# Lesson 6

# Rocks of the Earth

## Part 1: General

A. M. Celâl Şengör

The earth and other terrestrial or rocky planets, asteroids and comets consist of rocks. But what are rocks? Let us go back to the formal definitions we gave in lesson two of a rock and of a mineral:

A rock is any naturally formed, firm and coherent aggregate or mass of mineral matter that constitutes a part of the universe.

A mineral is a naturally occurring inorganic crystalline solid of a definite (variable within fixed limits) chemical composition.

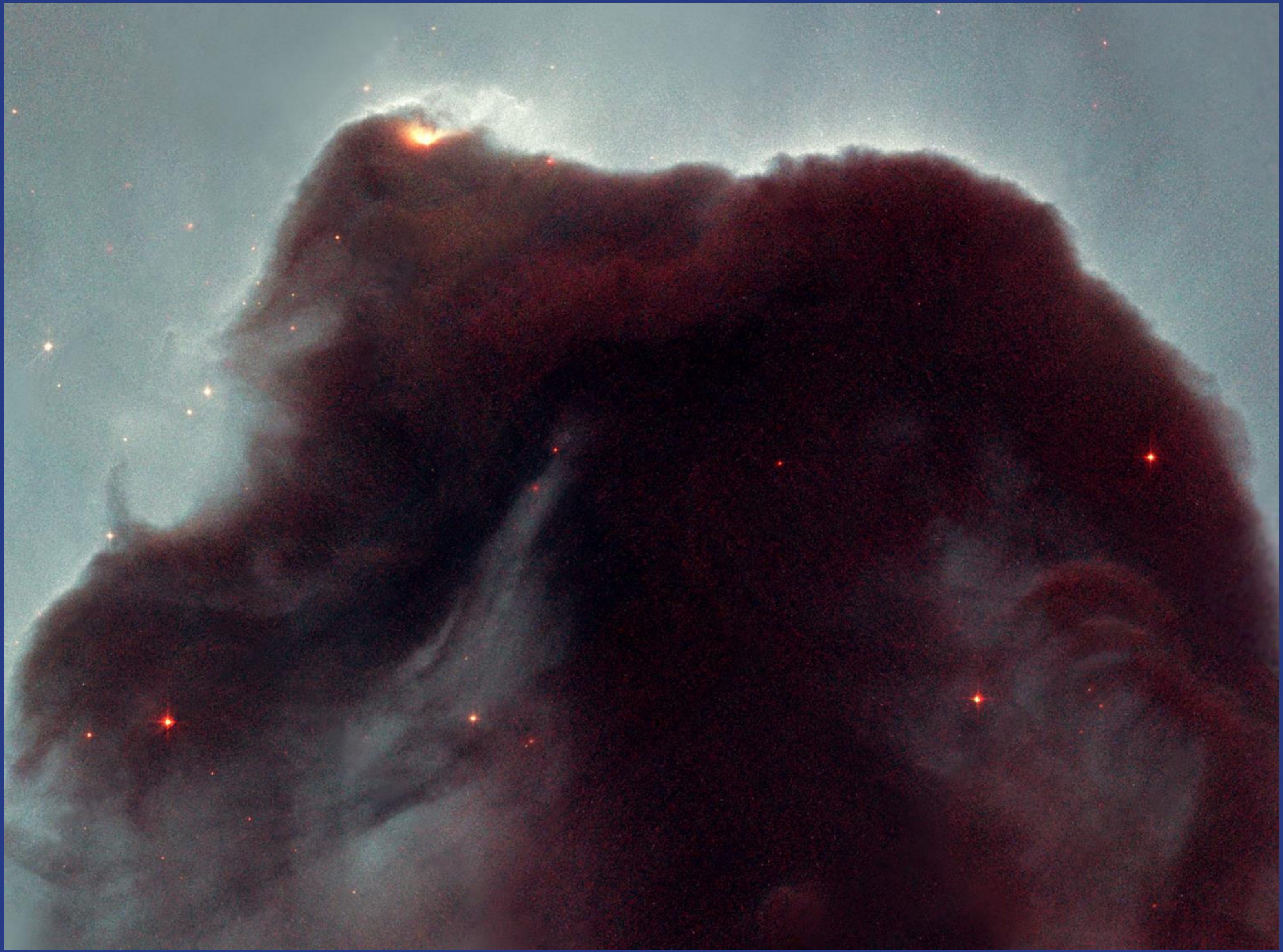
A naturally-occurring amorphous (i.e. without a long-range ordered structure) solid is called a mineraloid.

Rocks on earth and in other places in space form by means of three processes:

1. Agglomeration in space of space dust ("cosmic dust") that forms in stars and in supernovae. All stars and planets form through this mechanism that had begun with the Big Bang.

2. Internal processes of planets (on earth this is called internal geodynamics)

3. External processes of planets (on earth this is called external geodynamics)



Cosmic dust as seen by the Hubble telescope in the Horseshoe Nebula.

The internal processes on any planet or any other space object such as a star are the procesess that derive their energy from the object itself without any outside contribution. On earth, internal processes drive plate tectonics and the mantle convection, including the mantle plumes and consist of the following phenomena seen at the surface:

# 1. Fast events (time scale from a few seconds to a few days; at most months)

A. Earthquakes

B. Volcanism (in English also vulcanism or vulcanicity)

# 2. Slow events (time scale from hundreds of years to millions of years)

*WISON CYCLE* OF OCEAN OPENING AND CLOSING

*A. Plate boundary phenomena*

I. Orogeny (mountain-building)

II. Taphrogeny (rift-building)

III. Thallasogeny (ocean-building)

IV. Keirogeny (horizontal shear-belt-building)

Mainly horizontal motions

*B. Plate interior phenomena*

I. Mantle plume-related events

II. Purely isostasy-related events

Mainly vertical motions

The external processes on any planet or any other space object such as a star are the procesess that derive their energy from outside the object itself without any inside contribution. On earth, external processes derive their energy from the Sun and are divided into erosion and deposition phenomena seen at the surface. The erosion and deposition occur through the following family of processes:

1. Weathering: Weathering is the mechanical and chemical disintegration of rocks producing regolith.

2. Fluvial processes: Fluvial processes are those caused by flowing water.

3. Groundwater processes: These are processes caused by groundwater. Their chief representatives are processes of rock dissolution, called karstic processes.

4. Glacial processes: These are processes caused by flowing ice (glaciers, inland ice caps)

5. Periglacial processes: These are processes that result from seasonal freezing and thawing of the ground.

6. Eolian processes: These are processes of erosion and deposition caused by wind.

7. Coastal processes: These are processes that take place along the interface between large water bodies such as lakes, internal seas and oceans and land. Stream margins are not a part of the coastal processes, but are studied under fluvial processes.

8. Subaqueous processes: These are caused by events taking place in large water bodies, such as sediment deposition by various processes such as precipitation, settling, and current flow. Erosion also takes place under water.

9. Mass movements of diverse types both subaerial and subaqueous.

Erosional processes help to denude the land (i.e. lower its surface) and sedimentation helps to fill up topographic receptacles (i.e. raise their surface, except in the formation of upside-down sinters, such as stalactites)

There are also events that are mixed types, such as meteorite impact that has an outside energy source, but can create internal events such as magmatism and structuration of the earth's crust or even its entire lithosphere.

Lightening is an atmospheric event eventually created by the Sun's energy, but melts rocks creating fulgurites that are just magmatic glasses.

Isostasy is the floating of lithospheric or crustal panels on the mantle; i. e., it is an internal process. But it is at places and times triggered by climatic changes that are purely external events.

All internal, external and mixed processes create rocks.

Generally speaking internal processes are responsible for making

A. Magmatic

B. Metamorphic

C. Structural

rocks.

Generally speaking again, the external processes are responsible for making

A. Sedimentary

Rocks

Mixed processes also make diverse types of rocks. Meteorite impacts create magmatic, sedimentary (fallout ejecta) and metamorphic (shock metamorphism) rocks. Lightening creates magmatic rocks. Volcanoes can create sedimentary rocks (pyroclastics).

According to the processes that create them, the rocks therefore are grouped under four major classes:

1. Magmatic rocks that slowly crystallise creating crystalline substances or are rapidly quenched to create glasses from magma.

2. Sedimentary rocks are formed from mechanical or chemical precipitation from a liquid or gaseous or fluid medium such as air or water or ice.

3. Metamorphic rocks are those that change their composition and/or their texture without any melting. Metamorphic rocks form through solid metamorphosis of other types of rocks.

4. Structural rocks are those rocks formed by structural processes such as faulting or in ductile shear zones. They form either by granulation or plastic flow processes.

We shall begin our study of rocks with the magmatic rocks. They are also called igneous rocks. The word igneous is derived from the Latin word *ignis* meaning fire.

Magmatic rocks are classified in three ways:

1. According to composition
2. According to texture
3. According to depth of origin

According to composition the magmatic rocks are divided into three main groups:

MAGMATIC ROCKS

- Mafic group; in the past also known as basic group
  - Ultramafic rocks
  - Mafic rocks
- Intermediate group
- Felsic group; in the past also known as acid group

Let us start with the classification on the basis of depth of origin:

1. Surface ignous rocks (volcanic rocks)

2. Intermediate depth igneous rocks (subvolcanic rocks)

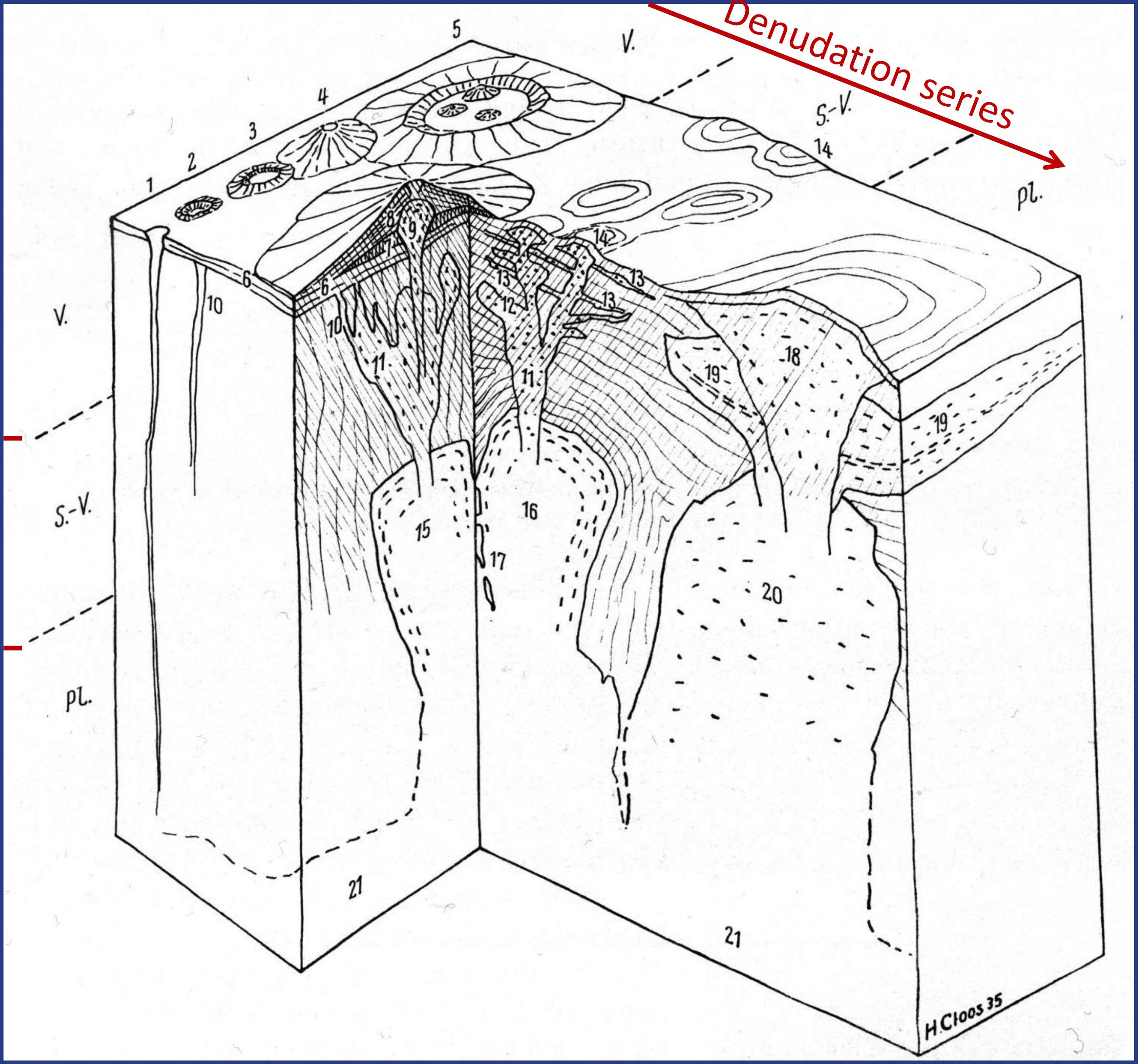
3. Deep igneous rocks (plutonic rocks; the name is derived from the Roman god of the subterranean world *Pluto*, equivalent of the Greek *Hades*).

These two classes are commonly grouped under the name plutonic rocks)

