2), hyaloclastites (7) and soft sediment deformation structures (1) in the Miocene rhyolitic dome of Pálháza, Hungary.

Hyaloclastite is a hydrated, tuff-like breccia that formed underwater at magma or lava/sediment contact. It also forms under ice sheets and generates hyaloclastite ridges.

Hyaloclastite comes from the combination of two Greek words:
ΰαλος (*uealos*=glass) and
κλάσις (*klasis*= a breaking)

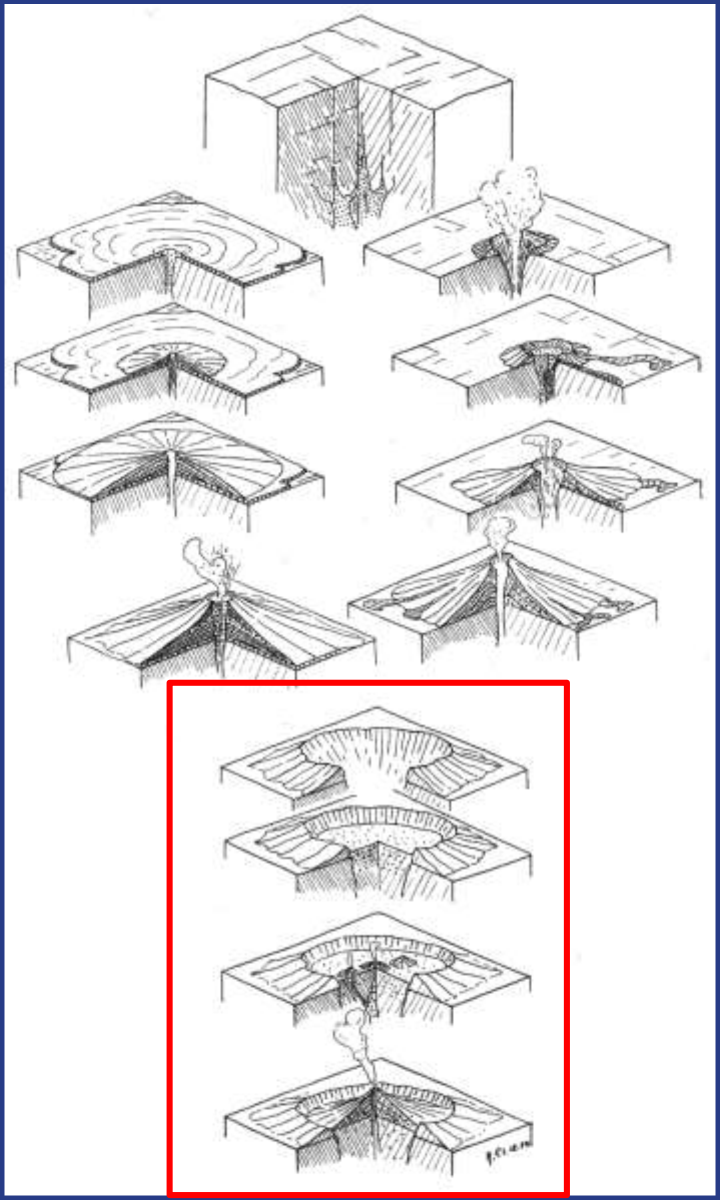
Hyaloclastite from an unknown locality

Hyaloclastite from the volcanic island of Réunion




Hyaloclastite ridges S of Skaldbreiður. These are sort of 'volcanic eskers' (View to the NNW)

Homework: Write an essay on palagonite tuff. It should be no shorter than one page and no longer than two pages.



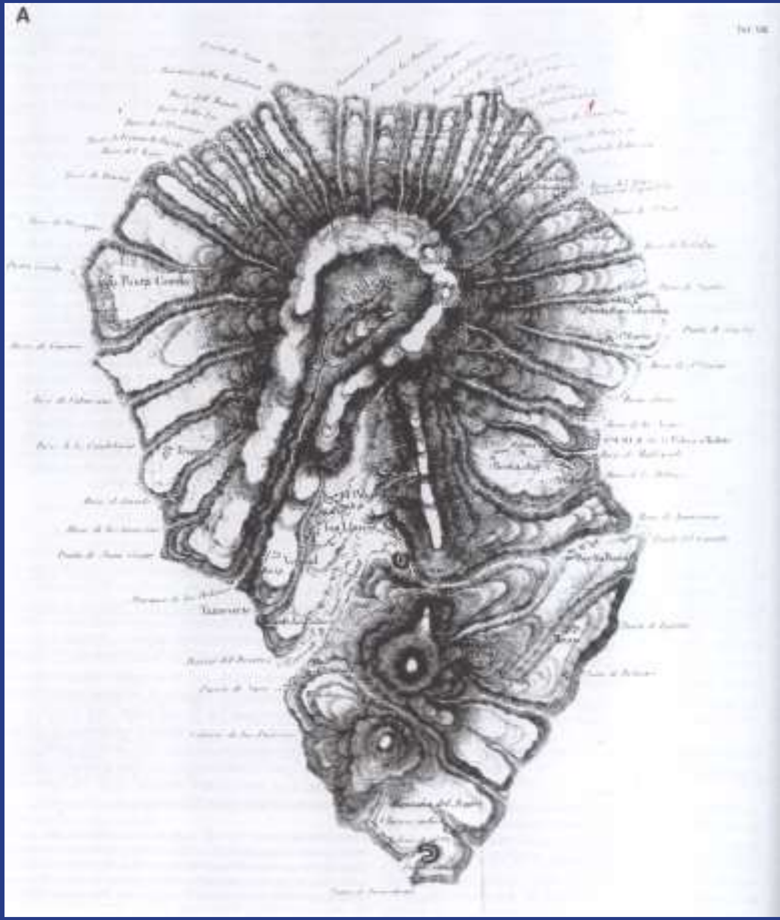

From H. Cloos 1936 *Einführung in die Geologie*

The last topic we wish to cover in our survey of igneous rocks that form at the surface of the earth is the topic of calderas. Calderas are sort of super craters that can destroy half a volcano when they form.

The word caldera comes from the Spanish and simply means a cooking pot. It was used for generations for the Caldera de Taburiente in the island of La Palma (San Miguel de la Palma)

Punta Gorda
ROQUE DE LOS MUCHACHOS
CALDERA
DE
TABURIENTE
LOMO DE LAS CHOZAS
Tijarafe
Los Llanos de Aridane
Tazacorte
El Paso
Sta Cruz de la Palma
Mazo
Fuencaliente
Punta de Fuencaliente

The term caldera was introduced into geology by the great German geologist Baron Leopold von Buch in 1815 upon his visit to the Canary Islands.




*The island of La Pálma, the Canaries*

The summit calderas of Mauna Loa

The largest of the summit calderas of the Mauna Loa

N19°26'6"
N19°25'30"
N19°24'54"
W155°17'24"
W155°16'48"
W155°16'12"
W155°15'36"
W155°15'
Kīlauea
N19°24'18"
N19°23'42"


Halema'uma'u
Crater rim
Kīlauea
caldera rim
caldera floor
Overlook crater
(summit vent)
Halema'uma'u
Crater floor
vent rim
caldera floor


Olympus Mons summit calderas

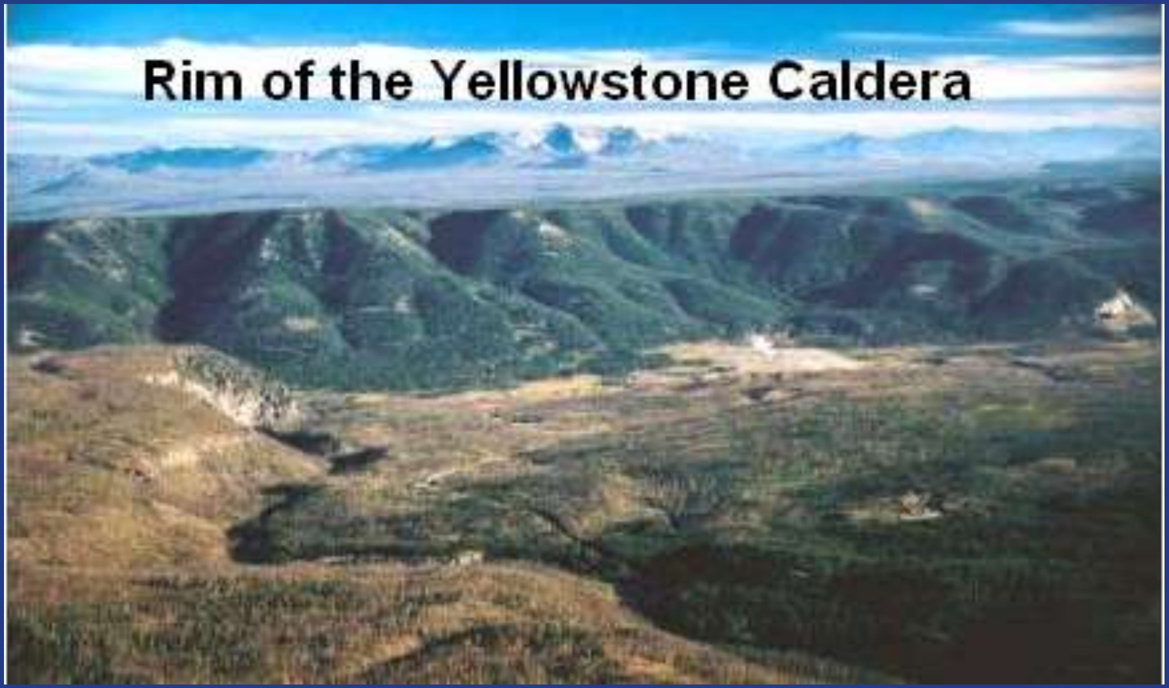

Caldera at the top of the Miyake Jima volcano, Izu Islands, Japan.

