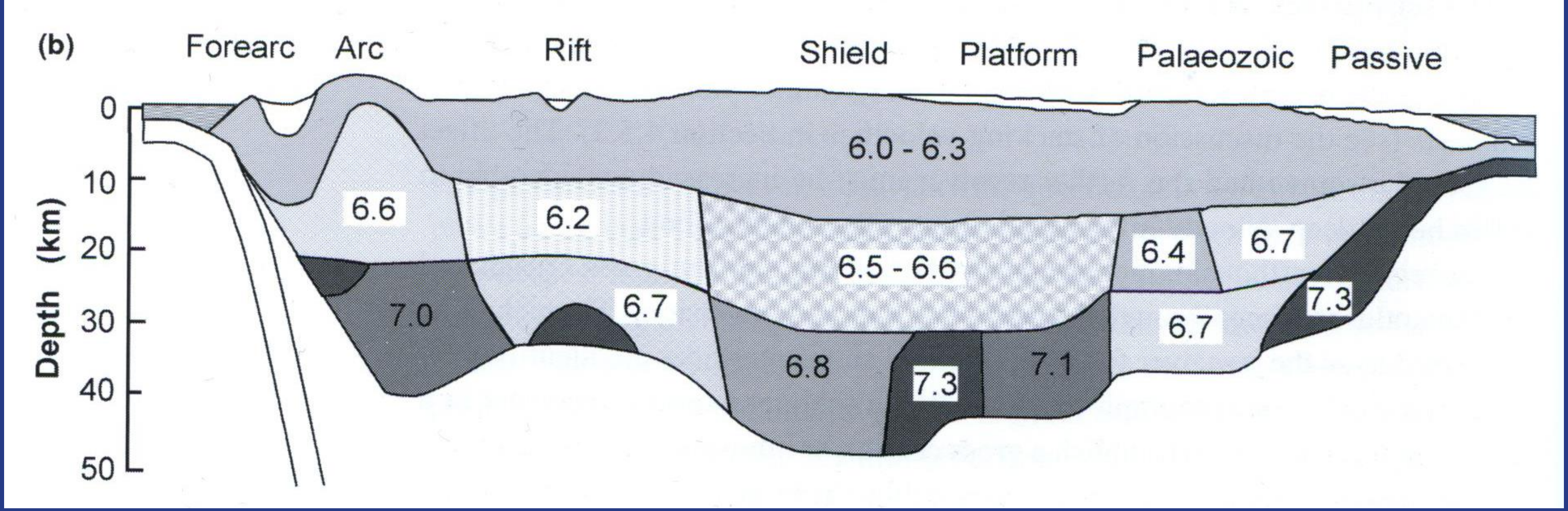


Distribution of velocities of longitudinal body waves (P waves) in an “ideal” continental crust. The numbers have the unit kilometre/second (km/s).

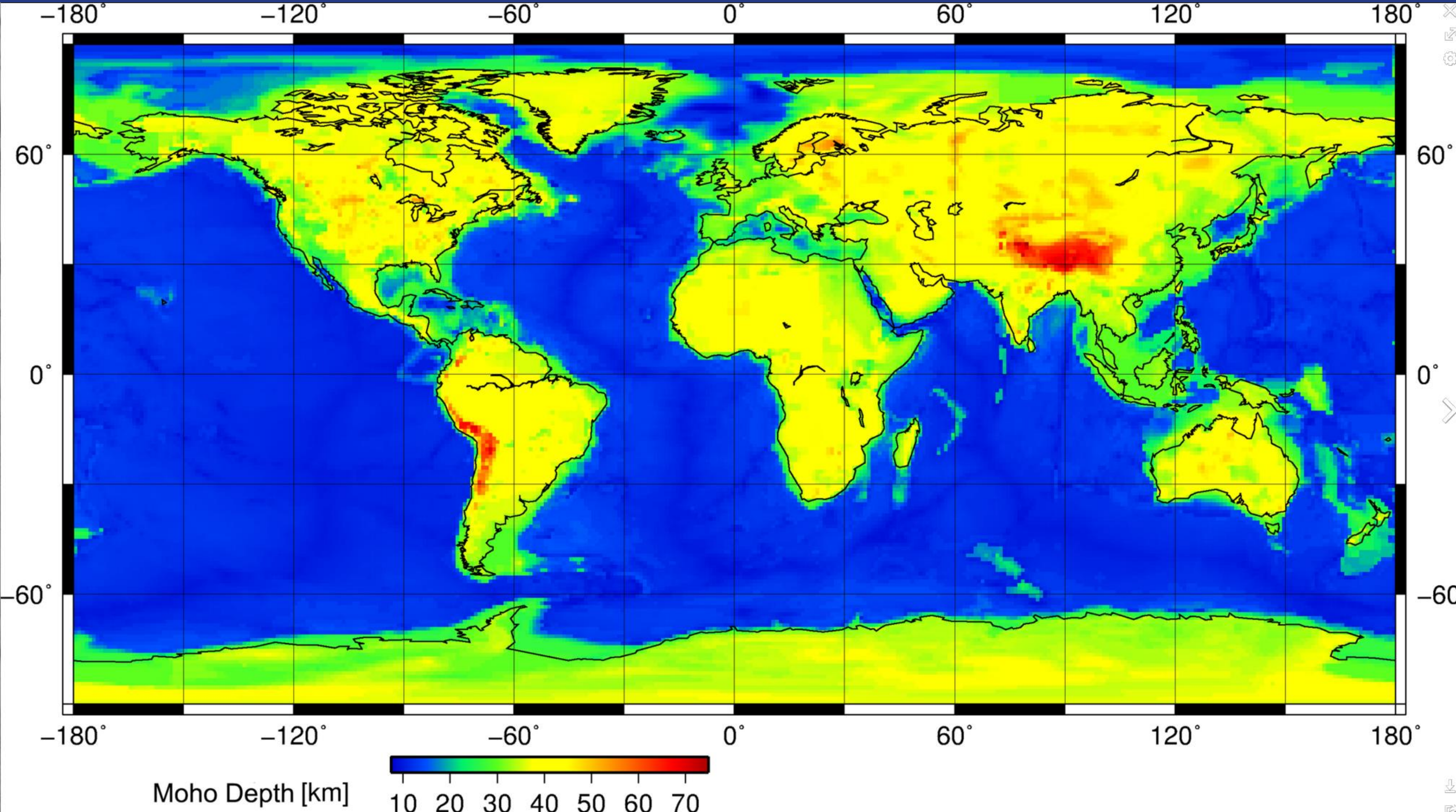
These velocities are related to the density of the rock in which the waves travel through the following equation:

$$v_l=\sqrt{(k+1.33\mu)/\rho}$$

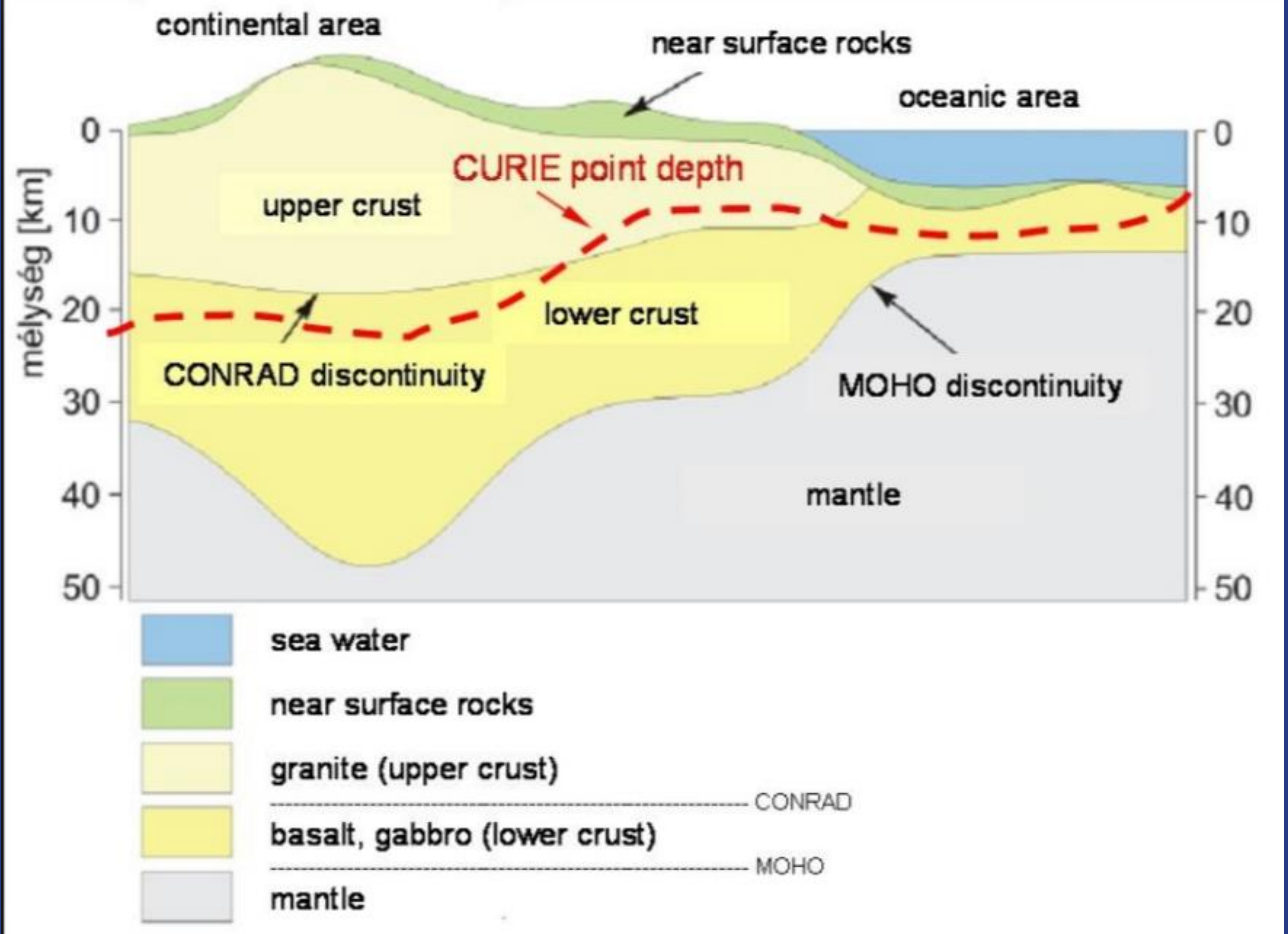
Where k is the modulus of incompressibility, μ is the shear modulus and ρ is density

Seismic velocities therefore give us an idea of the density distribution in the crust. We translate these into rock types using laboratory experiments in which the travel time of seismic waves across rock samples is measured.

	ELASTIC CONSTANTS 10^9 N / m^2		kg / m^3 g / cm^3	SEISMIC VELOCITIES km / s	
	Bulk Modulus (k)	Shear Modulus (μ)	Density (ρ)	Compres. Wave (V_p)	Shear Wave (V_s)
Air	0.0001	0	1.0 0.001	0.32	0
Water	2.2	0	1000 1.0	1.5	0
Ice	3.0	4.9	920 0.92	3.2	2.3
Shale	8.8	17	2400 2.4	3.6	2.6
Sandstone	24	17	2500 2.5	4.3	2.6
Salt	24	18	2200 2.2	4.7	2.9
Limestone	38	22	2700 2.7	5.0	2.9
Quartz	33	39	2700 2.7	5.7	3.8
Granite	88	22	2600 2.6	6.7	2.9
Peridotite	139	58	3300 3.3	8.1	4.2

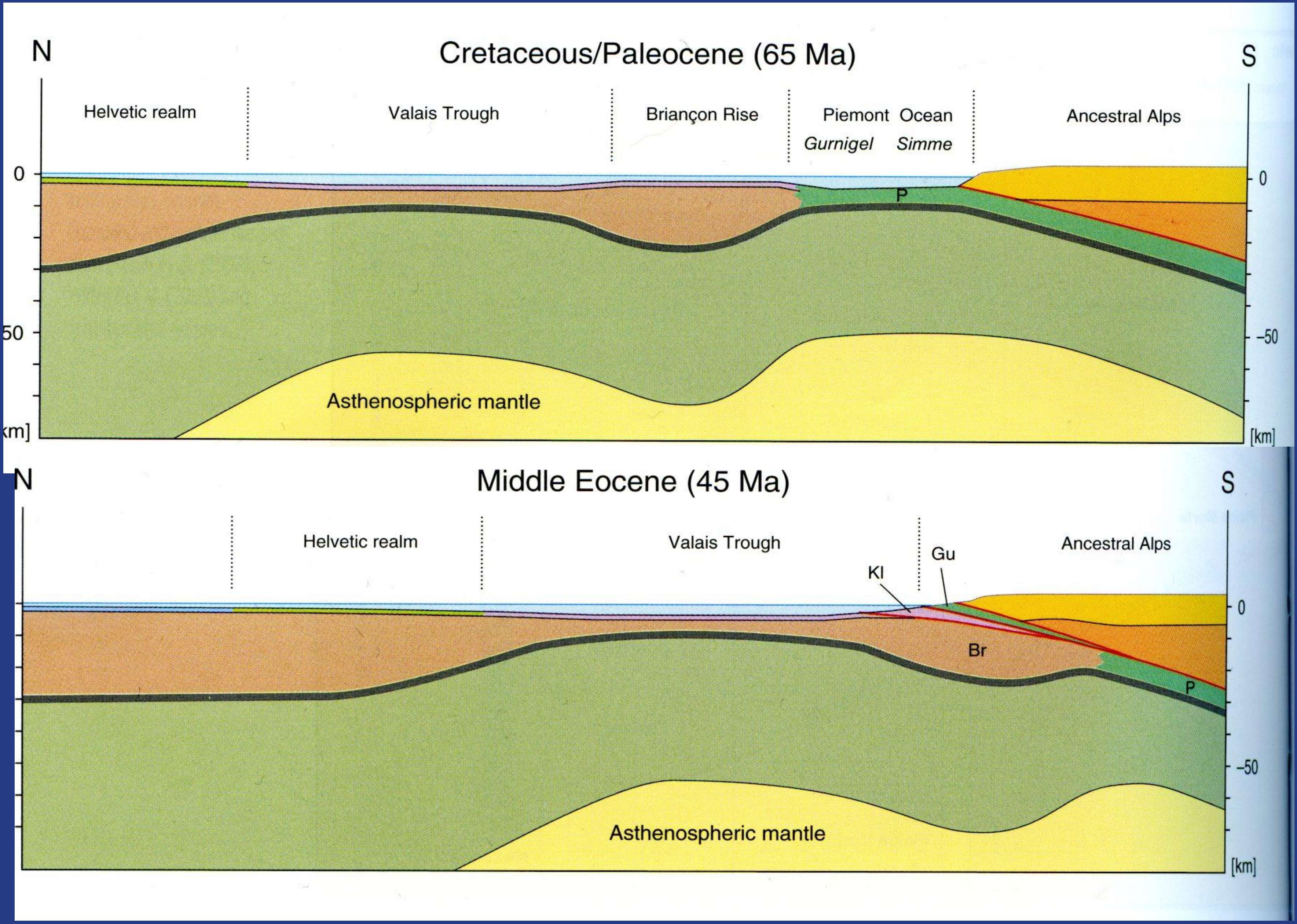


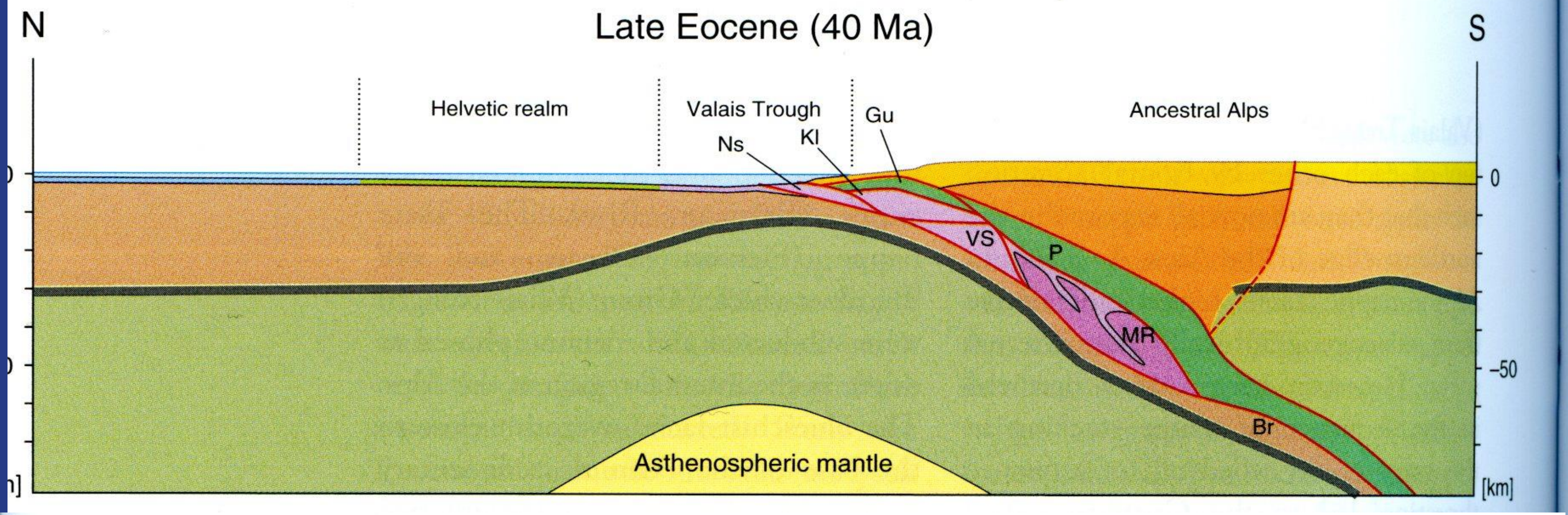
Map showing the Moho depth on earth. The Moho discontinuity marks the bottom of the earth's crust (both in the continents and in the oceans. Above it the seismic velocities reach values as high as 6.7 to 7.2 (basalt and gabbro) and immediately below it they reach 7.6 to 8.6 (peridotite). Since peridotites make up the mantle, below the Moho is the earth's mantle.

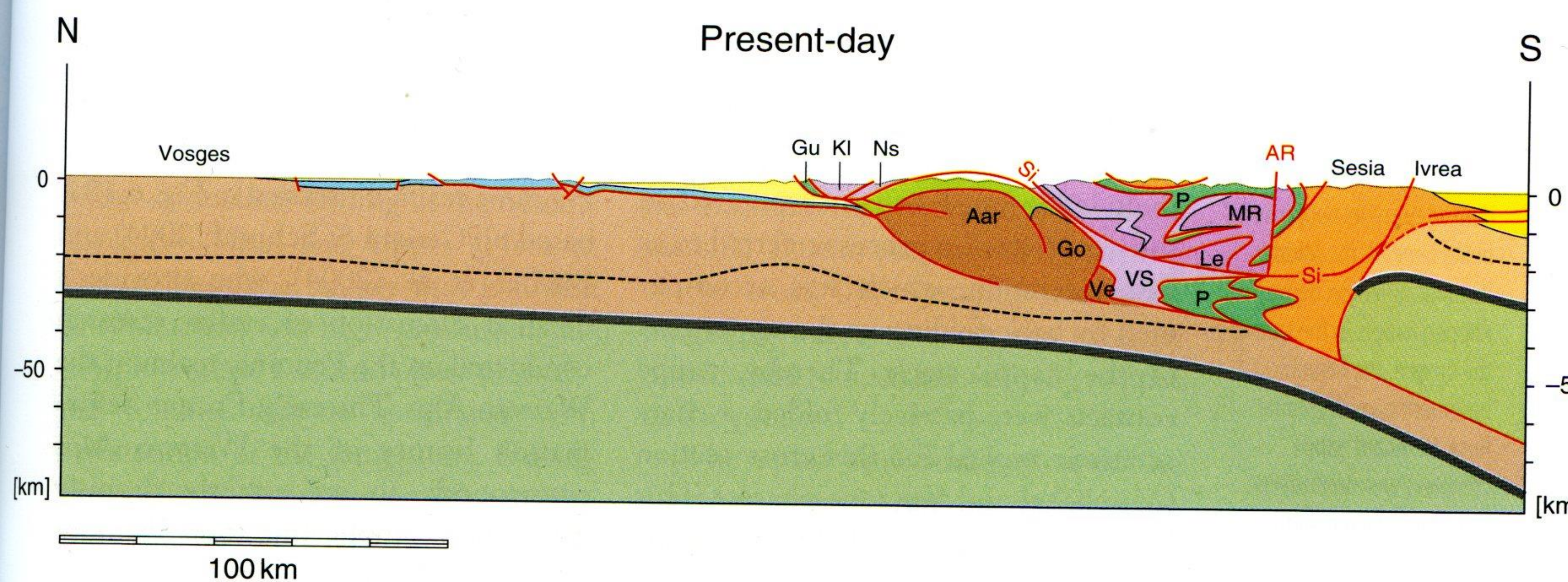


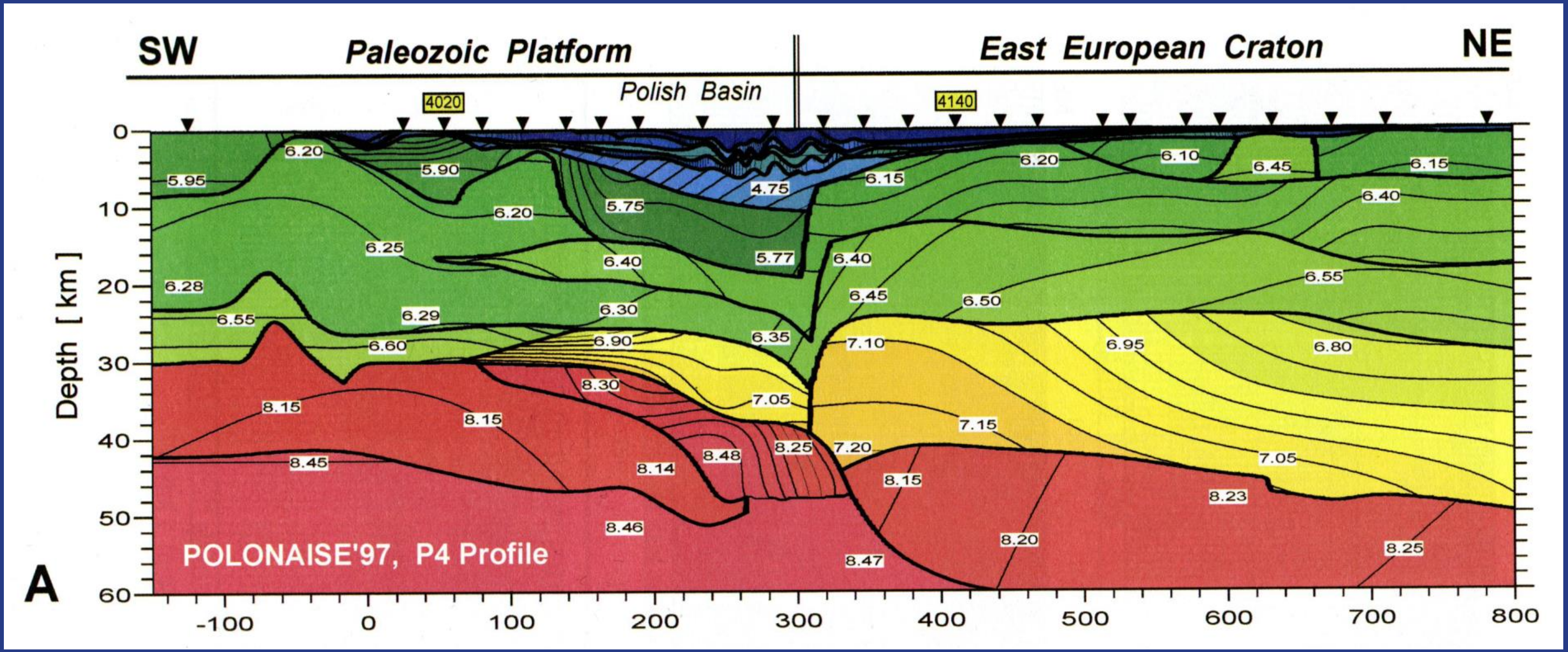
Schematic cross-section showing the Conrad discontinuity, across which the seismic velocities increase from “granite” velocities to “basalt” velocities.