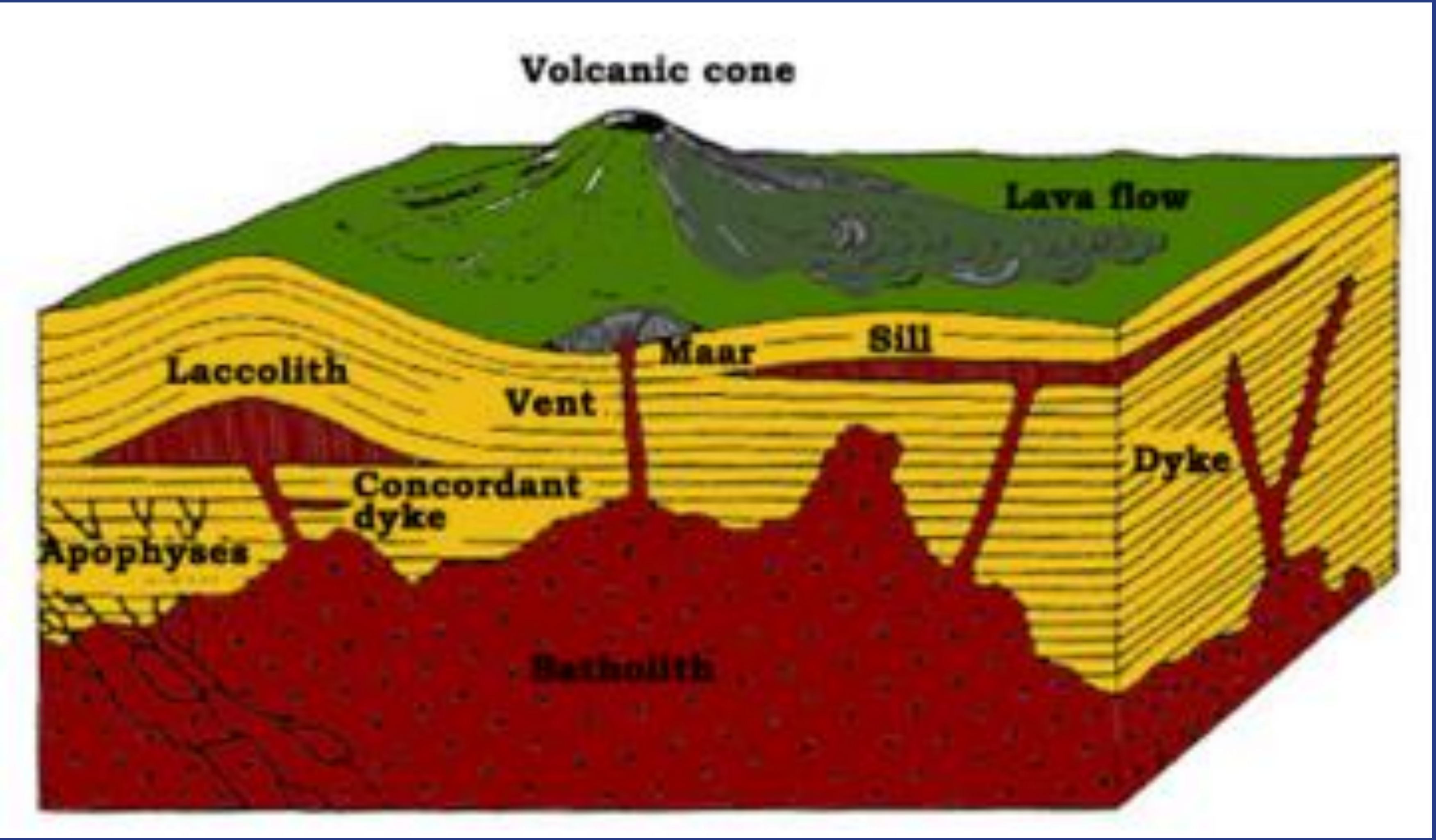
Volcanic

Sub-volcanic

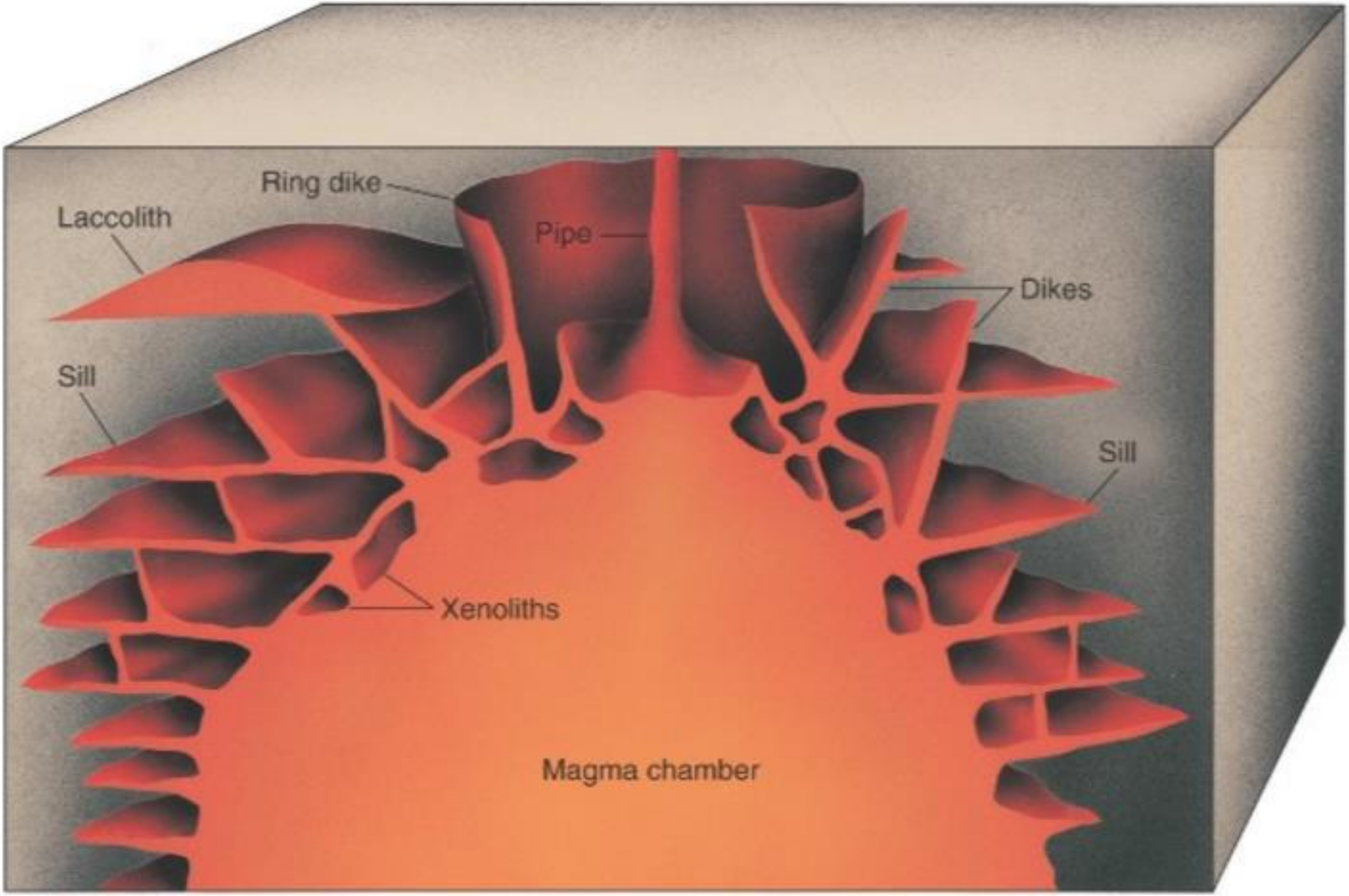
Plutonic



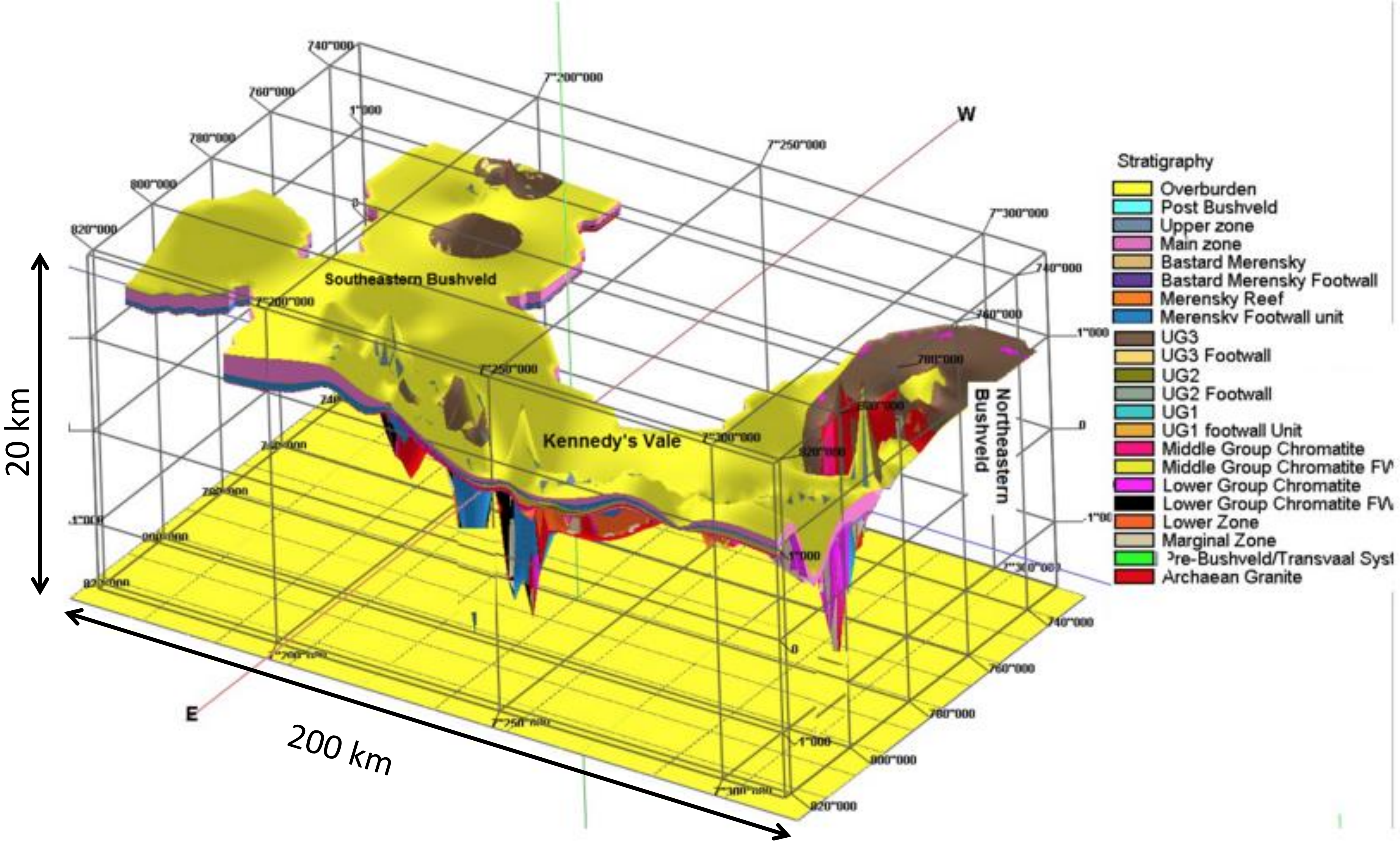

Places of origin of magmatic rocks (after Hans Cloos, 1936).




Some of the igneous rock bodies (from Árpád Dávid’s lectures). Most textbooks portray them as they are shown here. Yet they are not so simple and we need to look at their various shapes and see what we can learn from them as to their origin.

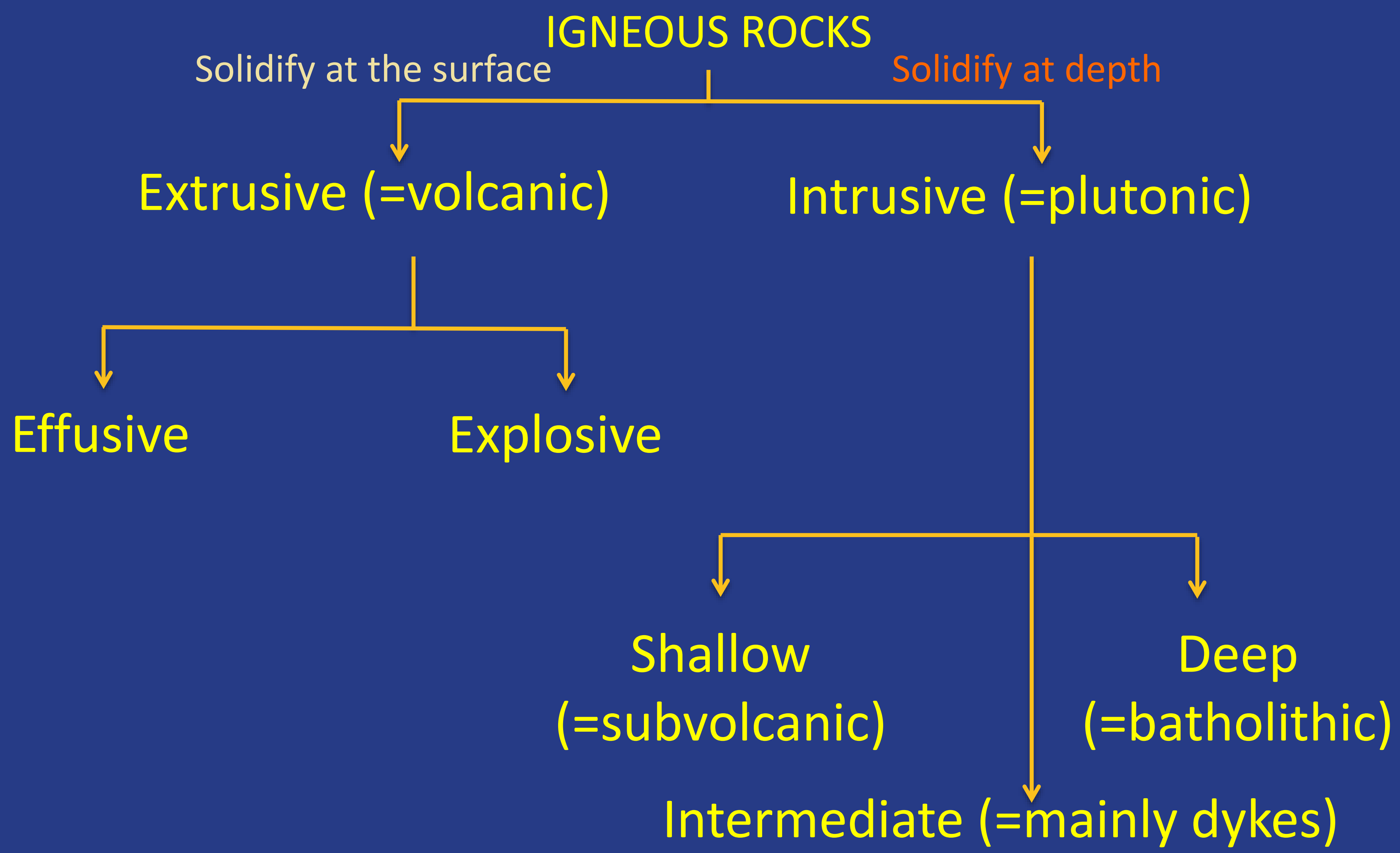



Here is another portrayal, but, again, it is misleading, because the geometry of forms are actually richer and some of the proportions shown are off by serious margins.




How can an intrusive complex such as the Bushveld in South Africa be classified? Here we are looking at an intrusion in a space some 20 km deep (the intrusion itself occupies at least a 4 to 5 km relief, in places more). What is it?

Let us remember the clasisfication of the igneous rocks into two main classes:



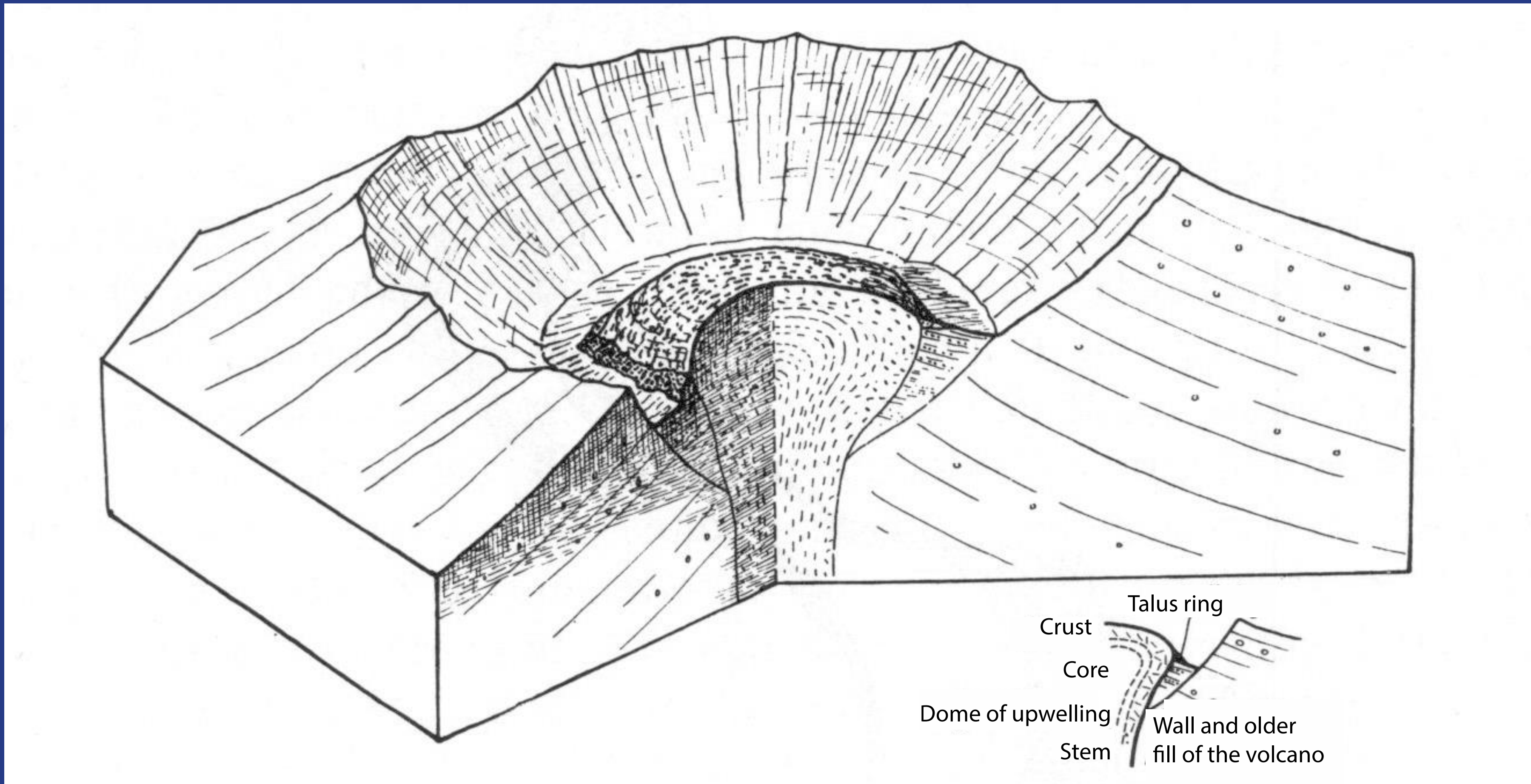
# Volcanic rocks according to the body they form

- Rocks formed by flow at or very near the surface
  - Lava domes
  - Lava flows
- Rocks thrown out by volcanoes and that fall onto the earth's surface in solid form (tephra from the Greek τέφρα {*tefra*=ash} )
  - Volcanic ash
    - Cold ash deposits (volcanic tuff)
    - Hot ash (*nueé ardente*) deposits: welded tuffs (including ignimbrites from the Latin *ignis*=fire and *imbri*=rain by Patrick Marshall from New Zealand)
  - Lapilli
  - Volcanic bomb and blocks

We now briefly look at the constructs built by magmatic rocks. We first consider those that are built by volcanic rocks at the surface.

Lava domes

(constructs built by viscous lava mainly of rhyolitic composition).




Block diagram of a lava dome from Hans Cloos (1936). The internal flow structure here shown is hypothetical, but to this day we have no data from the enterior of a subaerial lava dome

The lava dome within the crater of the Kelud volcano, Eastern Java, Indonesia in formation.

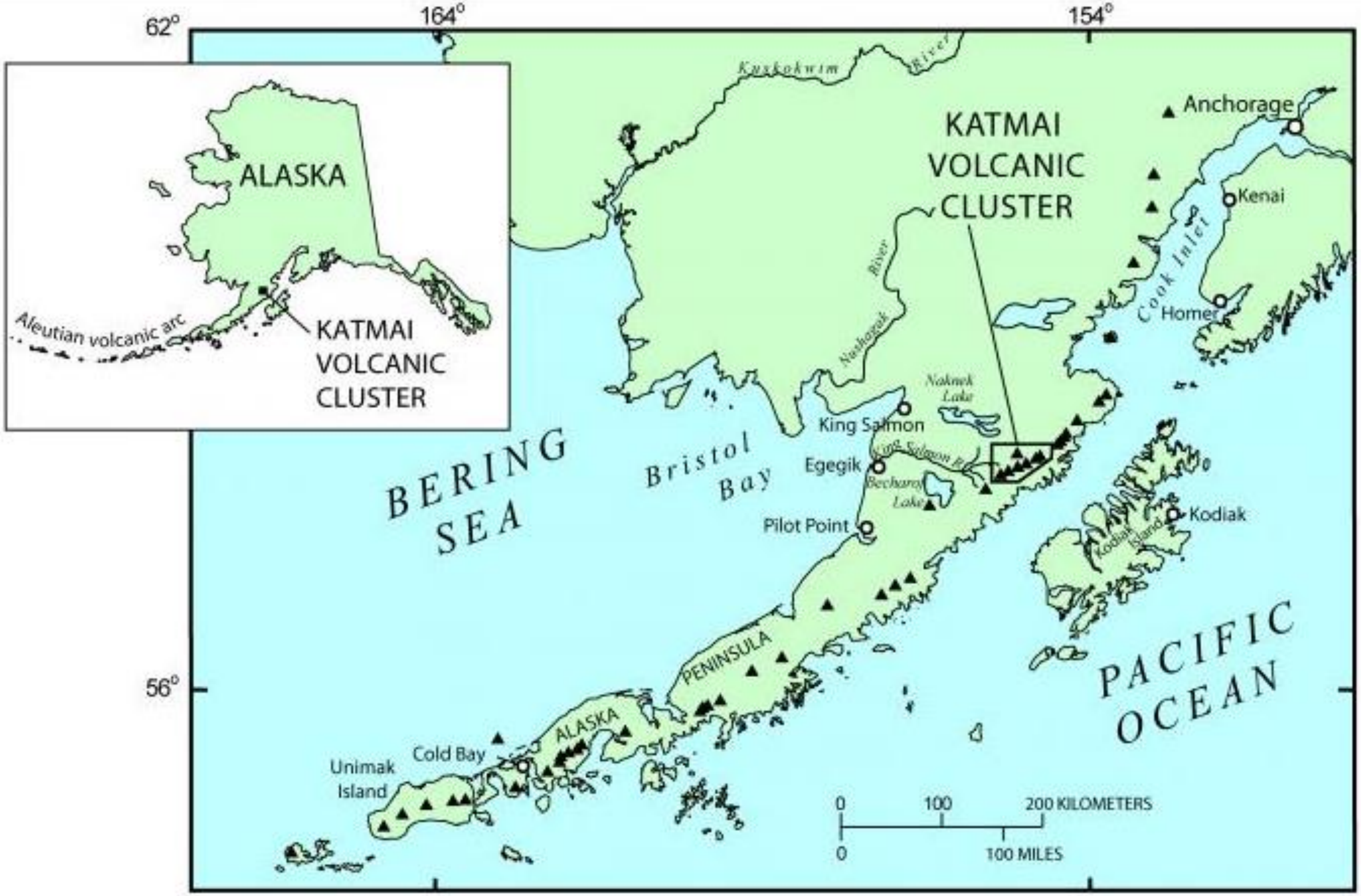
The lava dome within the crater of the Kelud volcano, close-up.