The caldera of the Nemrud stratovolcano, eastern Turkey

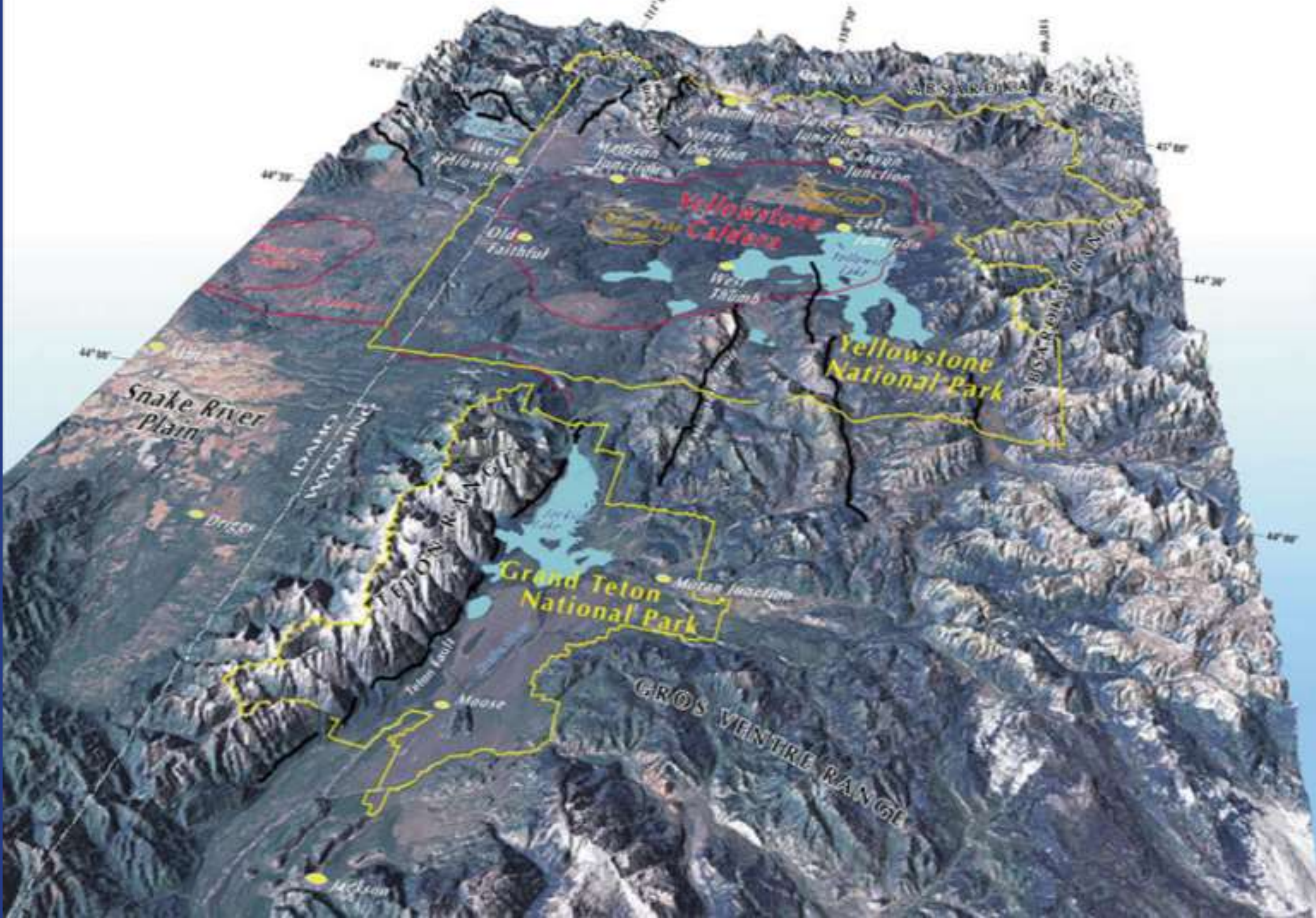
The Nemrud caldera from the ground: looking west

The northern wall of the Nemrud caldera from within the caldera. Note the layered structure.


The Yellowstone Caldera: the second largest caldera on earth, Wyoming, USA


Rim of the Yellowstone Caldera

## The Yellowstone-Teton Geologic System



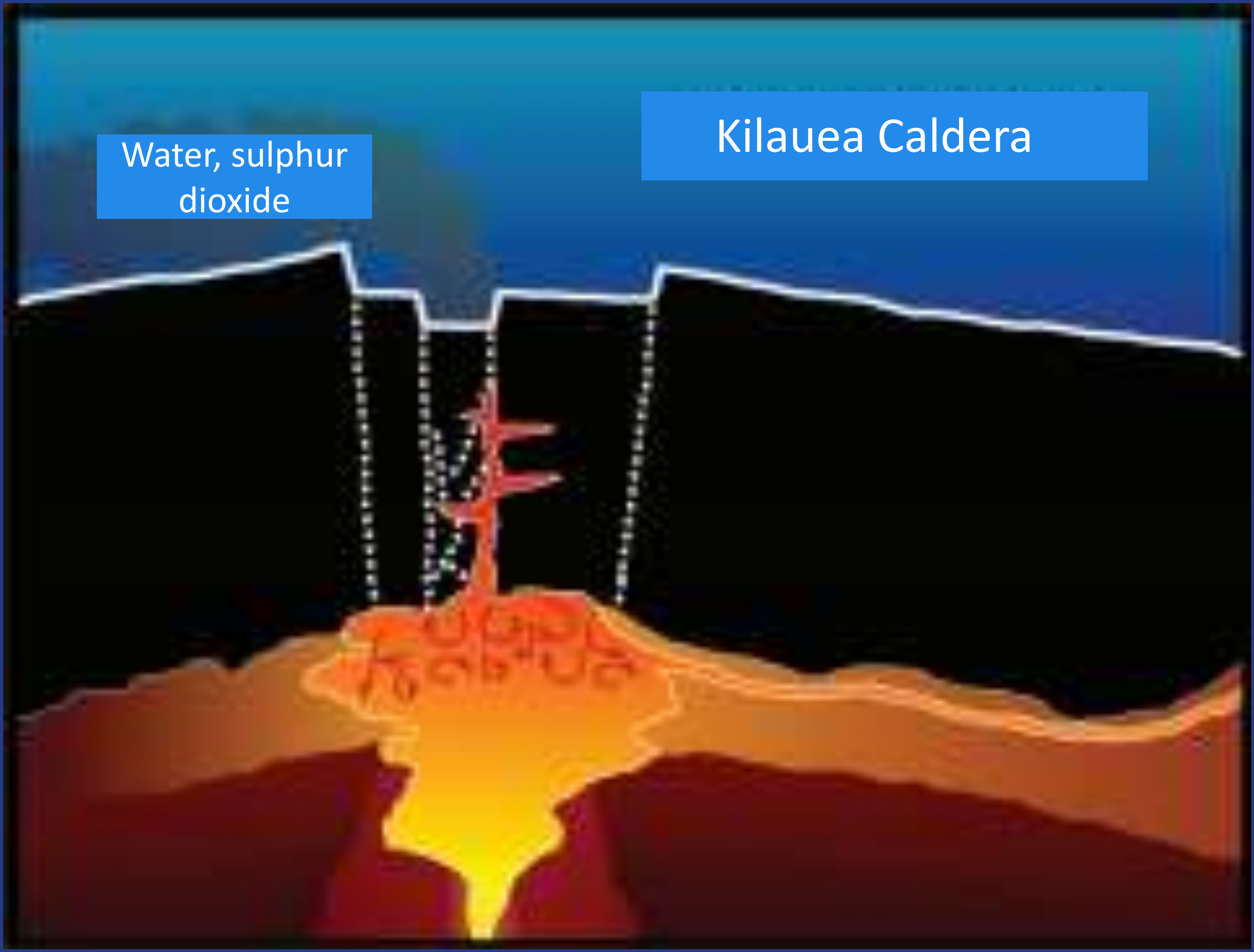
# How do calderas form?