However, the geological observations suggest that the structure of the crust cannot be that simple. Let us look at the structure and evolution of the Alps, for example:

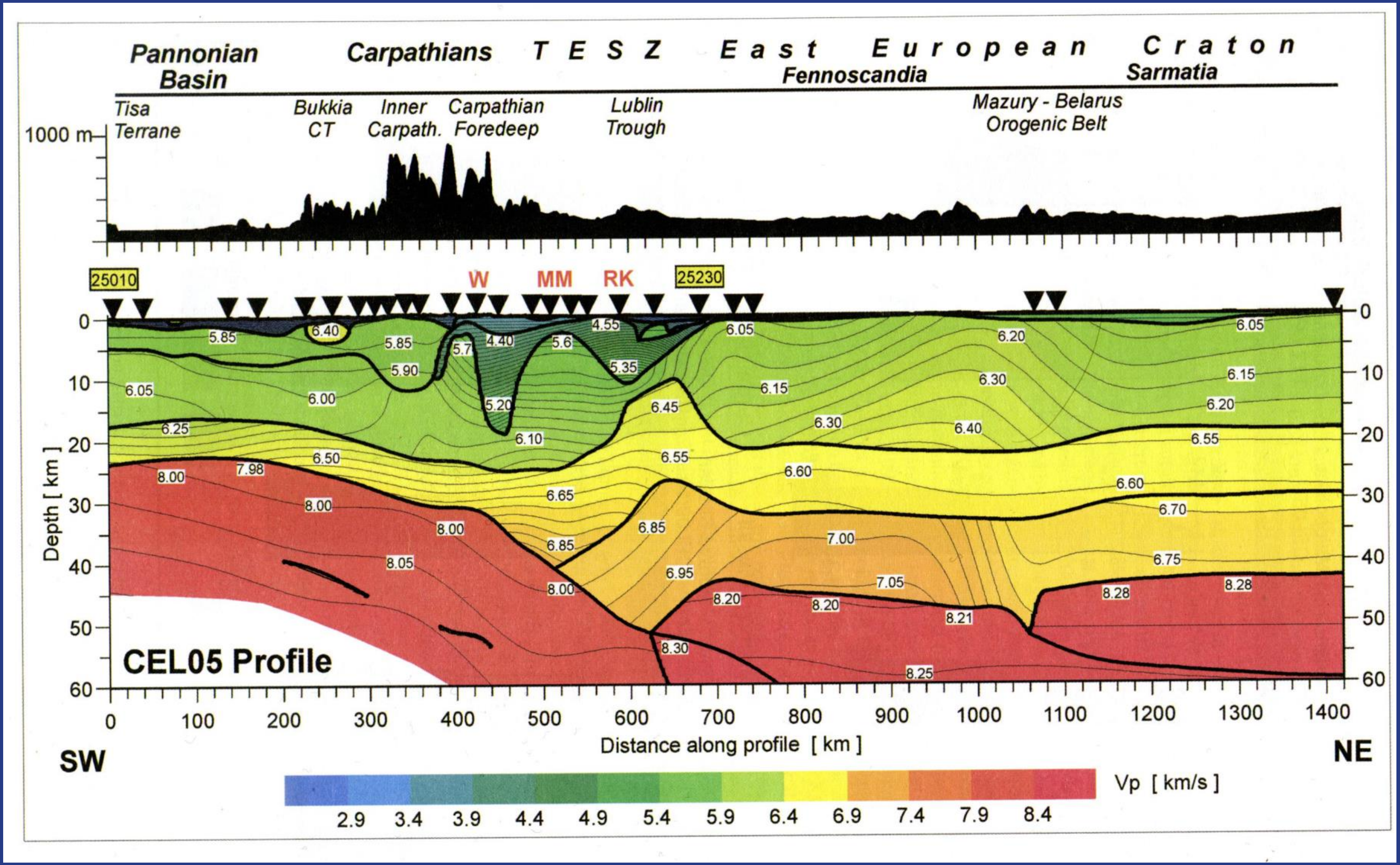



N
Late Eocene (40 Ma)
S
Helvetic realm
Valais Trough
Gu
Ancestral Alps
Ns
Kl
0
VS
P
MR
–50
Br
Asthenospheric mantle
[km]


N
Present-day
S
Vosges
Gu
Kl
Ns
Si
AR
Sesia
Ivrea
0
Aar
P
MR
Go
Le
Si
Ve
VS
P
–50
[km]
100 km



Distribution of P-wave velocities in Europe along the Polonaise P4 profile from Russia to Germany



Distribution of P-wave velocities in Europe along the CEL05 profile from the Baltics to Hungary

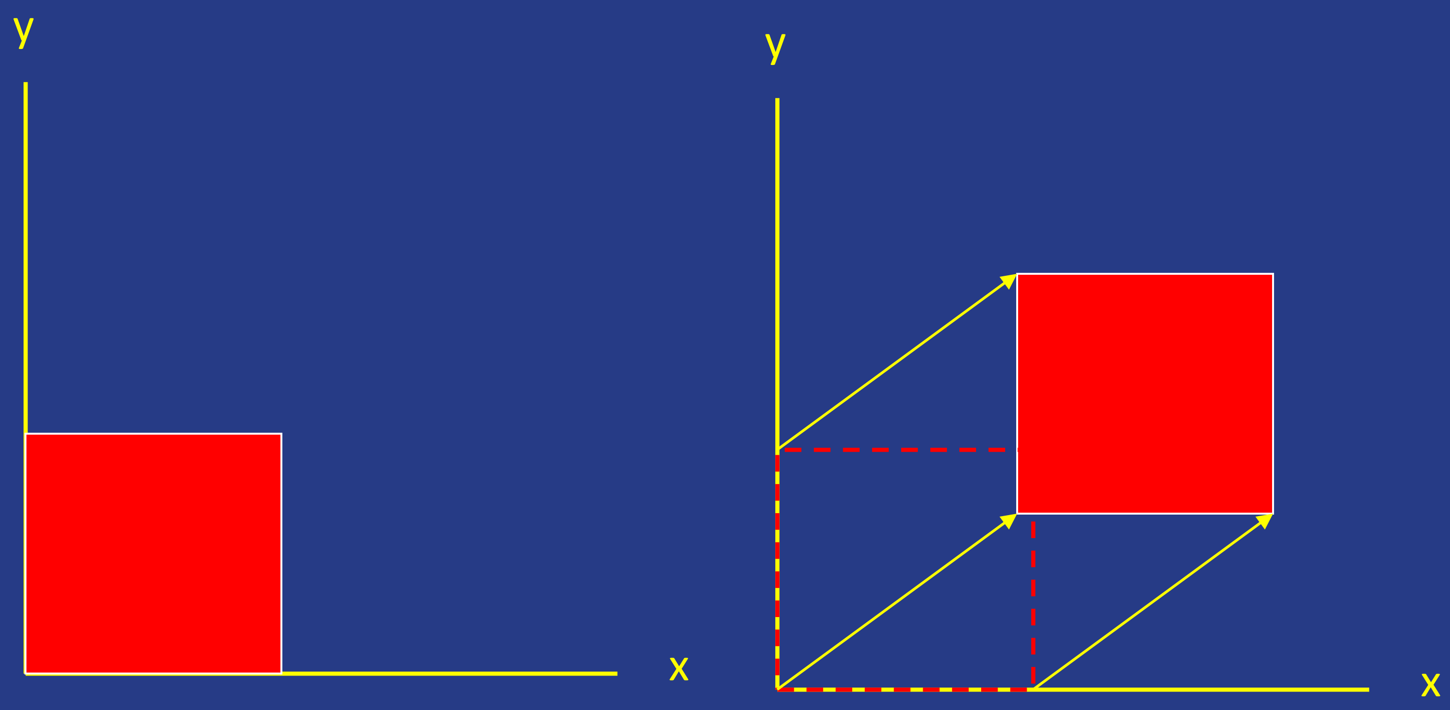
The mechanical behaviour of the continental crust, i.e. its reaction to forces deforming it, is a function of its rheology.

The term rheology refers both to the flow characteristics of substances and to the science that studies such flow. The term rheology was coined in 1920 by the American chemist Eugene Cook Bingham and was derived from the Greek words ῥέω (*rheo*="flow”) and -λογία (*logia*=discourse of).

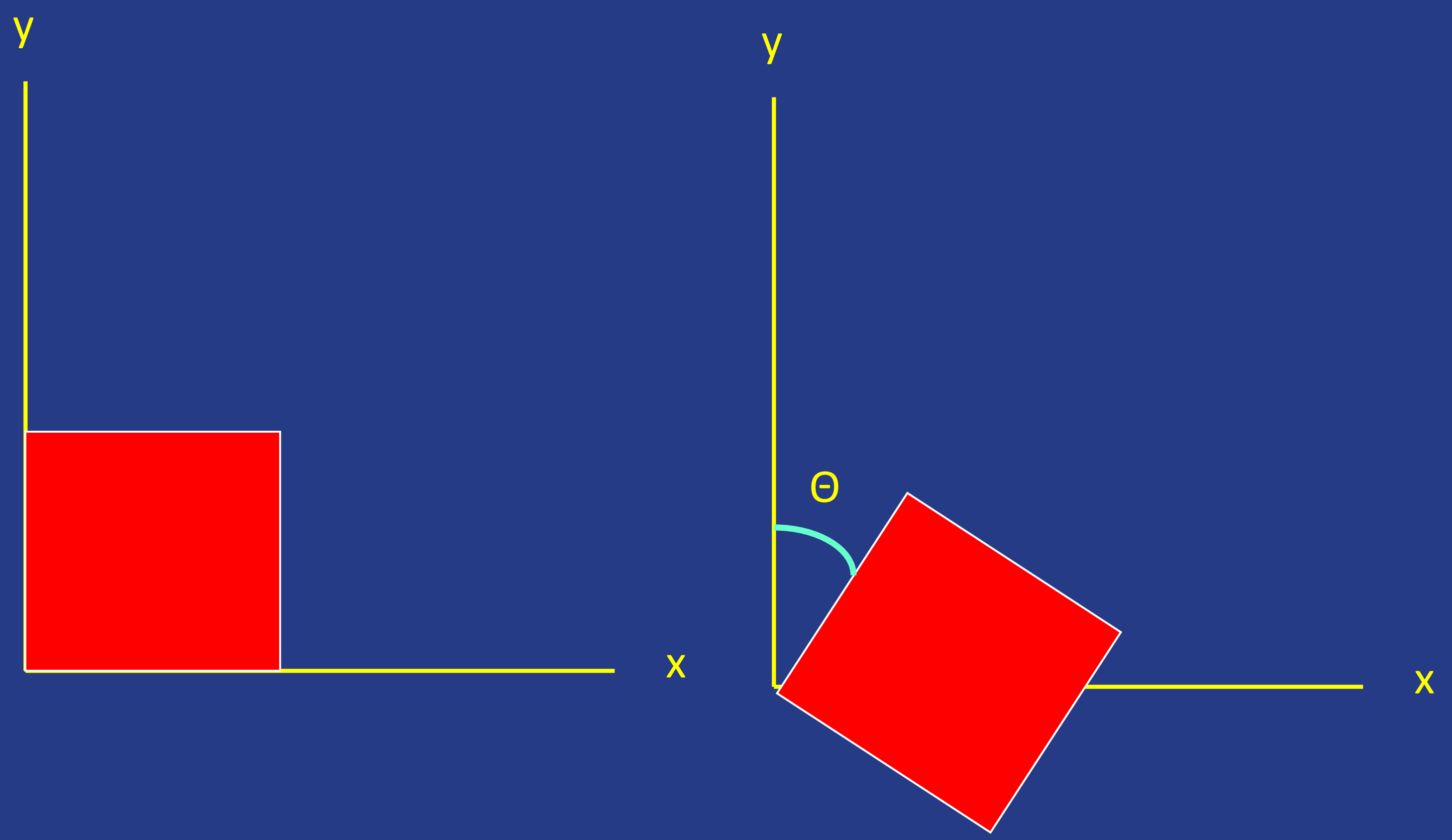
The substances change their location, orientation and shape under applied forces. Those changes are collectively called deformation. Deformation has three components:

1. Change of location (translation).
2. Change of orientation (rotation).
3. Change of shape (strain).

Change of location involves translation on a plane surface

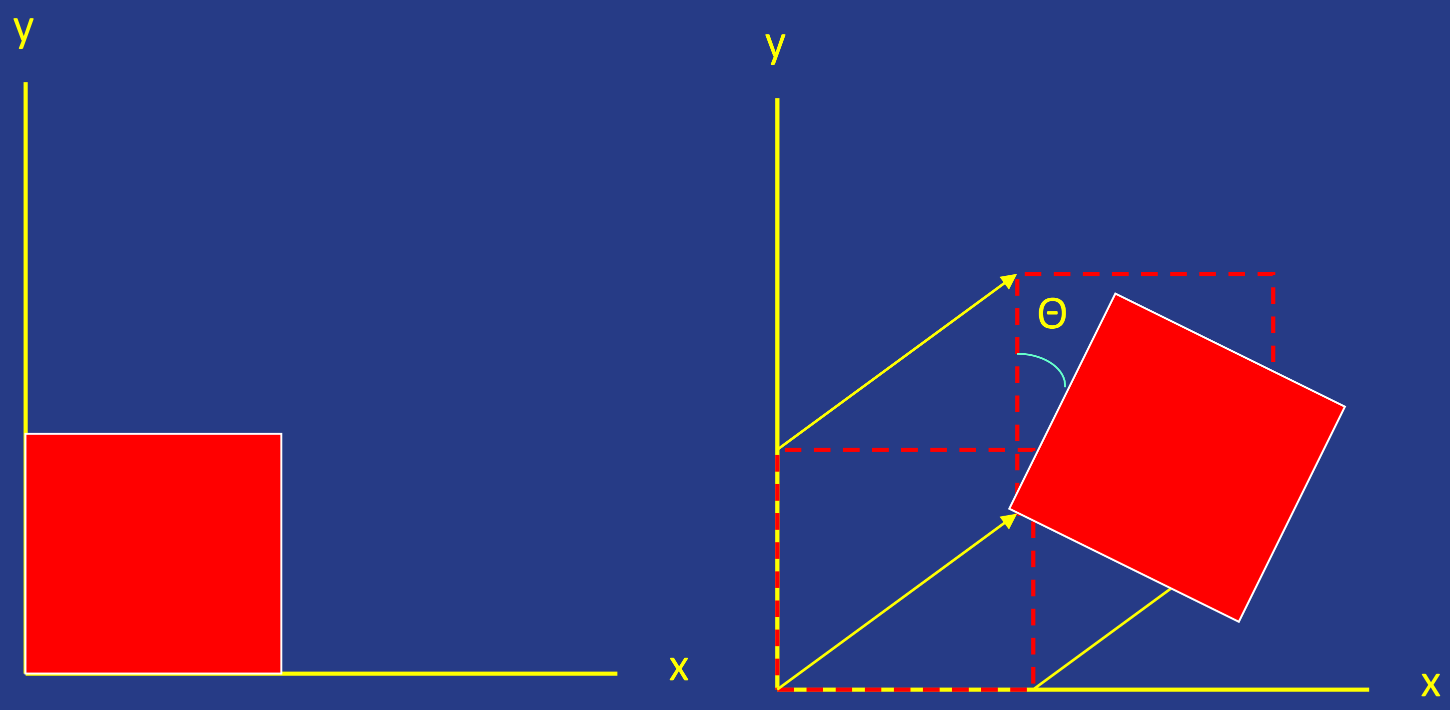


Both change of orientation and location must be measured against an external reference frame:



Change in orientation: Rotation around an angle Θ

Rotation (change in orientation) and translation (change in location) may take place together



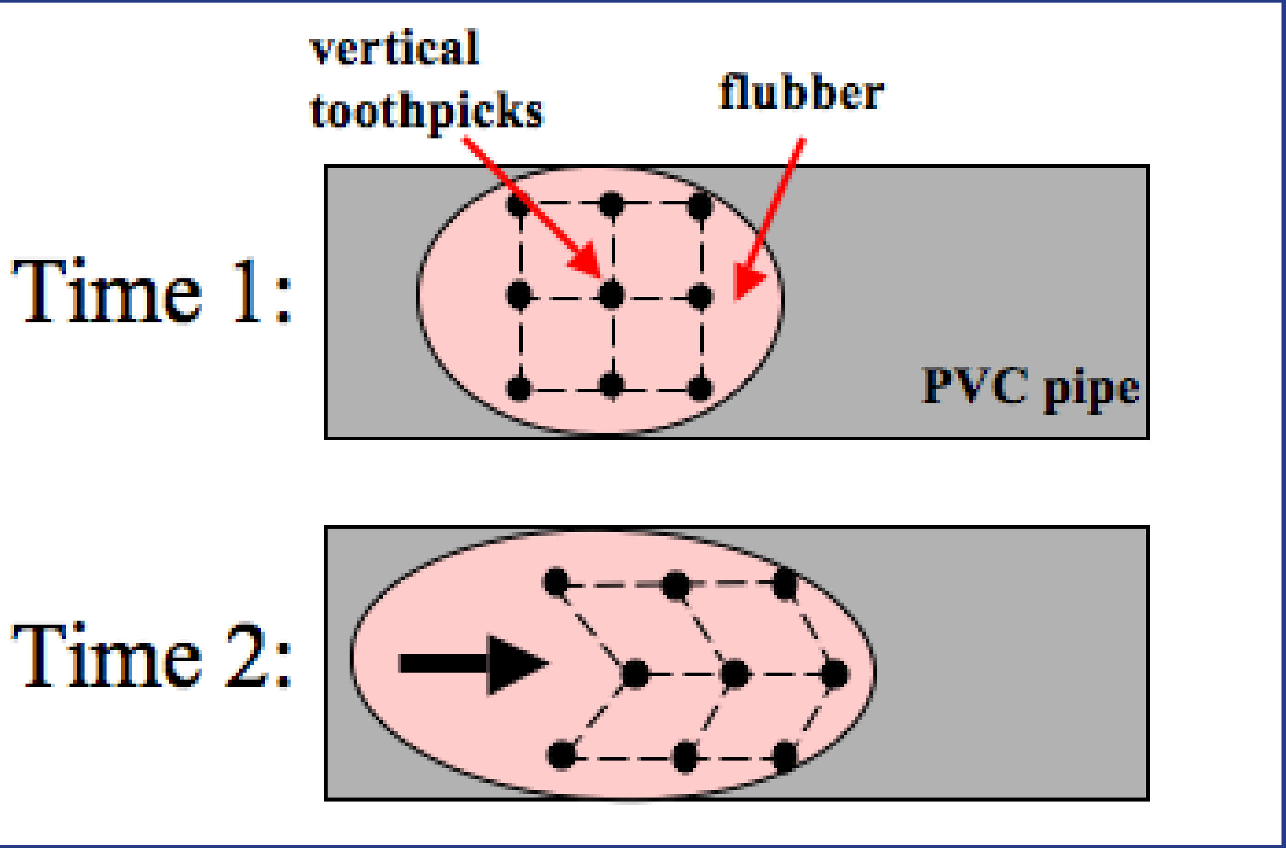
Homework:

Answer the questions:

1. Is the change of location on the surface of a sphere a translation or a rotation?

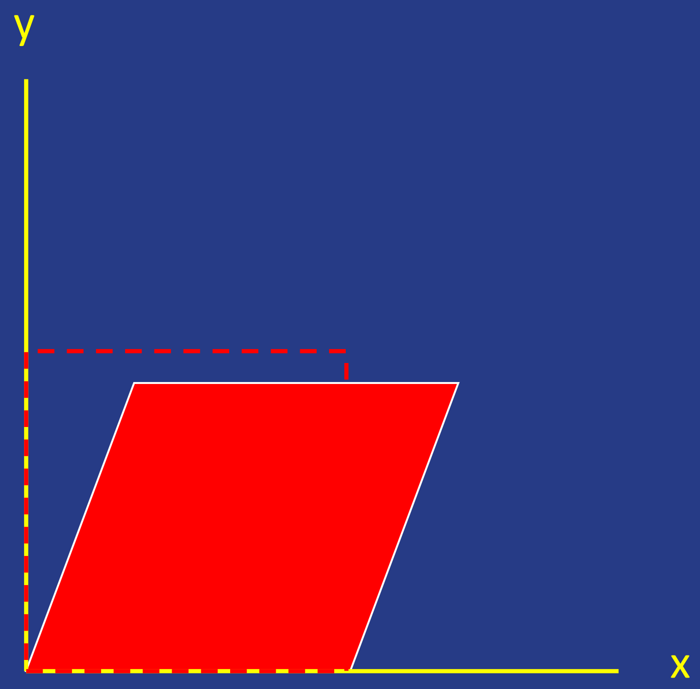
2. How would you describe it mathematically?

Change of shape, i.e., strain, is measured with respect to an internal reference frame

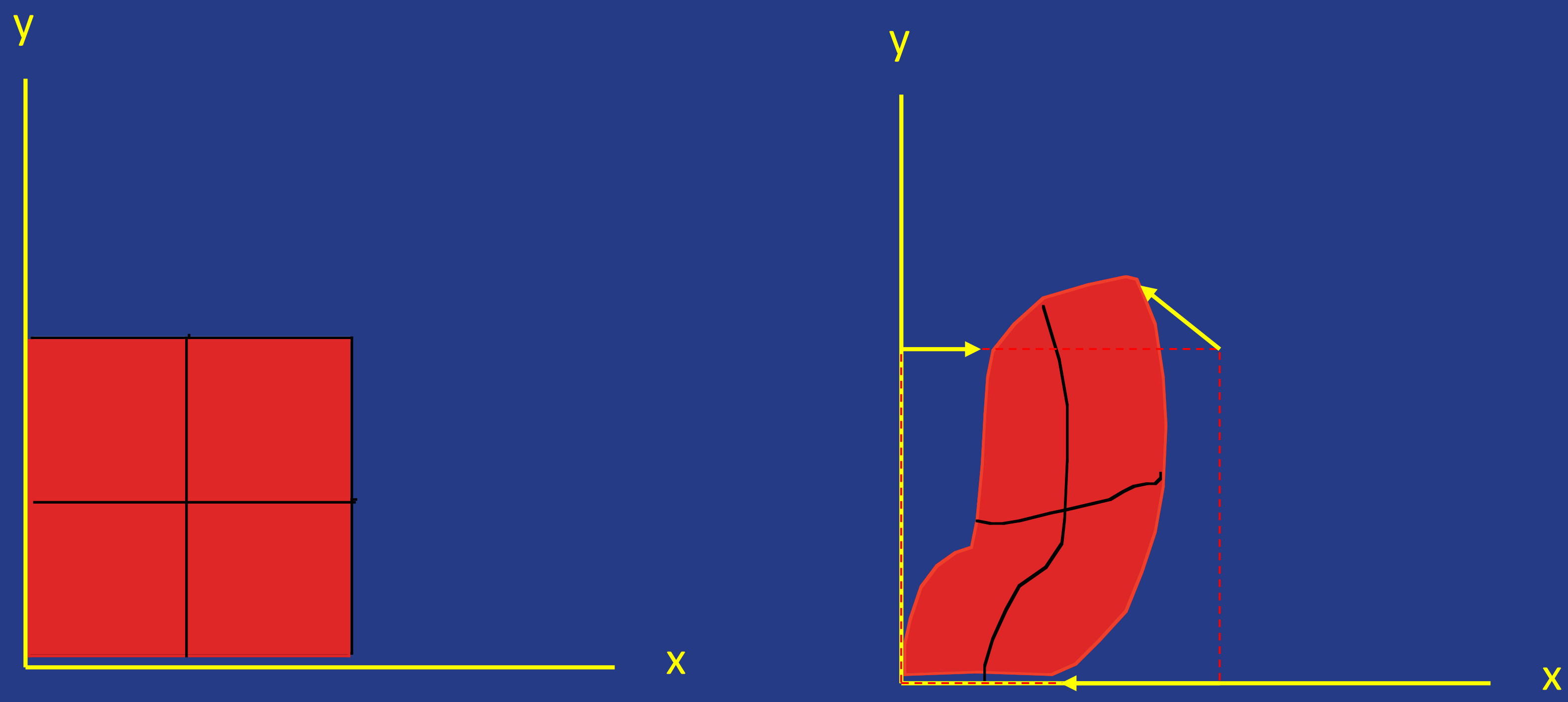


The toothpicks here form an internal reference frame. In time 2, the toothpicks have moved with respect to those of time 1

Change of shape may be homogeneous, i.e., when every smallest part of the object undergoes the same kind and amount of change of shape.



Or it may be inhomogeneous, every part changing shape in a different manner and amount

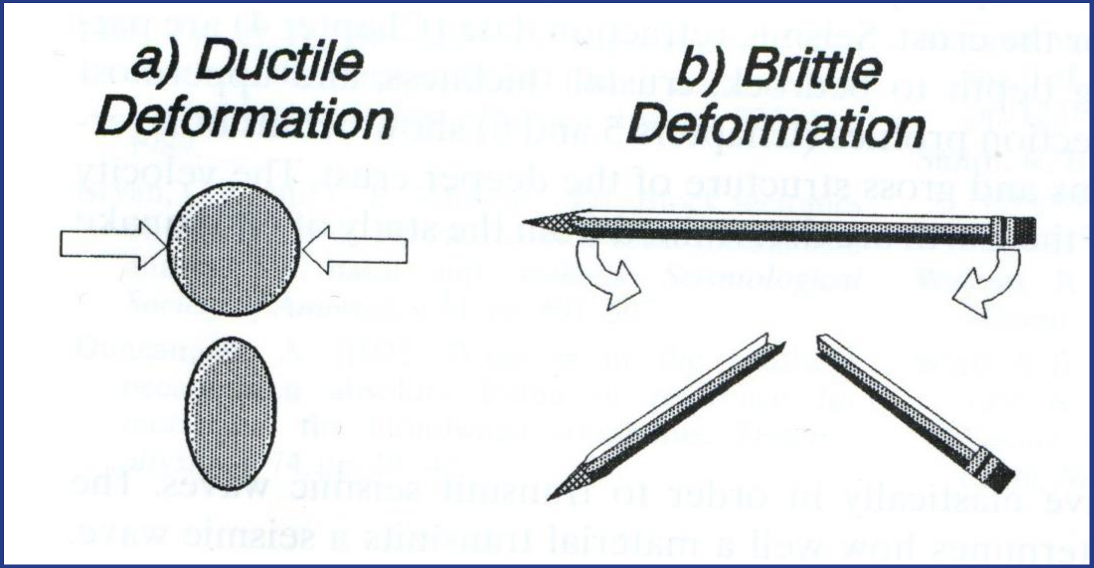


A complete description of a state of deformation must include all three aspects of deformation: change of shape, which is called **strain**, change of orientation, which is called rotation, and change of location,which is called translation.

Solids my respond to forces either by breaking (brittle deformation) or by flowing (ductile deformation).

Whether a solid will deform in a brittle or ductile manner will depend on four things:

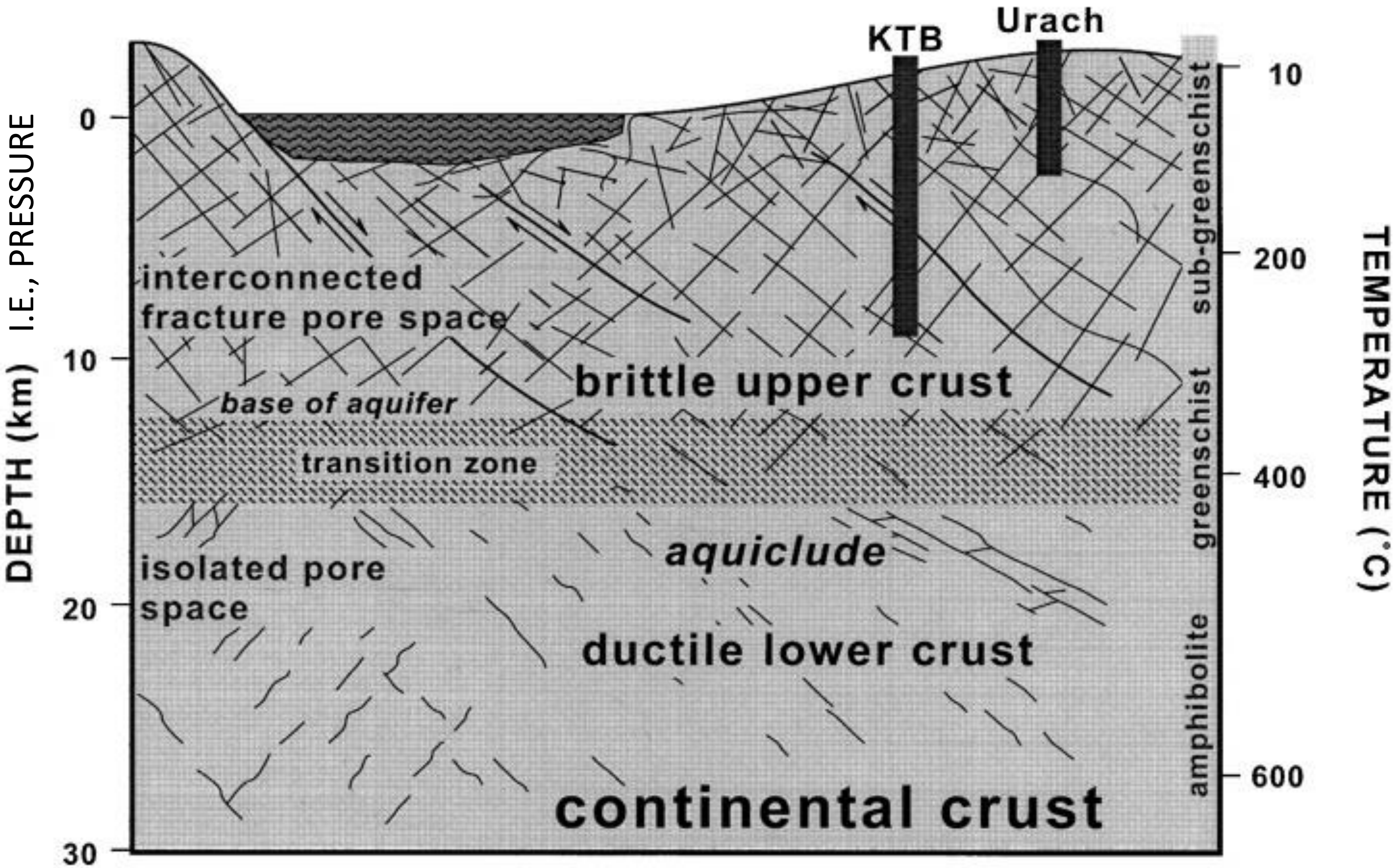
1. Composition



2. Temperature

3. Pressure

4. Strain rate (how fast the deformation occurs)



Rheological layering of the continental crust

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

1. Surface igneous rocks (volcanic rocks)

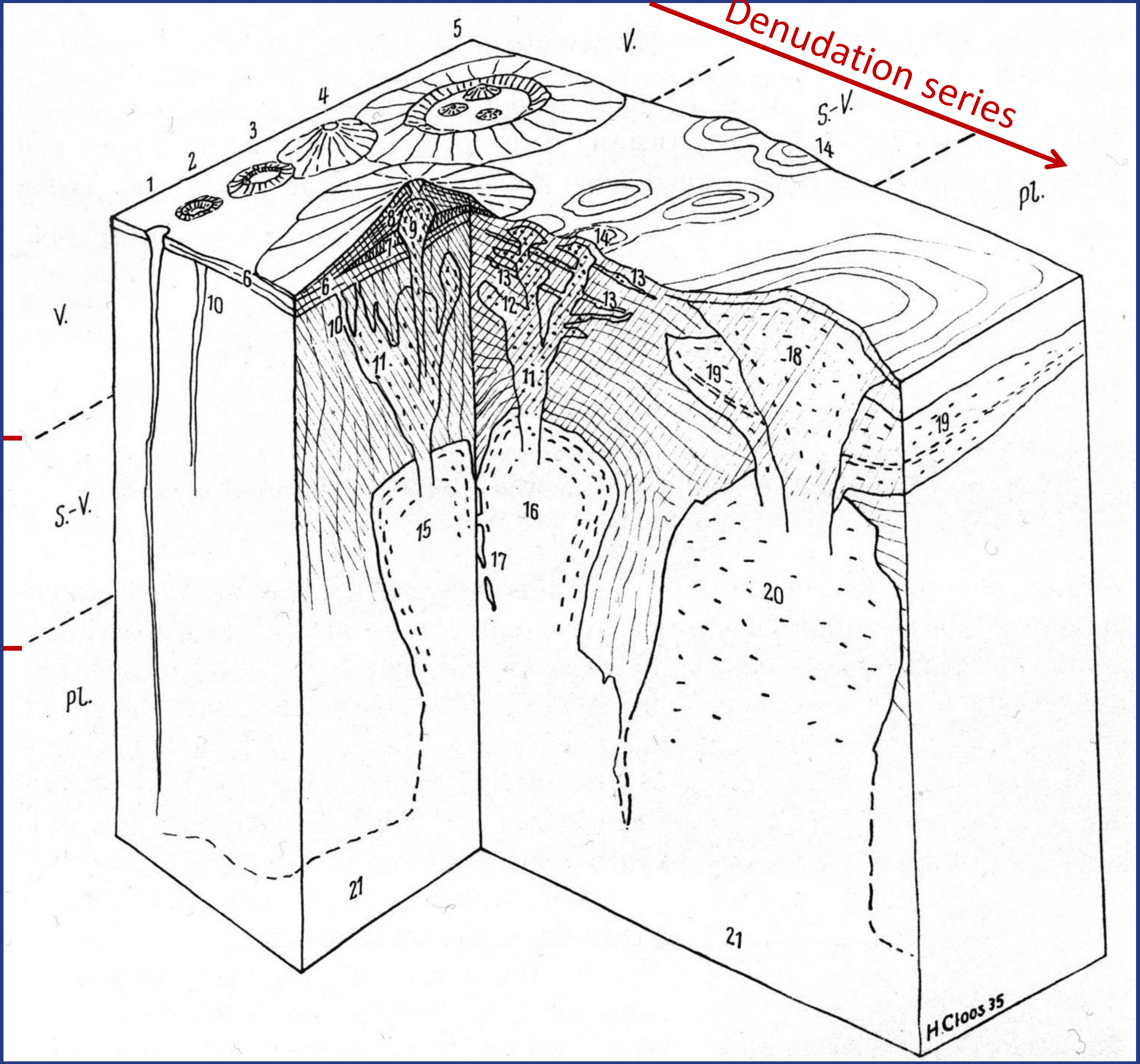
2. Intermediate depth igneous rocks (subvolcanic rocks)