The rhyolitic lava dome of the Chaitién volcano,
Andes Mountains, Chile



The lava dome seen from space
and its location in the Andes.

The rhyolitic lava dome of the Novarupta volcano, Alaska, USA



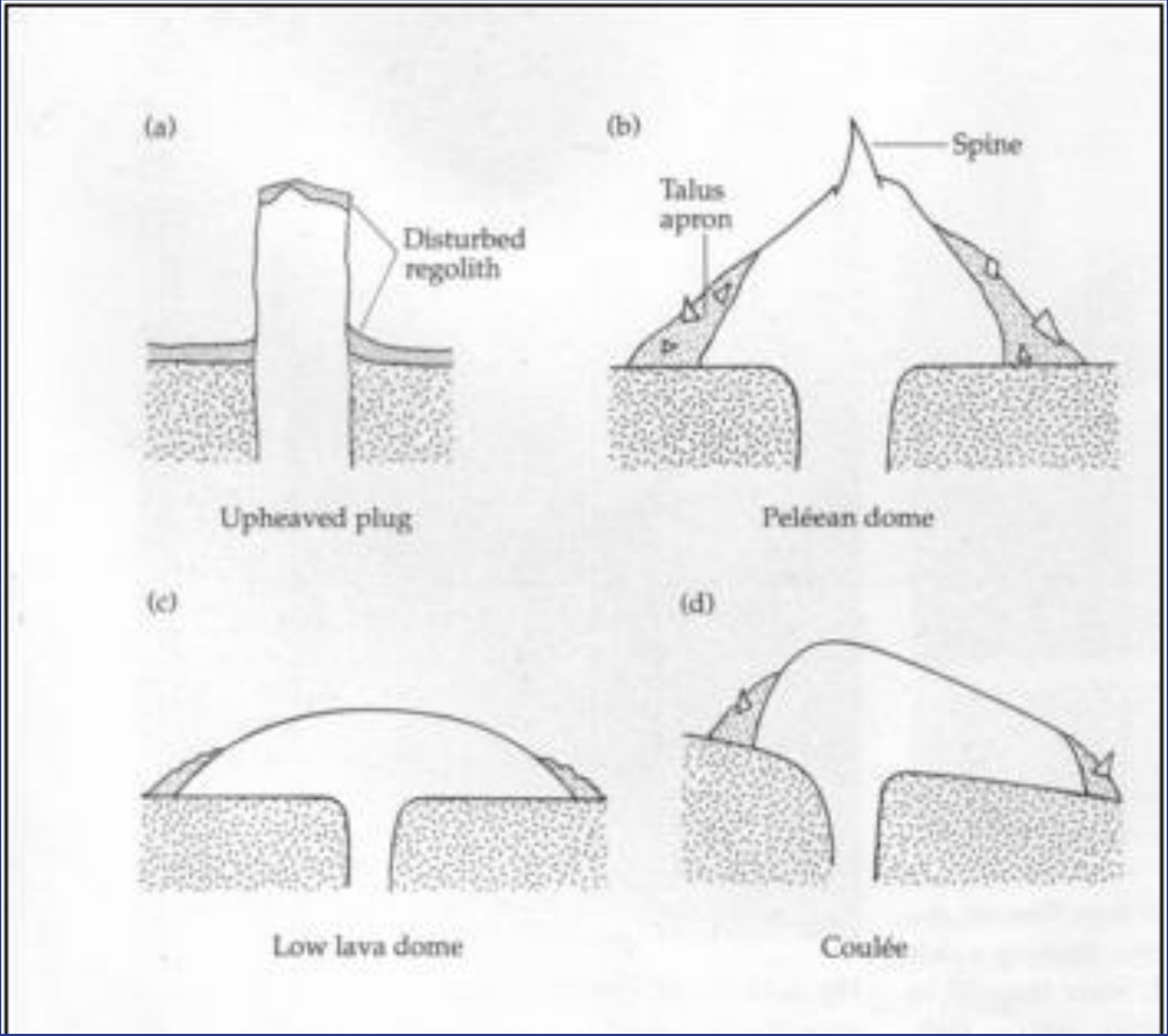

Novarupta is within the Katmai volcanic cluster

Lava dome within the Mt. St. Helens crater created after the catastrophic 1980 eruption.

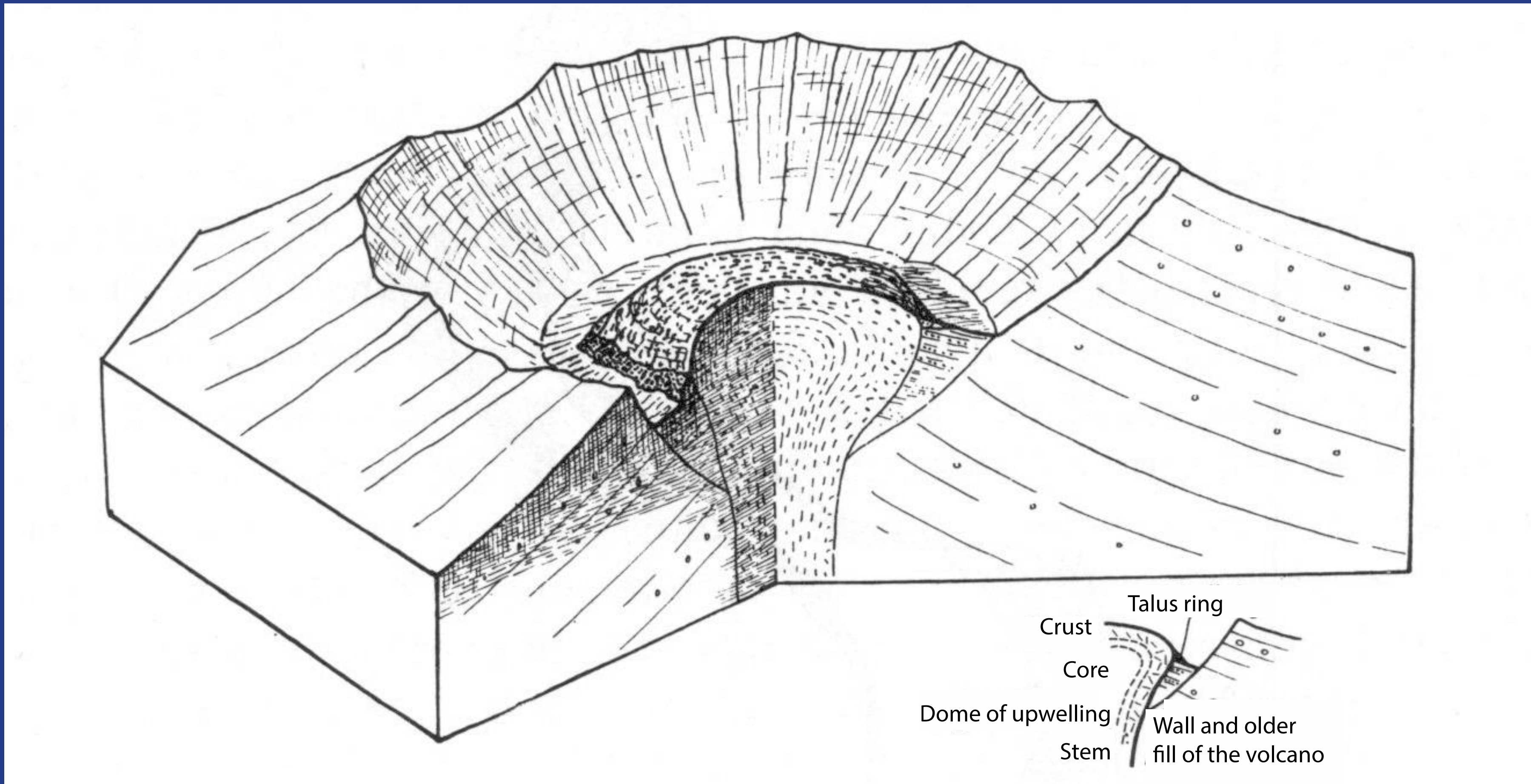

The location of Mt. St. Helens

Lava dome forming during the 2006 eruption
of the Merapi volcano in Java, Indonesia


The location of Merapi in Java

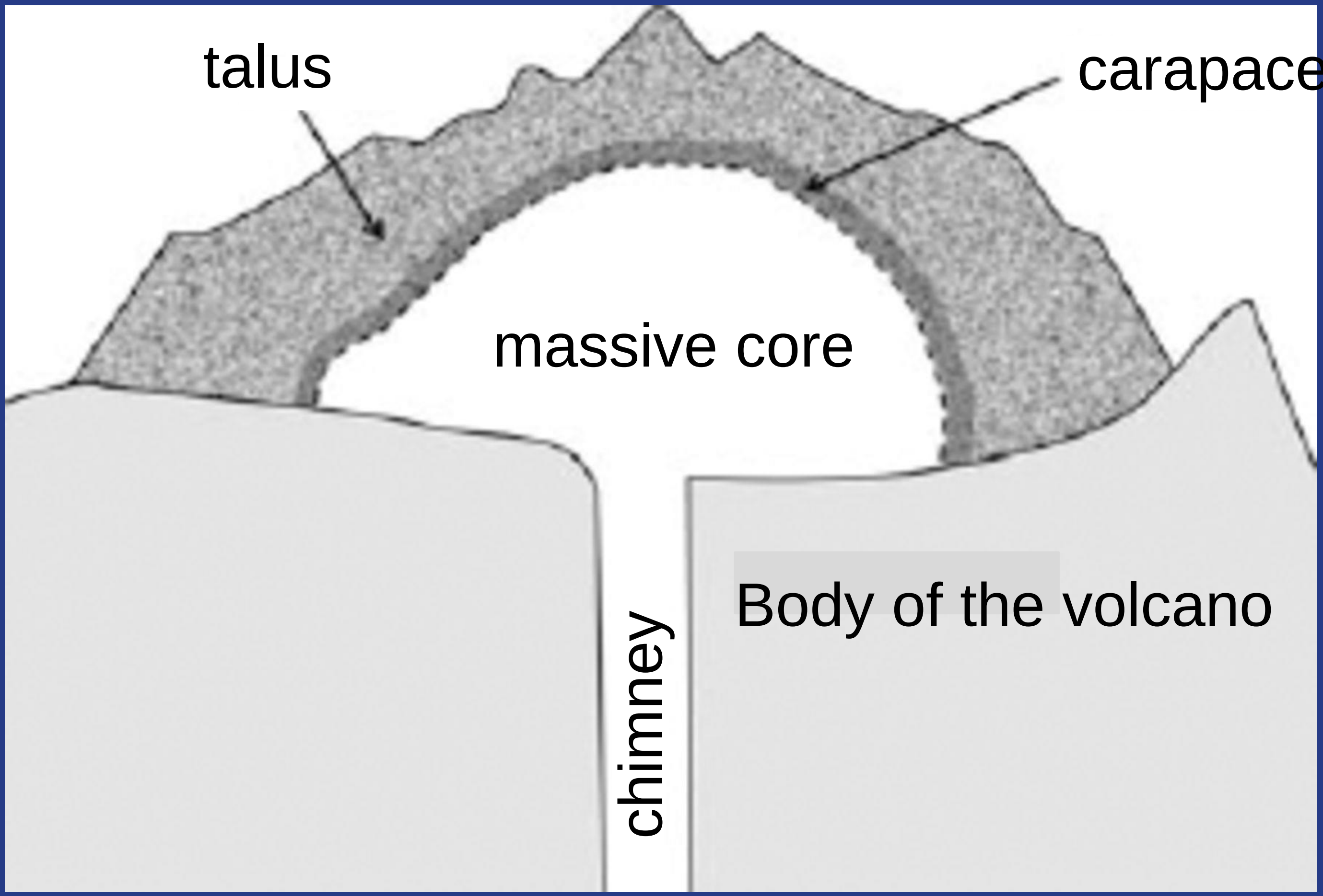



A morphological (i.e. according to their shape) classification of lava domes (from Blake, 1999)

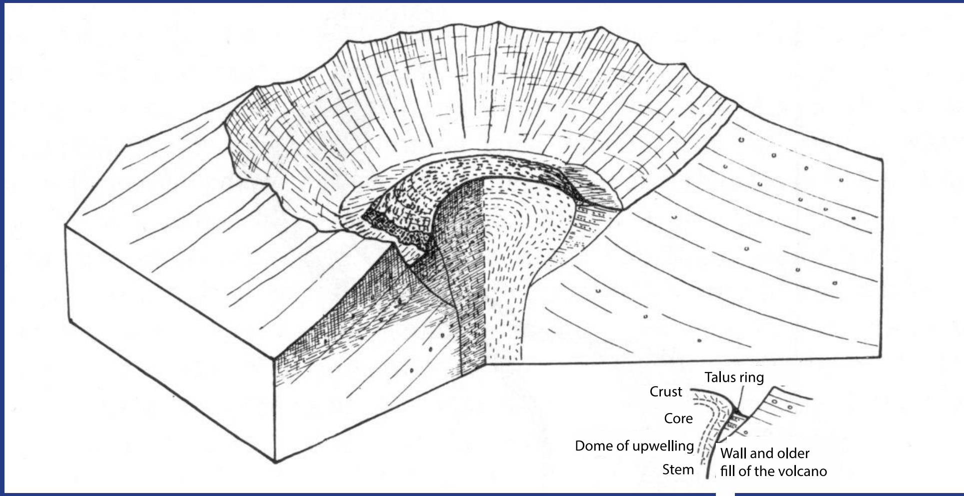



Block diagram of a lava dome from Hans Cloos (1936). The internal flow structure here shown is hypothetical, but to this day we have no data from the enterior of a subaerial lava dome

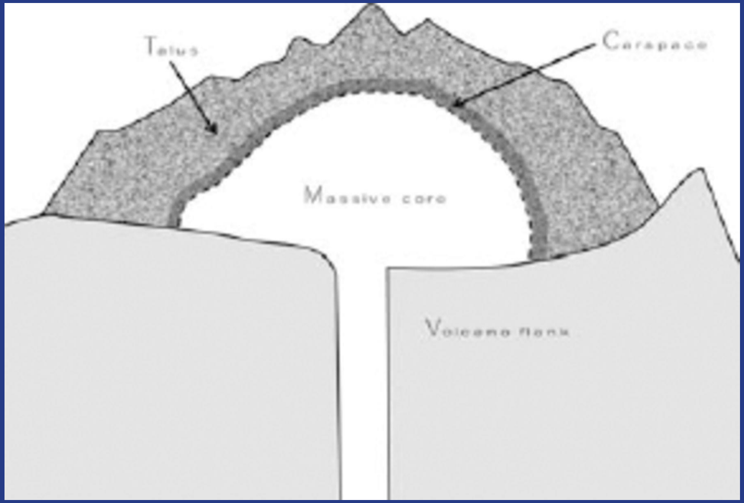
## Schematic cross section of a simplified endogenous lava dome comprised of an outer solidified surface (termed the talus) that enshrouds the massive hot lava dome core.




Modified from A. J. Hale Geophys. J. Int. 2008;volume 174 pages 391-417




Hans Cloos 1936




A. J. Hale 2008

The most recent publication on a subject is not necessarily the best!

Hornitos (from the Spanish “small oven”)
(constructs built by lava of low viscosity mainly of basaltic composition).

An active hornito in the Afar volcanic region in East Africa.