There are two main mechanisms of caldera formation

By subsidence (Hawaiian type)

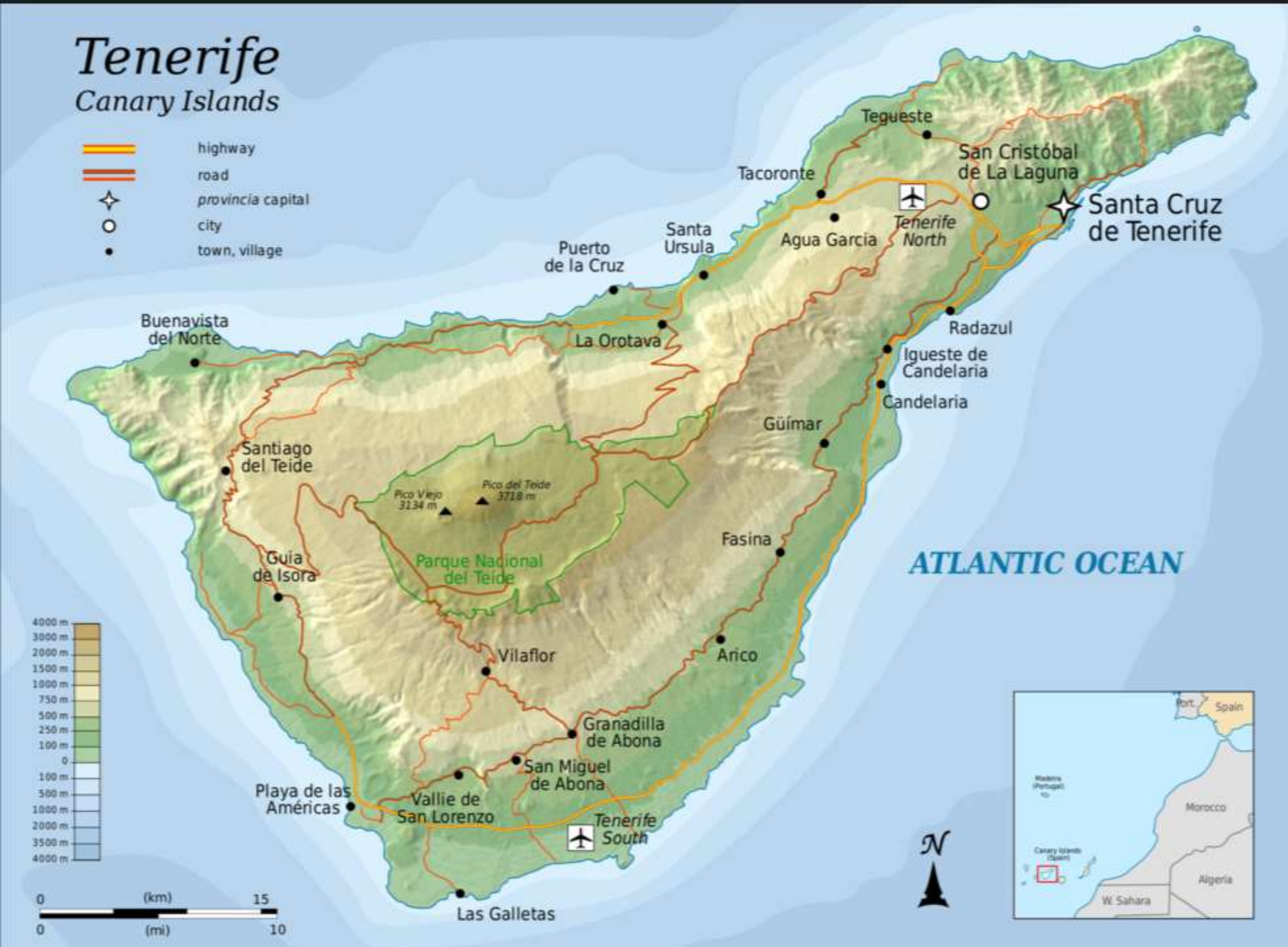
By explosion (Plinian type)

# Calderas that form by subsidence (Hawaiian type)

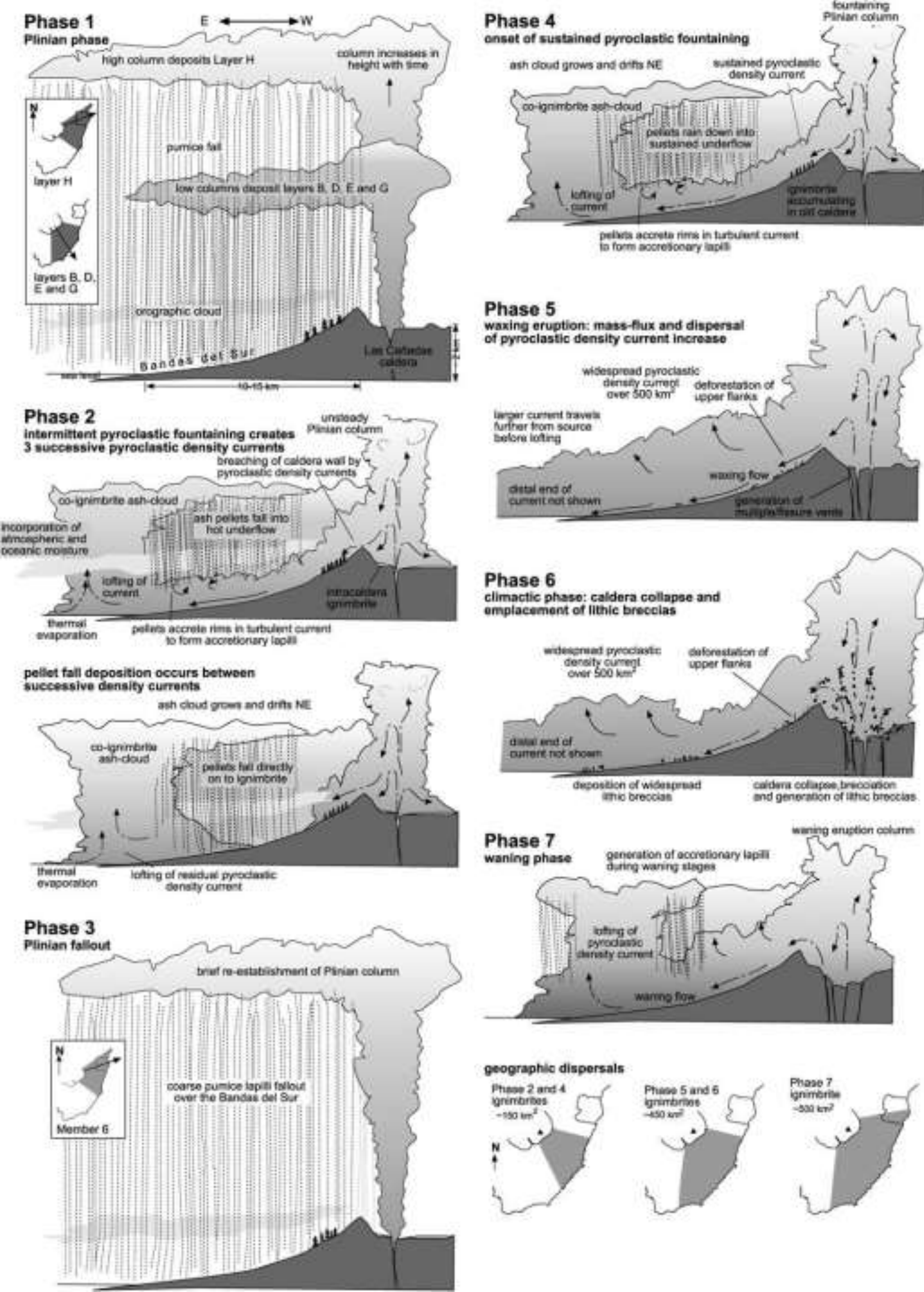



The top of the shield subsides into the magma chamber. Magma escaping from the sides or from vents closer to the centre of the subsident area fills the caldera.