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

Volcanic

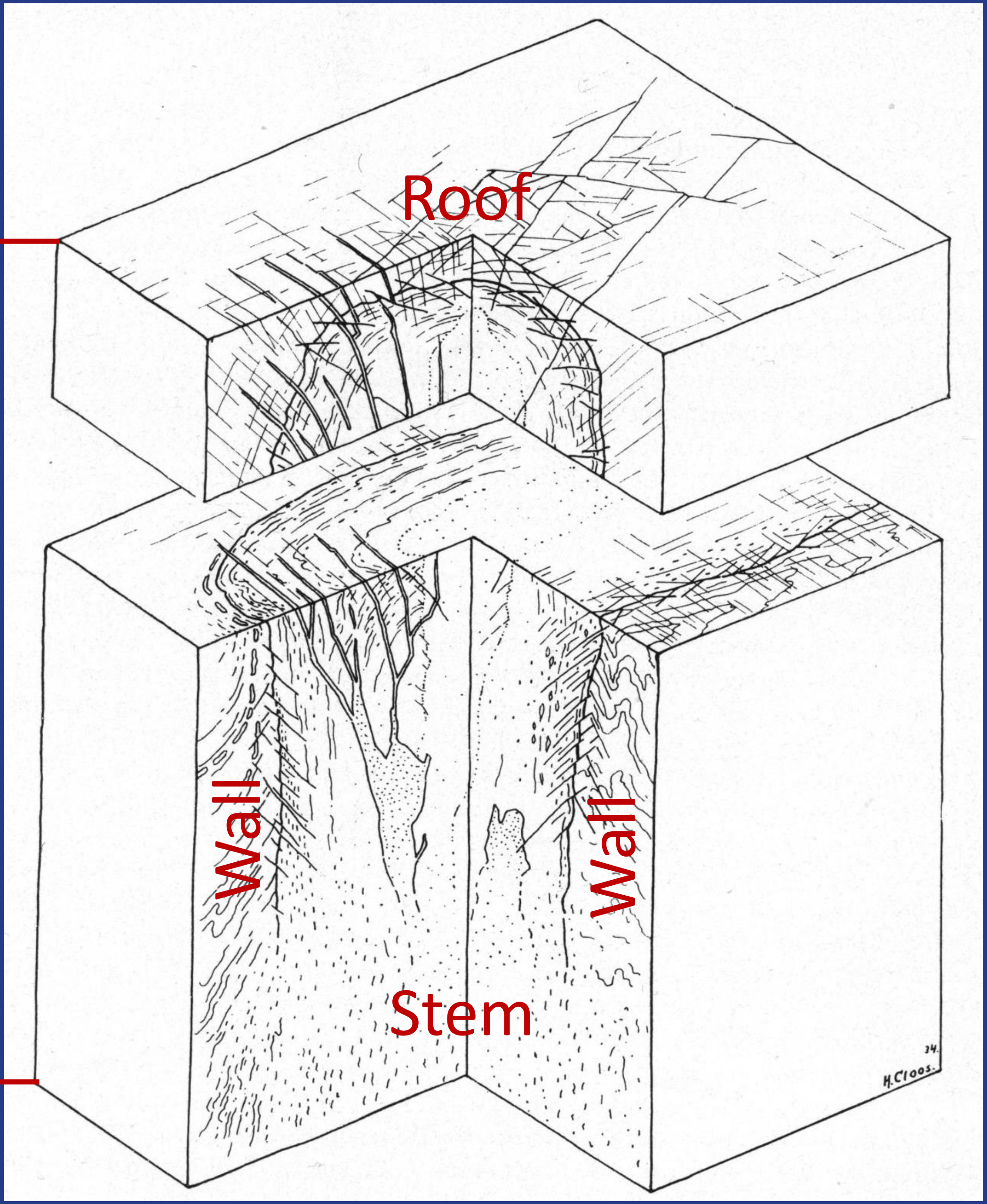
Sub-volcanic

Plutonic



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

c. 13-17 km



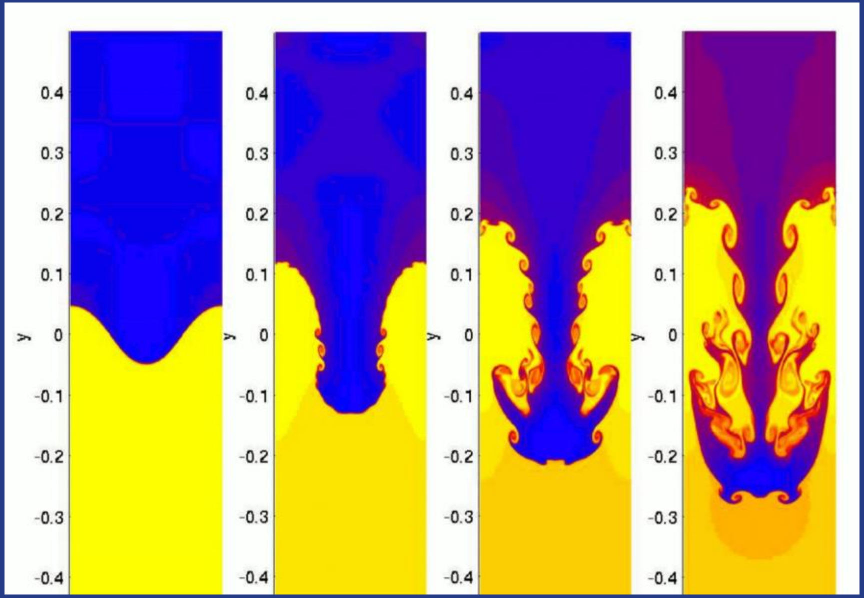
c. 19-25 km

A schematic view of a pluton. Notice the increasingly more brittle nature of the structure as one ascends in the crust. From Cloos 1936.

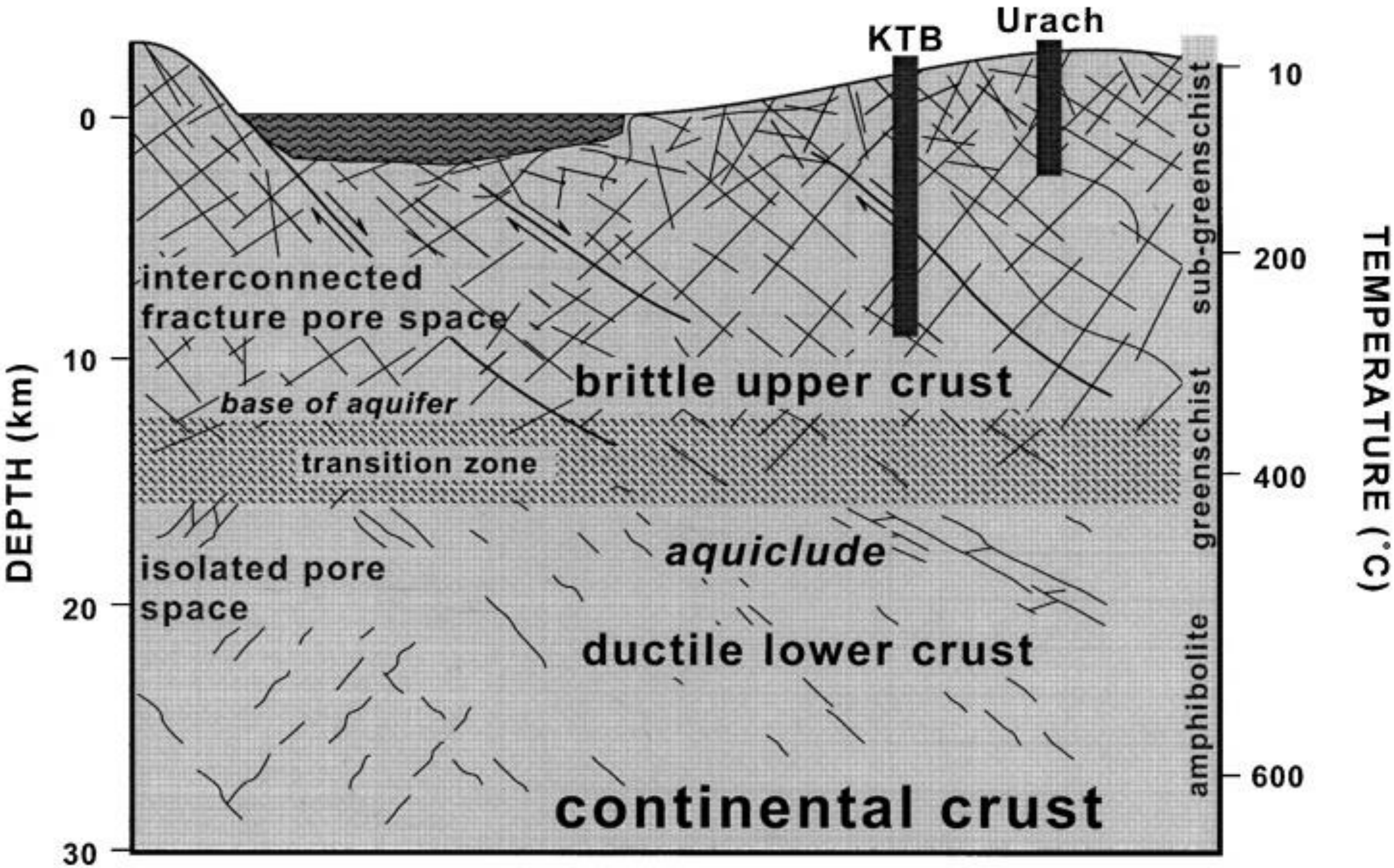
Most plutons rise as diapirs.

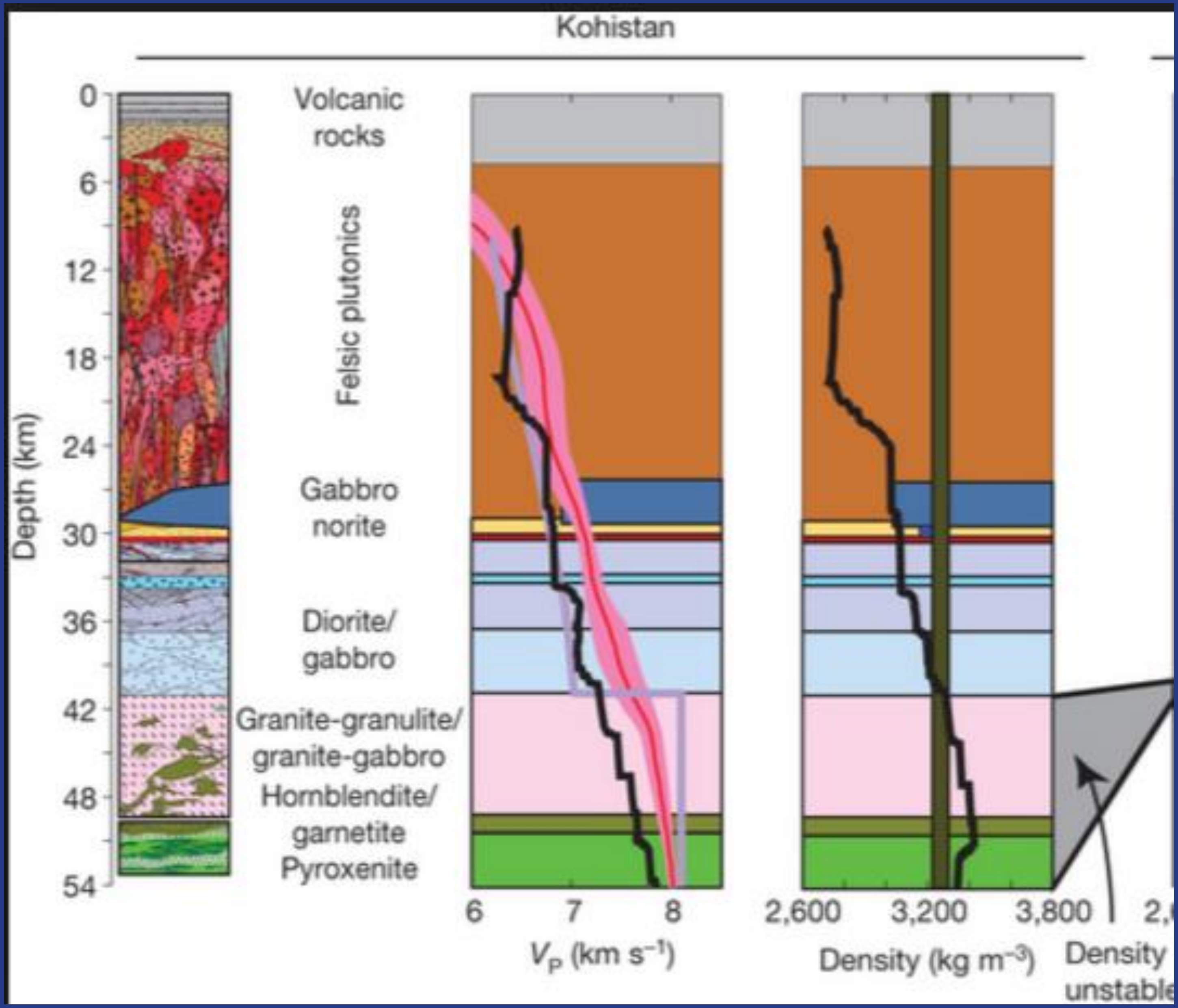
What is a diapir?

A diapir may be described as a reverse drop. It rises in a surrounding material of higher density. In geology, various rock types, such as salt, shale or magmatic rocks may build diapirs. The word diapir was introduced by the Romanian geologist Ludovic Mrazek in 1910 from the Greek word διαπείρειν (*diaperein*= to pierce through)

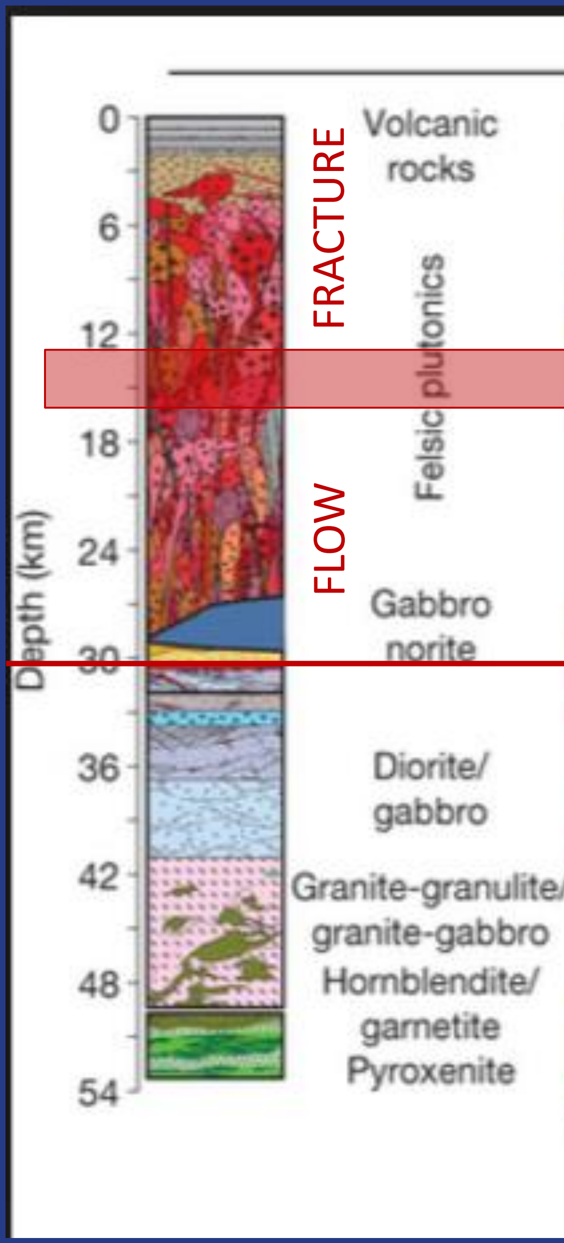


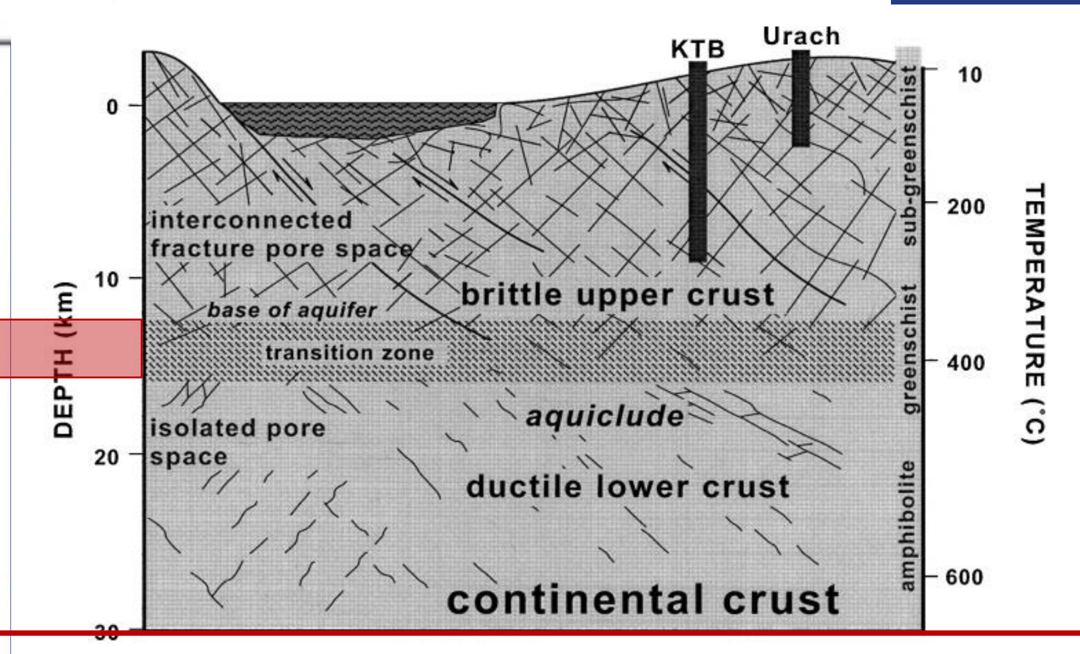
Raleigh-Taylor instability


KTB
Urach
0
10
20
30
DEPTH (km)
10
200
400
600
TEMPERATURE (°C)
sub-greenschist
greenschist
amphibolite
interconnected fracture pore space
brittle upper crust
base of aquifer
transition zone
aquiclude
isolated pore space
ductile lower crust
continental crust



Cross-section of the continental crust of the Kohistan area, northern Pakistan (Himalaya)





Upper crust: Intrusions fill spaces created by brittle to semi-brittle deformation

Lower crust: Intrusions make spaces created by diapirism and flow deformation of surrounding crust

1. Surface igneous rocks (volcanic rocks)

UPPER CRUST

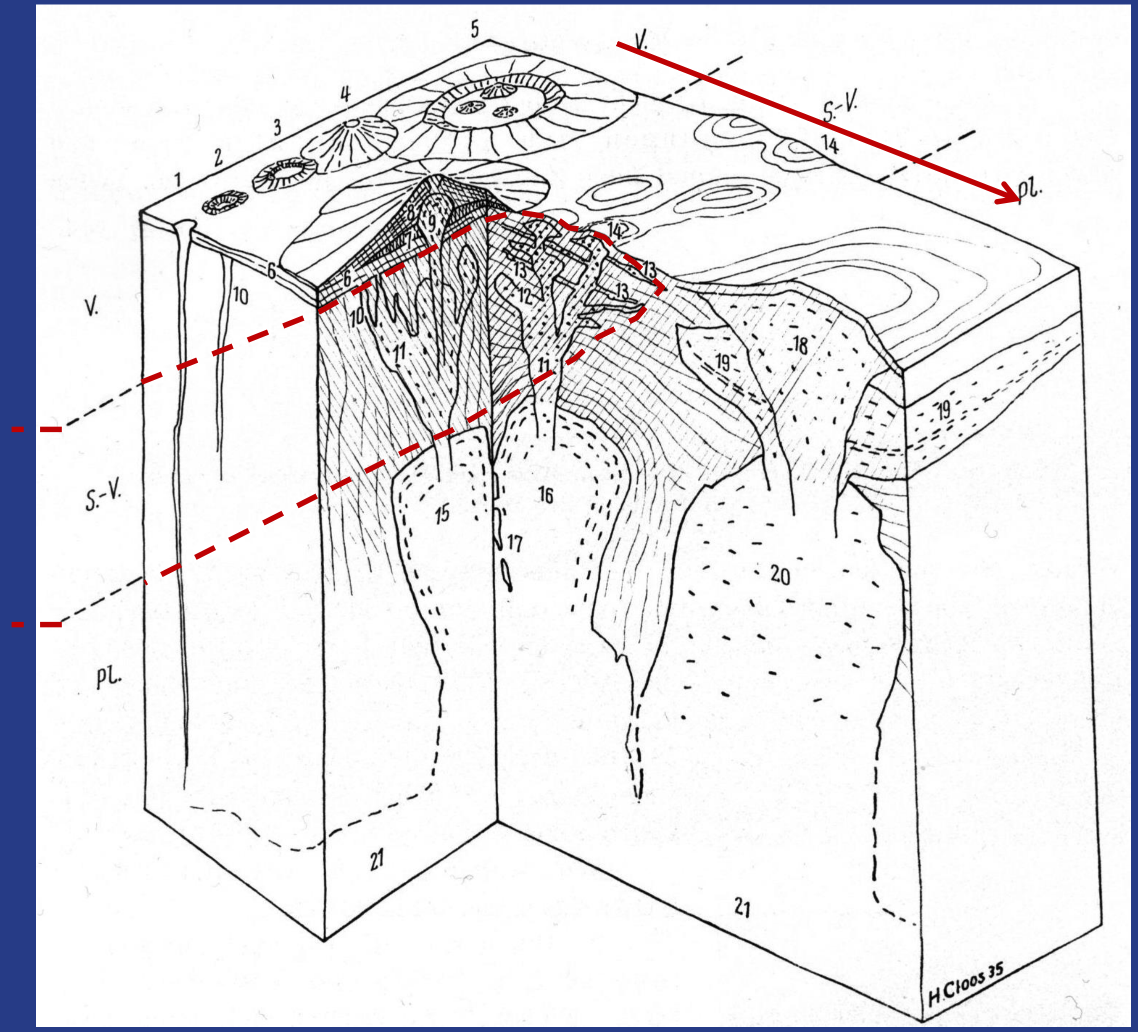
2. Intermediate depth igneous rocks (subvolcanic rocks)

LOWER CRUST

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

Intermediate depth igneous rocks (subvolcanic rocks)

Intermediate depth igneous rocks and bodies.



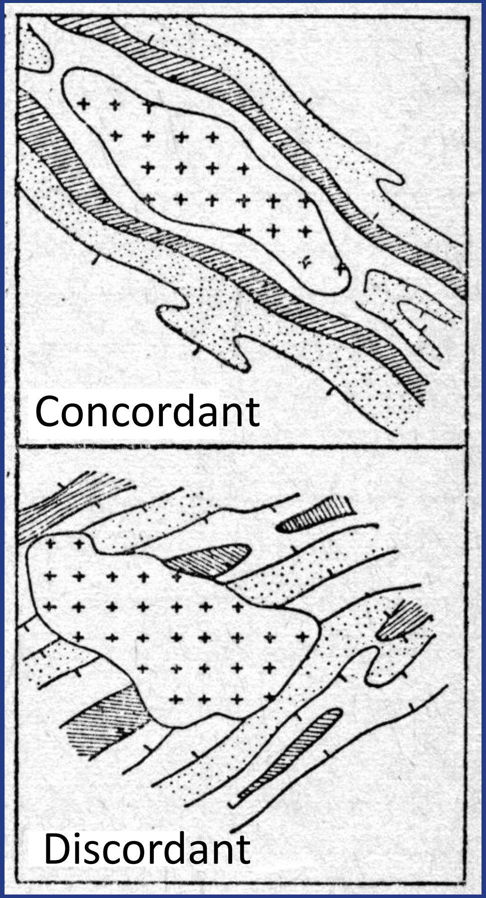
Intermediate depth or subvolcanic igneous rock bodies are the following:

Dyke (dike in American and old British spelling)
Sill
Phacolith
Akmolith
Bysmalith
Harpolith
Ductolith
Ethmolith
Lopolith
Spenolith
Cactolith
Chonolith

Intrusive bodies may be concordant or discordant.

A concordant intrusive body has boundaries parallel or subparallel with the fabric and texture of the surronding country rock (i.e. the rock(s) into which it intruded).

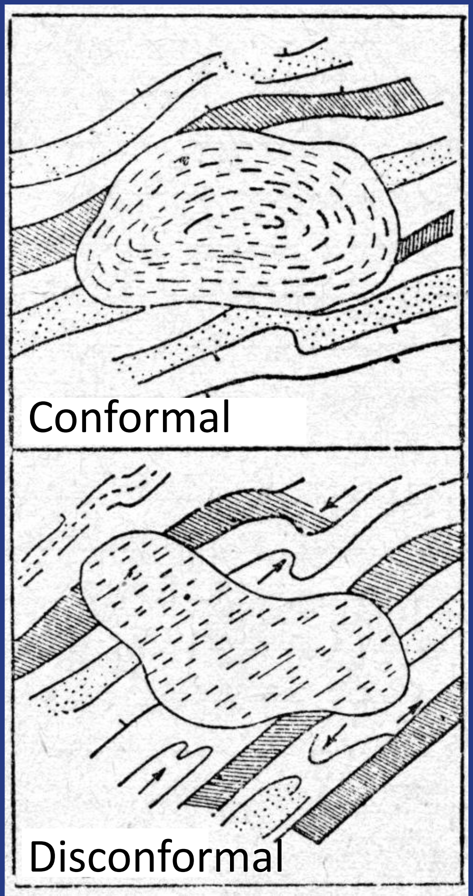
The boundaries of a discordant intrusive body truncates (or "cuts") the fabric and texture of the surrounding country rock.