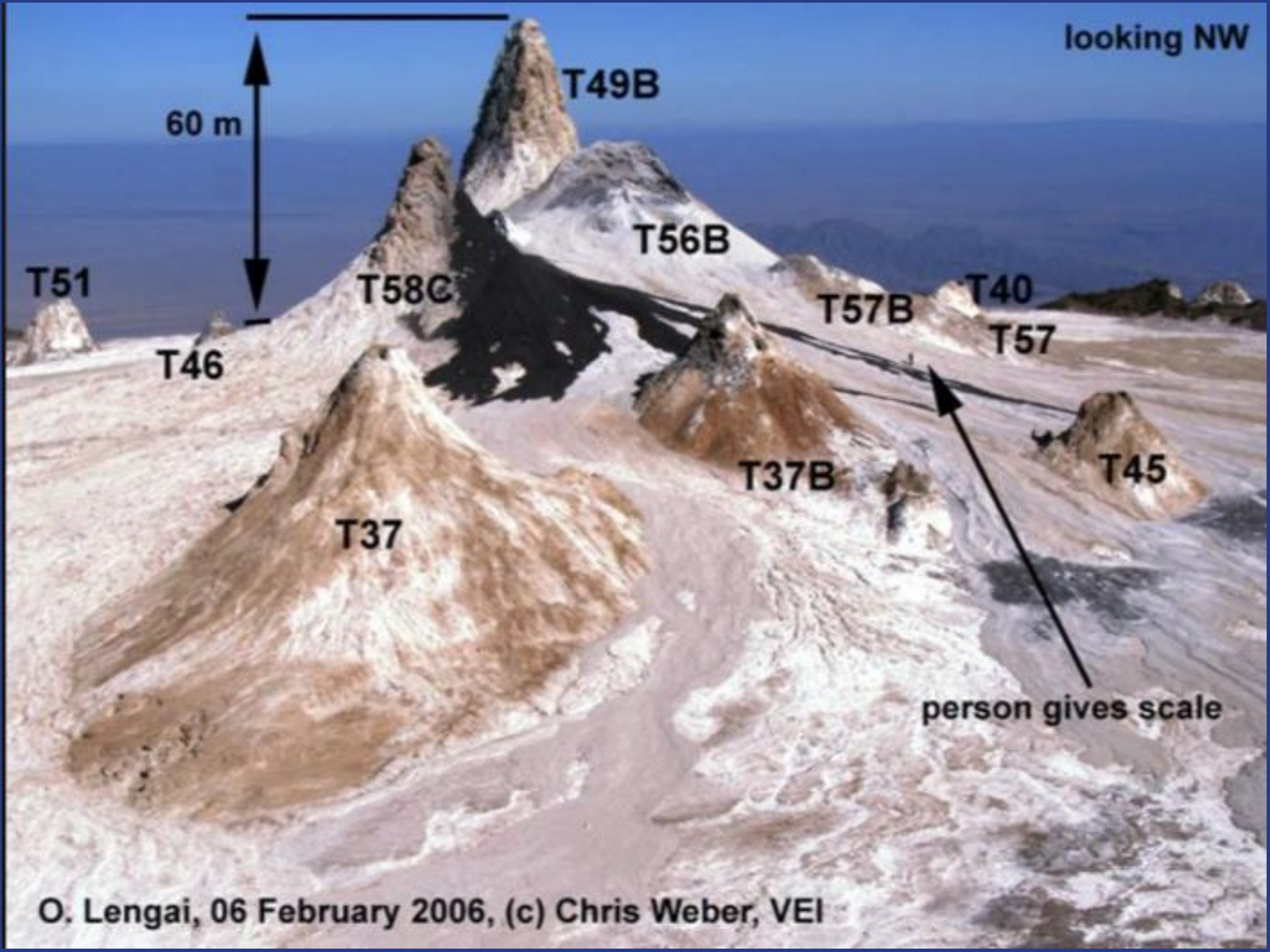
Geologist collecting spatter samples from the surface of a pahoehoe lava flow near a hornito, near Kilauea, Hawaii, USA.

A hornito in formation in the Kilauea volcano, Hawaii, USA

Another hornito on the Kilauea volcano, Hawaii

A hornito in Iceland

A carbonatite hornito on the Ol Doinyo Lengai in Tanzania




Hornito cluster at the top of Ol Doinyo Lengai, a carbonatite volcano near Lake Natron, East Africa

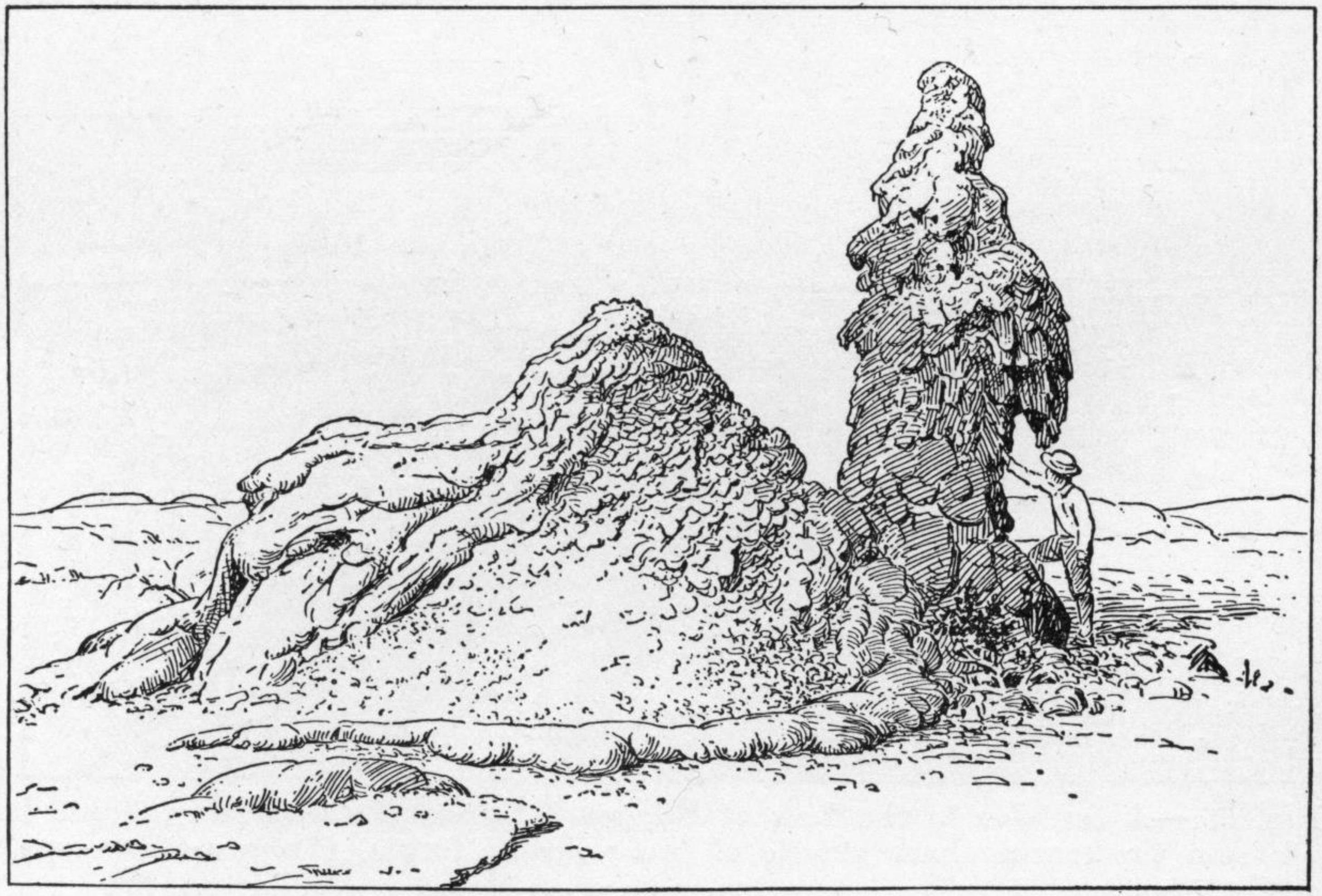
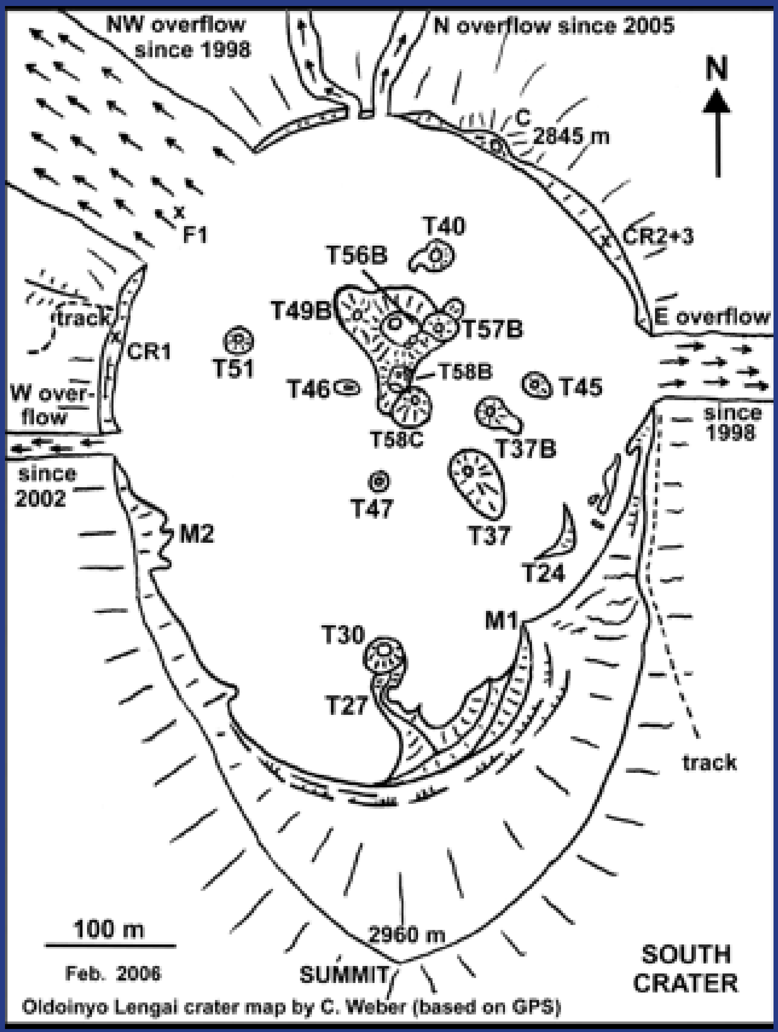


Fig. 70.—Driblet cone near the Kamaklaia cones, Hawaii. (*From a photograph by H. E. Wilson, July 14, 1911.*)

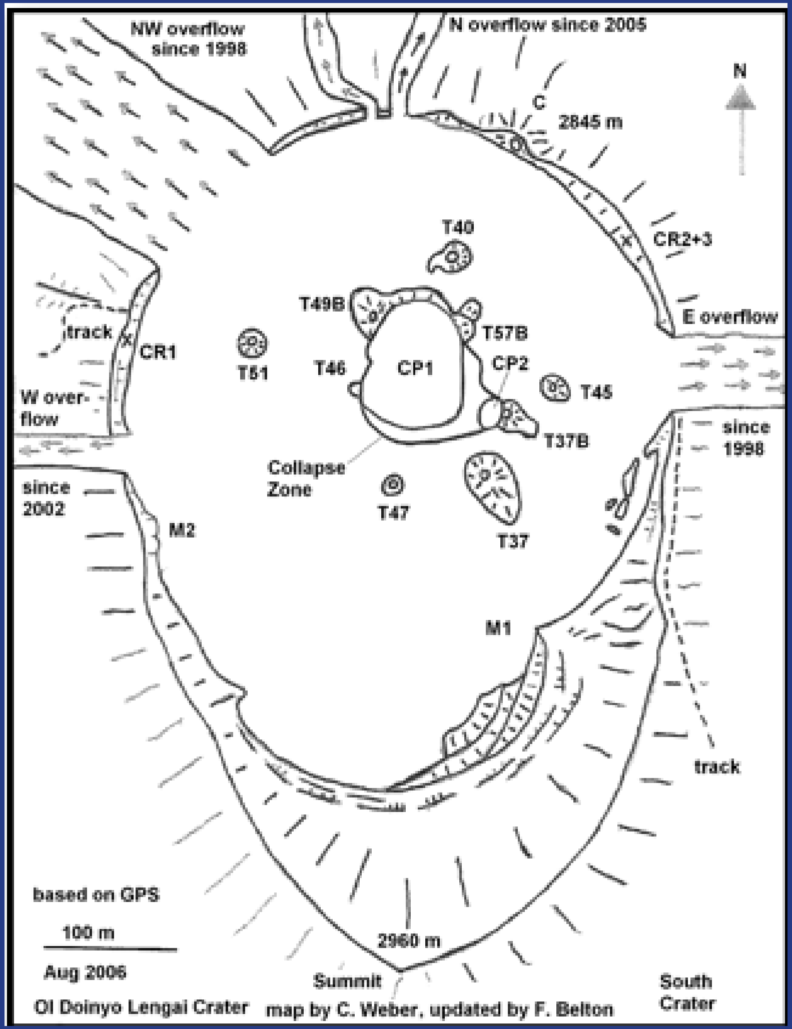
In the North American geological literature, hornitos are also called driblets meaning things that drip (this figure is from Daly's 1933 book entitled *Igneous Rocks and the Depths of the Earth*).

Hornitos are usually not connected to the main chimney of the volcano, but form atop lava tunnels on a spreading lava sheet. That is why they are said to be “rootless”.

Hornitos are also ephemeral structures and get destroyed during individual eruptions. Below is an example from the crater of Ol Doinyo Lengai in Tanzania, East Africa




February 2006




August 2006, after the March-April 2006 eruption

The main volcanic edifices: the volcanic mountains themselves

An efusive eruption: Kilauea Volcano, Hawaii

An explosive eruption: Mt. Pinatubo Volcano, Philippines

The explosivity of a volcano may be measured using the German volcanologist Alfred Rittmann’s explosivity index (E) which is calculated as:

$$E = \frac{\text{Solid material erupted (tephra)}}{\text{Total material erupted}} \times 100$$

Two American geologists, Chris Newhall and Stephen Self suggested a new way of measuring the explosivity index (they call it VEI) in 1982. Volume of products, eruption cloud height and qualitative observations are used to determine the E value. The scale is logarithmic and open-ended. So far it ranges from 0 to 8, but it does not necessarily mean that E=9 eruptions cannot exist. It simply means that explosive eruptions with such a high E value have not been detected yet.

This is a highly subjective way of measuring the E. *I would personally not use it*. Moreover it can only be used for eruptions that can be directly observed. I would recommend sticking with Rittmann's suggestion, which he first made in his 1936 book *Vulkane und Ihre Tätigkeit* (1936, p. 162). In the third, much enlarged and updated edition published in 1981, Rittmann repeated the same suggestion with reference to his 1936 book.

| VEI | Ejecta volume(bulk) | Classification | Description | Plume | Frequency | Tropospheric injection | Stratospheric injection[2] | Examples |
|---|---|---|---|---|---|---|---|---|
| 0 | < 10,000 $m^3$ | Hawaiian | Effusive | < 100 m | constant | negligible | none | Kīlauea, Piton de la Fournaise, Erebus |
| 1 | > 10,000 $m^3$ | Hawaiian / Strombolian | Gentle | 100 m–1 km | daily | minor | none | Nyiragongo (2002), Raoul Island (2006), Stromboli Island - (continuous since Roman times to present) |
| 2 | > 1,000,000 $m^3$ | Strombolian / Vulcanian/Hawaiian | Explosive | 1–5 km | weekly | moderate | none | Unzen (1792), Cumbre Vieja (1949), Galeras (1993), Sinabung (2010) |
| 3 | > 10,000,000 $m^3$ | Vulcanian / Peléan/Sub-Plinian/Hawaiian | Catastrophic | 3–15 km | few months | substantial | possible | Nevado del Ruiz (1985), Lassen Peak (1915), Soufrière Hills (1995), Nabro (2011) |
| 4 | > 0.1 $km^3$ | Peléan / Plinian/Sub-Plinian | Cataclysmic | > 10 km (Plinian or sub-Plinian) | ≥ 1 yr | substantial | definite | Mayon (1814), Pelée (1902), Galunggung (1982), Eyjafjallajökull (2010) |
| 5 | > 1 $km^3$ | Peléan/Plinian | Paroxysmic | > 10 km (Plinian) | ≥ 10 yrs | substantial | significant | Vesuvius (79), Fuji (1707), Mount Tarawera (1886), St. Helens (1980), Puyehue (2011) |
| 6 | > 10 $km^3$ | Plinian / Ultra-Plinian/Ignimbrite | Colossal | > 20 km | ≥ 100 yrs | substantial | substantial | Veniaminof (c. 1750 BC), Huaynaputina (1600), Krakatoa (1883), Novarupta (1912), Pinatubo (1991), Laacher See (c. 12,900 BC) |
| 7 | > 100 $km^3$ | Ultra-Plinian/Plinian/Ignimbrite | Super-colossal | > 20 km | ≥ 1,000 yrs | substantial | substantial | Mazama (c. 5600 BC), Thera (c. 1620 BC), Taupo (180), Samalas (Mount Rinjani) (1257), Tambora (1815) |
| 8 | > 1,000 $km^3$ | Ignimbrite/Plinian/Ultra-Plinian | Mega-colossal | > 20 km | ≥ 10,000 yrs | vast | vast | La Garita Caldera (26.3 Ma), Yellowstone (640,000 BC), Toba (74,000 BC), Taupo (24,500 BC) |

# Classification of eruptions according to the Volcanic Explosivity Index (VEI) of Newhall and Self (1982).

Newhall, C. G. and Self, S., 1982, The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism: *Journal of Geophysical Research (Oceans)*, v. 87, pp. 1231-1238

We now turn to the internal structure of volcanoes that can be very diverse.