# Calderas that form by explosion (Plinian type)


Tenerife
Canary Islands
highway
road
provincia capital
city
town, village
Teguește
San Cristóbal
de La Laguna
Tacoronte
Santa Cruz
de Tenerife
Agua Garcia
Tenerife
North
Santa
Ursula
Puerto
de la Cruz
Buenavista
del Norte
La Orotava
Radazul
Igueste de
Candelaria
Candelaria
Güímar
Santiago
del Teide
Pico Viejo
3134 m
Pico del Teide
3718 m
Parque Nacional
del Teide
Guia
de Isora
Fasina
ATLANTIC OCEAN
Vilaflor
Arico
Granadilla
de Abona
San Miguel
de Abona
Playa de las
Américas
Vallie de
San Lorenzo
Tenerife
South
Las Galletas
N
4000 m
3000 m
2000 m
1500 m
1000 m
750 m
500 m
250 m
100 m
0
100 m
500 m
1000 m
2000 m
3500 m
4000 m
0
(km)
15
0
(mi)
10
Port.
Spain
Morocco
Algeria
W. Sahara

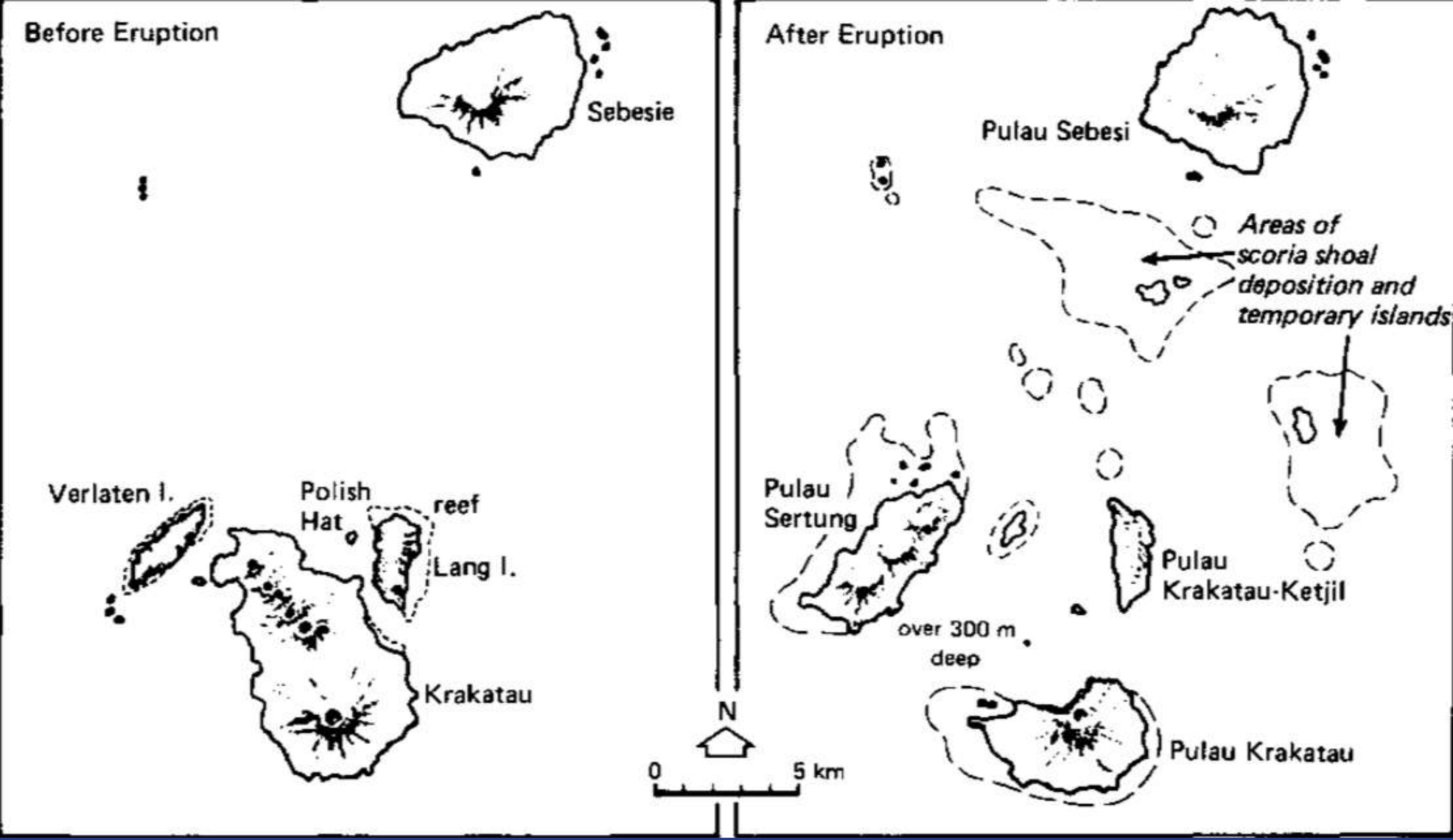
Las Cañadas Caldera and the Pico de Teide and the Pico Viejo that later grew in it. The age of the caldera is about 273,000 years.



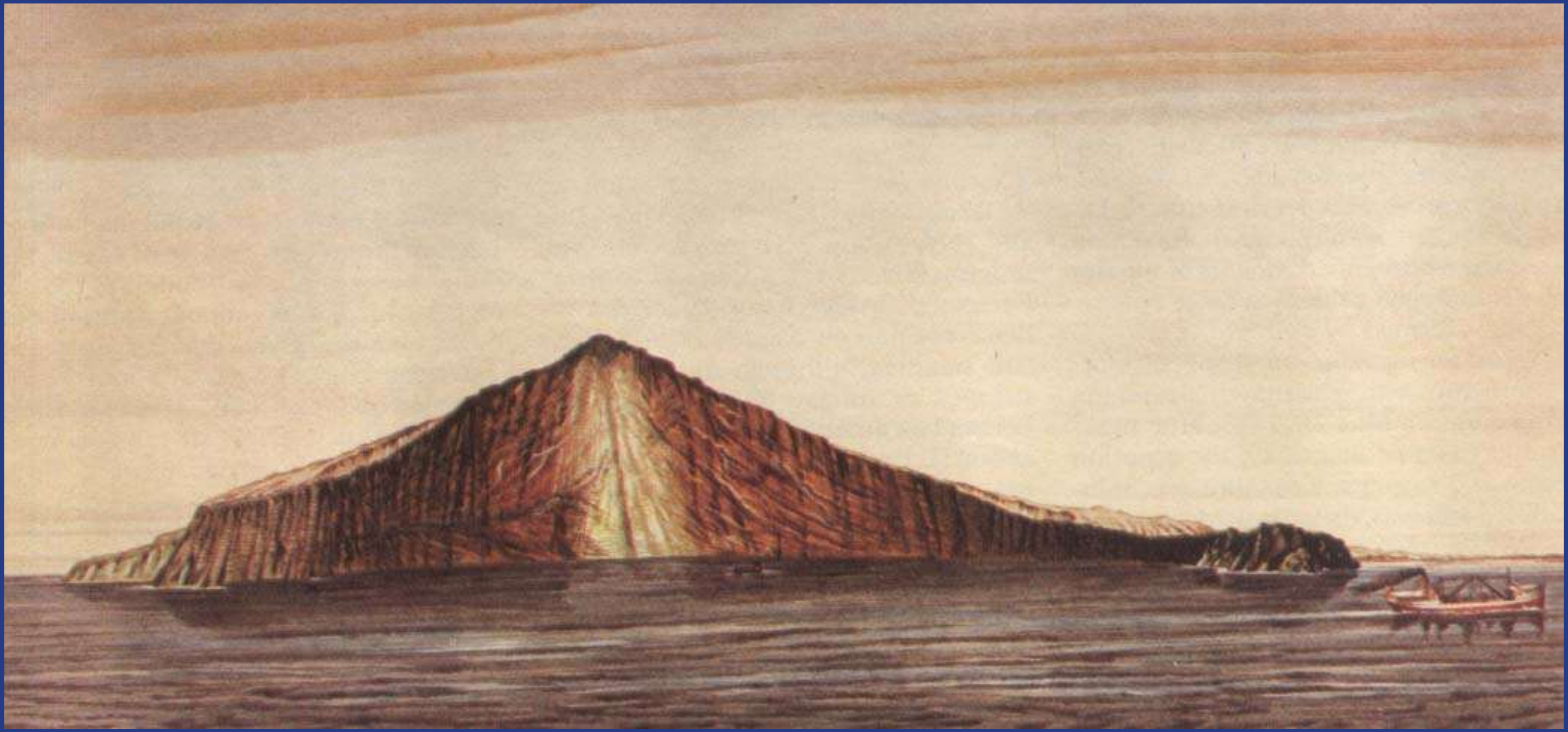

Stages in the evolution of the Las Cañadas Caldera, Tenerife, Canary Islands, Spain. From Brown and Branney (2004)

Of the calderas that form by explosion the best known is Krakatoa that erupted in 1883 and formed a large explosion caldera, creating one of the greatest volcanic disasters in history