Intrusive bodies may be conformal or disconformal.

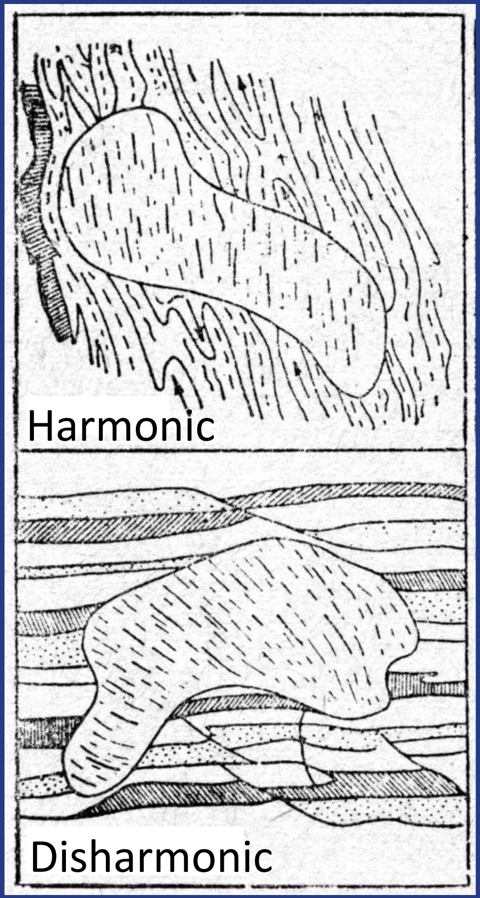
An intrusive body is called conformal if its internal fabric is parallel with its boundaries.

An intrusive body is called disconformal if its internal fabric is truncated by (or “cut” by) its boundaries.



Intrusive bodies may be harmonic or disharmonic.

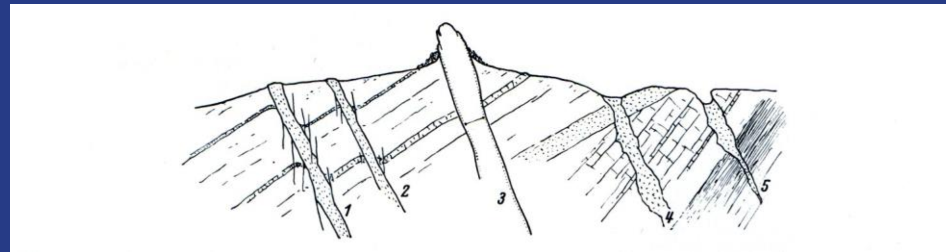
An intrusive body is said to be harmonic when its internal fabric is parallel with that of its country rock.



An intrusive body is said to be disharmonic when its internal fabric is truncated (or "cut") by that of its country rock.

Dyke: A dyke is a parallel- to subparallel-sided, tabular, discordant, mostly conformal and usually disharmonic intrusion.When very narrow (a few cm) and branching and tapering, it is called a vein. There is a continuum of transition from dykes to veins.

The word dyke is an old Saxon word meaning wall or ditch. The name was applied to dykes, because when they are more resistant to erosion than their country rock, they stand like walls. When they are less resistant than their country rock, they form ditches.



Various dykes. 1 and 2 have been intruded along normal faults

Late Cretaceous dyke near Anadolukavağı, İstanbul

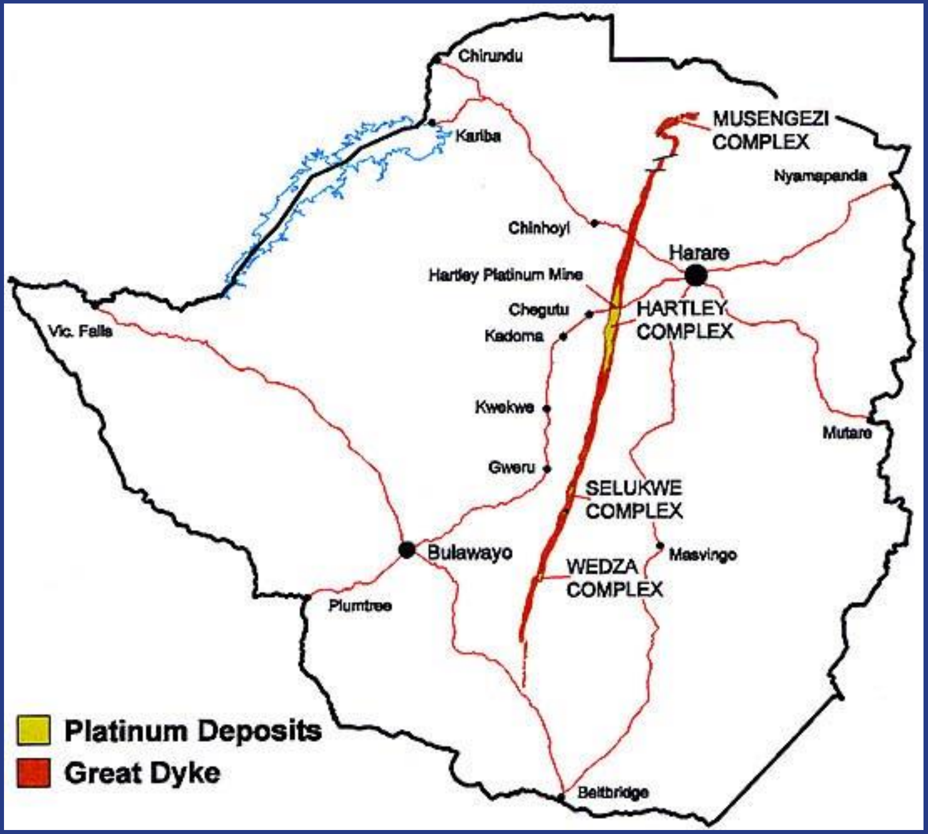
Dykes on the Island of Mull, Scotland, UK

Basaltic dykes cutting granite in Schoodic Peninsula,
Acadia National Park, Maine, USA.

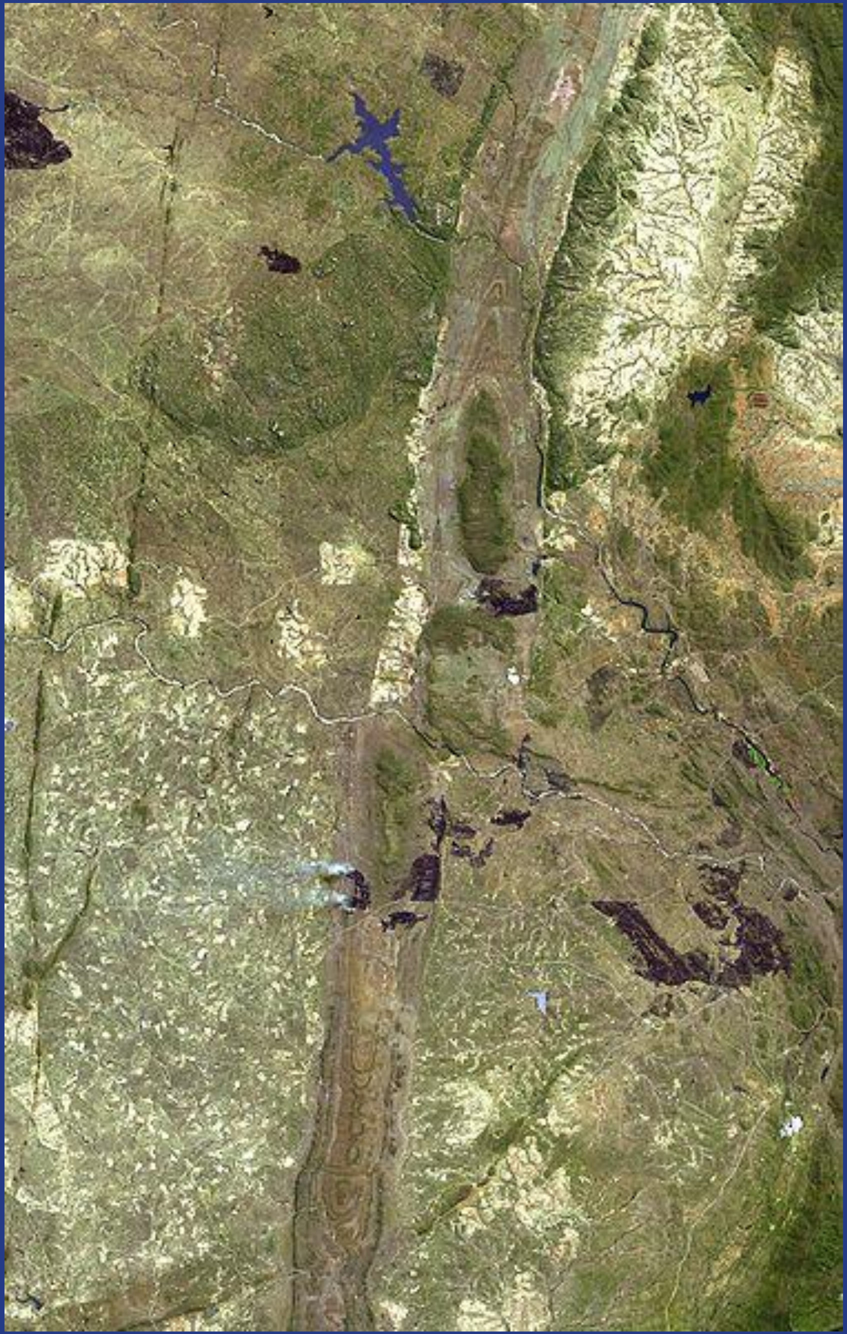
Basaltic dyke cutting granite, Scoodic Peninsula,
Acadia National Park, Maine, USA

A huge Precambrian basaltic dyke in South Africa

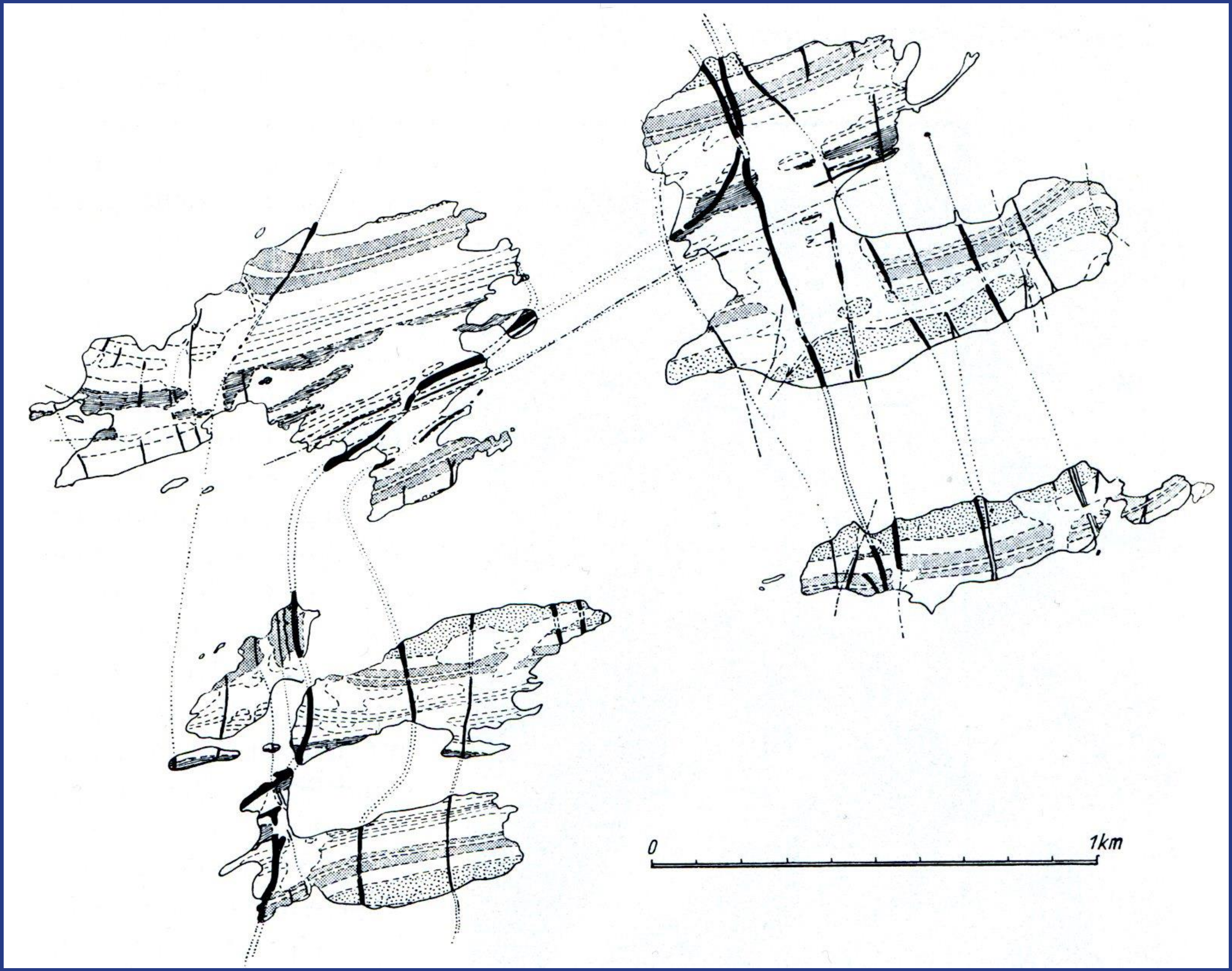
The word’s largest known dyke



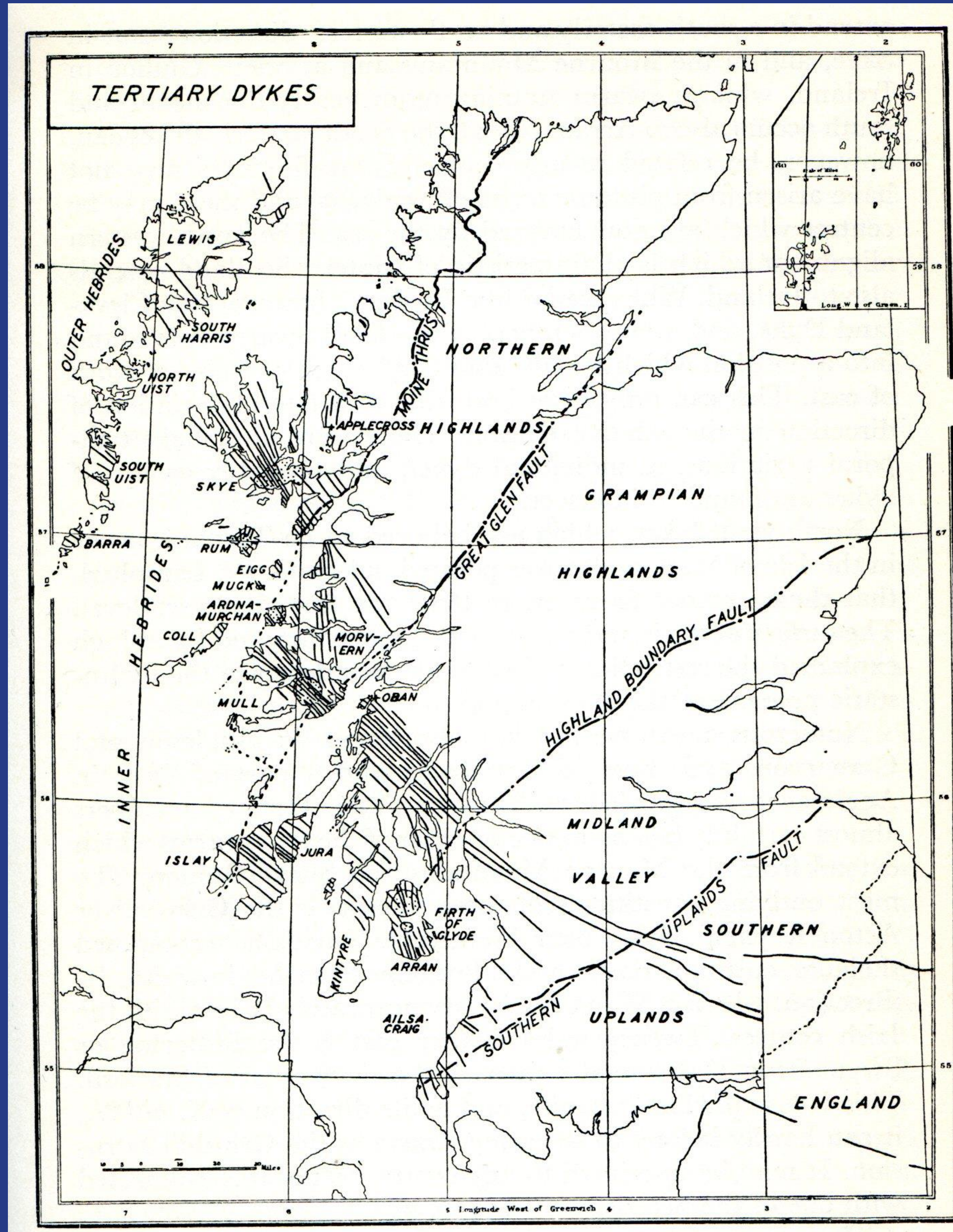
The *Great Dyke* of Zimbabwe. It is about 550 km long and at its widest spans a width of some 12 km. It is 2.575 billion years old.



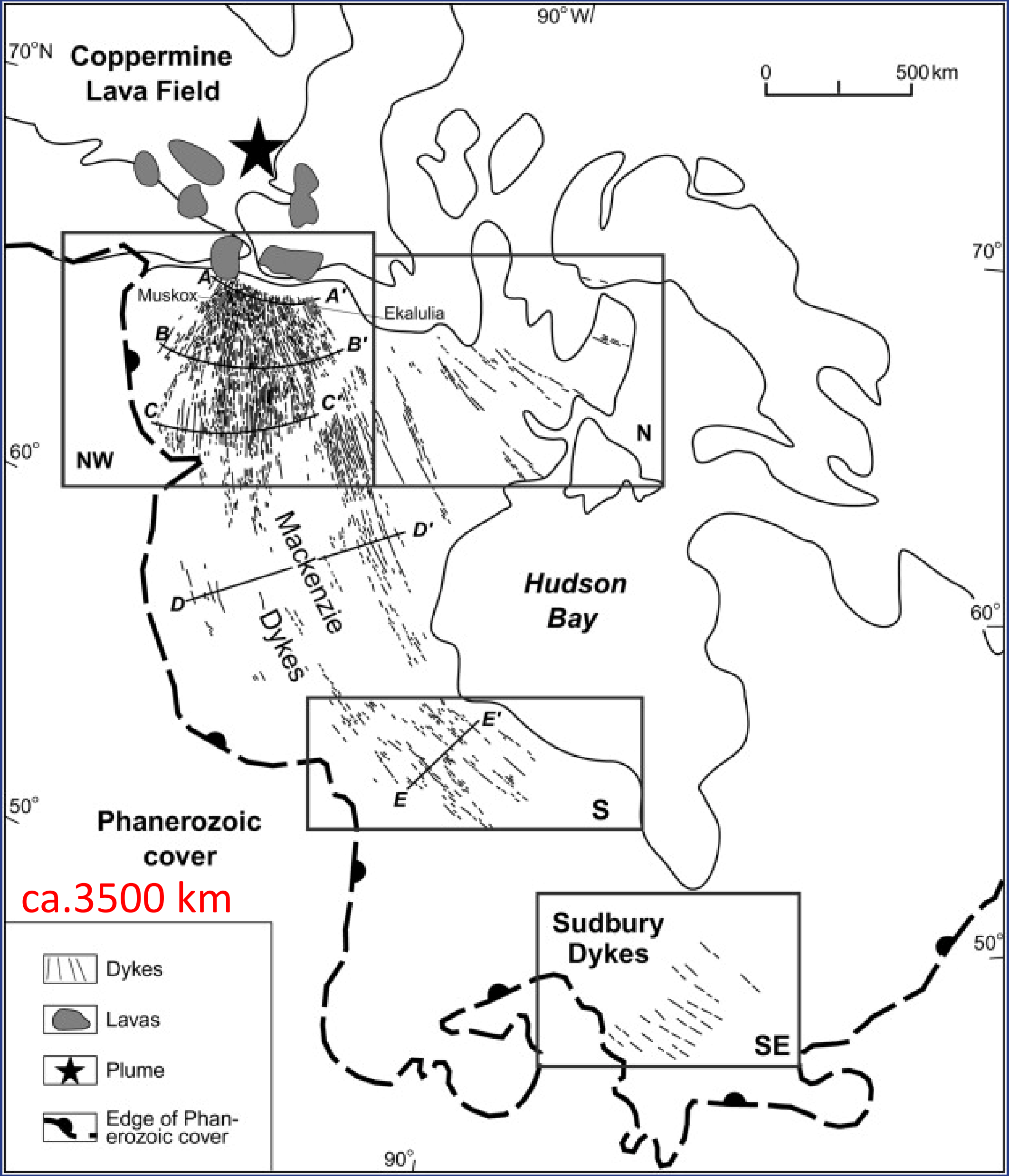
Satellite picture of the Great Dyke in Zimbabwe. The dyke is some 10 to 12 km wide in this picture. The age of the Great Dyke is 2500 million years.



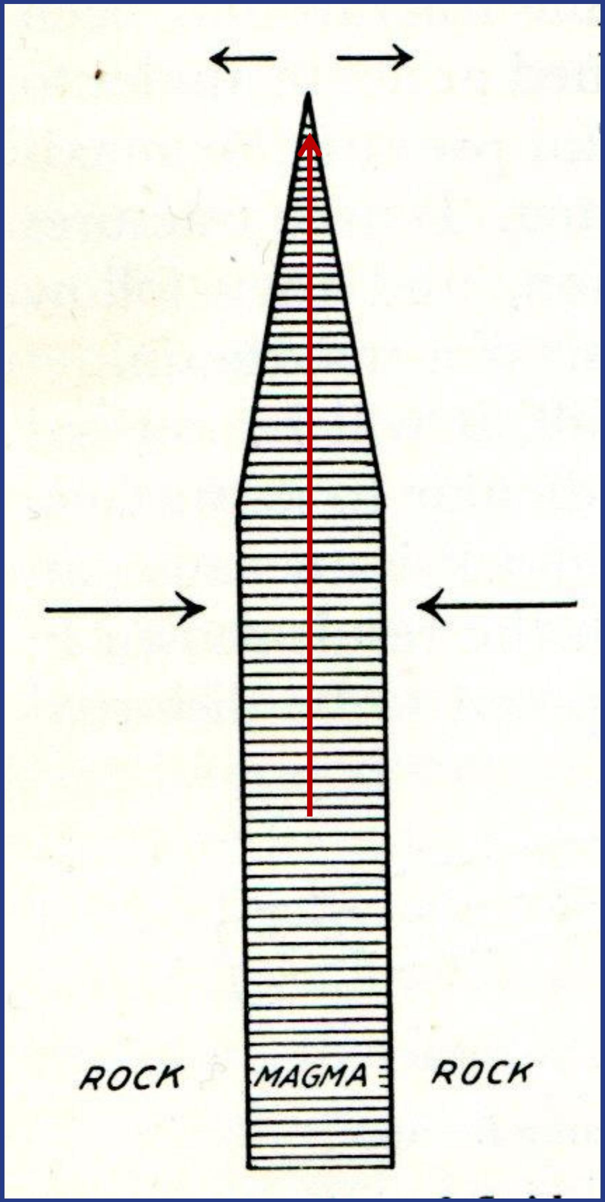
Dykes cutting through folded Silurian sedimentary rocks, Fjord Islands near Oslo, Norway (from Hans Cloos, 1937). As seen in this map dykes usually occur in groups called “swarms”



The Palaeogene (about 60 to 55 ma ago) dyke swarm of



The largest preserved dyke swarm on earth: the Mackenzie Dyke Swarm in Canada (ca. 1267 Ma old) represents some 500.000 km^3 lava! (Coppermine River Group)



Model for dyke propagation. The tip of the dyke has the largest stress concentration.

What is stress?

So far we talked about force causing deformation. But force is mass times acceleration.

$F = m \cdot A$

This equation cannot be applied to any surface. So if we divide force by surface area, we obtain an expression for stress:

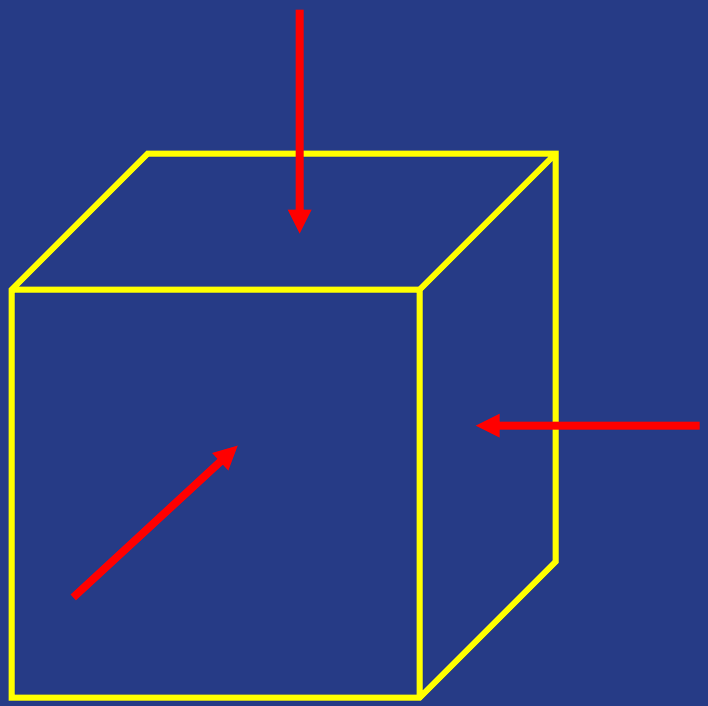
$\rho = F/A$

As the area to which a force is applied becomes smaller, the stress on that area increases.

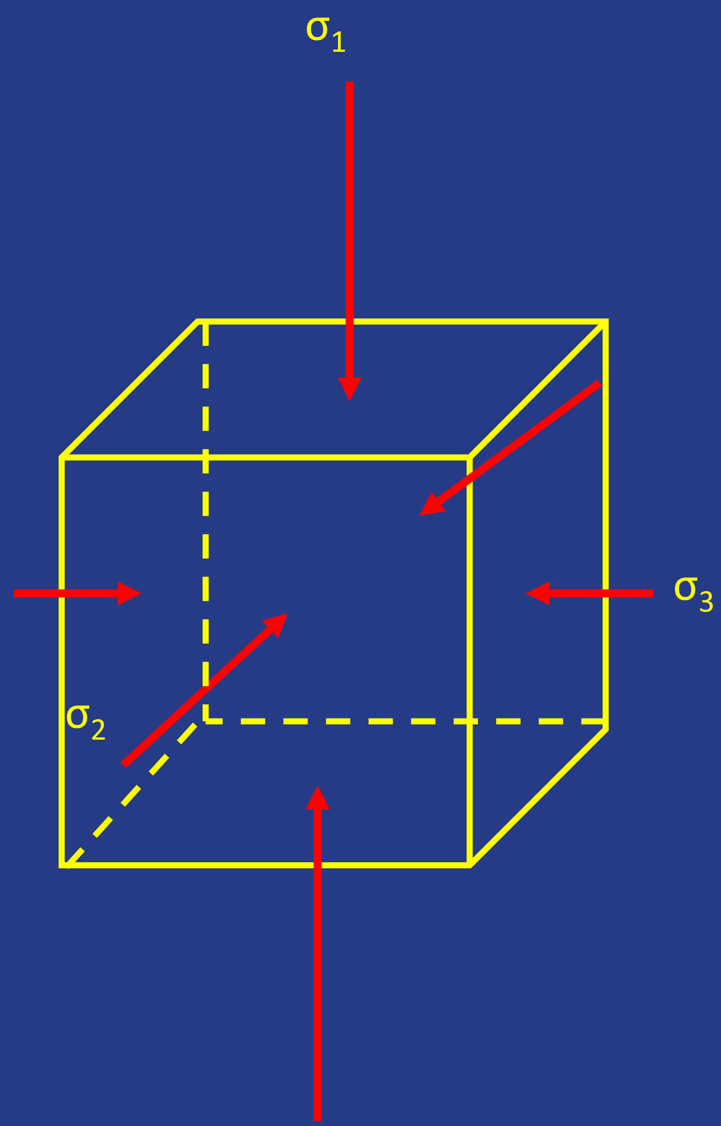
There are two kinds of stresses: normal and shear.