Until about the seventies of the twentieth century, volcanic edifices created by eruptions were classified as:

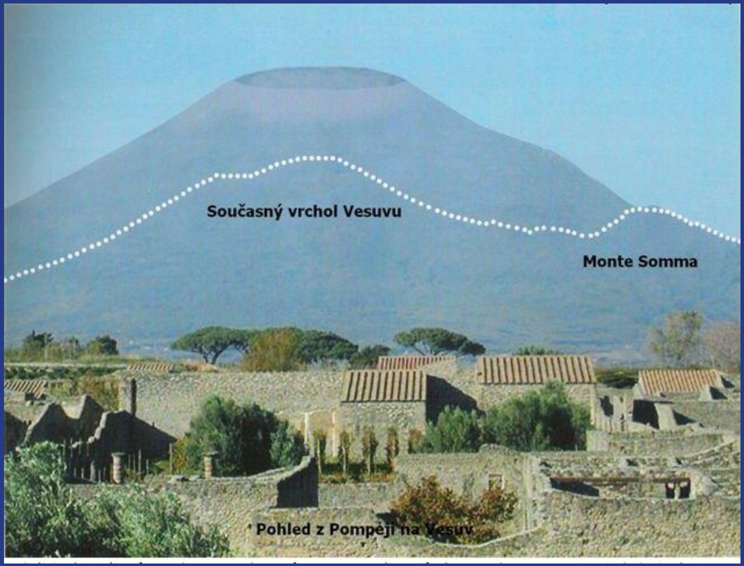
1. Hawaiian shield volcanoes

2. Strombolian stratovolcanoes

3. Vulcano-type stratovolcanoes

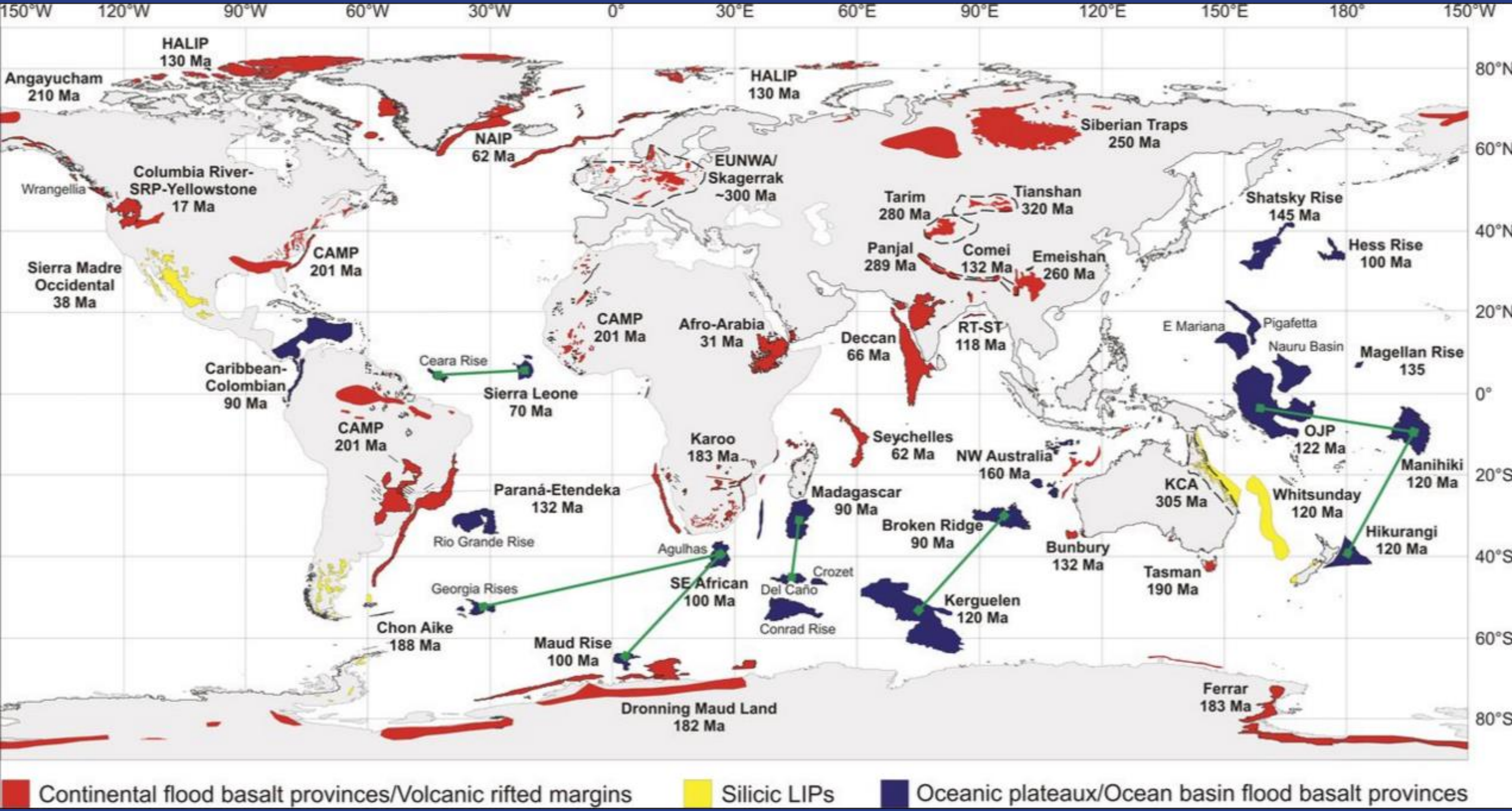
1. Vesuvian or Peléan type stratovolcanoes +calderas produced by Plinian eruptions.

Vesuvius and Monte Somma today

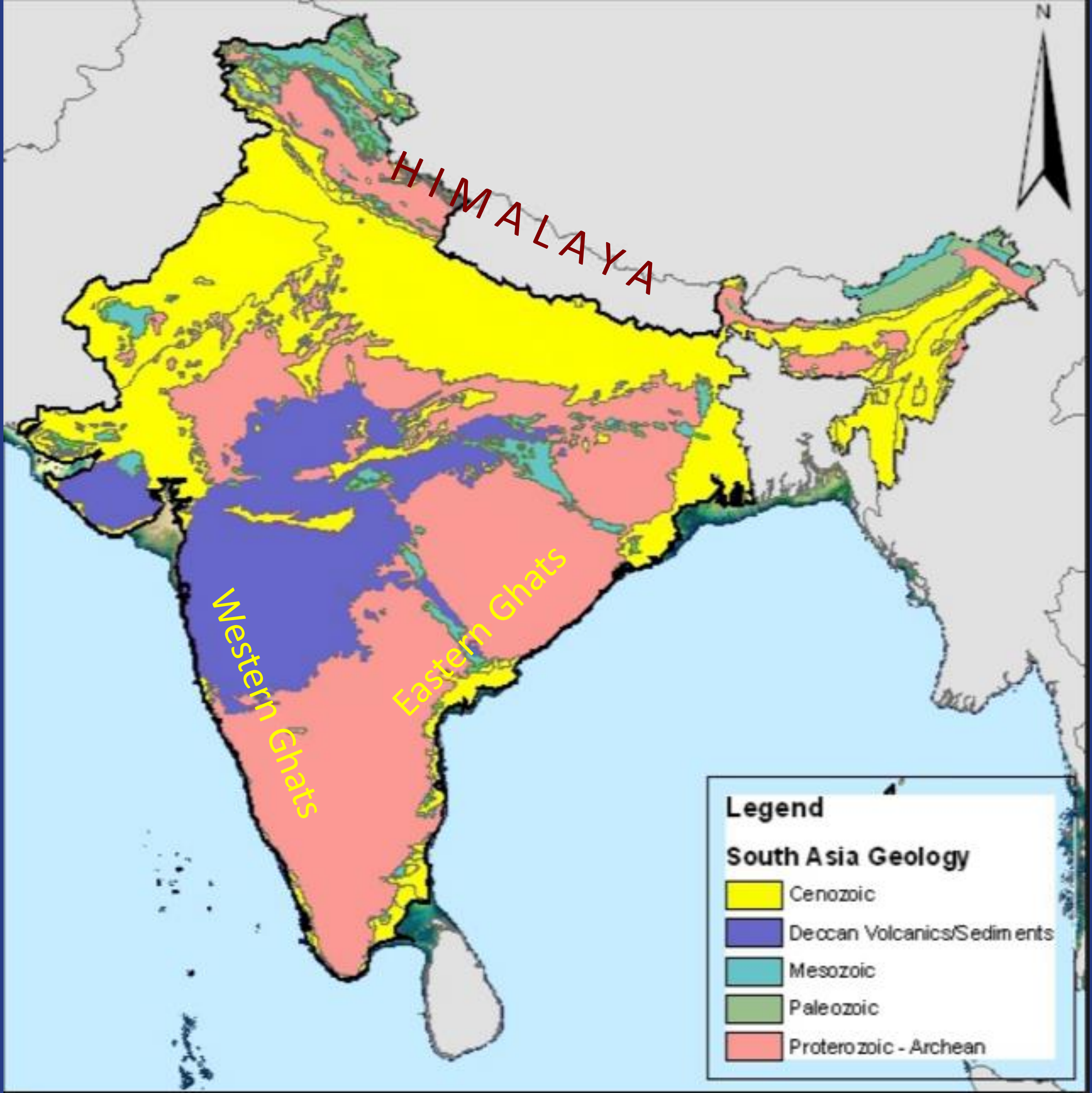



Vesuvius before the 79CE eruption (reconstructed)

Vesuvius blew its top off during the 79 CE eruption. Monte Somma is only a poor remnant of the older, larger Vesuvius.

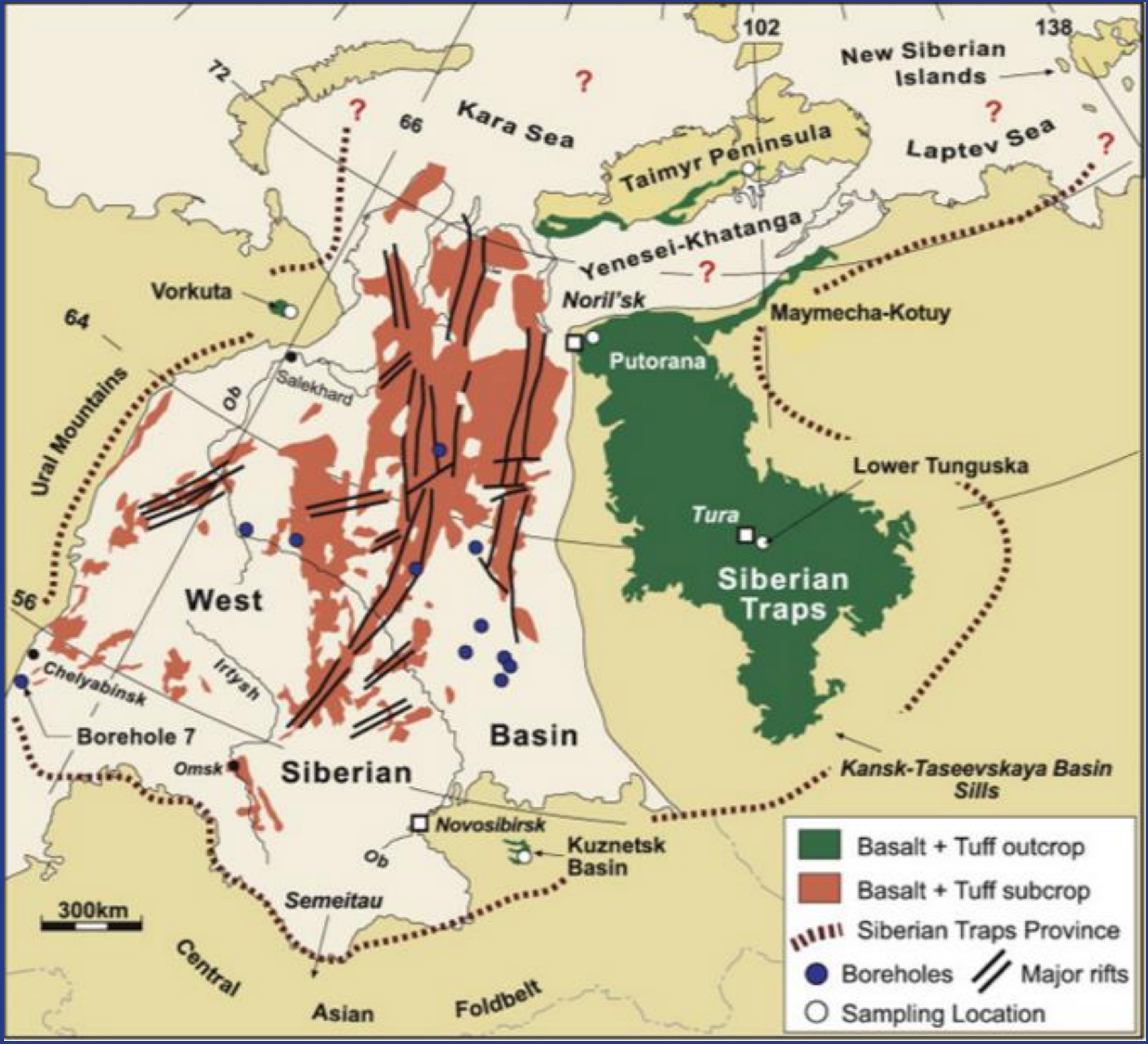



Large Igneous Provinces (LIP). Most are immense flood basalt flows, the largest being the Tunguska (or Siberian) traps exceeding 7 million km$^2$ (seven times the size of Turkey!!)

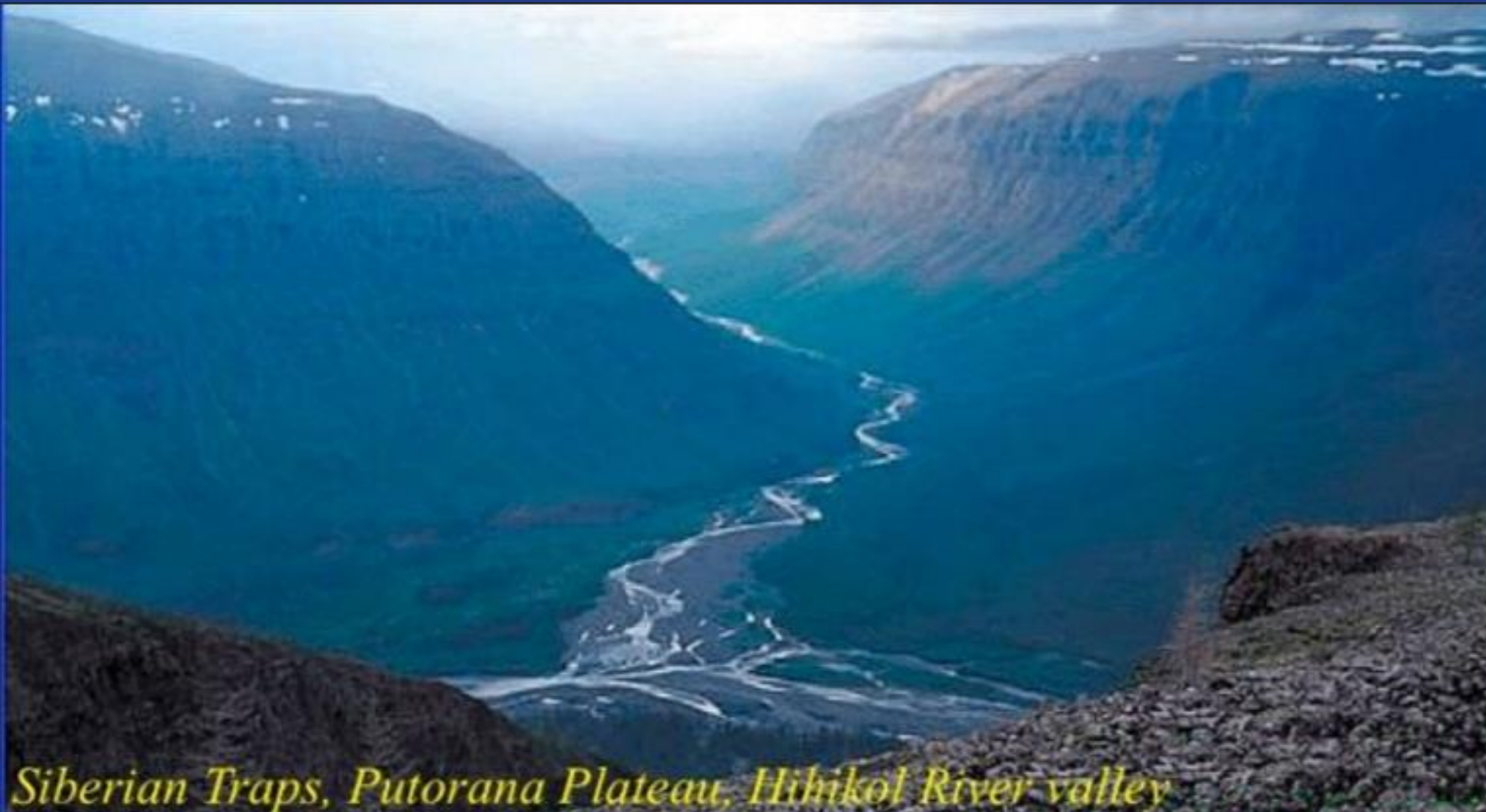


N
HIMALAYA
Western Ghats
Eastern Ghats
Legend
South Asia Geology
Cenozoic
Deccan Volcanics/Sediments
Mesozoic
Paleozoic
Proterozoic - Archean

The same kind of table flows also characterise much of the volcanism in Iceland
Photo: Prof. Dr. Murat Karaçorlu