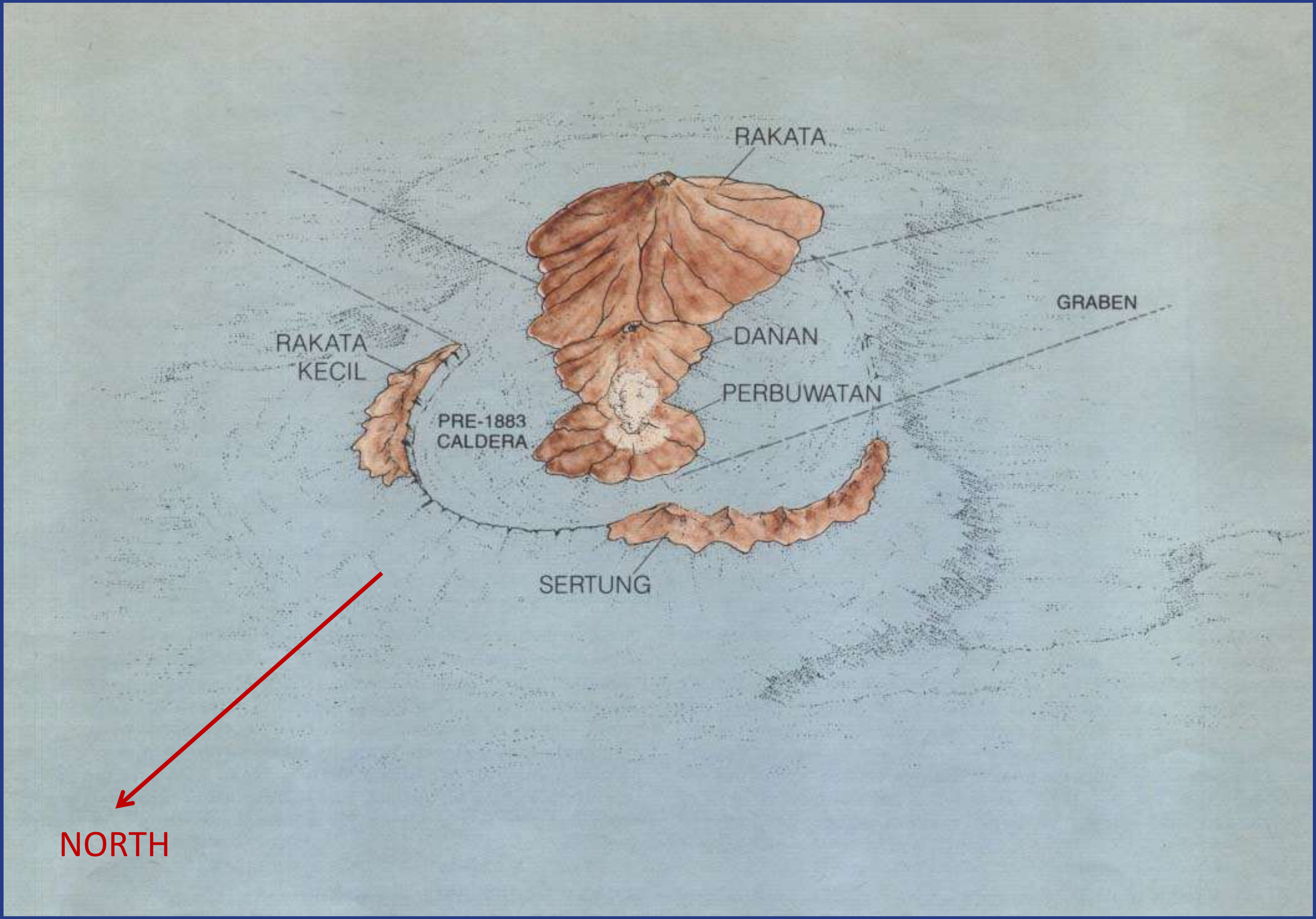

The Krakatoa Islands, Sunda Strait, Indonesia



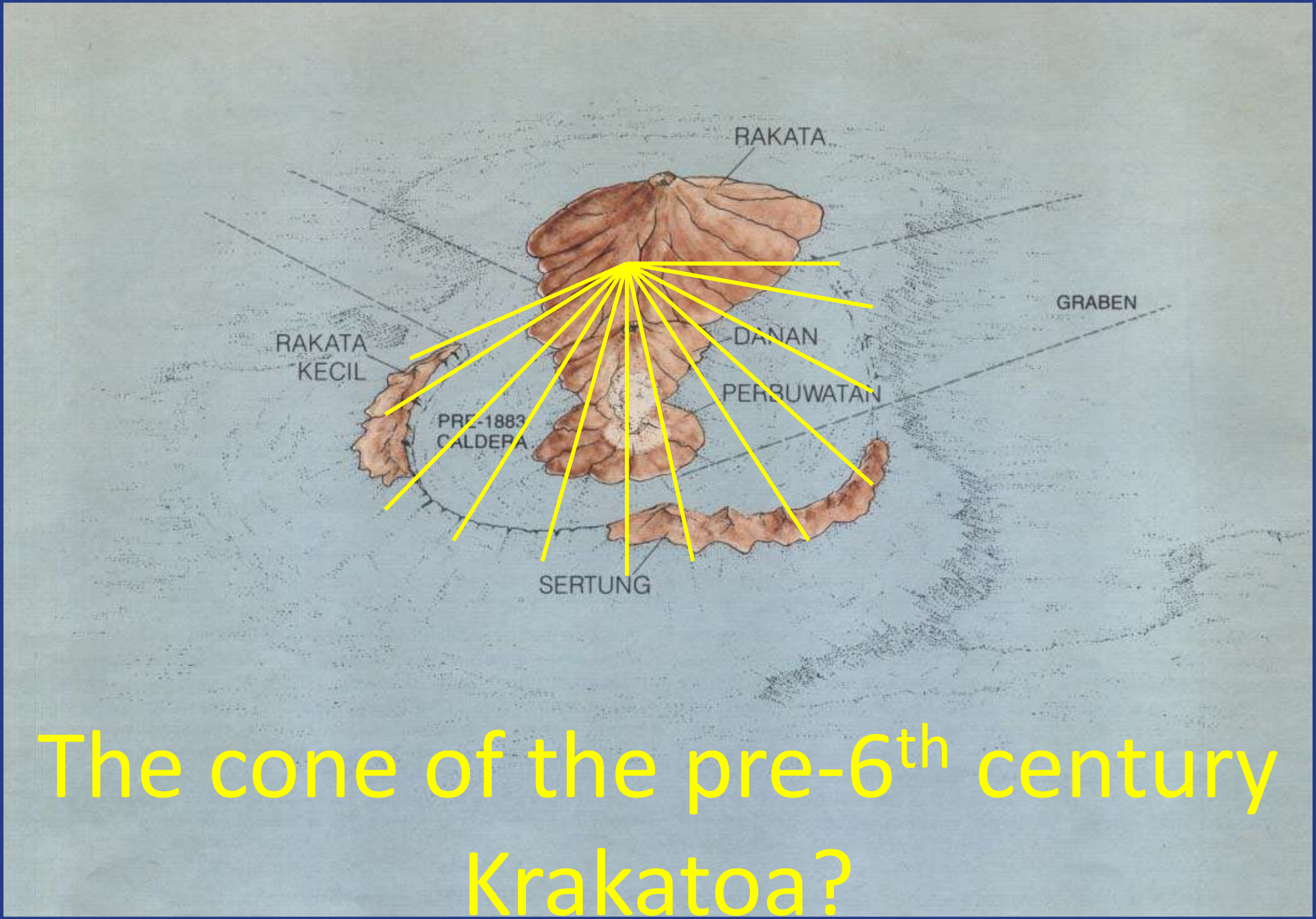

The changes in the geography of Krakatoa after its historic 1883 eruption



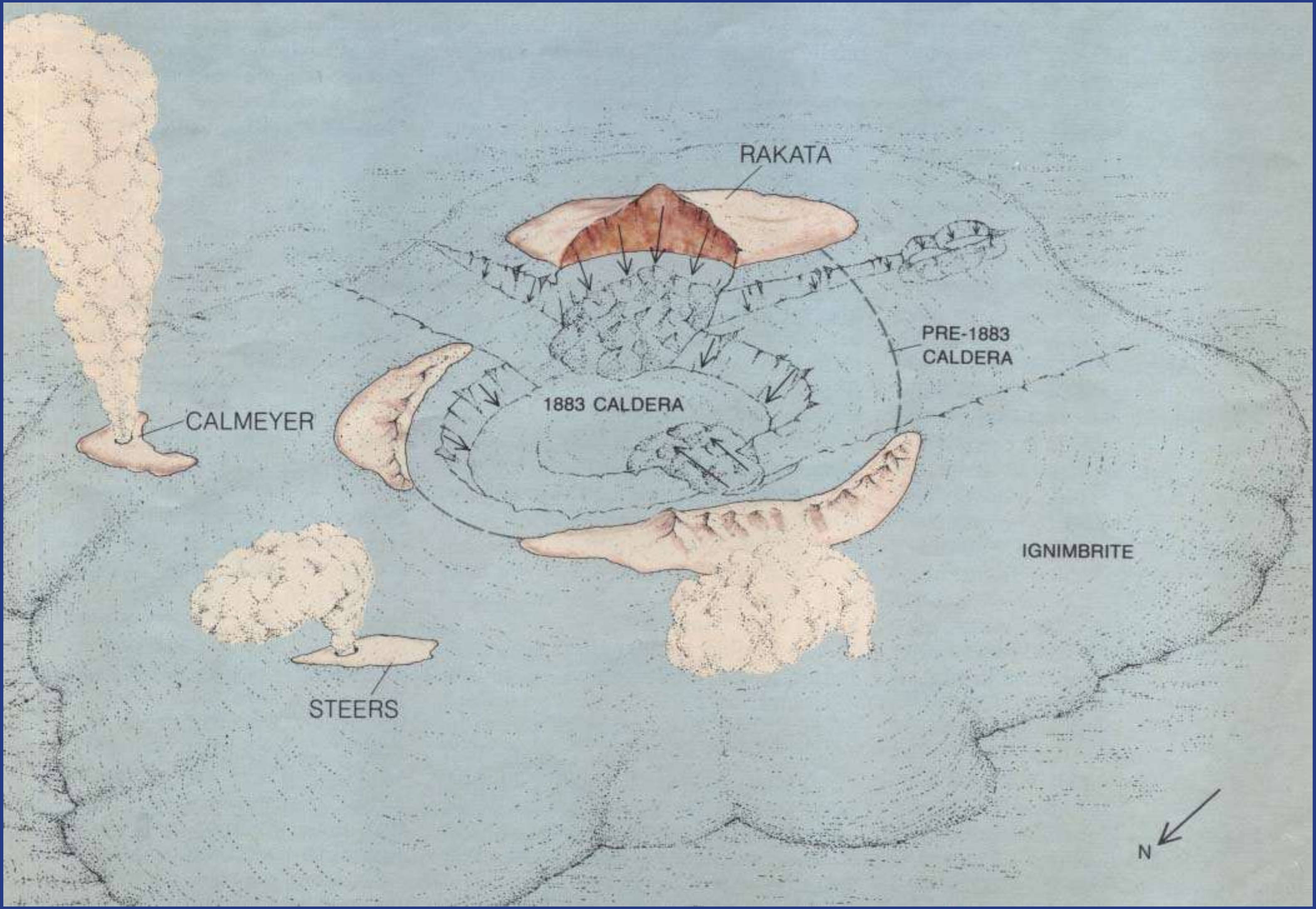
The Rakata island seen from within the Krakatoa explosion