Normal stresses act perpendicularly on a surface, whereas shear stresses act parallel with the surface

Normal stresses: These stresses apply perpendicularly onto a surface

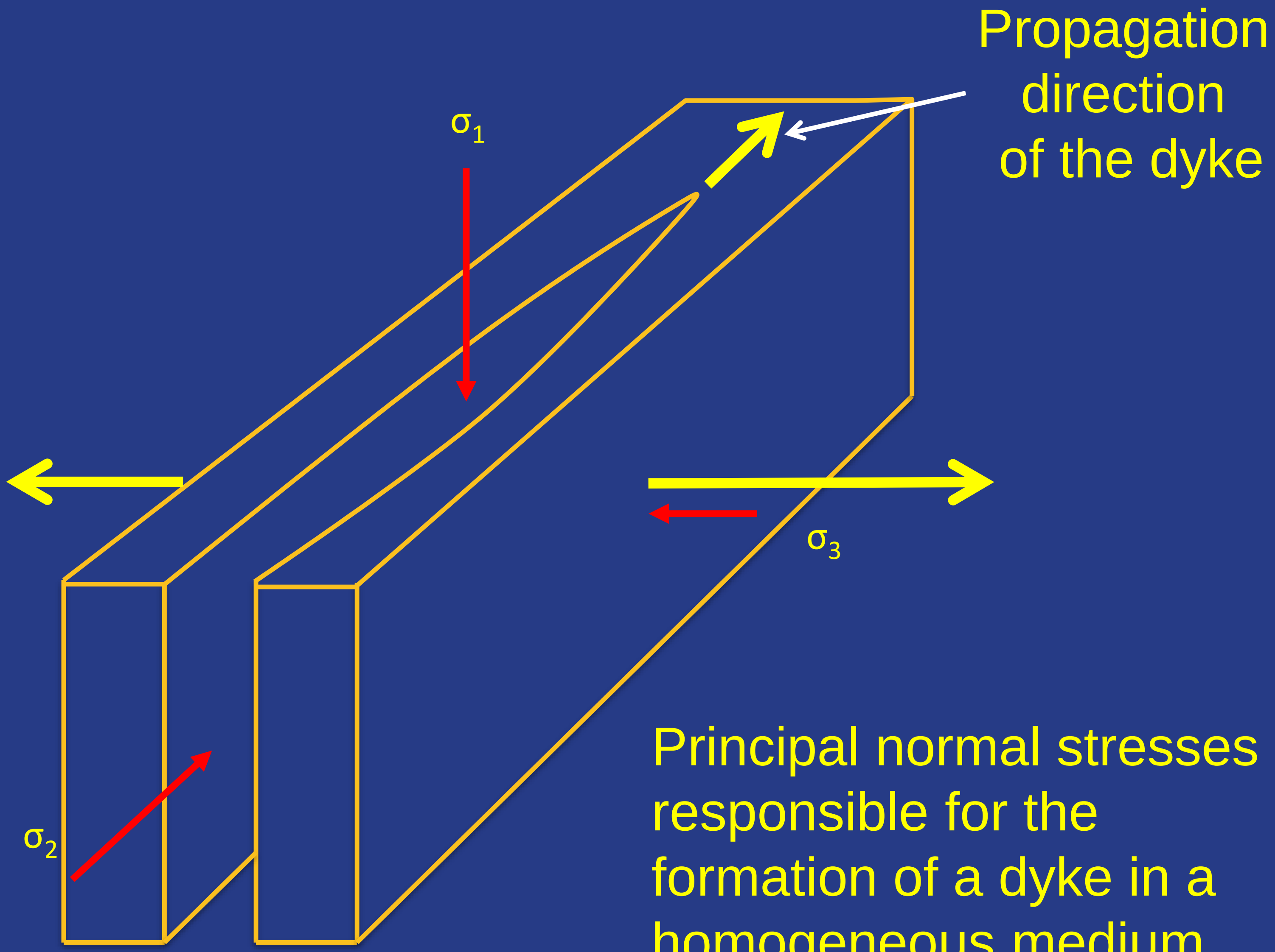


Because action=reaction, all stresses acting on a body come in opposite pairs. This is naturally also true for normal stresses.



Also not all stresses are of equal magnitude. We therefore call the greatest stress acting on a body σ_1 and the smallest, σ_3.

Liquids cannot sustain shear stresses. Since dykes are filled with liquid magma, we do not here consider the shear stresses.

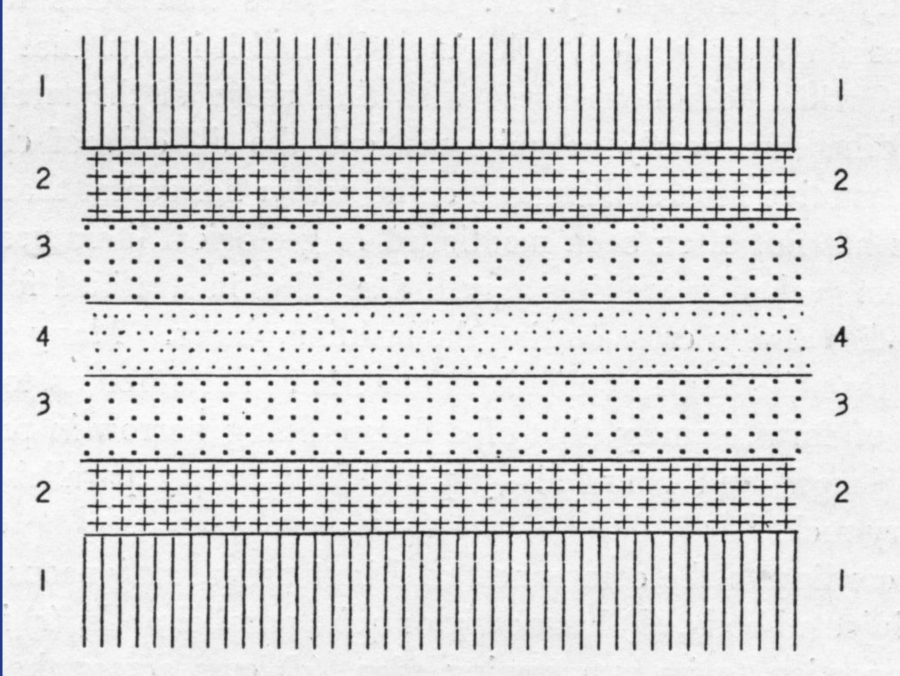


Principal normal stresses responsible for the formation of a dyke in a homogeneous medium according to Anderson's theory of dyke formation (1942, 1951)

Because dykes form by filling with liquid magma, they are the only sure indicators of the orientation of regional principal stresses.

The great Canadian geologist Reginald Aldworth Daly cited the famous textbook by Scottish geologist Sir Archibald Geikie entitled *Text-Book of Geology*, v. II, to call multiple dykes:

“compound intrusions in dyke form, due to successive injections of homogeneous material on the same fissure” (Daly, 1905)



Already in 1954, the Canadian geologist Bob Baragar described, in an unpublished industry report, the process of continuous dyke injection into the same locus of extension from the Betts Pond ophiolites in Newfoundland, Canada. He called the dykes that thus formed "sheeted dykes". We now know that sheeted dykes form along the mid-oceanic ridges and lead to the formation of new oceanic crust.

(*Betts Pond area, Burlington Peninsula, Newfoundland*: Report to Falconbridge Nickel Mines, deposited in the archive of the Newfondland Department of Mines)

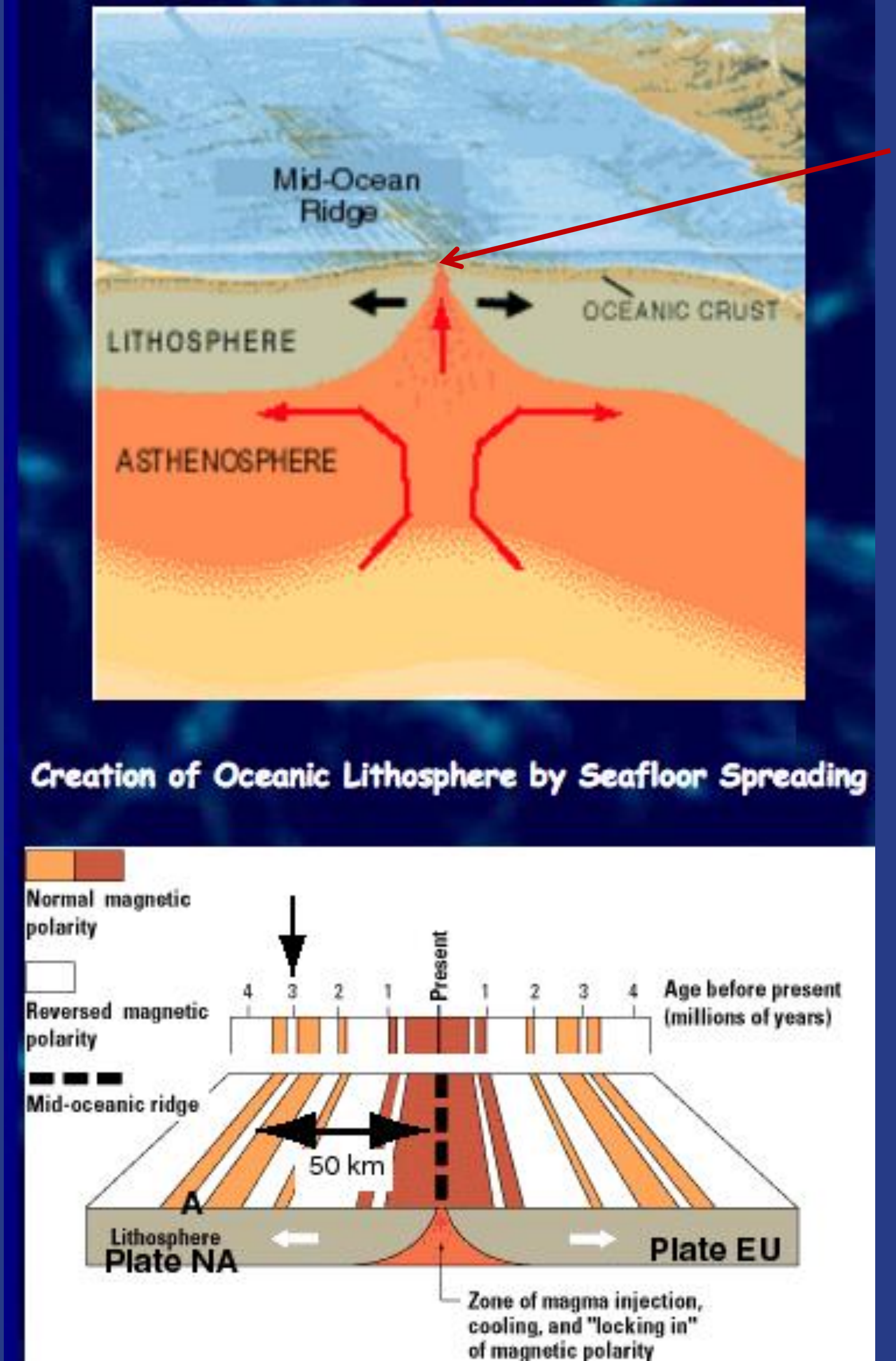
W. R. A. "Bob" Baragar (1926-)

Sheeted dykes, Troodos ophiolite, Cyprus

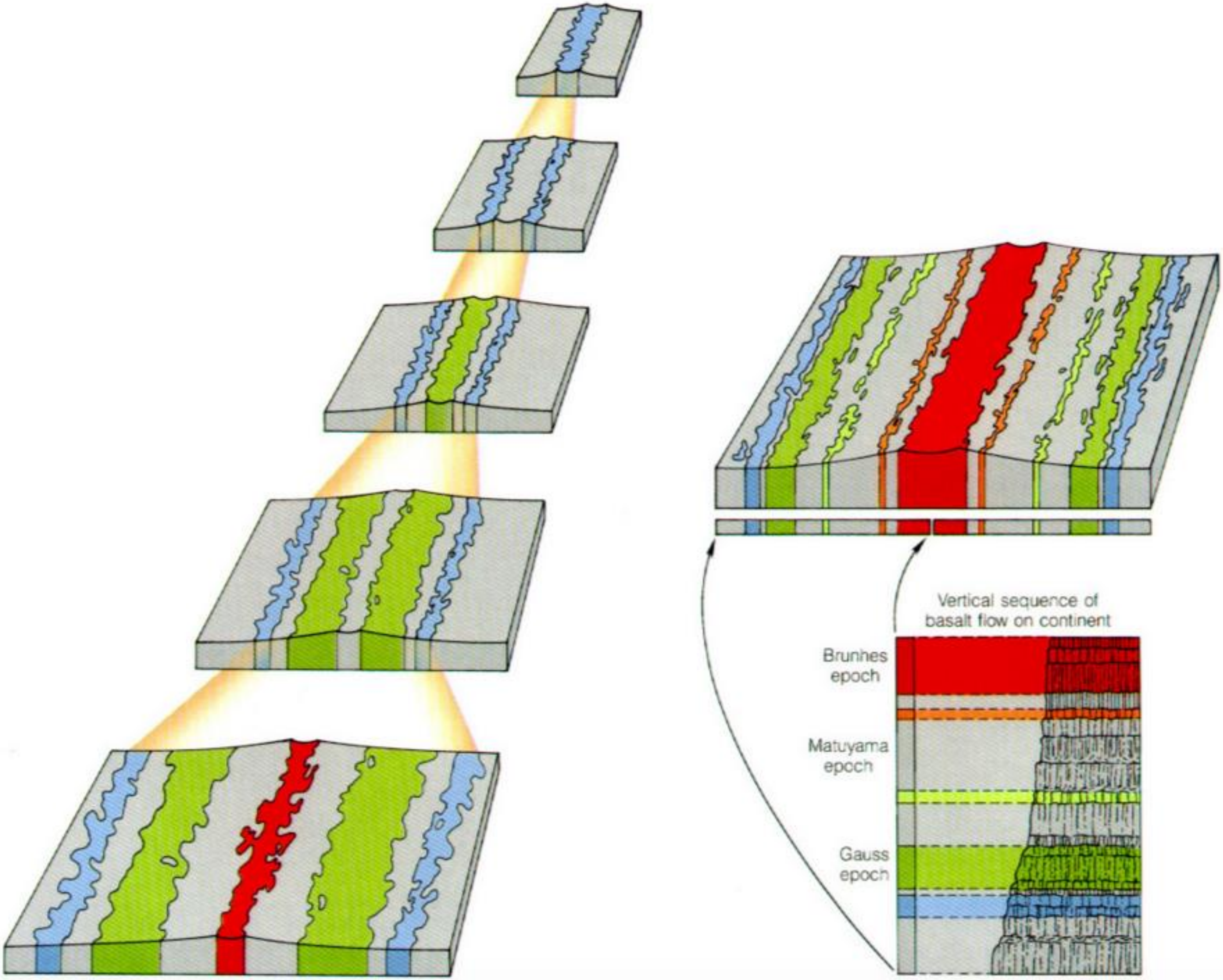
Sheeted dykes in the Kenai ophiolite,
Alaska, USA

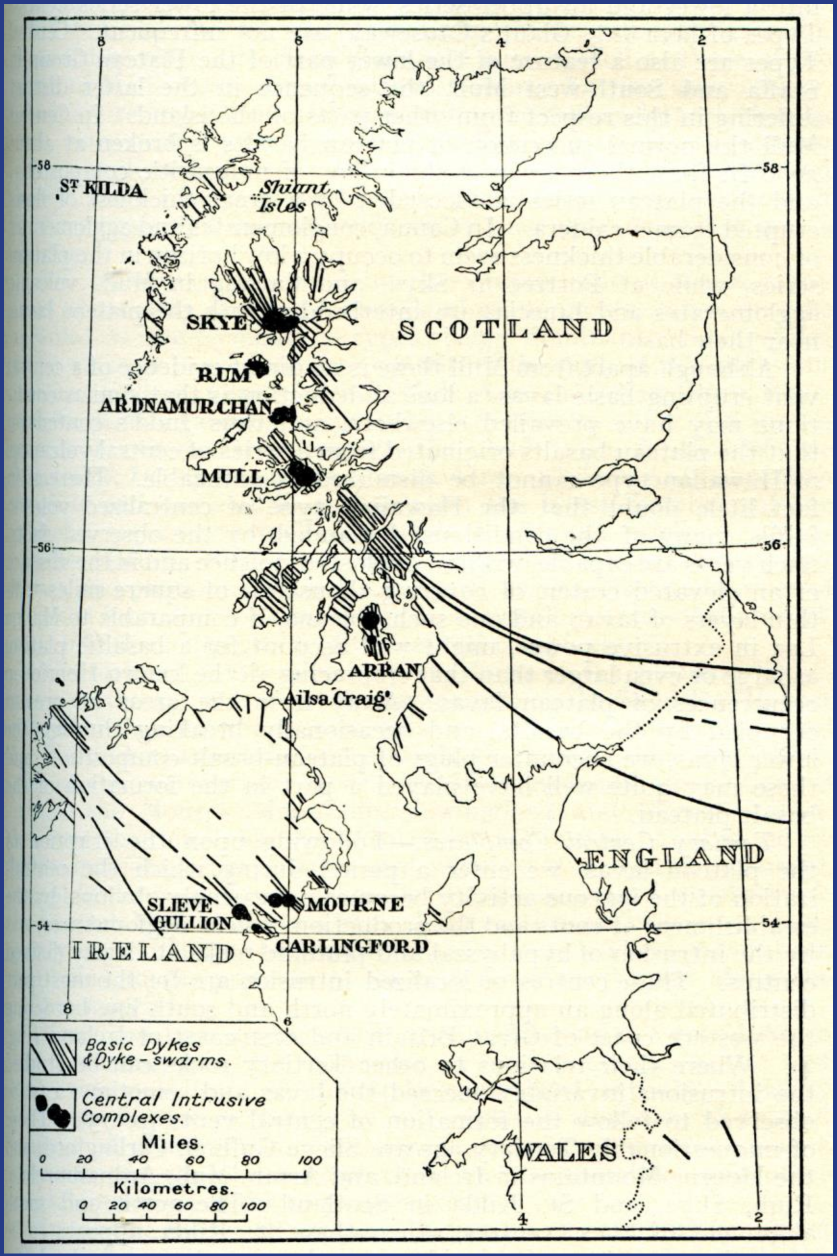
Splitting of a pre-existent dyke by a younger dyke in a sheeted dyke complex.

The mid-oceanic ridge system in the world: these are the places where sea-floor spreading creates new ocean floor

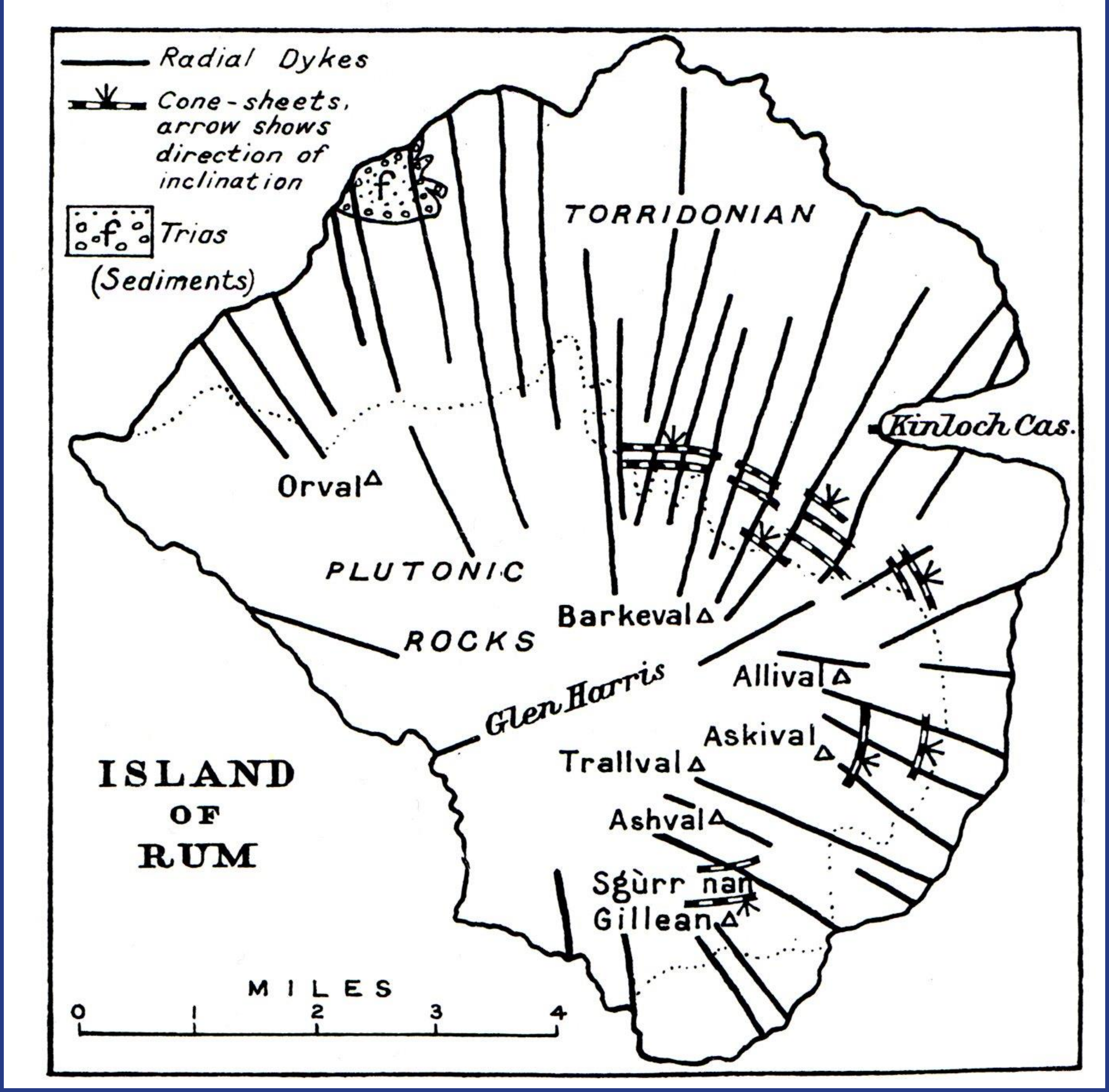


This is where
sheeted
dyke injection
happens

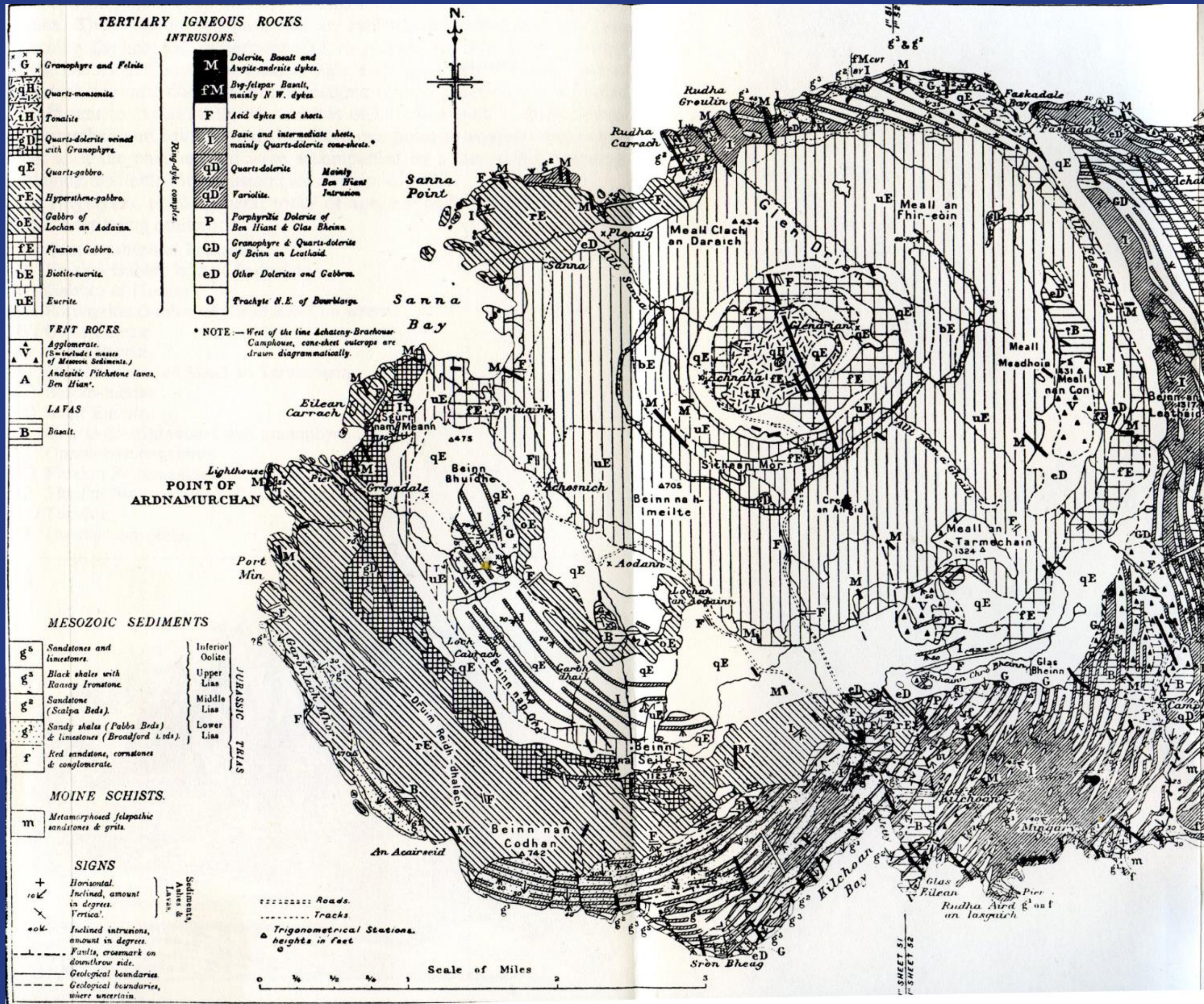

Vertical sequence of
basalt flow on continent
Brunhes
epoch
Matuyama
epoch
Gauss
epoch



Let us go back to the Palaeogene dyke swarm of Scotland. Look carefully at the islands of Skye, Rum, Ardnamurchan, Mull and Arran. The black centres are intrusions that were once roots of volcanoes

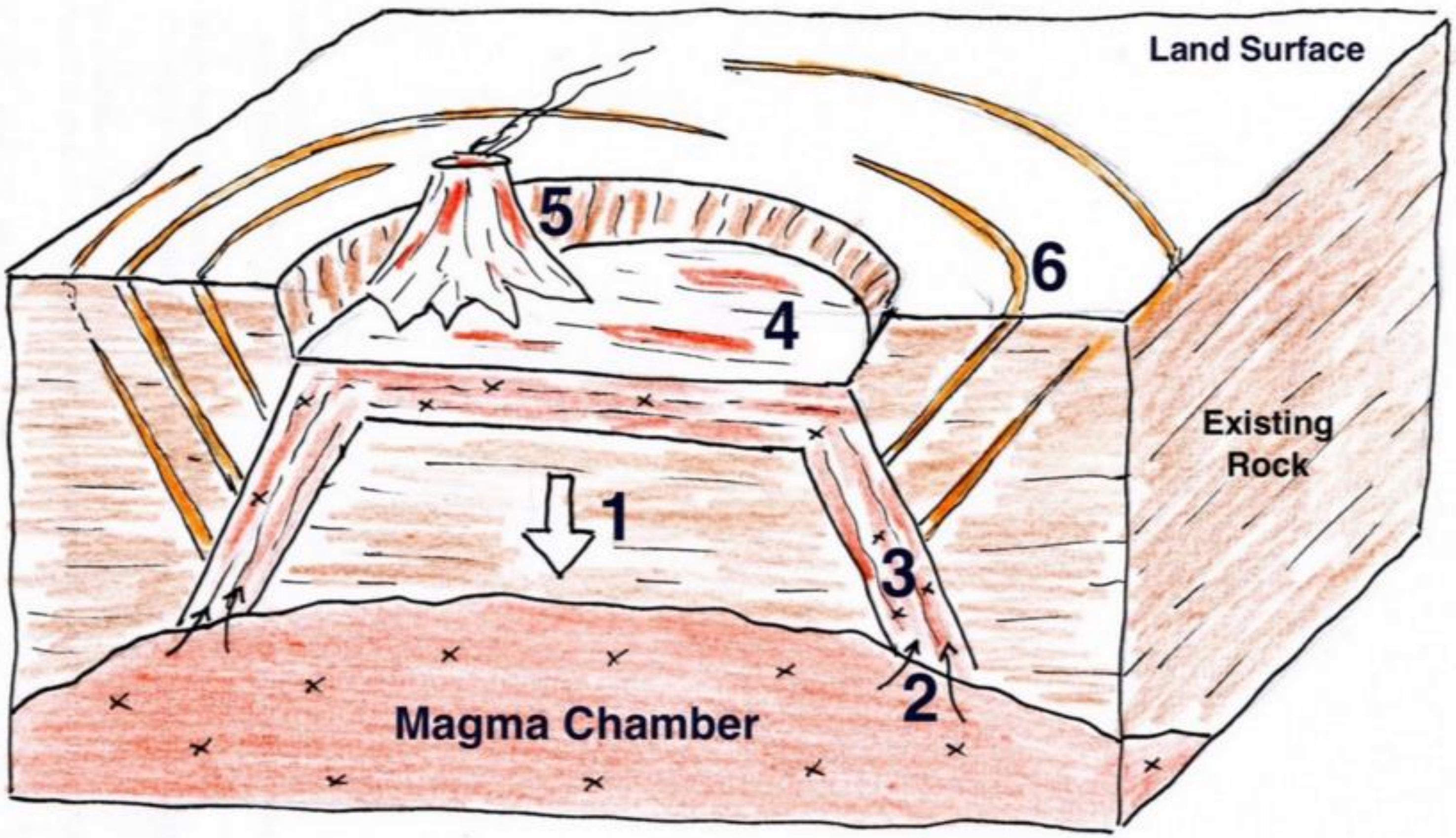


Radial and concentric (=ring) dykes of the Island of Rum.