The distribution of the Tunguska (=Siberian) traps


Siberian Traps, Putorana Plateau, Hihikol River valley

Effusive

Explosive

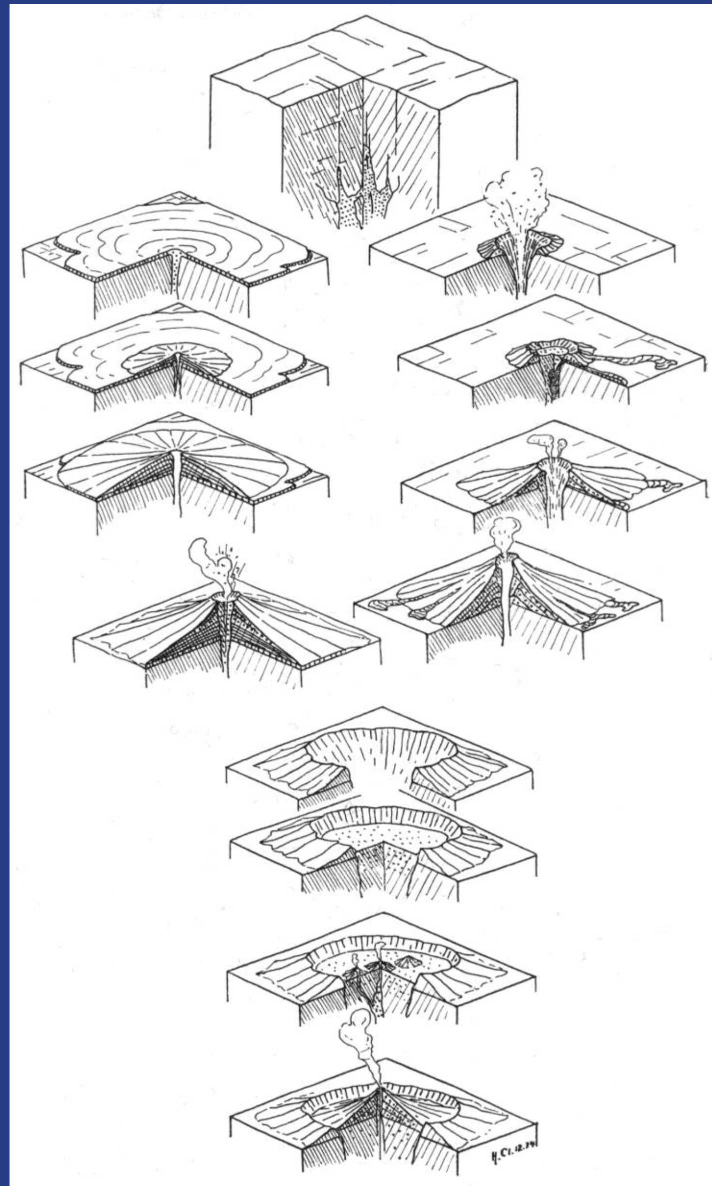


Table volcanoes

Table-shield volcanoes

Shield volcanoes

Mixed volcanoes

Maars

Maar w/ lava flow

Ash volcanoes

Mixed volcanoes

Caldera

Filled caldera

Second generation volcanoes

Vesuv-Stage

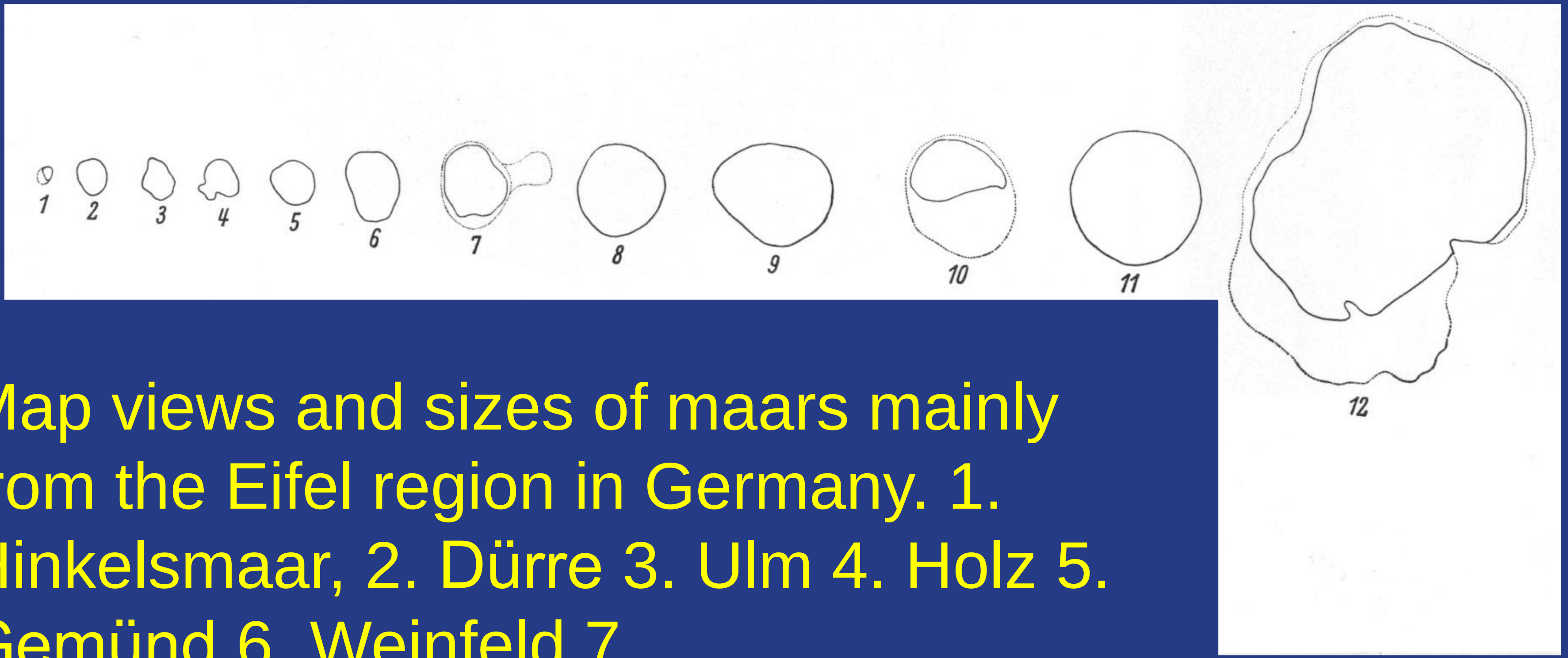
From H. Cloos 1936 *Einführung in die Geologie*

# Maars and diatremes

Weinfelder Maar: one of the three maars originally described in the Eifel region of Germany

The three originally described maars: Gemünd, Weinfeld and Schalkenmehren

Zengena Lake Maar in Ethiopia

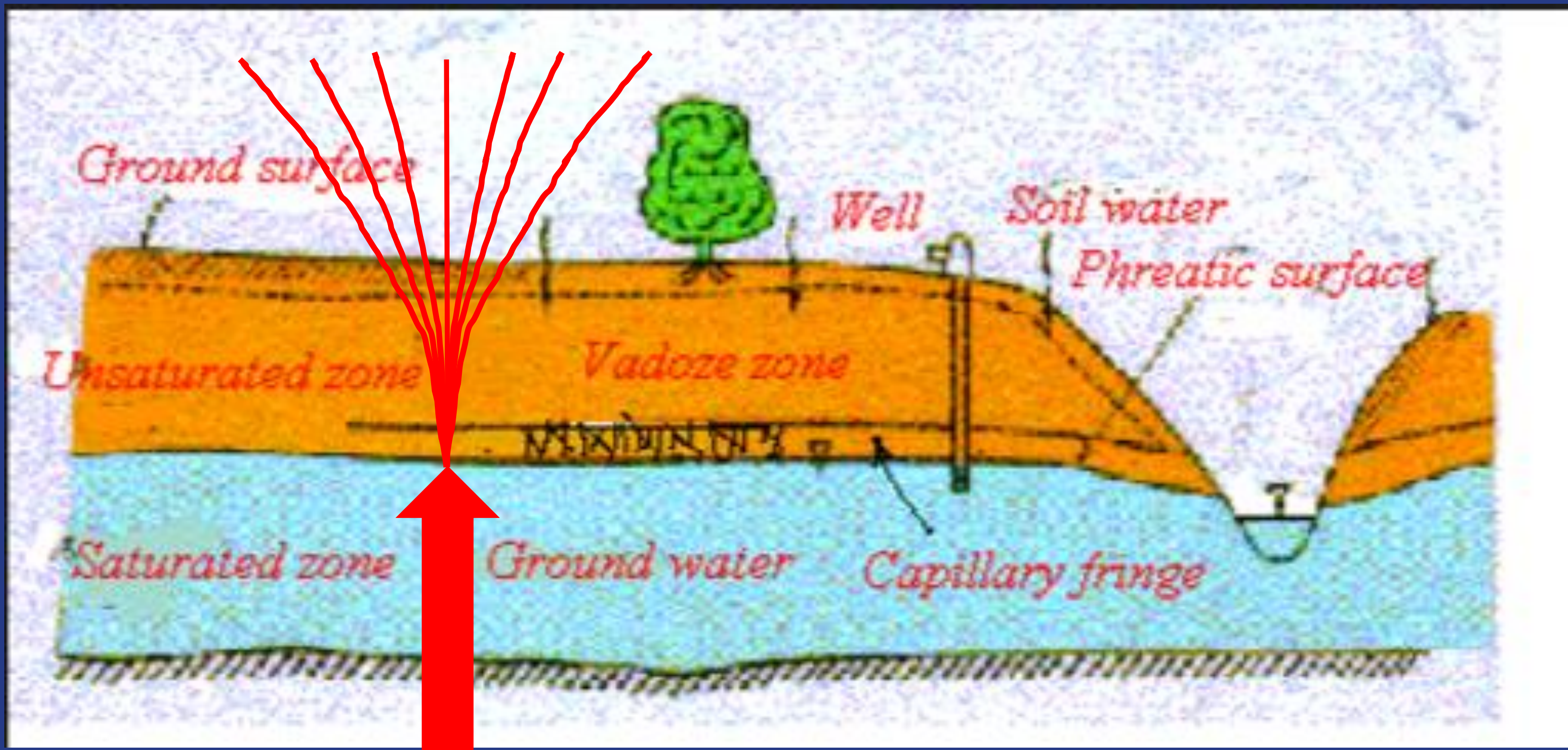



Map views and sizes of maars mainly from the Eifel region in Germany. 1. Hinkelsmaar, 2. Dürre 3. Ulm 4. Holz 5. Gemünd 6. Weinfeld 7. Schlankenmehren 8. Pulver 9. Moosbruch 10. Meerfeld, 11. Salzpfanne 12.  Pretoria (South Africa) 12. Laach Lake (from Hans Cloos 1936)

1km

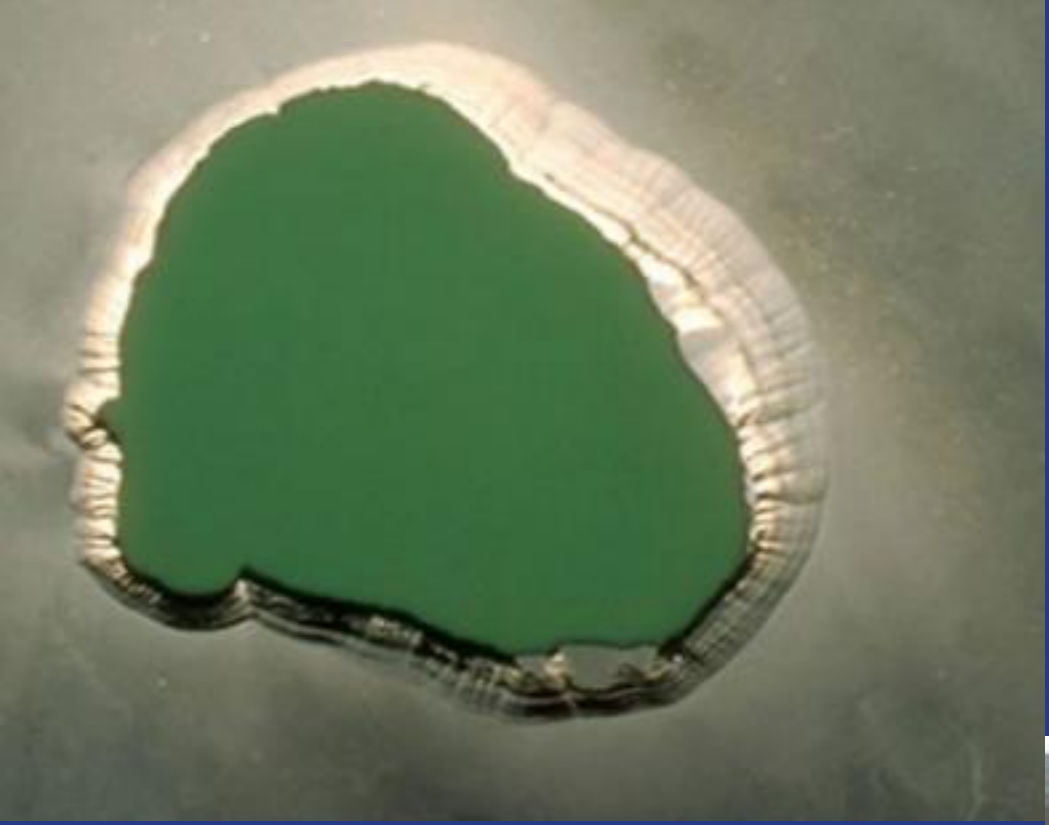
Maar is the morphological form and comes from the German word *Meer*=sea. The volcanoes forming maars are called diatremes.

Diatremes form when a rising body of magma comes into contact with the water table (phreatic zone) and creates a spectacular explosion (called phreatic eruptions). Diatremes create maars, which are essentially purely explosive crters and generally have no associated lavas. They only erupt tephra.




A phreatomagmatic eruption: Rising magma comes into contact with the phreatic zone and instantly evaporates the water which expands to cause the eruption. Almost all violent eruptions in volcanoes are related to water vapour.

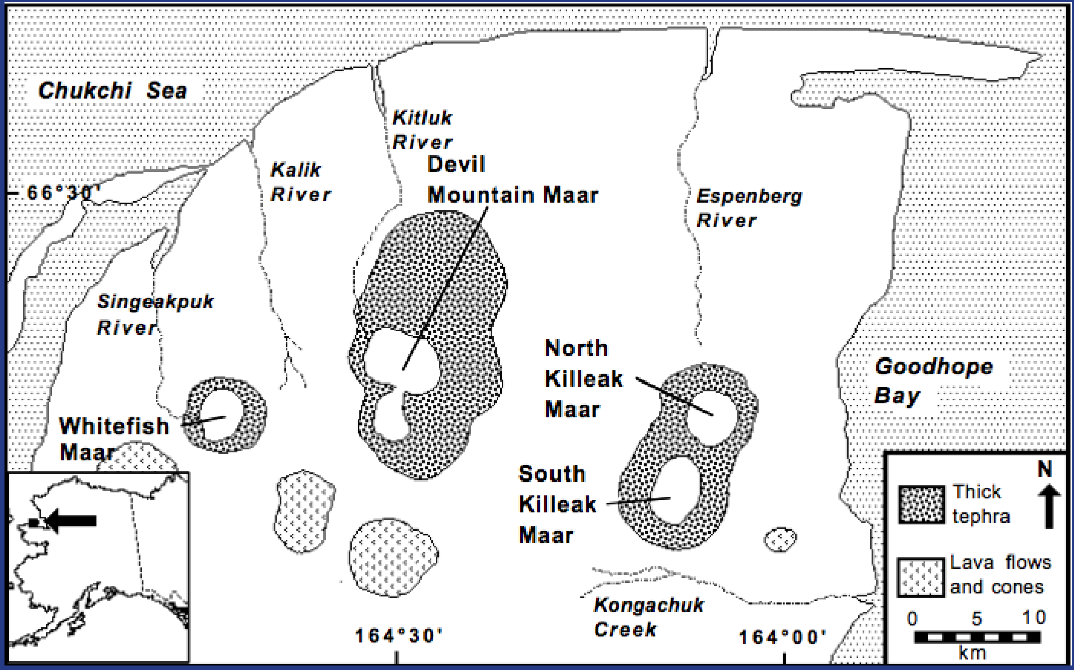
The Ukinrek Maar eruption in Alaska in 1977

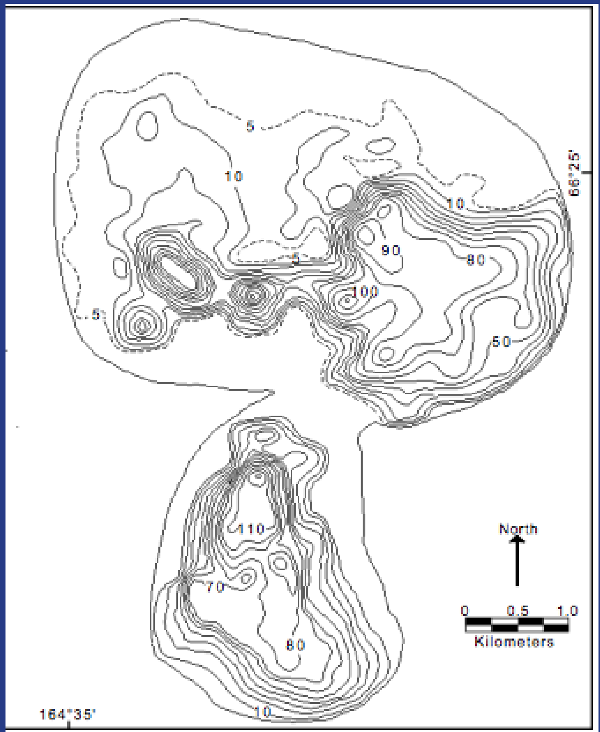


The Ukinrek Maar in Alaska; air photo

The crater margin of the Ukinrek Maar in Alaska; note the layered volcanic tuff

The Devil Mountain lakes in the Seward Peninsula, Alaska are the largest maar lakes in the world. Their diameter reaches 8 km. The reason for their large size is the violence of the eruption tp0at created the maars because of the magma/permafrost contact