caldera. The yellow discoloration around the shaft is sulphur




# Situation before the eruption

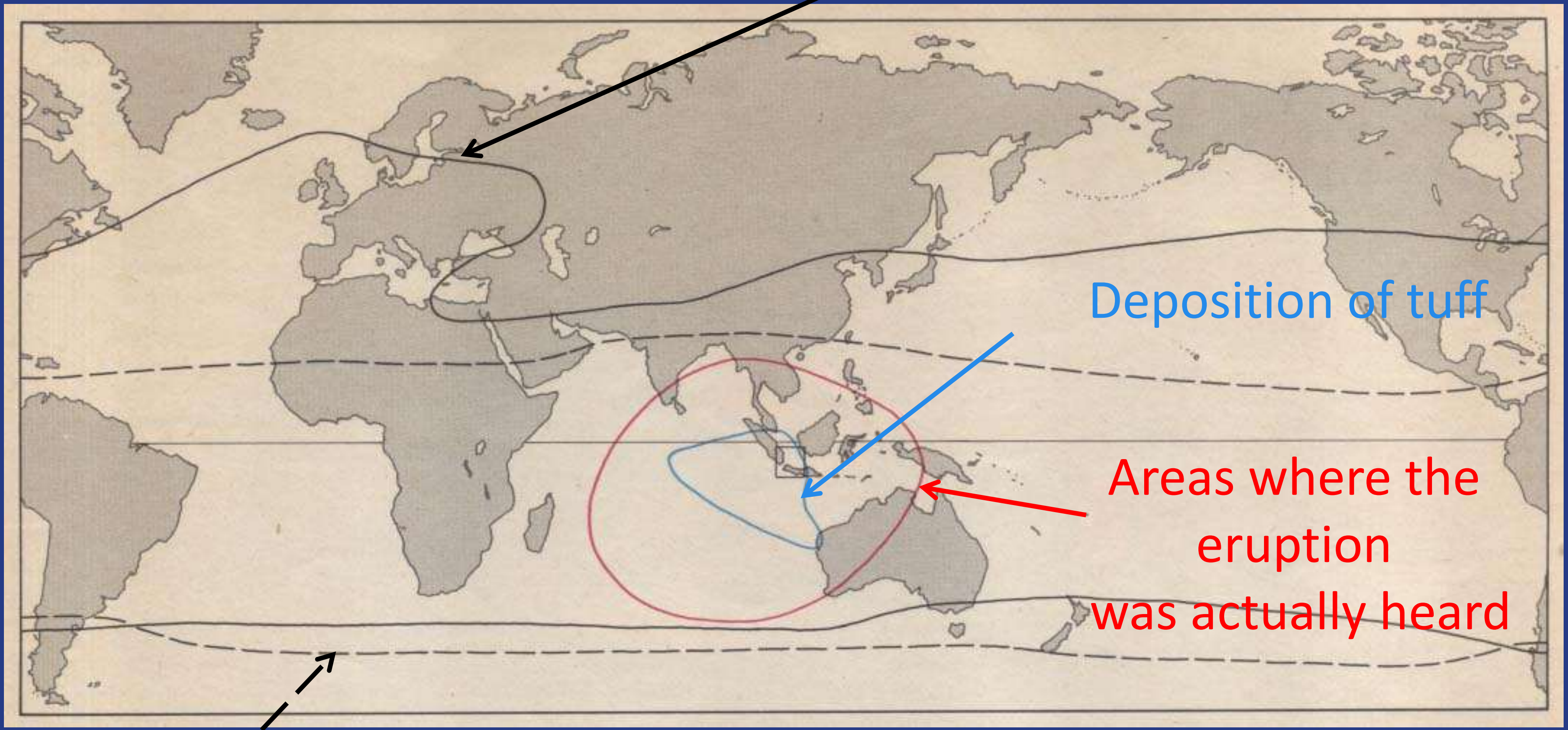



The cone of the pre-6th century Krakatoa?



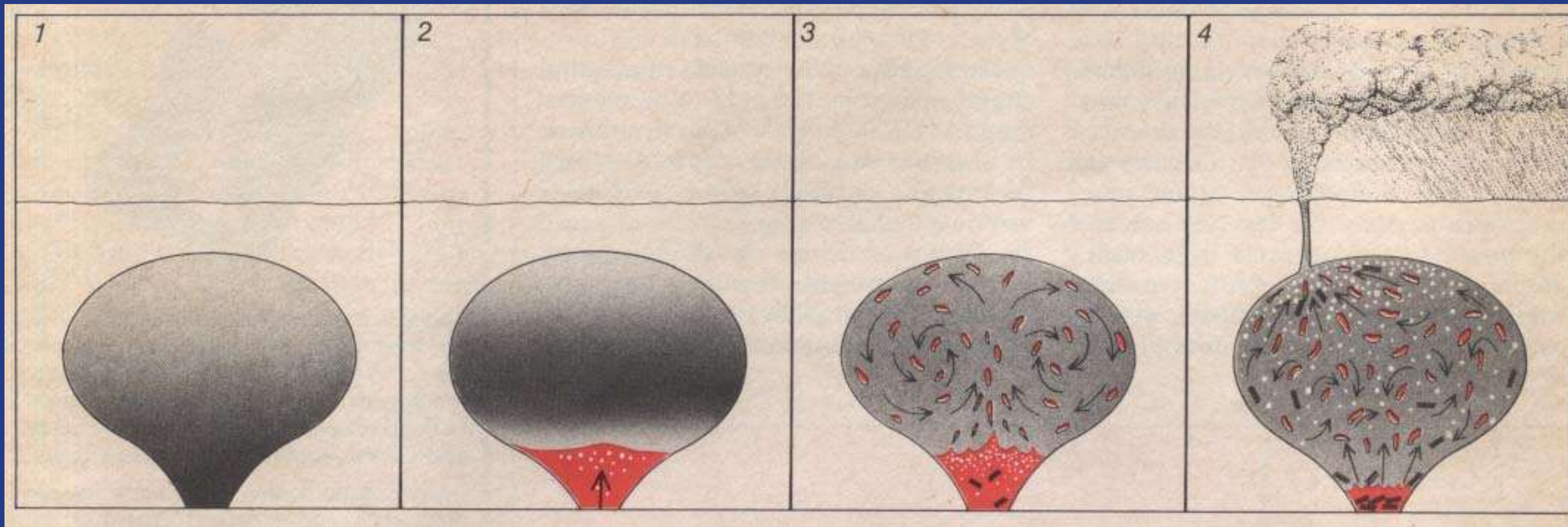

After the eruption and the formation of the caldera. Notice the ignimbrite thrown out.