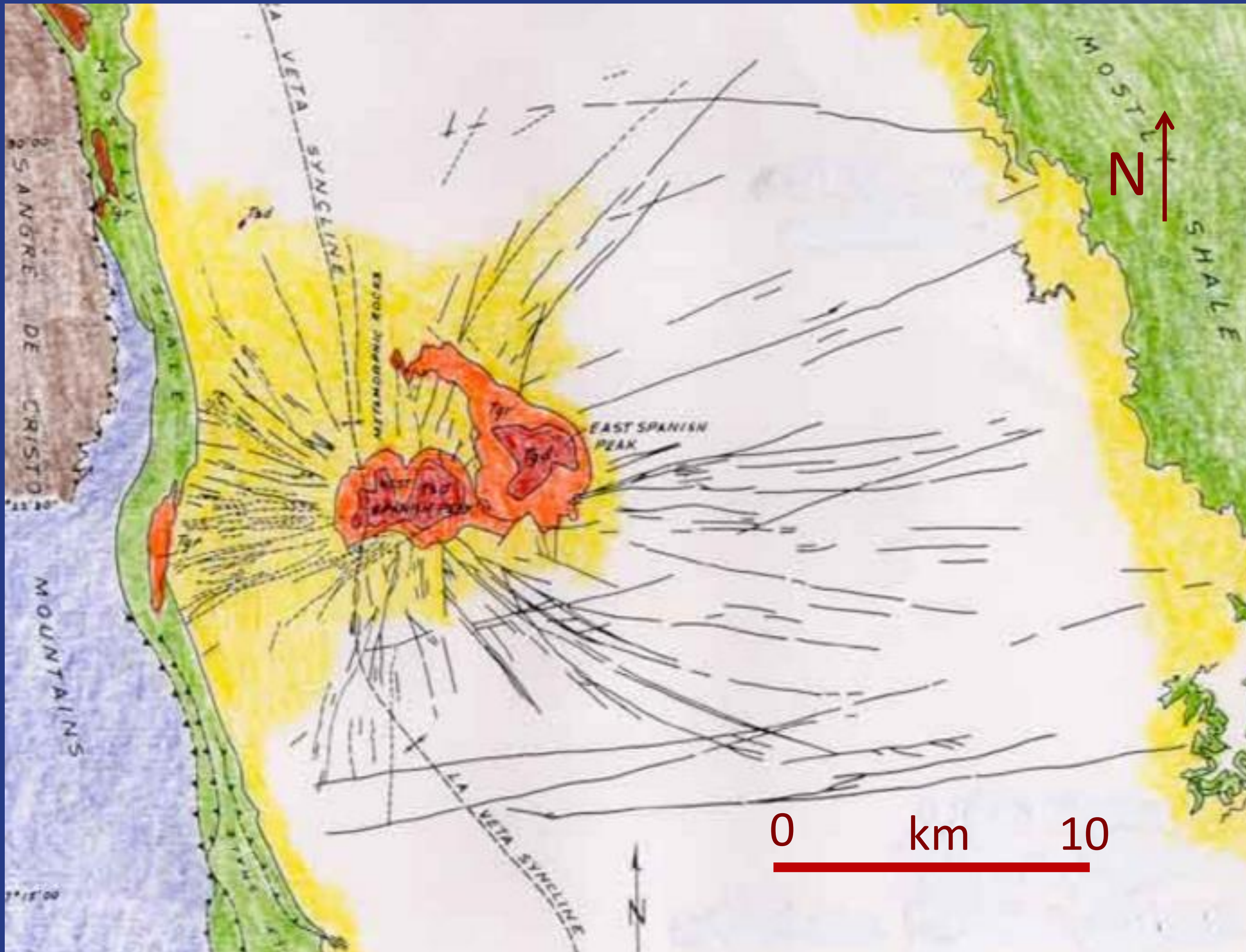


Radial and concentric dykes of Ardnamurchan

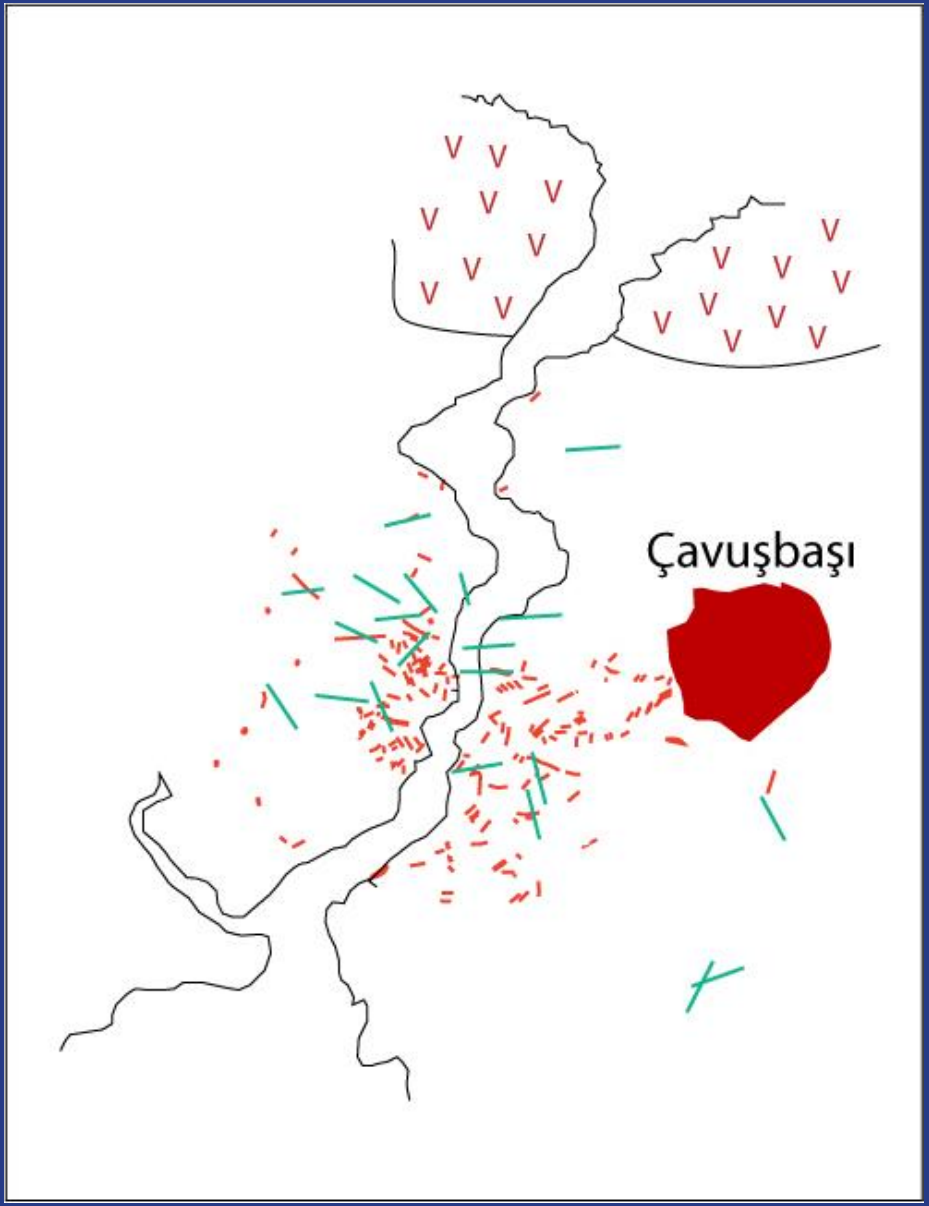
Volcanic Ring Complex, Ardnamurchan



A pair of large radial dykes emanating from the volcanic neck of the Shiprock Mountains, New Mexico, USA

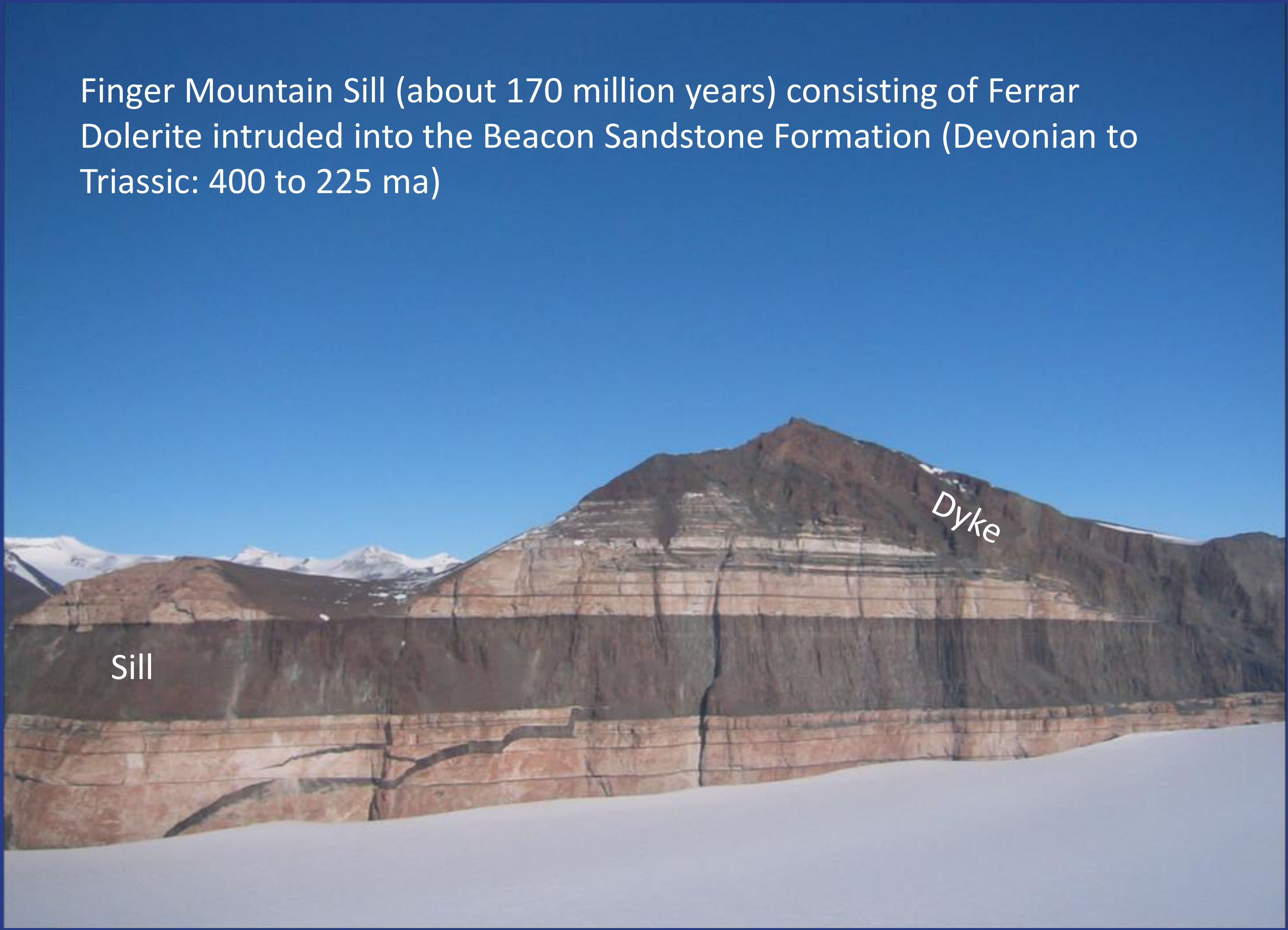


Spanish Peaks, Colorado, USA. Red is augite-granite-porphyry, orange is granite porphyry. Black lines are the dykes.



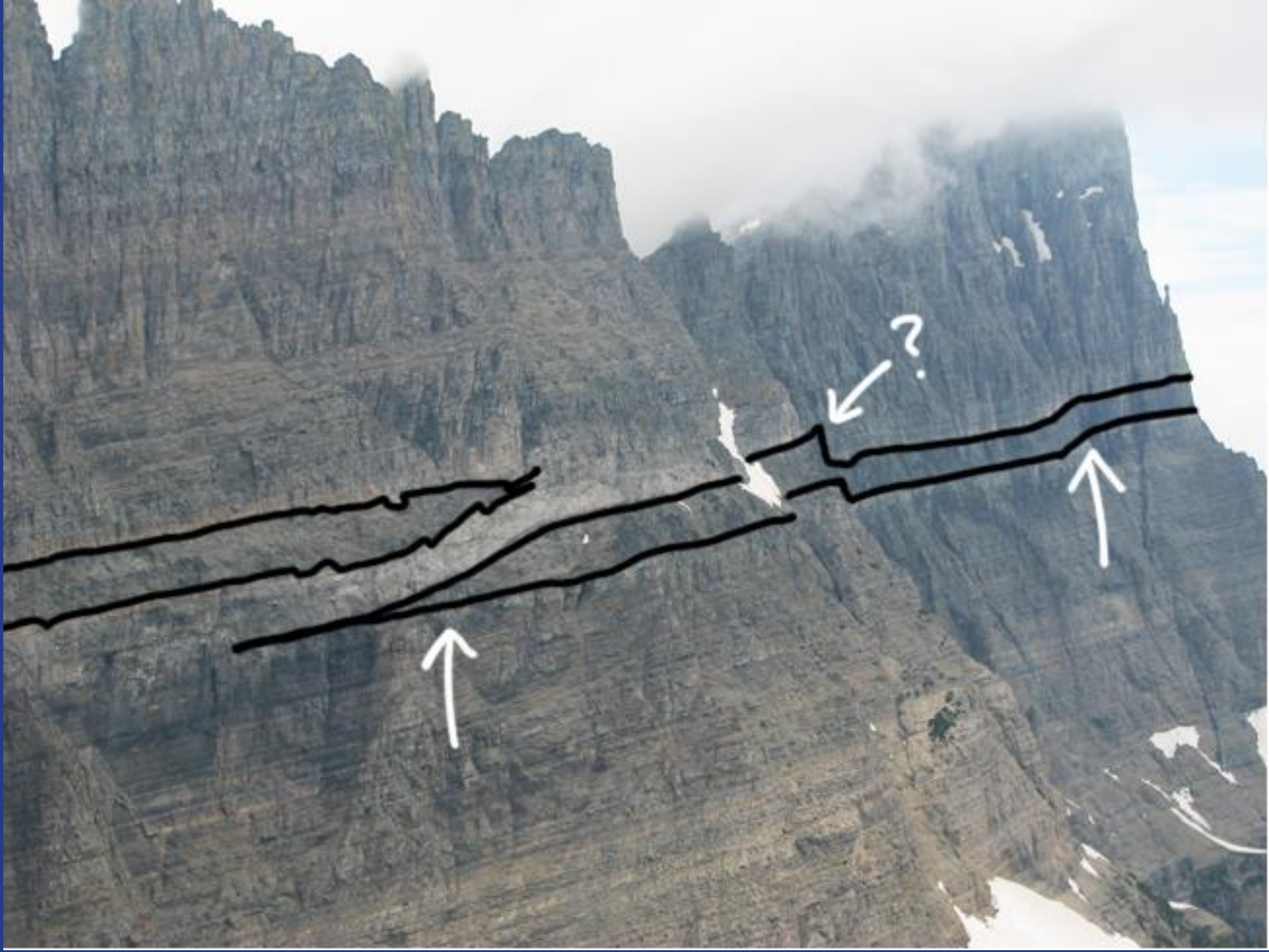
Radial dykes emanating from the Çavuşbaşı Granodiorite in İstanbul, which was a part of a volcanic magma chamber of about 65 millions of years of age.

Sill: A sill is a parallel- to subparallel-sided, tabular, concordant, mostly conformal and usually harmonic intrusion. The term comes from the slabs used in thresholds.



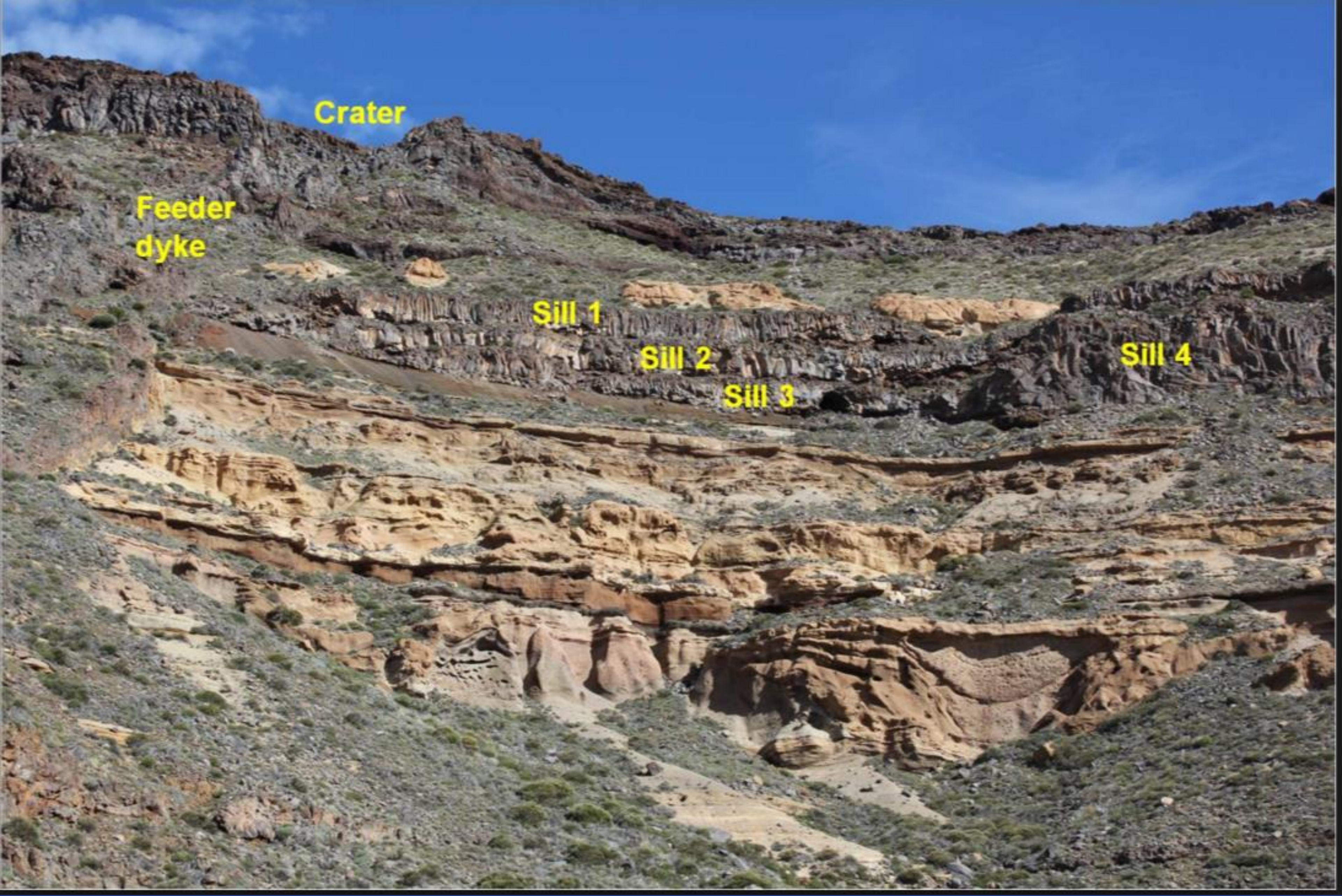
A granite sill used in a threshold in a home.

The Purcell Sill intruding the Proterozoic Belt Supergroup, Montana, USA



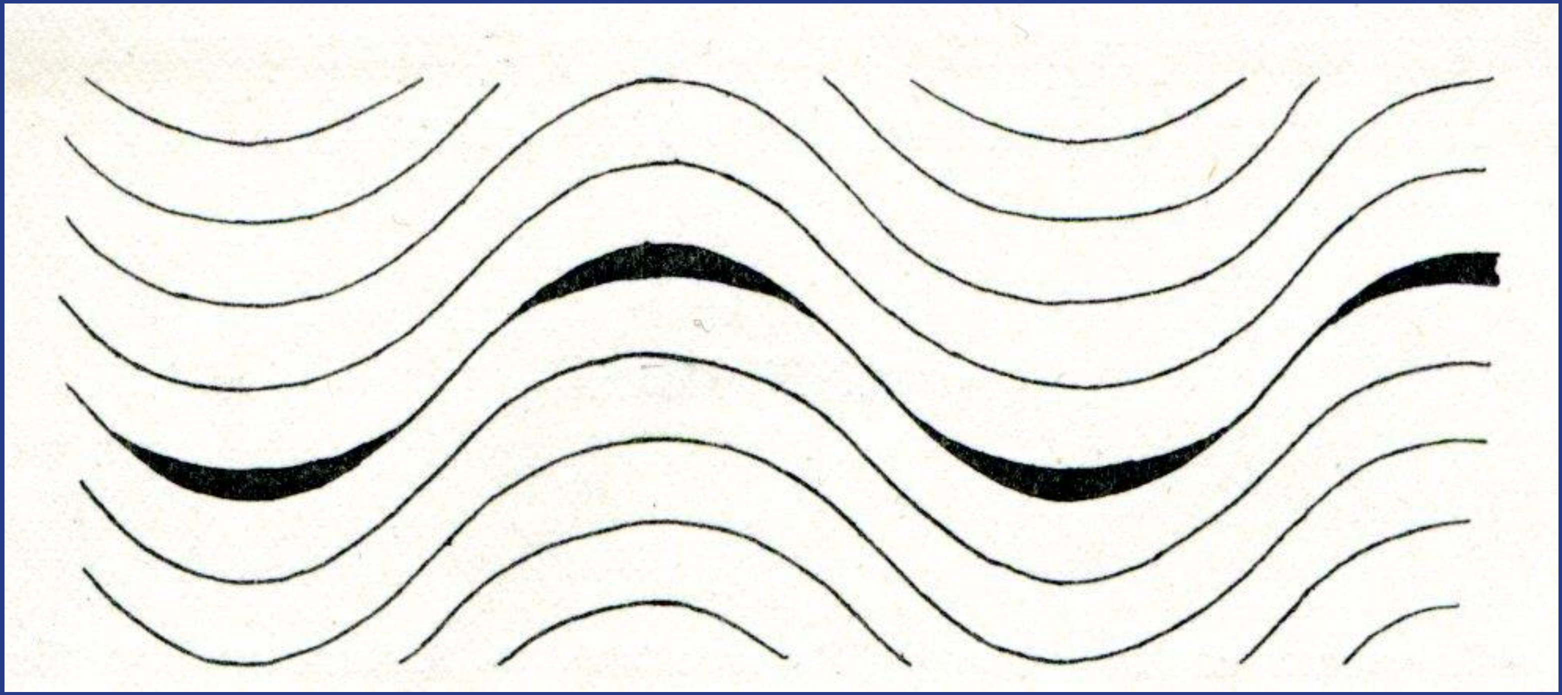
The Purcell Sill highlighted.

The Purcell sill shownig contact metamorphic aureole around it (lighter coloured rock)

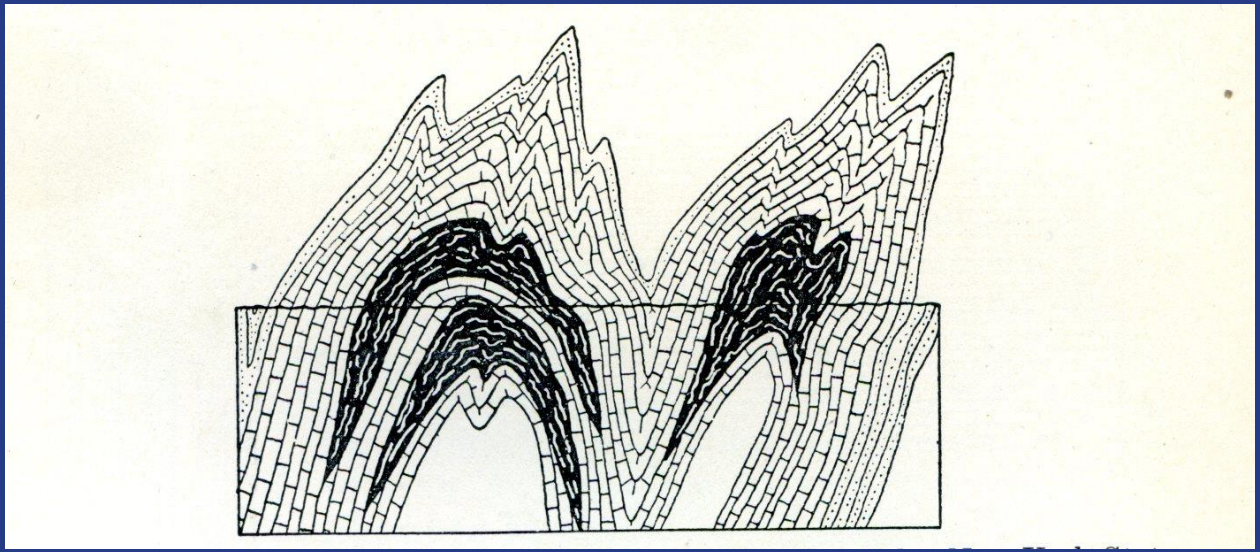


Sills and a feeder dyke, Tenerife, Canary Islands.