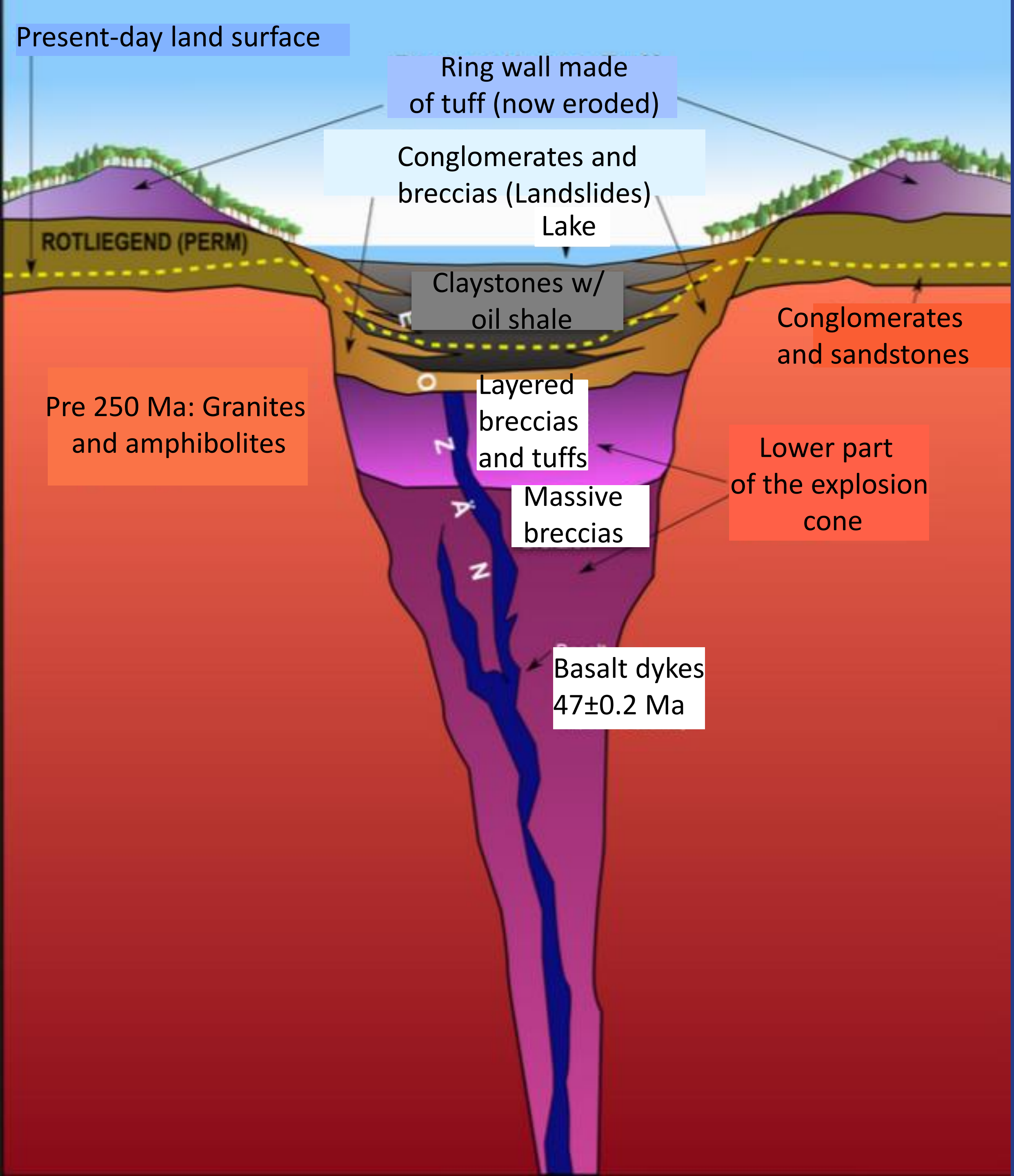




Bathymetry of Devil Mountain lakes (from Begét et al., 1996).

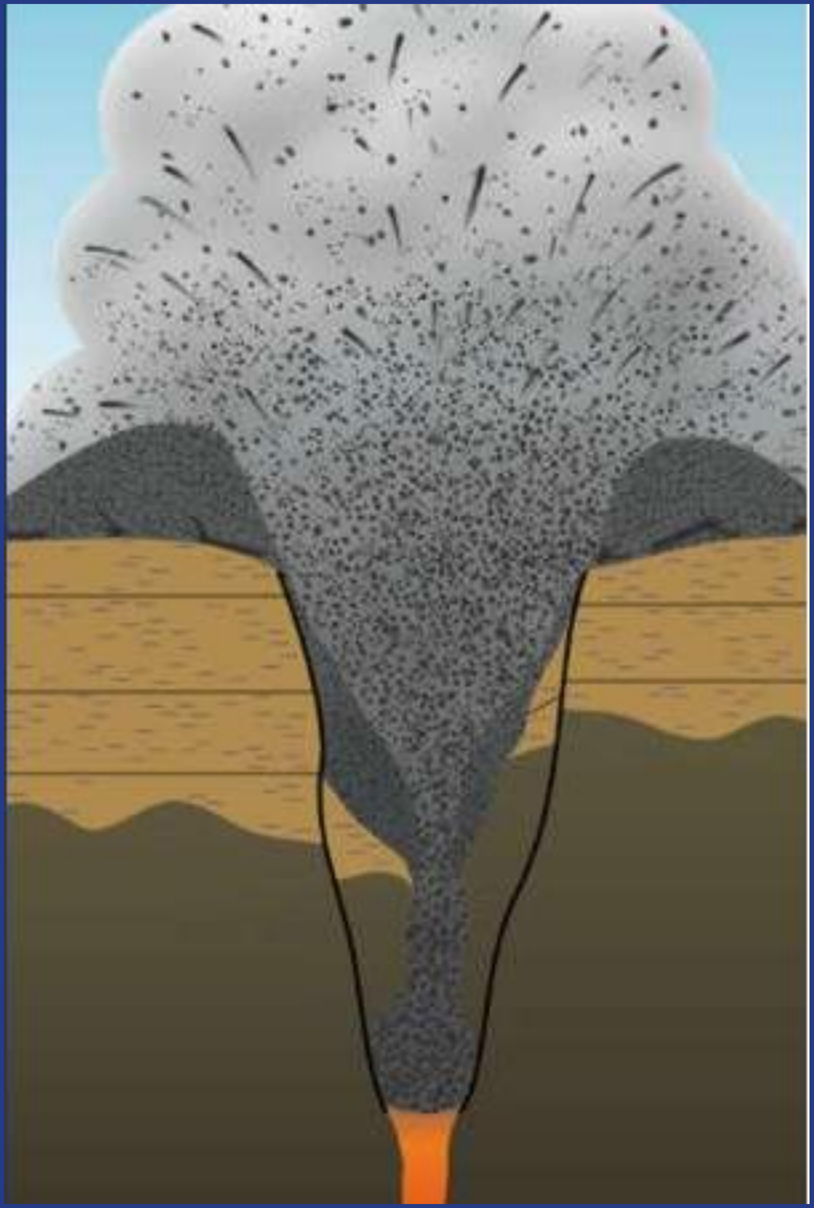
After cinder cones, maars are the most widespread volcanic forms on earth.

Cas, R. A. F., and Wright, J. V., 1987, *Volcanic Successions: Modern and Ancient*: Allen and Unwin, London, 578 pp.




A 50 million year-old maar: the Messel in Germany.

Messel is the best-known maar in the world.



The origin of the maar of Messel
some 50 million years ago

The location of the
Messel maar

# Shield volcanoes

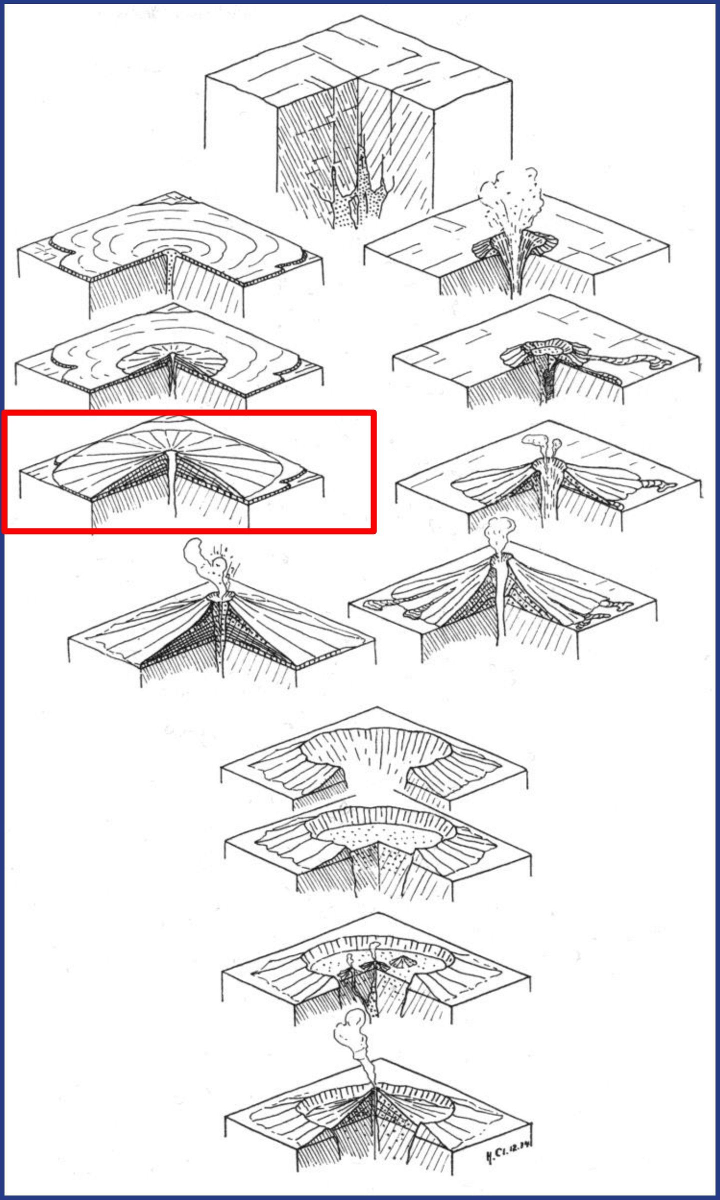
Effusive

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

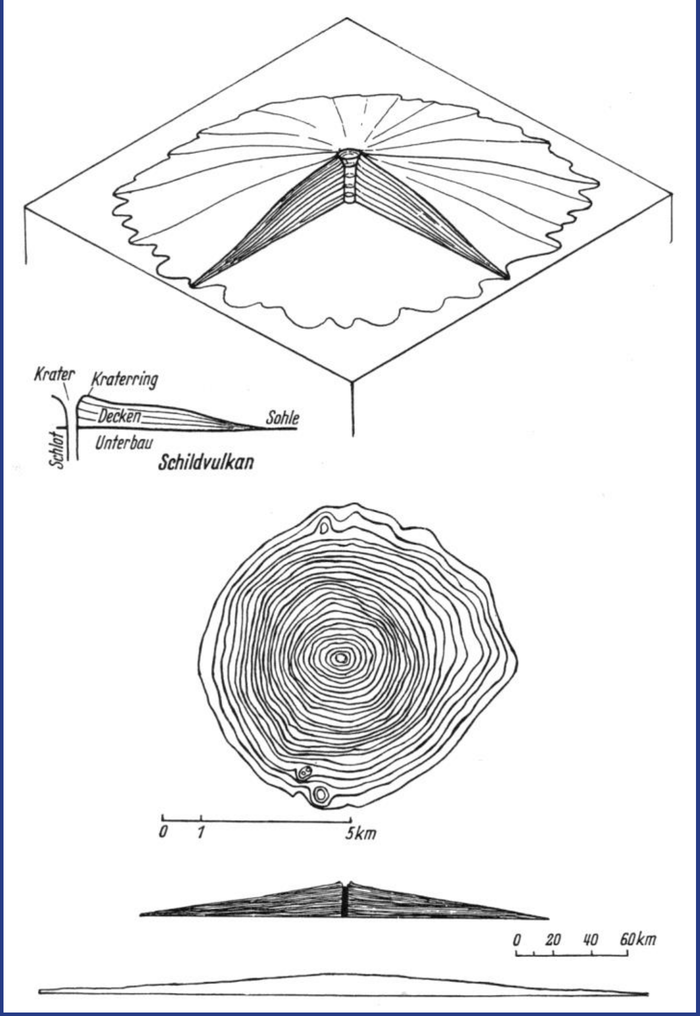
Vesuv-Stage

From H. Cloos 1936 *Einführung in die Geologie*

Mauna Loa, on the Big Island of Hawaii, USA. The “type” shield volcano.

An ideal shield volcano

Cross-section of the ideal shield volcano (half)



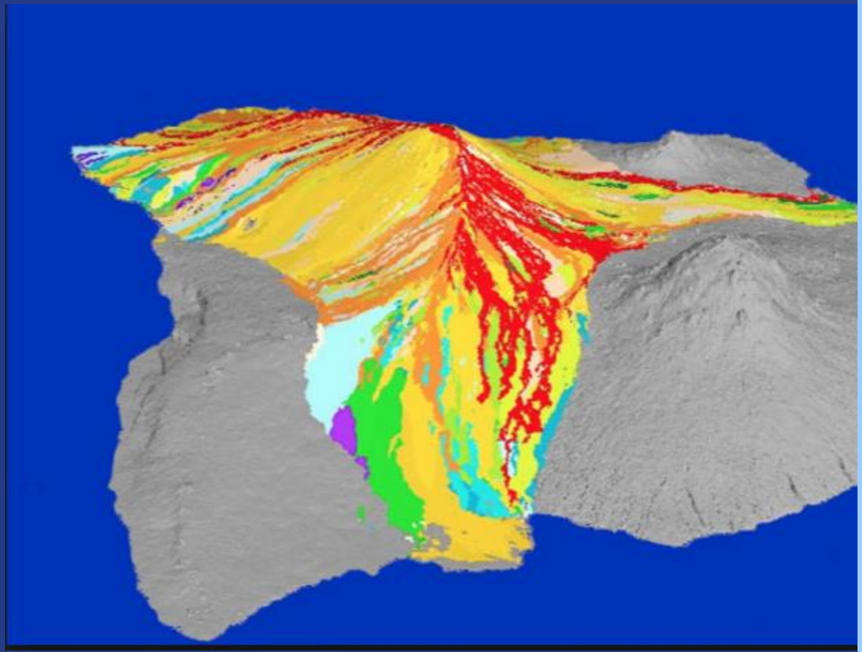

The Skjaldbreid shield volcano, Iceland (map view)

Skjaldbreid cross-section

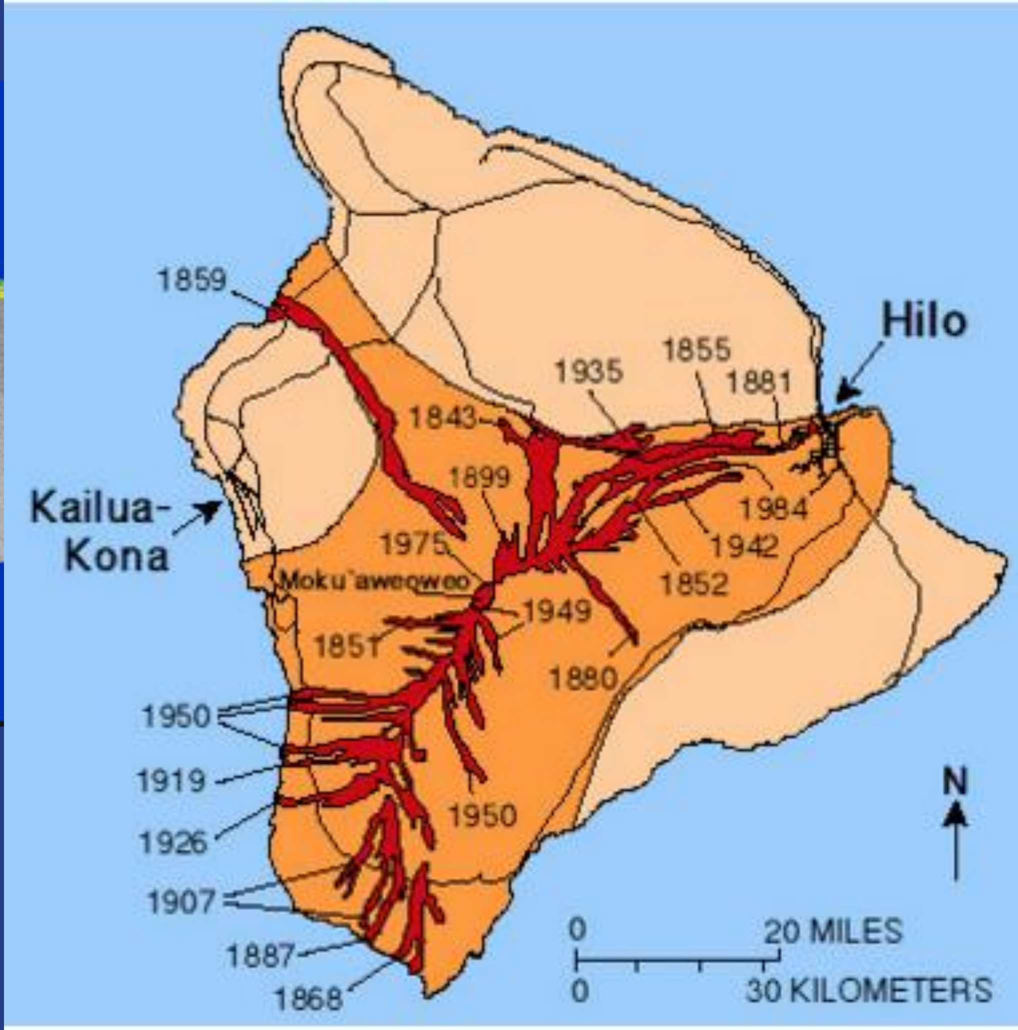
Mauna Loa cross-section for comparison

From Hans Cloos 1936

# Skjaldbreid shield volcano, Iceland



Historical Mauna Loa lava flows




These flows from 1833 to 2000 cover some 16% of the entire surface of the volcano, so some 10,400 km $^2$. Since total area of the volcano is 65,000 km $^2$ , it would take some 1000 years to cover the entire surface by individual lava flows. Since the island is some 10,000 m above the ocean floor and has an age of 400,000 years, every 1000 years some 25 m must have been added to the edifice. This means that every hundred years some 2 m thickness is added, which is roughly correct.