Atmospheric events caused by the ash thrown into the stratosphere (November 1883 observations)




# The global effects of Krakatoa (Francis and Self 1983)

Atmospheric events caused by the ash thrown into the stratosphere (before 22 September 1883)

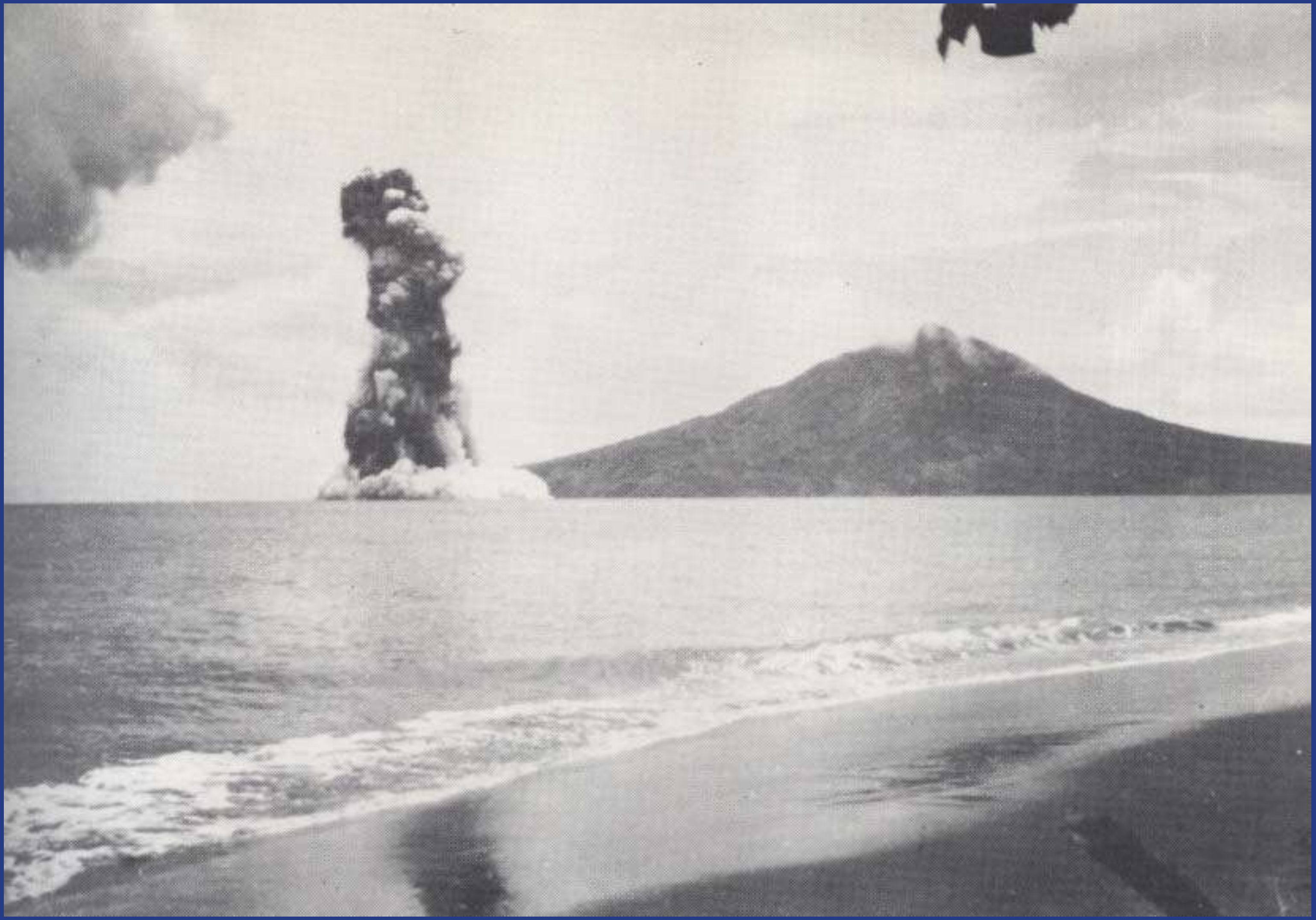



The eruption mechanism of Krakatoa


After the eruption and the formation of the caldera and the location of the future Anak Krakatoa (=child of Krakatoa)