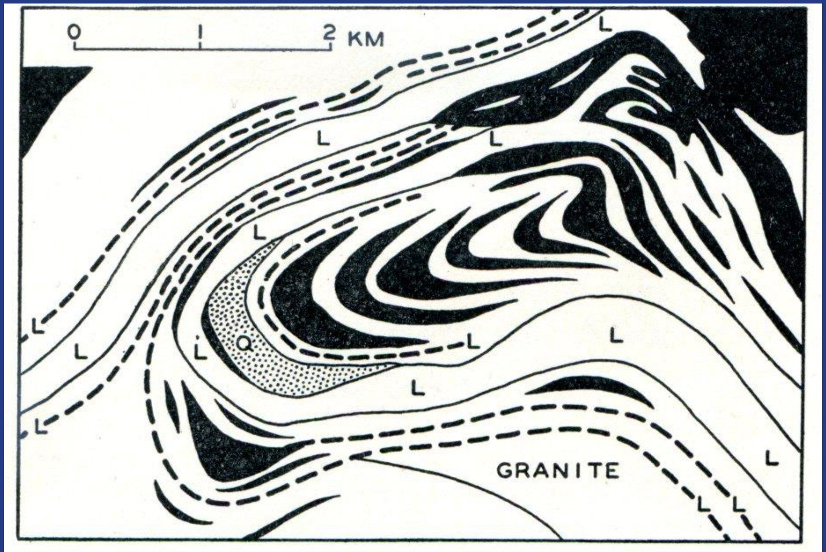
Lopolith: is defined as a lenticular, centrally sunken, generally concordant, intrusive mass, with its thickness approximately one-tenth to one-twentieth of its width or diameter. It was introduced in 1918 by the American geologist Frank Fitch Grout to describe the Duluth Gabbro and associated intrusions in the Precambrian of the Canadian Shield. The term derives from the Greek λοπάς (*lopas*=flat dish) and λίθος (*lithos*=stone).



Phacoliths, first proposed by the great British petrographer Alfred Harker in 1909, in his *The Natural History of Igneous Rocks*, p. 77, as “phacolite”. The figure is from Harker’s book. Harker emphasised that the phacoliths were not sills with attenuated limbs, but injections into the spaces created at the crests and troughs of growing folds during the folding.



Phacoliths in the Governeur and Reservoir Hill area, reconstructed above the erosion surface, New York State, USA (from Daly, 1914, p. 88)

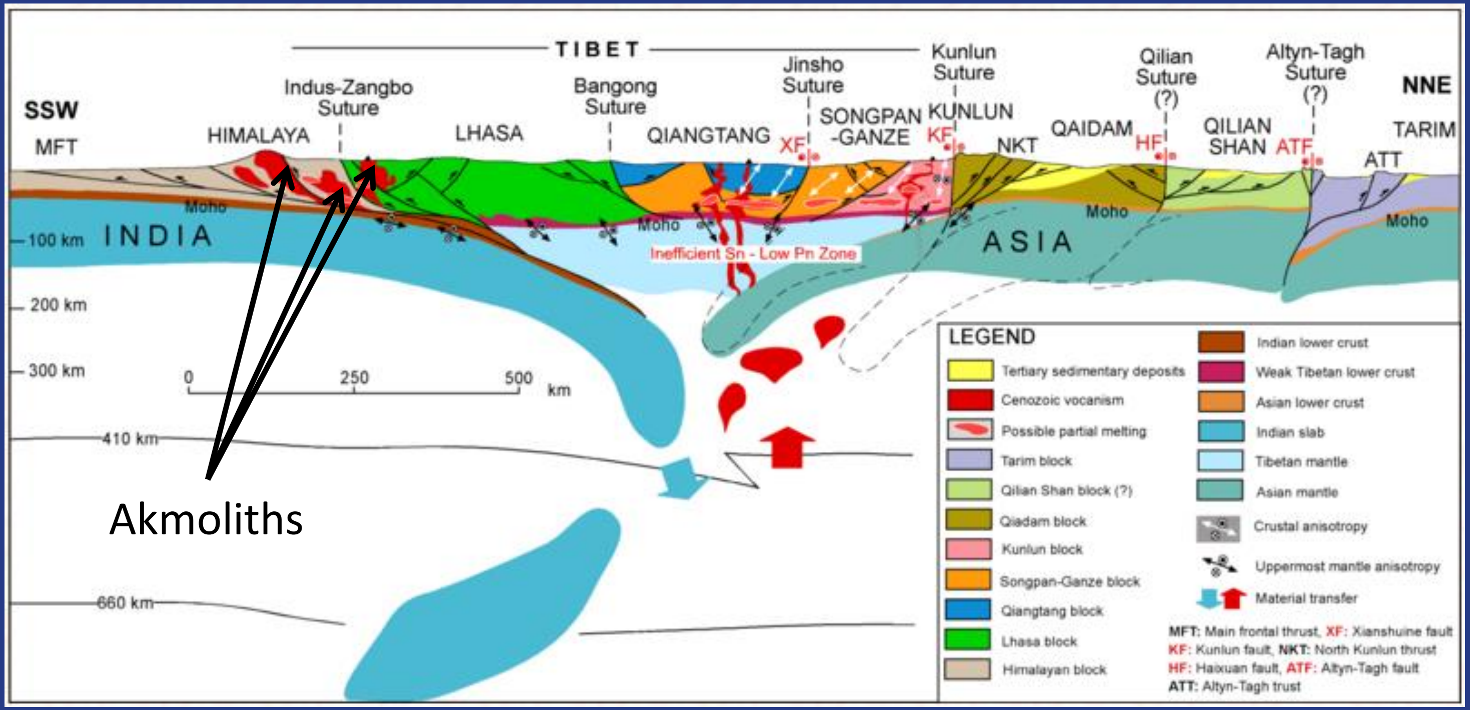


Precambrian phacoliths, South Africa (from Daly, 1914, p. 89).

Rising Wolf Mountain dolerite phacolith,
Glacier National Park, Montana, USA

Rising Wolf Mountain
Phacolith at a distance.

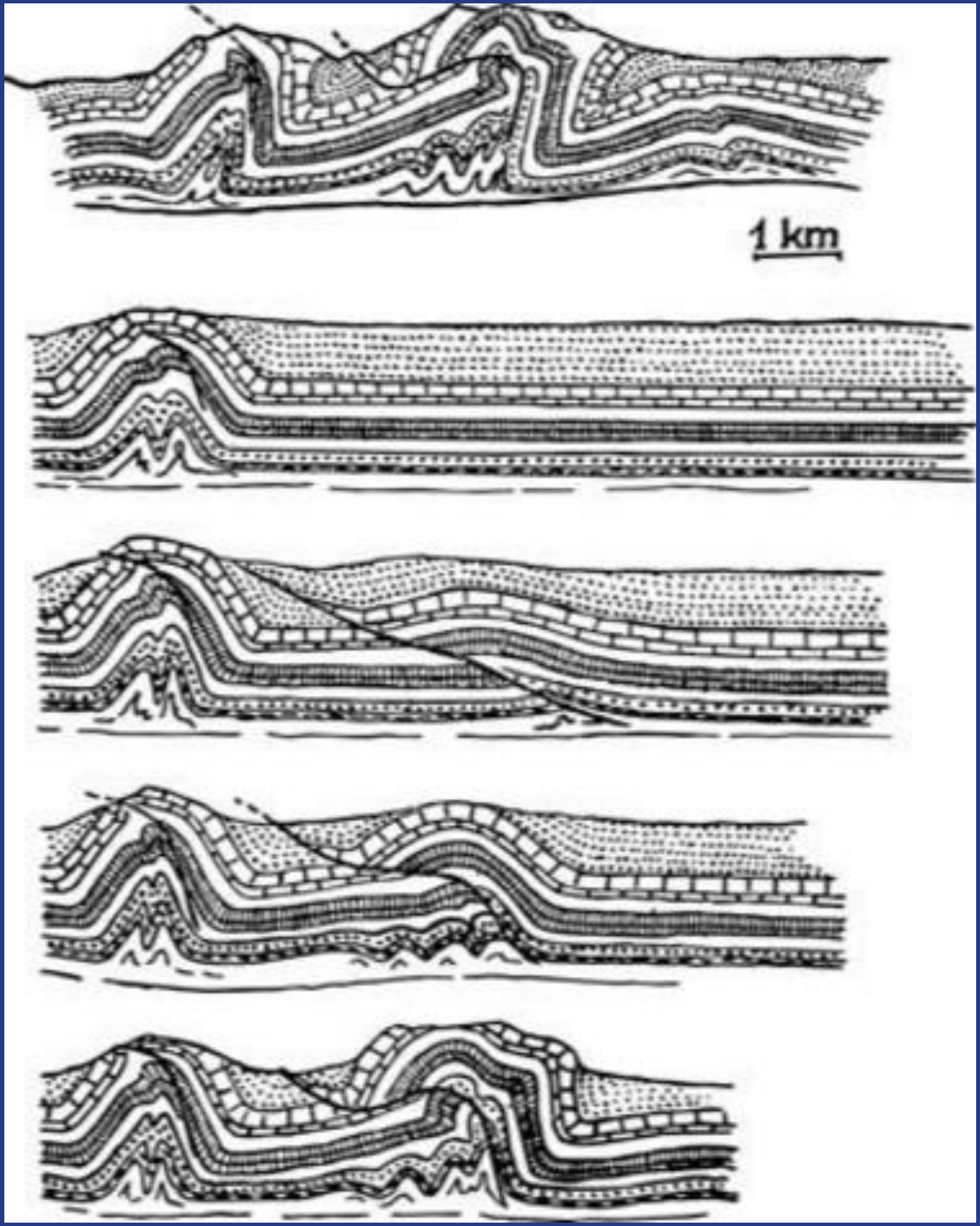
Akmolith (also spelled acmolith): An igneous body intruded along a décollement, i.e., detachment, surface with or without tongue-like intrusions into thrust surfaces dipping into the décollement. This term was proposed by the German geologist Otto Heinrich Erdmannsdörffer in 1924 from the Greek ἀκμή (*akme*= blade, edge) and λίθος (*lithos*=stone).



Here we have encountered two new terms meaning the same thing:

Décollement (meaning “ungluing” in French) and detachment. They refer to the detachment of a rock body, generally sedimentary, from its substratum and its movement parallel with the detachment boundary. This is like the folding of a rug or a blanket on the floor.

A “detached” towel



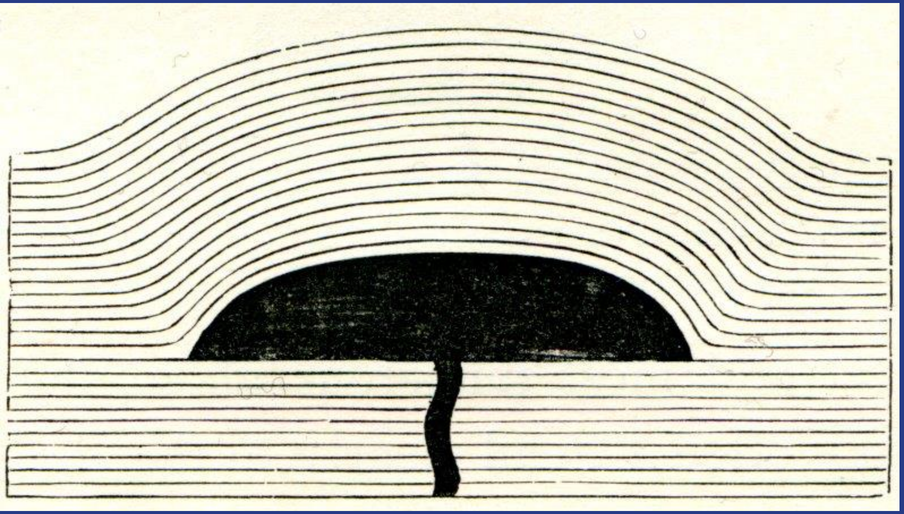
Folding over a décollement surface in the Jura Mountains, Switzerland

Ductolith: is a horizontal, concordant, conformal and harmonic intrusion with a tear-drop section. It has also been called a “headed dyke” or a “horizontal plug”. It was proposed by the American geologist David Griggs in 1939 for a presumed laccolith feeder in the Highwood Mountains in Montana, USA. It is derived from the Latin *ductus* meaning conducting, line, trail and λίθος (*lithos*=stone).

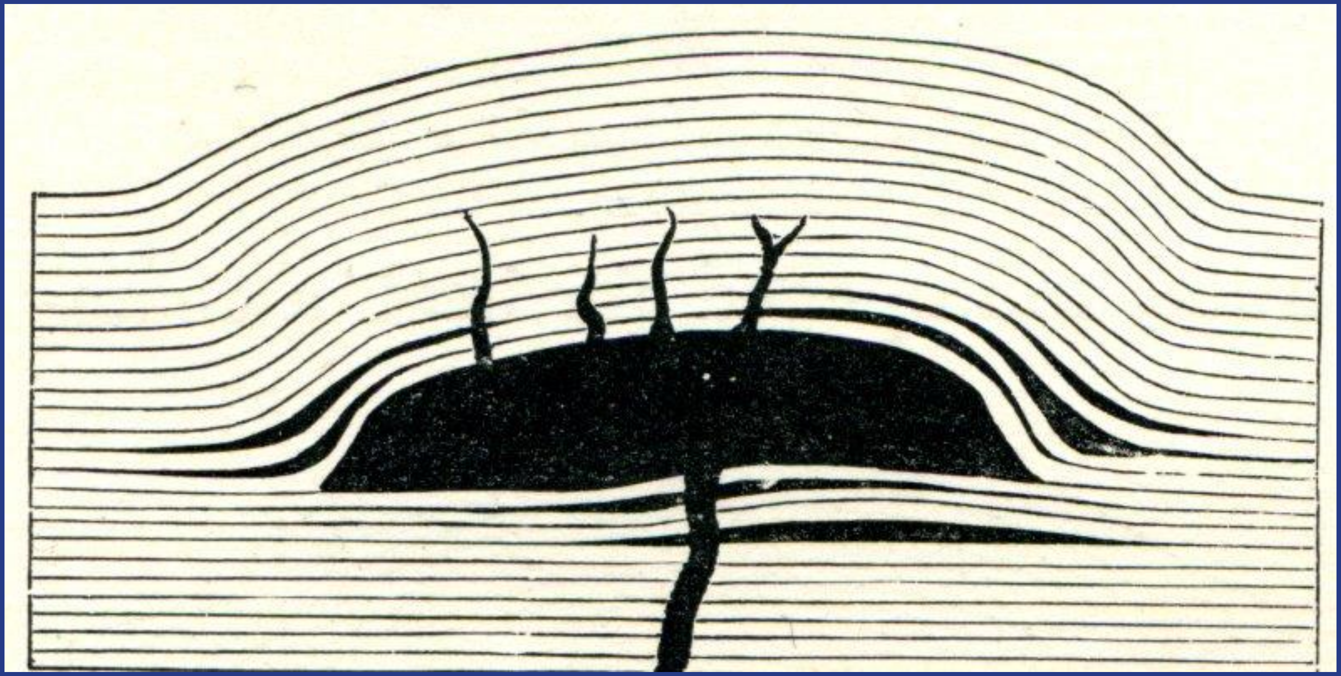
Griggs regrettably provided no figure for this feature.

Laccolith (originally introduced by Gilbert in 1877 as Laccolite): An igneous body, formed by magma insinuating itself between two strata and opening for itself a chamber by lifting all the superior beds.

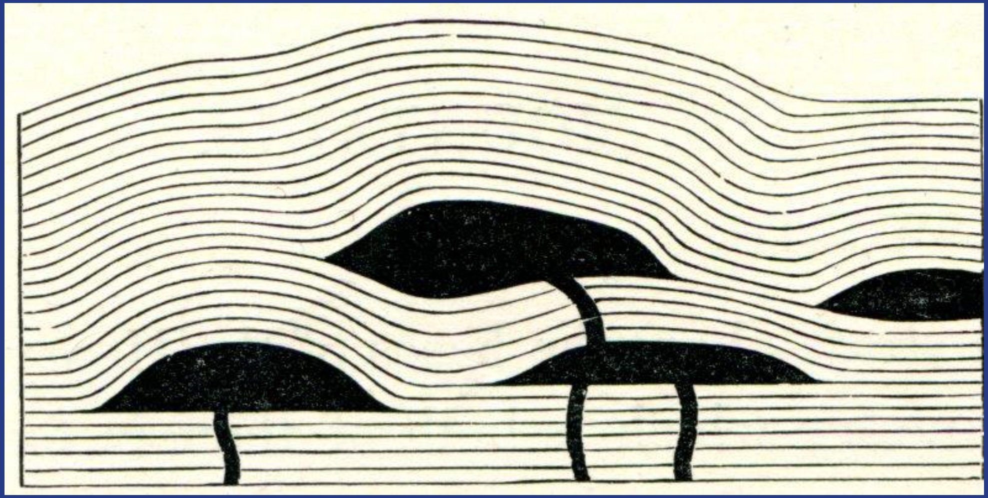
Gilbert derived the term laccolite from the Greek λάκκος (*lakkos*=cistern) and λίθος (*lithos*=stone)



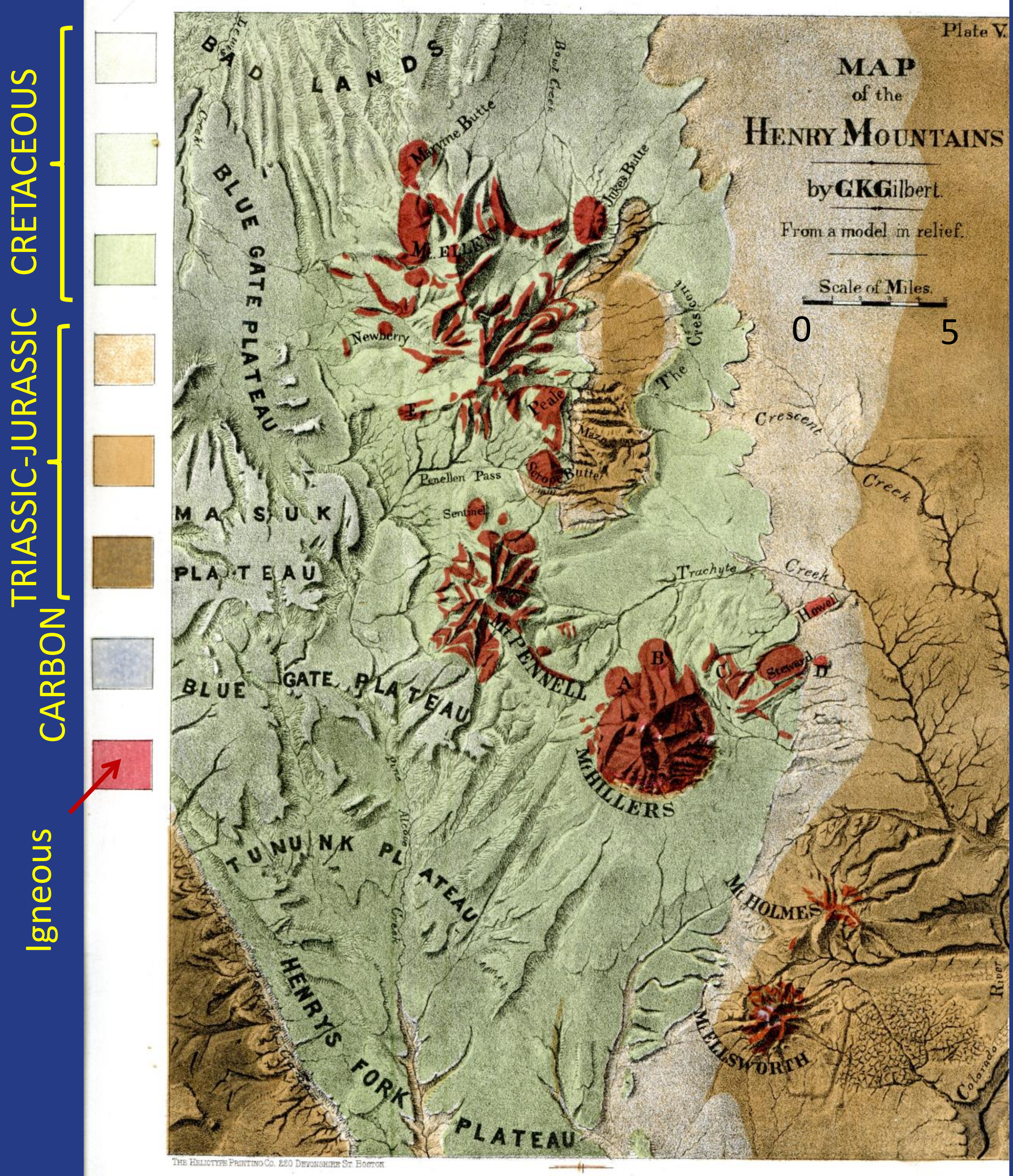
A schematic cross-section of a laccolith (from Gilbert 1877)



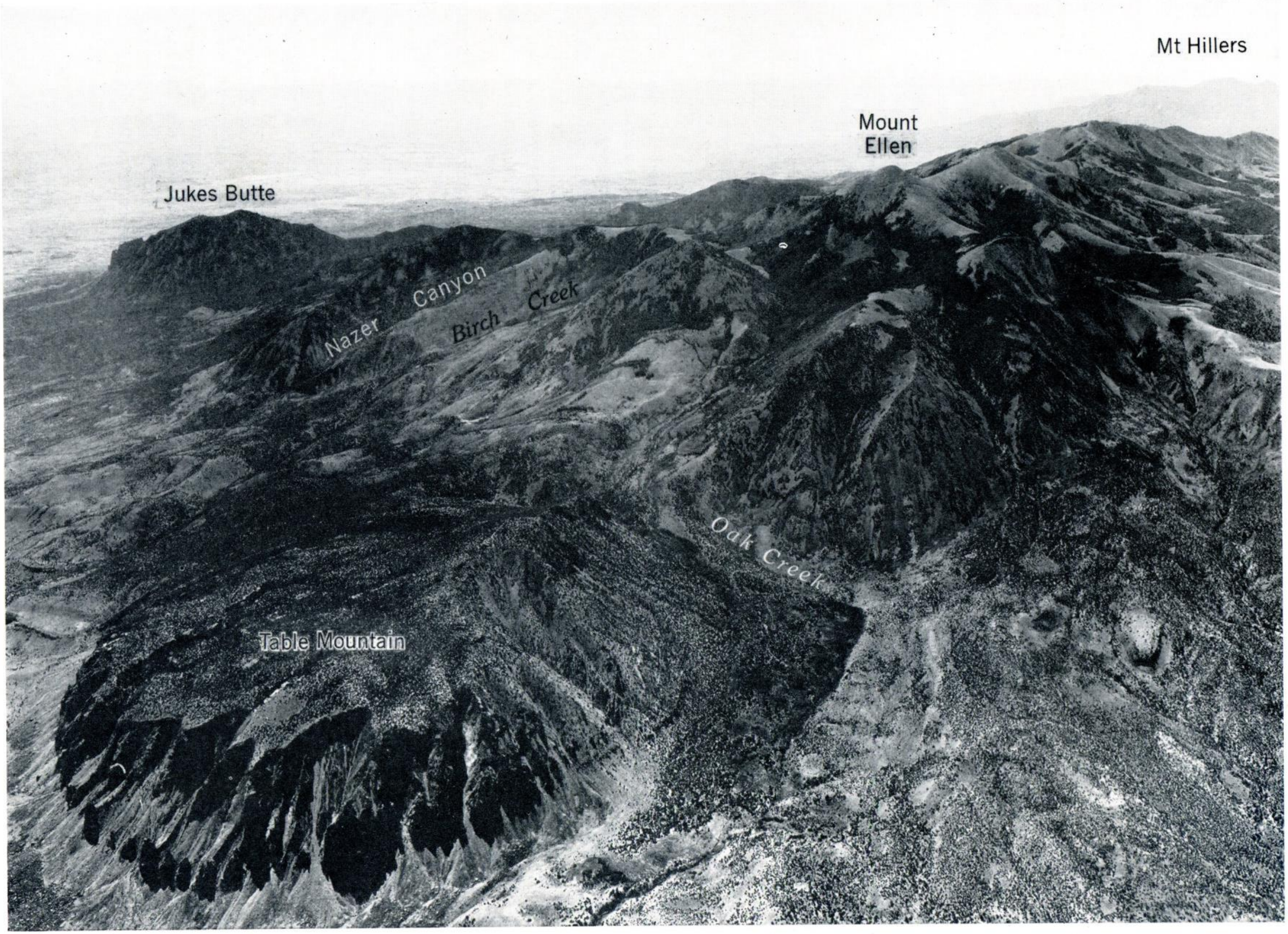
Ideal cross-section of a laccolith with accompanying sheets and dykes (from Gilbert, 1877)

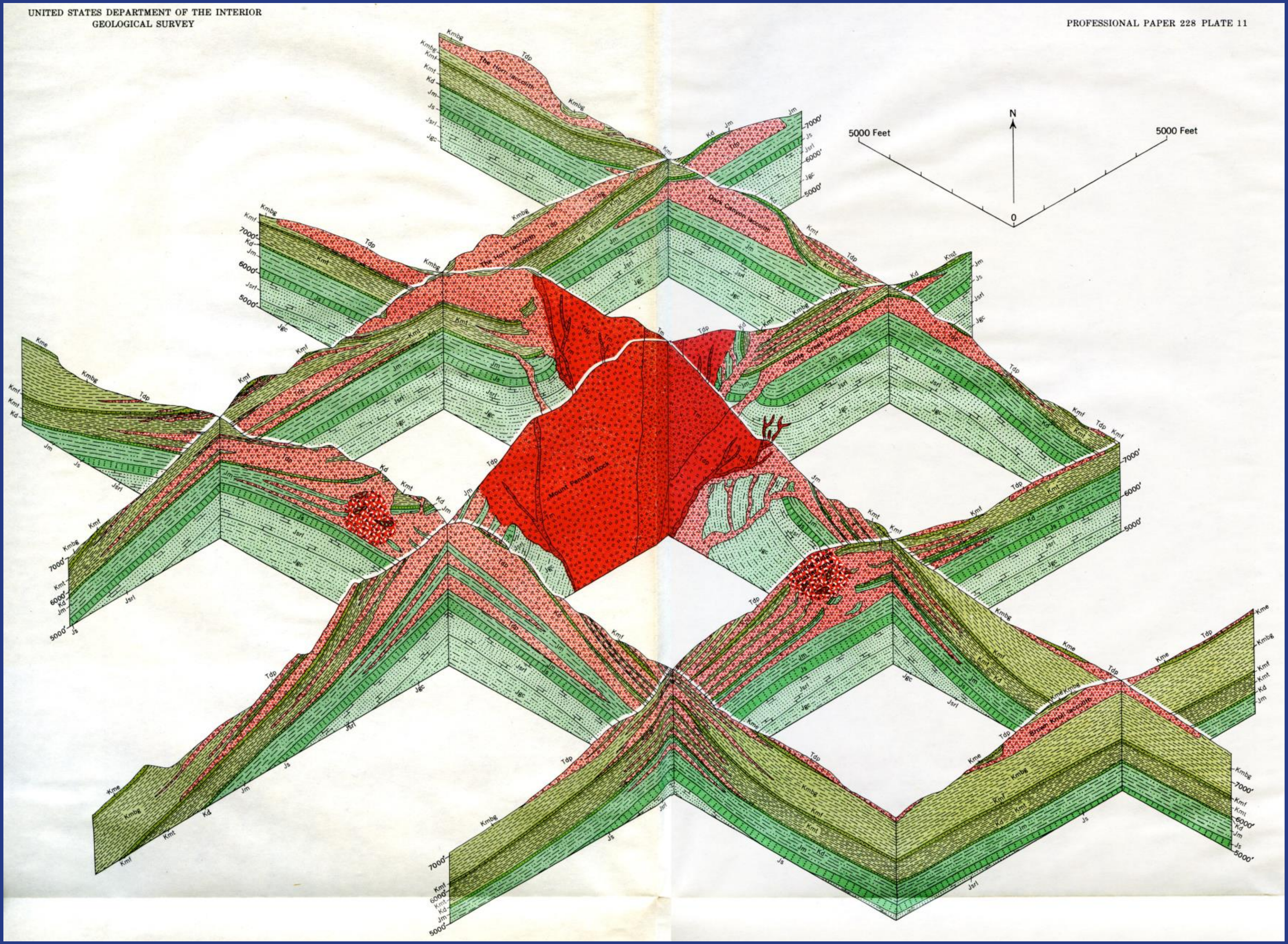


Ideal cross-section of grouped laccoliths (from Gilbert 1877)