This is what those individual lava flows you have seen in the last slide looked like when they were active

Island of Hawaii occupies roughly 10,500 $km^2$. It accumulated this surface area in about 400,000 years. The Siberian traps are  some 7 million $km^2$, so they contain 700 times the Hawaiian surface area! Some claim that the total eruption time of the Siberian traps took only 500,000 years, almost the same time span as the Island of Hawaii. I have difficulty understanding this.

The summit calderas of Mauna Loa

The largest of the summit calderas of the Mauna Loa

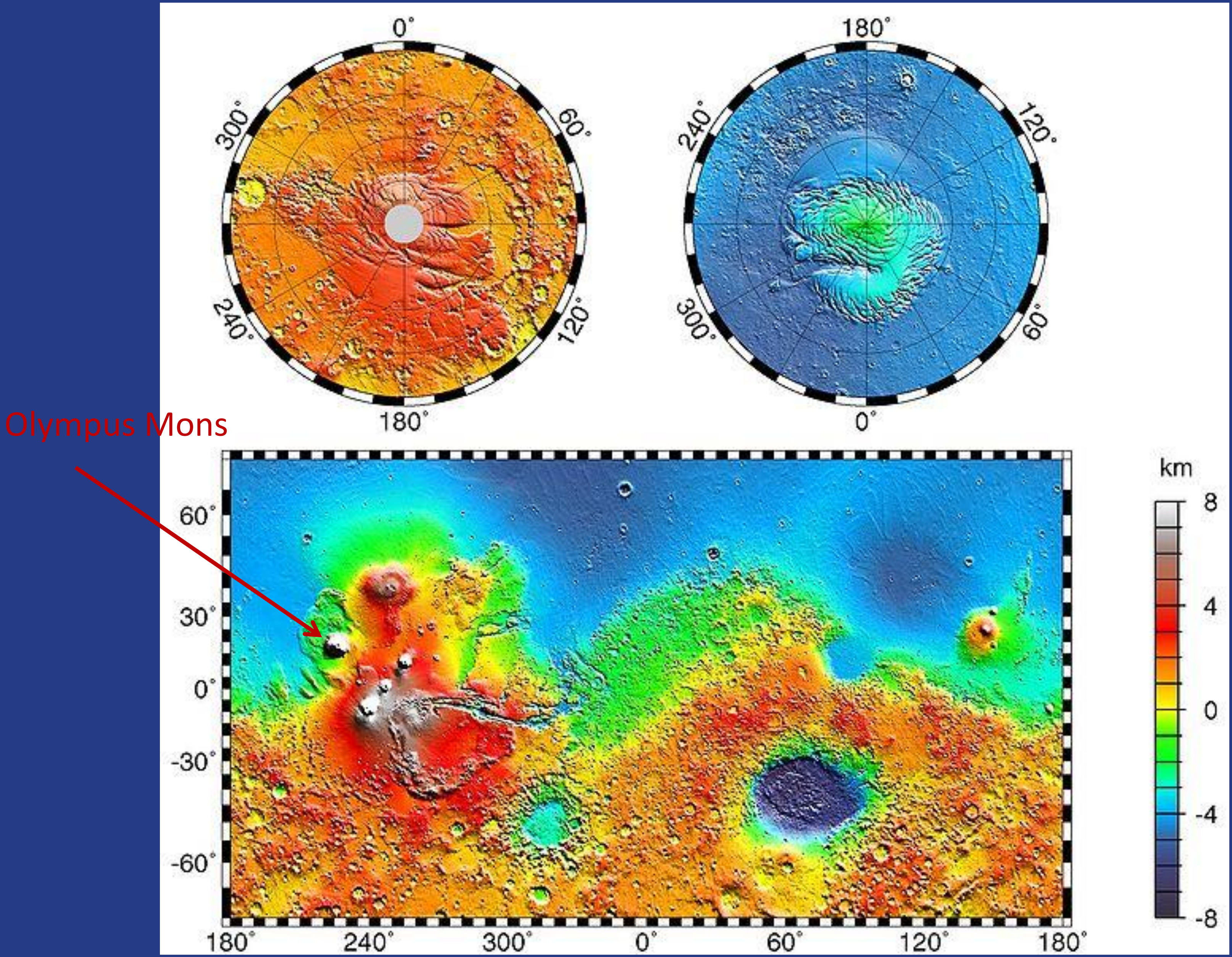

N20°06'
N19°54'
N19°42'
N19°30'
156°06'
W155°54'
W155°42'
W155°30'
W155°18'
W155°06'
W154°54'
Kīlauea
N19°18'
N19°06'
N18°54'


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"

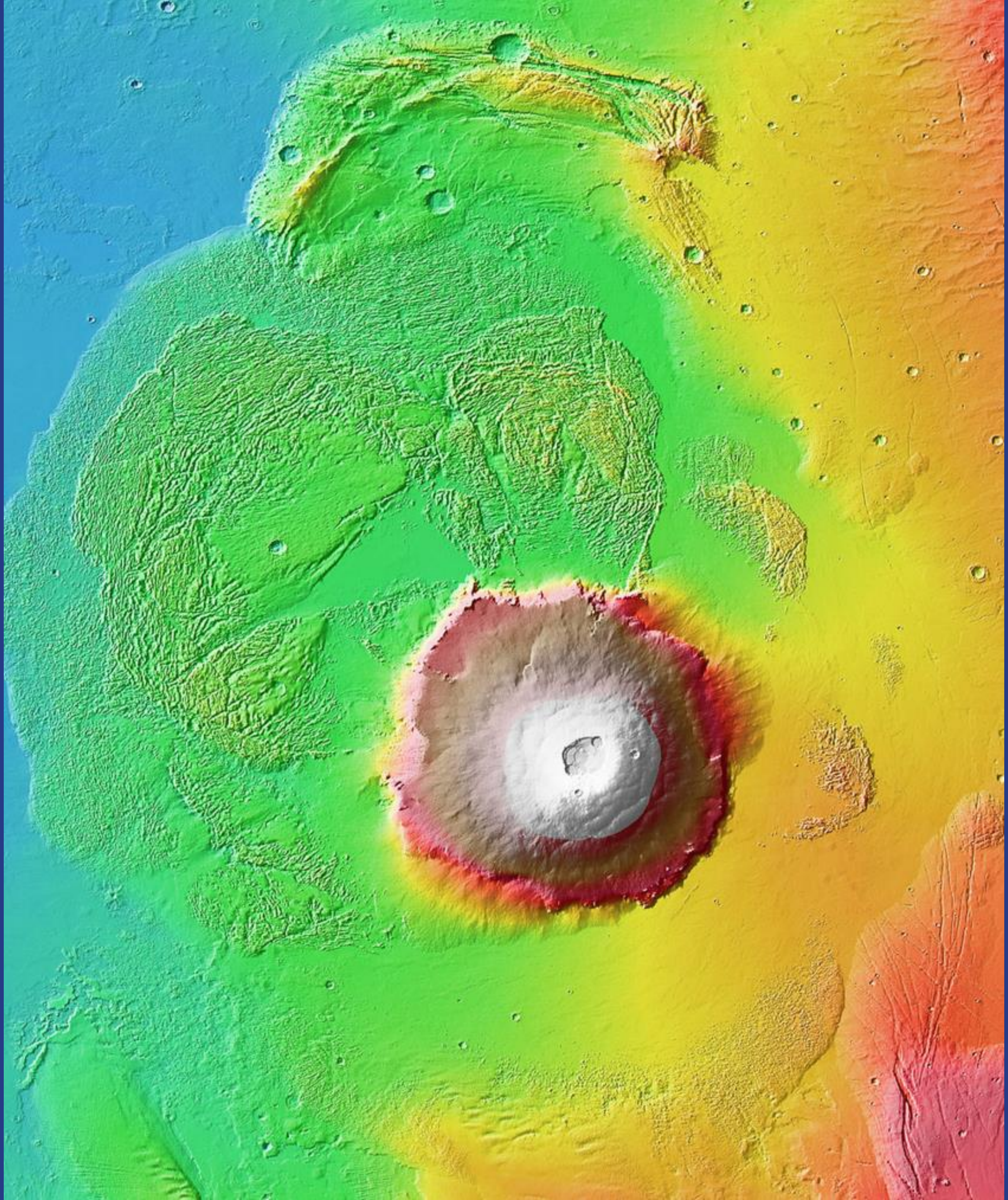
Halema‘uma‘u
Crater rim
Kīlauea
caldera rim
caldera floor
Overlook crater
(summit vent)
Halema‘uma‘u
Crater floor
vent rim
caldera floor

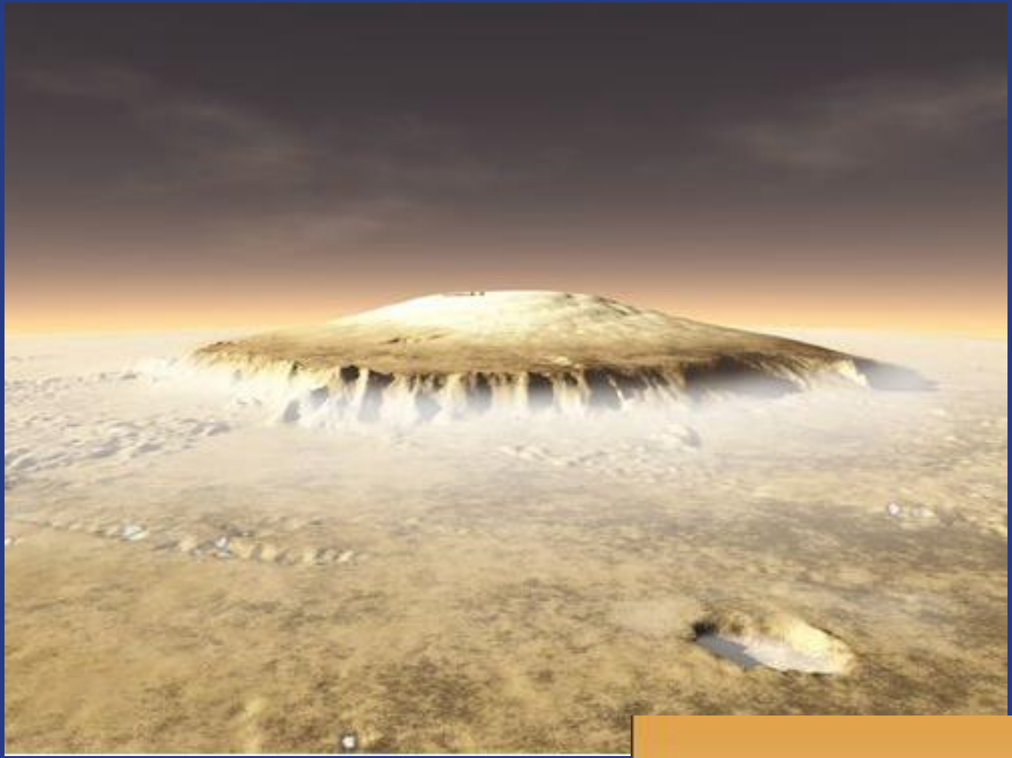
Collapse of a portion of the floor of the Halema’uma’u caldera on 3rd May 2015

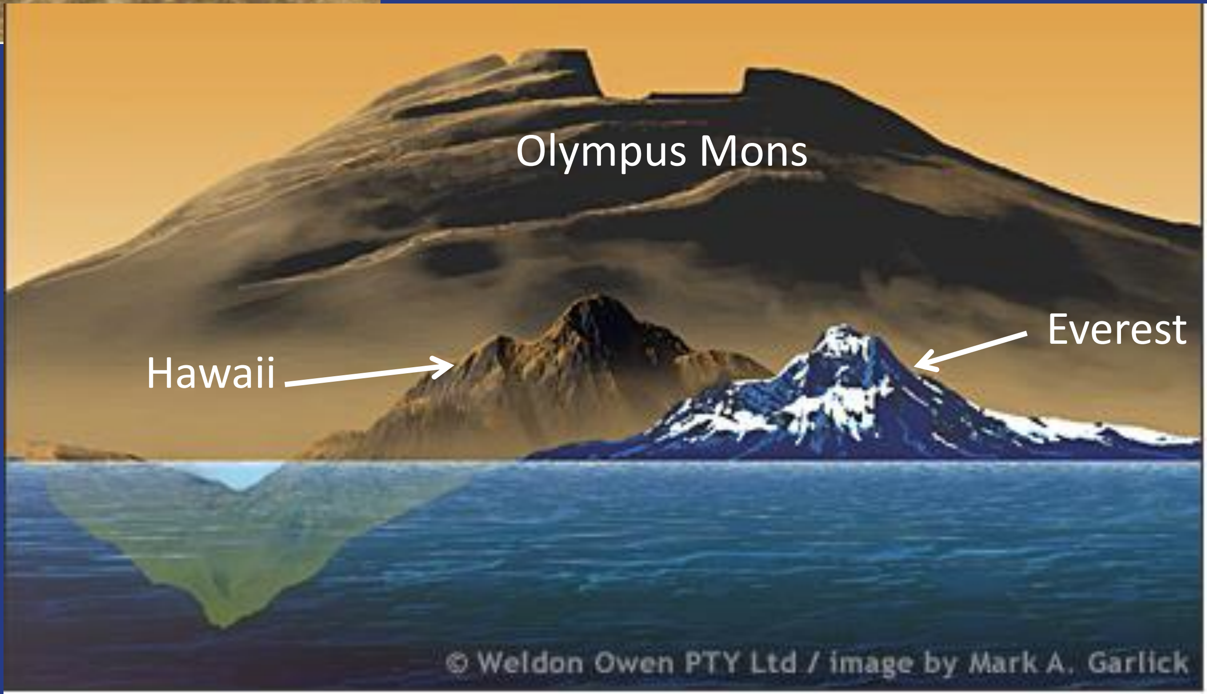
Titian Ramsay Peale’s rendering of the 1842 eruption of Kilauea. Notice that the summit caldera had turned into a lava lake.

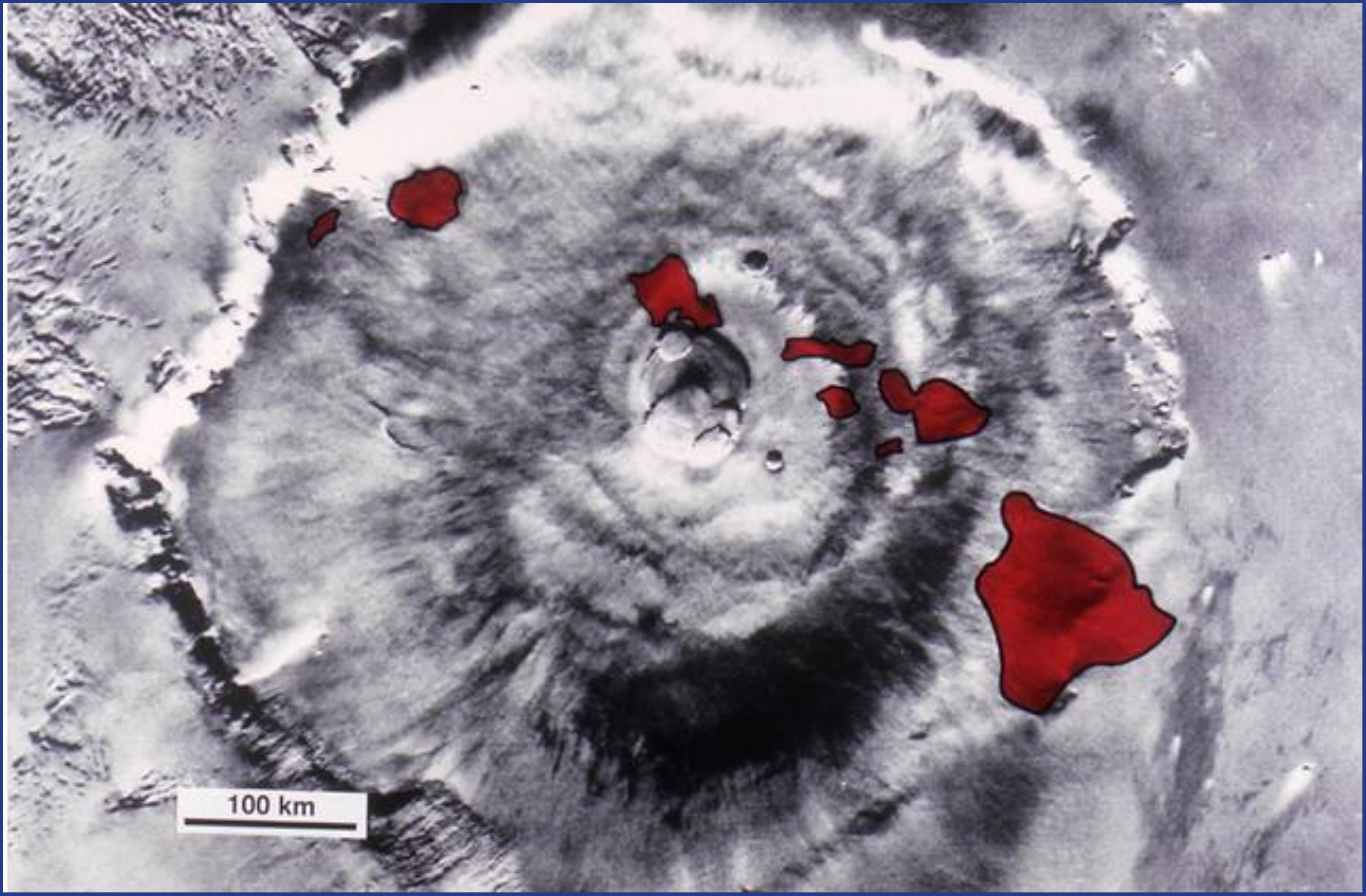



# Topography of Mars






Olympus Mons
Everest
Hawaii
© Weldon Owen PTY Ltd / image by Mark A. Garlick




Olympus Mons and the Hawaiian islands compared


Olympus Mons summit calderas


Calderas of shield volcanoes greatly resemble each other. So how do they form?