24th January 1928

24th January 1928 + 6 seconds



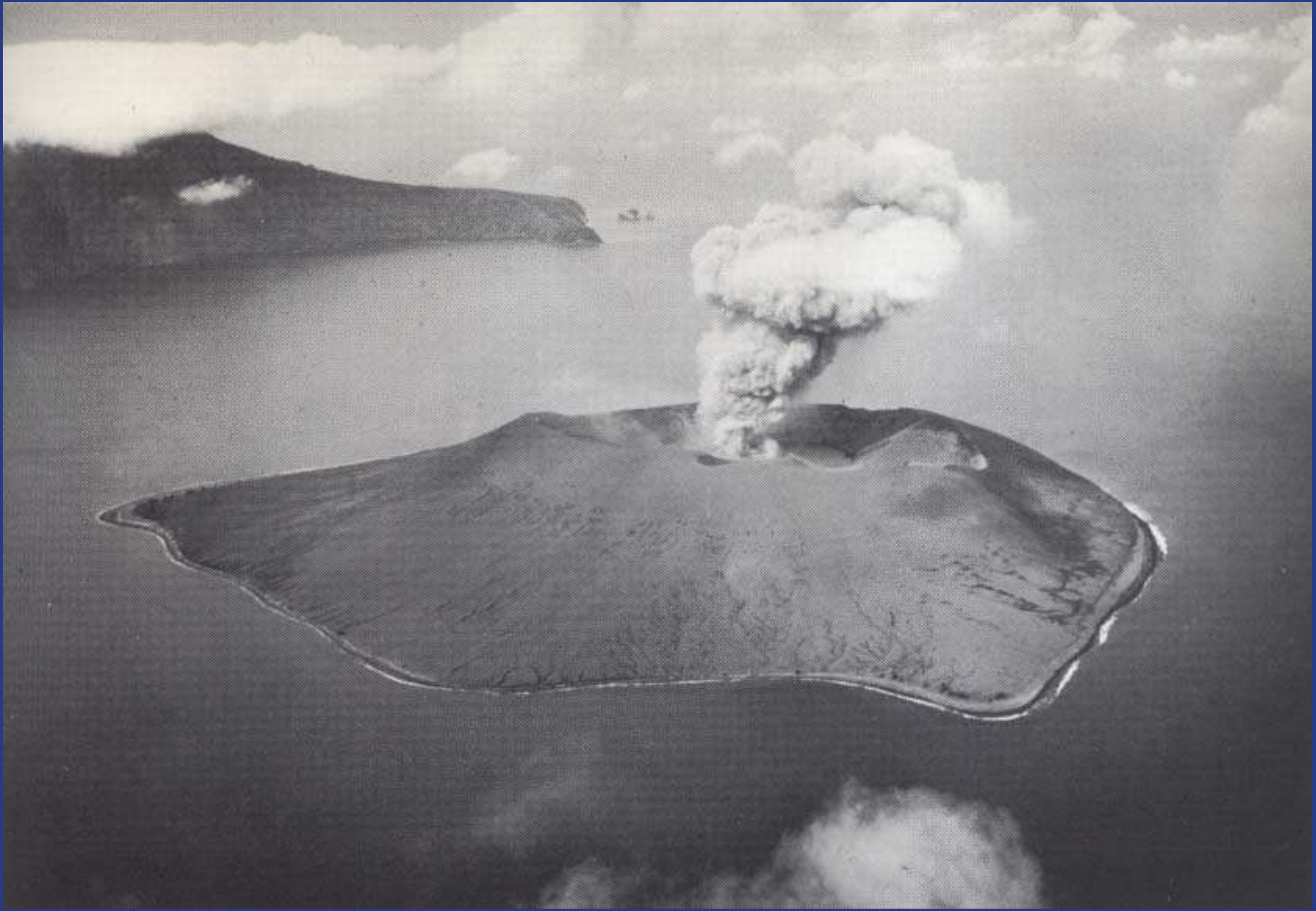
24th January 1928 + 12 seconds

24th January 1928 + 18 seconds

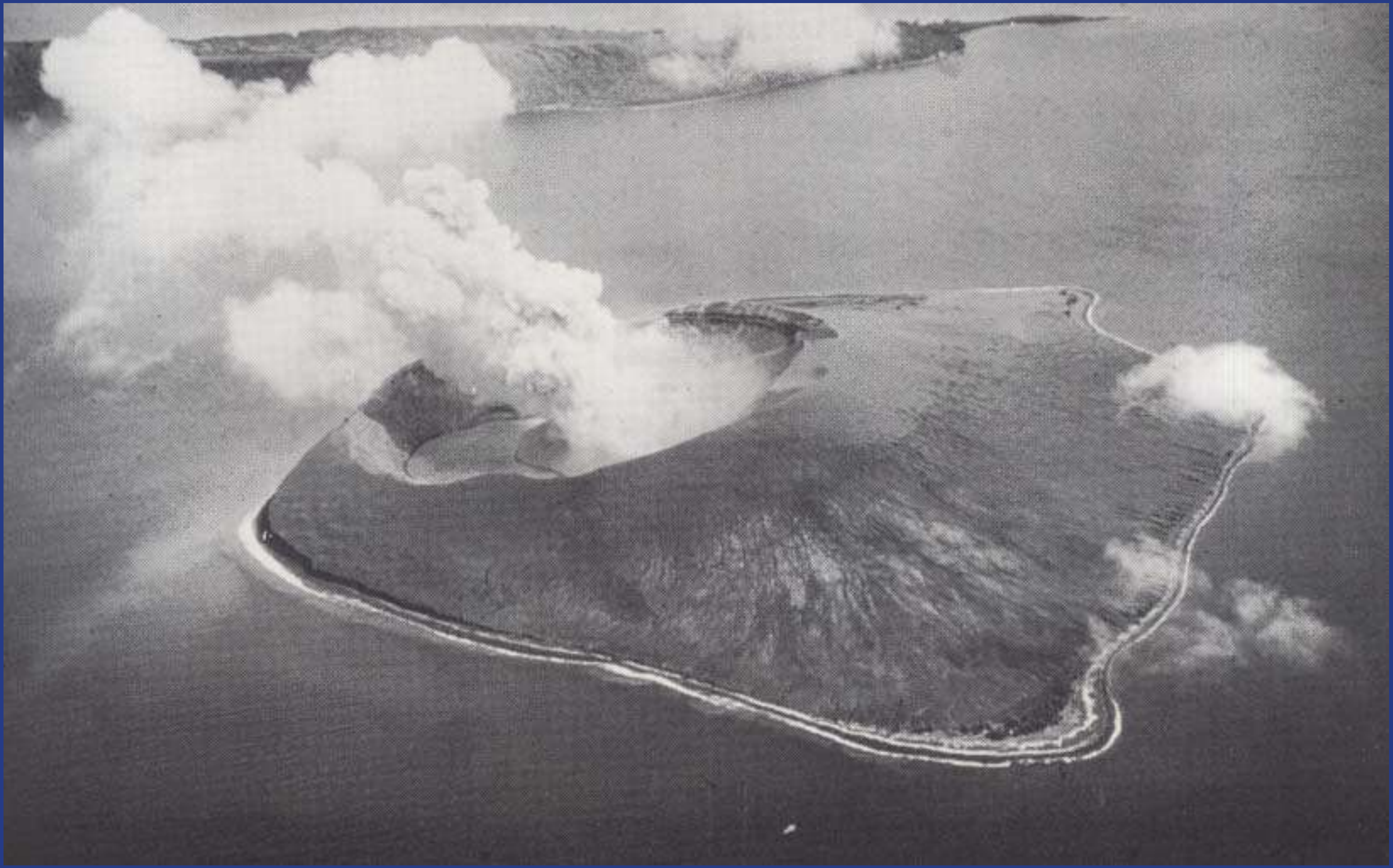
24th January 1928 + 24 seconds

24th January 1928 + 30 seconds

Anak Krakatoa 1929



Anak Krakatoa June 1959



Anak Krakatoa June 1959, another view

Anak Krakatoa 1960

Anak Krakatoa today

Effusive

Explosive

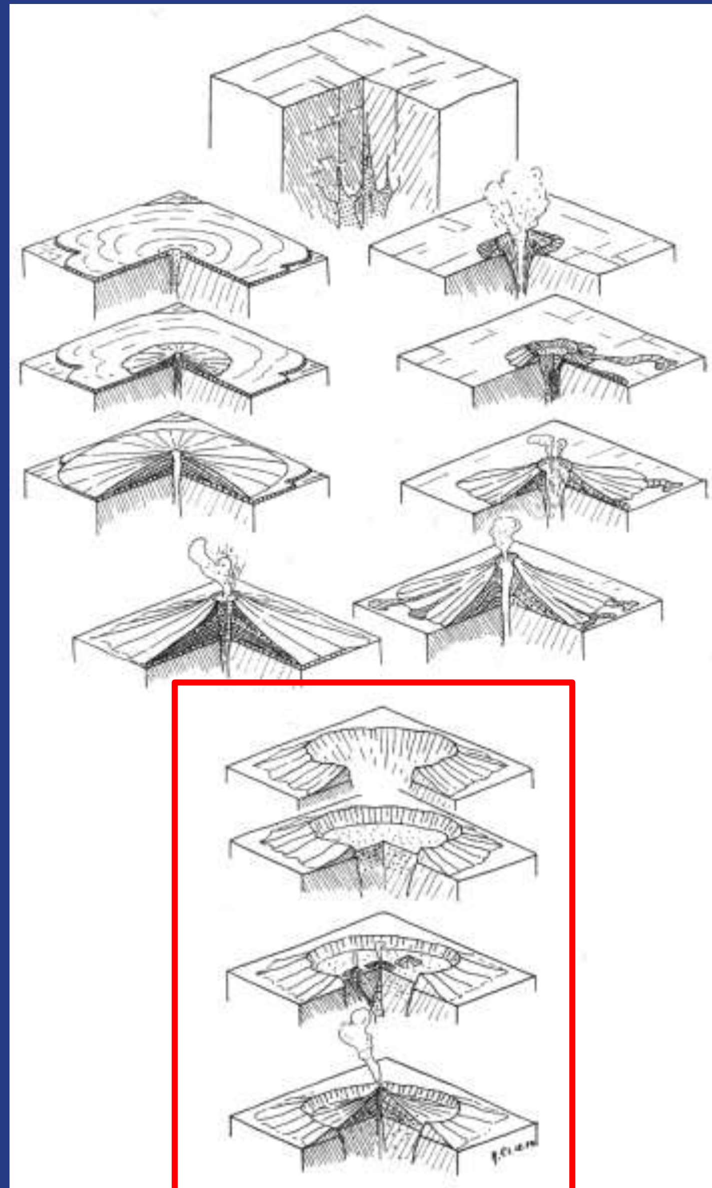


Table volcanoes

Table-shield volcanoes

Shield volcanoes

Mixed volcanoes

Maars

Maar w/ lava flow

Ash volcanoes

Mixed volcanoes

Caldera

Filled caldera

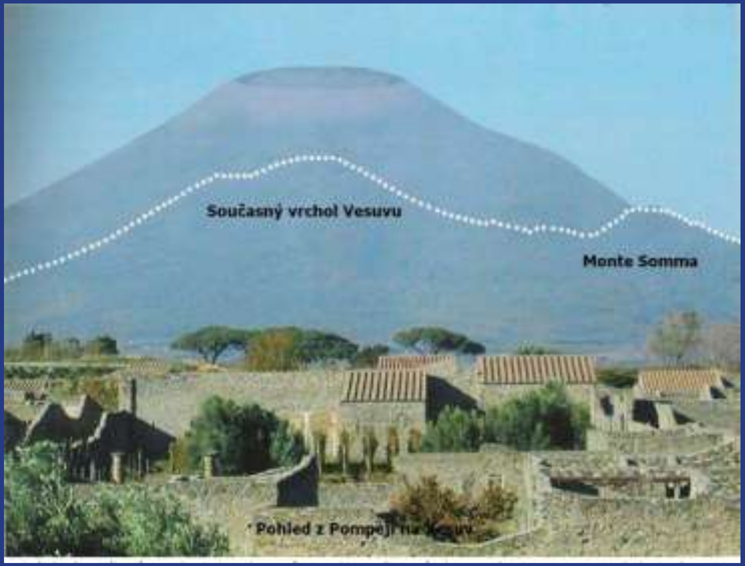
Second generation volcanoes

Vesuv-Stage

From H. Cloos 1936 *Einführung in die Geologie*


Monte Somma
Vesuvius


Vesuvius
Monte
Somma


Současný vrchol Vesuvu
Monte Somma
Pohled z Pompejí

Homework:

Read the following paper:

Brown, R. J. and Branney, M. J., 2004, Event-stratigraphy of a caldera forming ignimbrite eruption on Tenerife: the 273 ka Pois Formation: *Bulletin of Volcanology*, v. 66, pp. 392-416.

1. Make a written list of technical terms you do not understand and give them to Nalan or Semih.

2. Be ready to make a 10 minute presentation summarising it in class (in English). I may call upon 2 or 3 of you to do so.