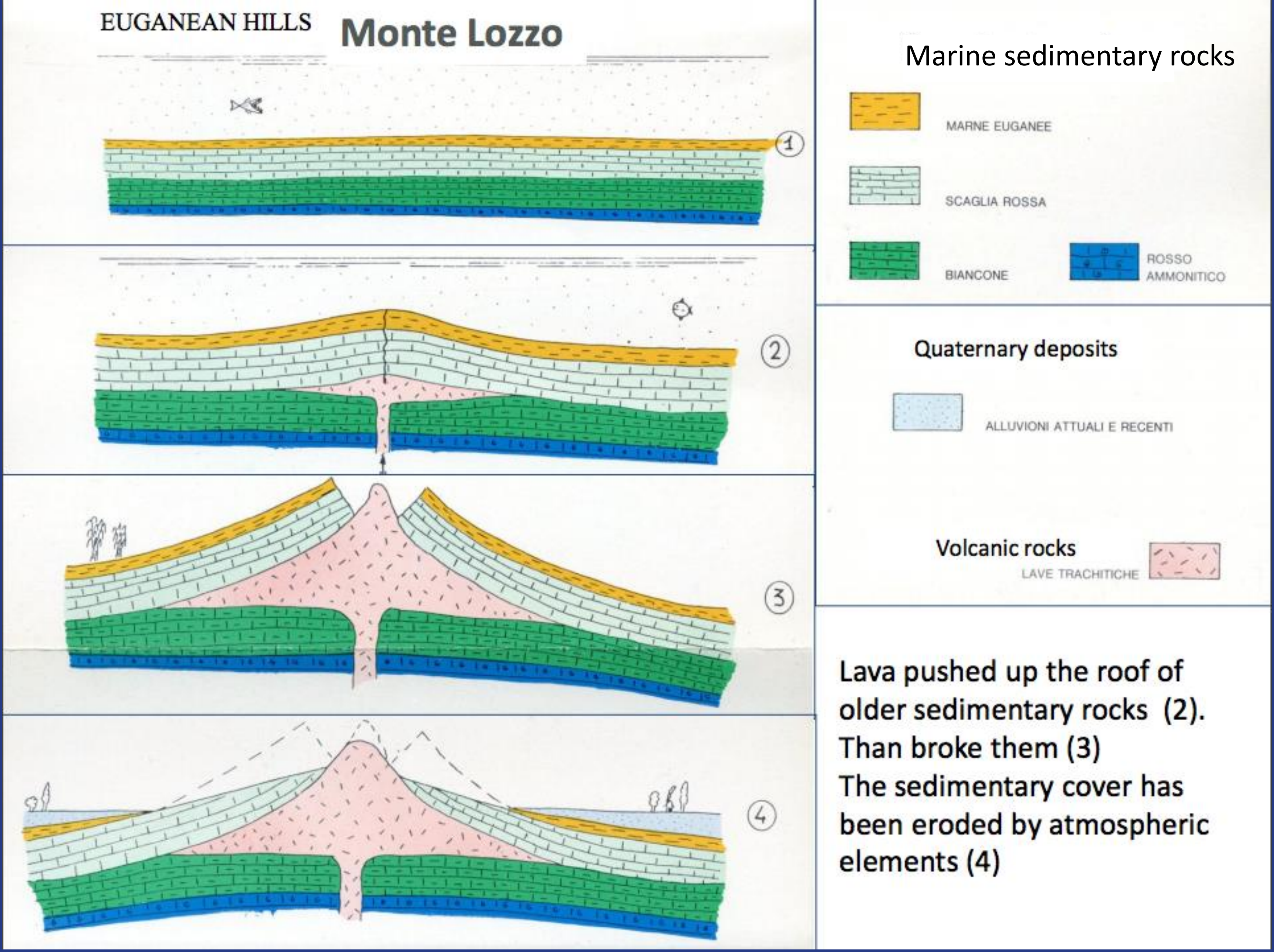


Geological map of the Henry Mountains region, Utah, showing the laccoliths (in red)


Mt Hillers
Mount Ellen
Jukes Butte
Nazer Canyon
Birch Creek
Oak Creek
Table Mountain



Fence diagram showing the geometry of the intrusions in Mount Pennell, Henry Mountains, Utah, USA (from Hunt et al., 1953)



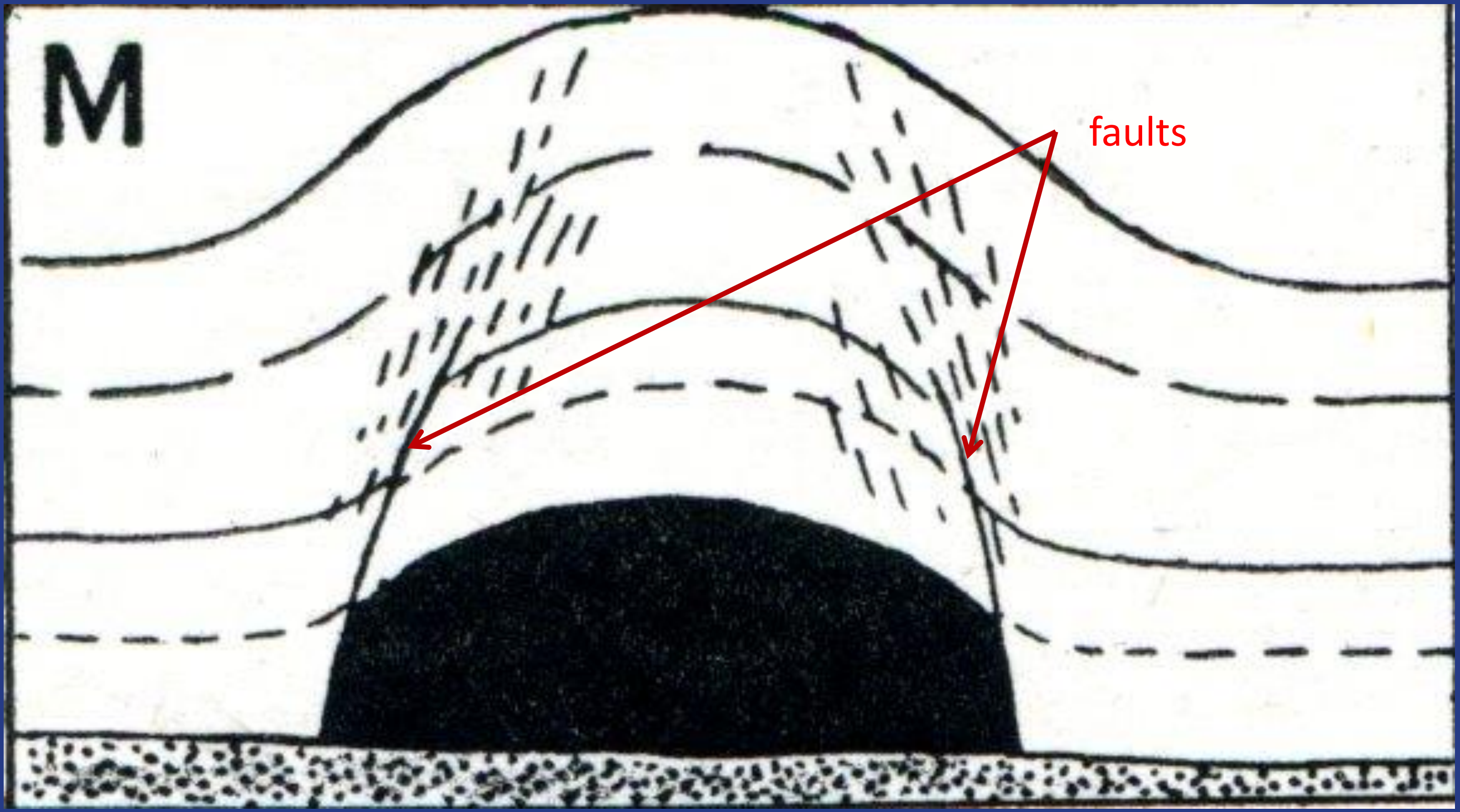
Lava pushed up the roof of older sedimentary rocks (2).
Than broke them (3)
The sedimentary cover has been eroded by atmospheric elements (4)

A laccolith from Europe: Monte Lozzo in the Euganean Hills, northern Italy

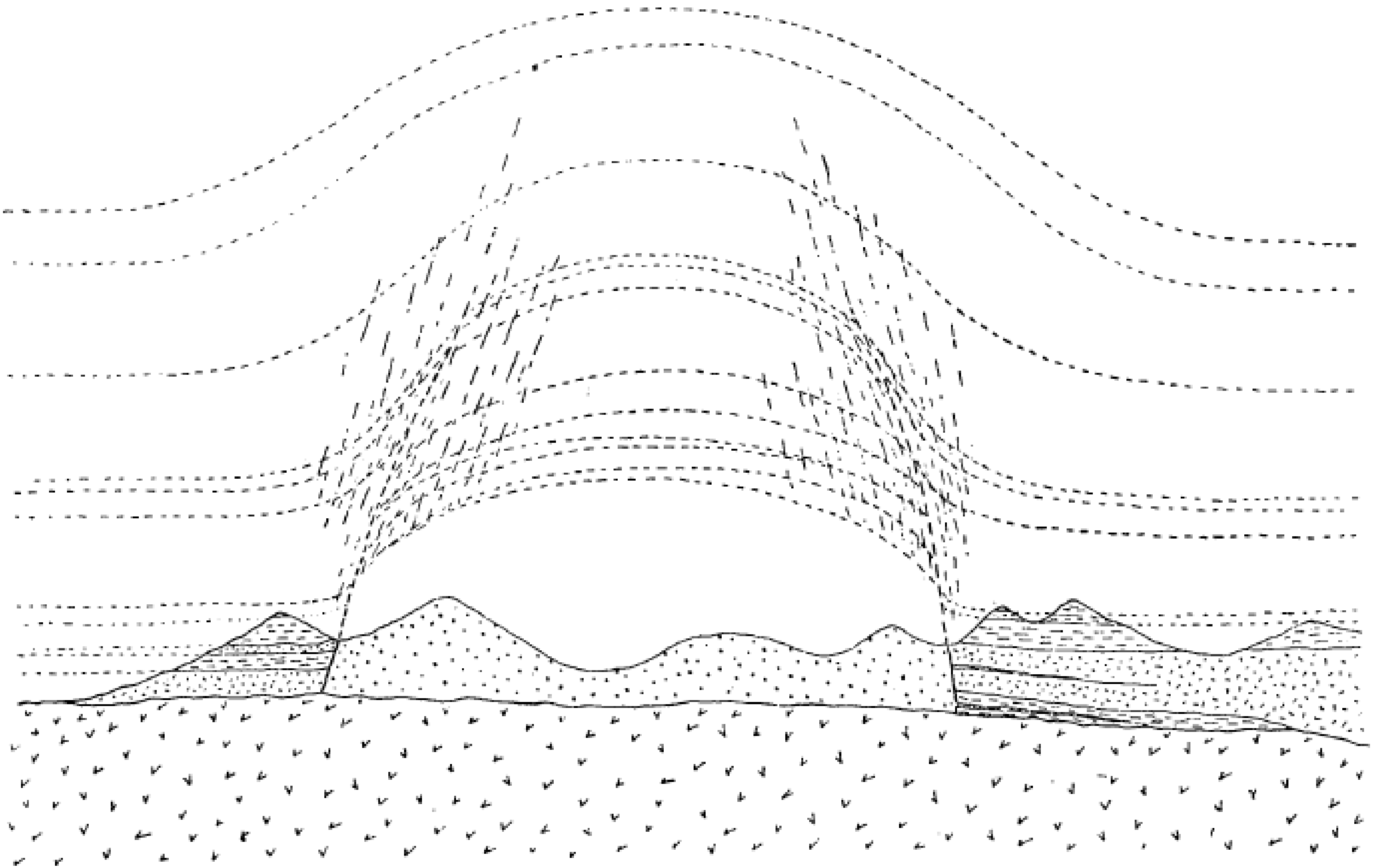
Monte Lozzo in the Euganean Hills, northern Italy

The Traprain Law, a 320 million-year old laccolith from Scotland.

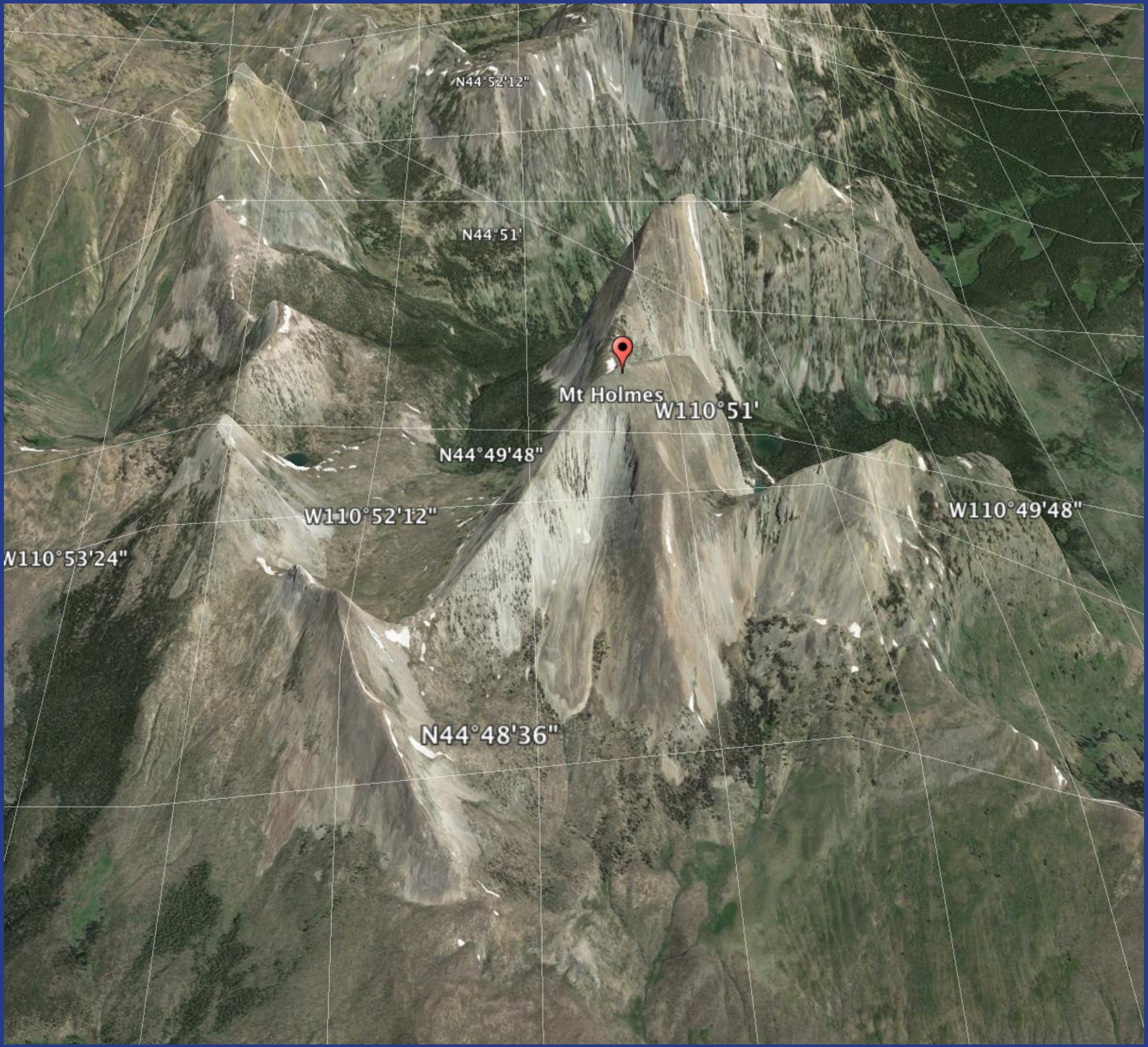
Traprain Law, seen from the north.



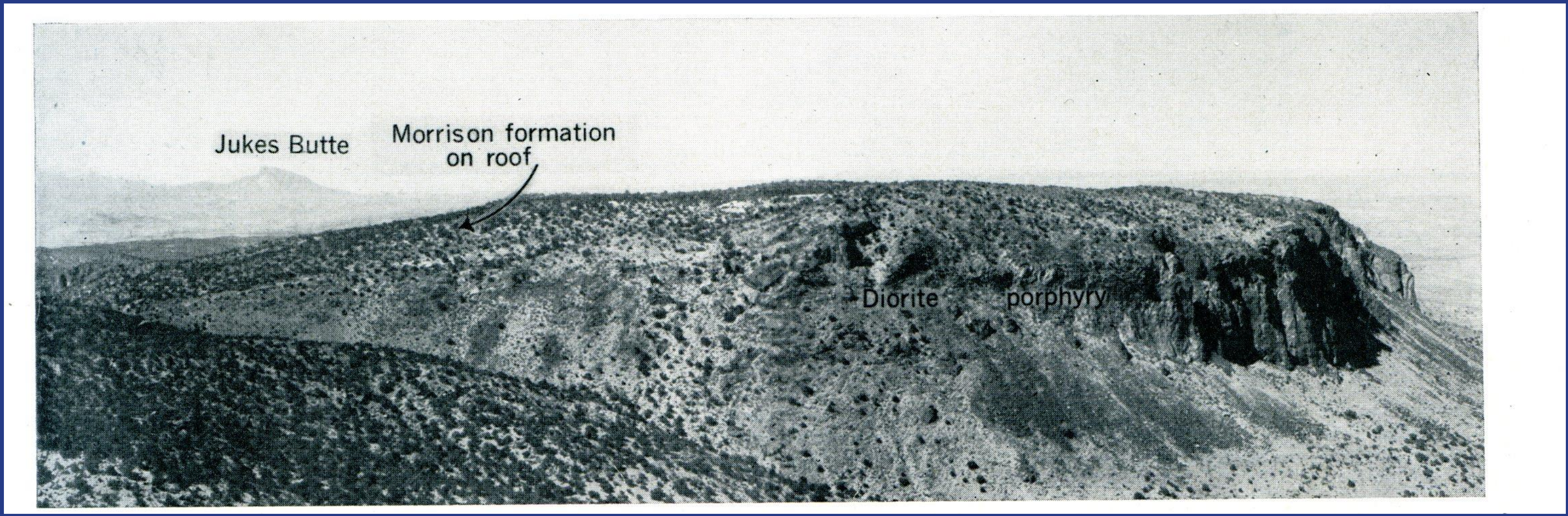
The term bysmalith was proposed by Iddings in 1898 for a more-or-less cylindrical body of igneous rock that forcefully injected and pushed like a piston the overlying rock carapace. It was derived from the Greek βύσμα (*bysma*=plug) and λίθος (*lithos*=stone)



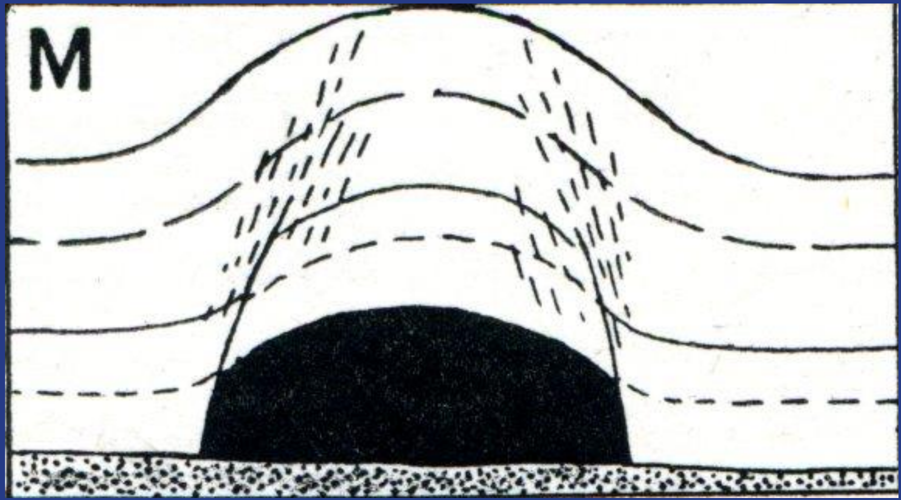
The Mt. Holmes dacite porphyry bysmalith
according to Iddings 1898.



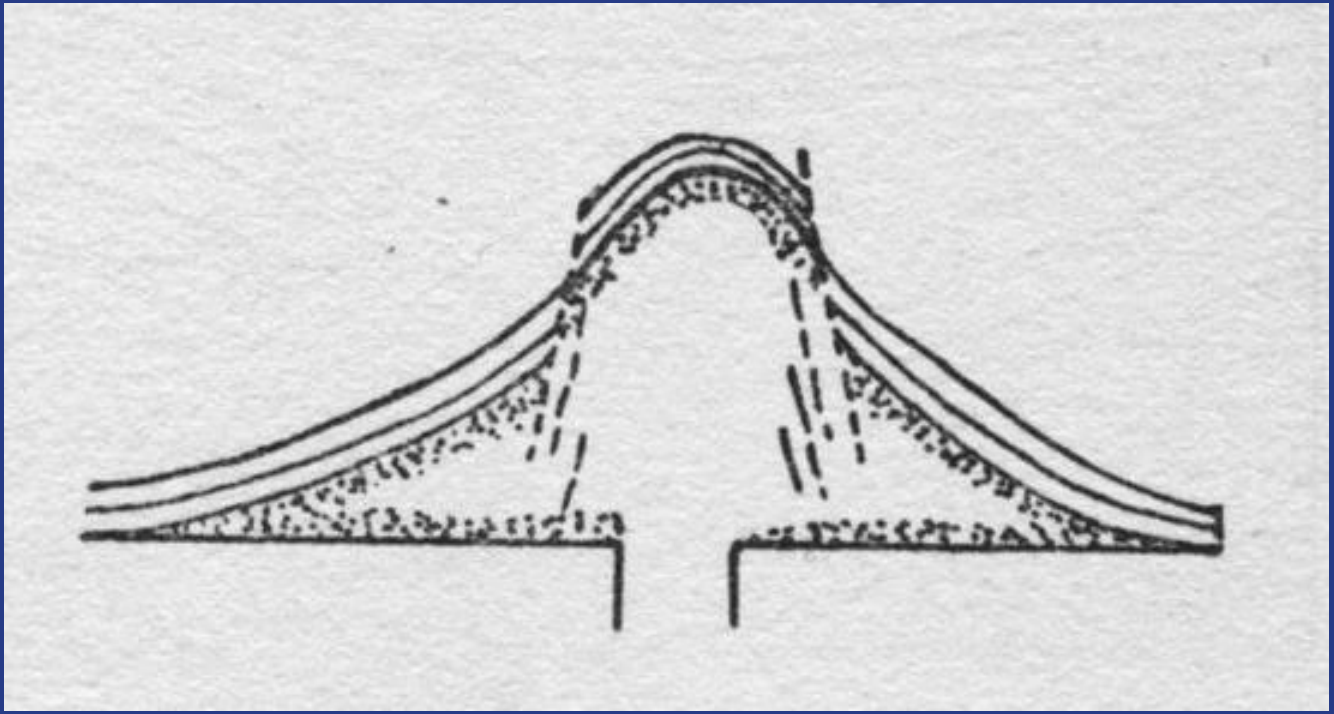
The Mt. Holmes dacite porphyry bysmalith, Yellowstone National Park, Wyoming, USA



View across the Black Mesa on Mt. Hillers; Mt. Hillers diorite porphyry is a bysmalith.



The Table Mountain Bysmalith, Henry Mountains, Utah, USA



The great British petrologist George Walter Tyrell considered bysmaliths as faulted forms of laccoliths. Some of the occurrences in the Henry Mountains, such as the bysmalith of the Table Mountain, seem to support his view.

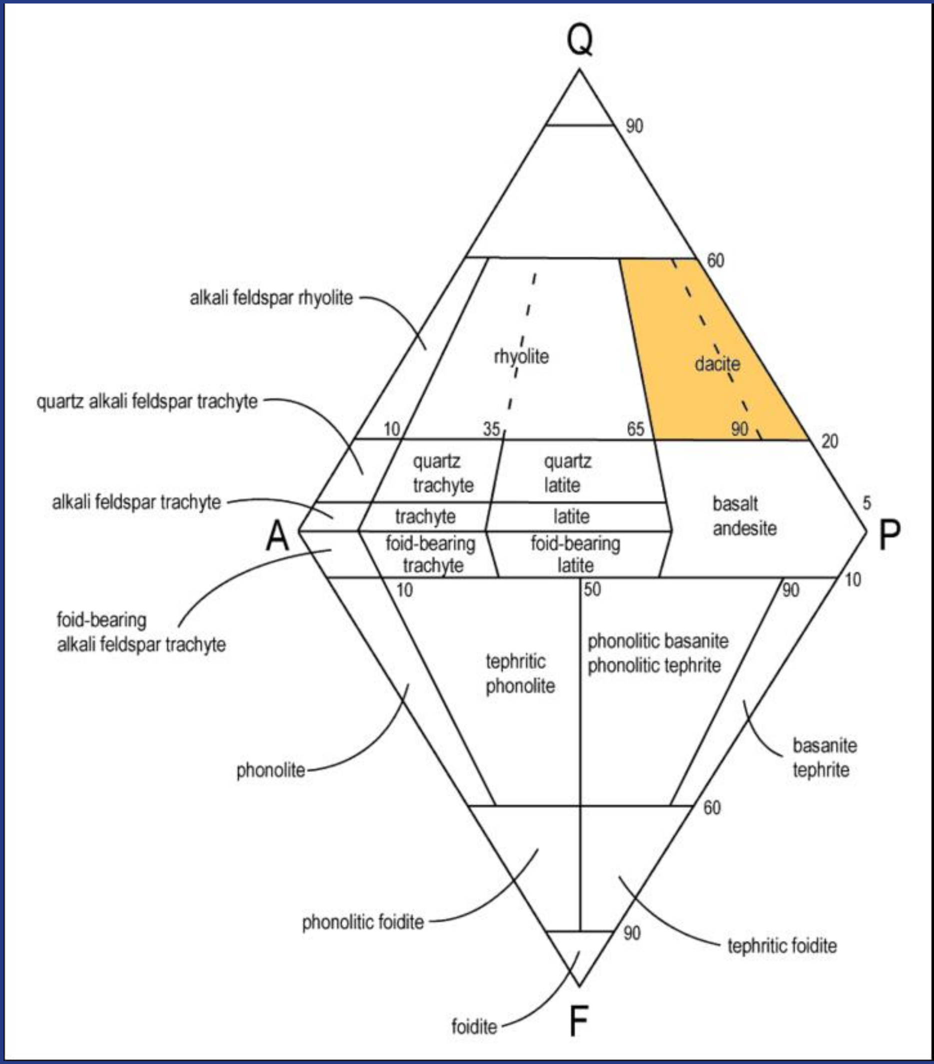
This schematic section is from Tyrell 1929.

Here we encountered two new words: one, a rock type, dacite, and the other a structure, fault.

We need to learn what they are:

Dacite, also called a quartz andesite, is a volcanic rock with aphanitic to porphyritic texture and with a composition between an andesite and a rhyolite. The rock may have up to 80 % plagioclase, up to 40 % quartz, 25% alkali feldspars.

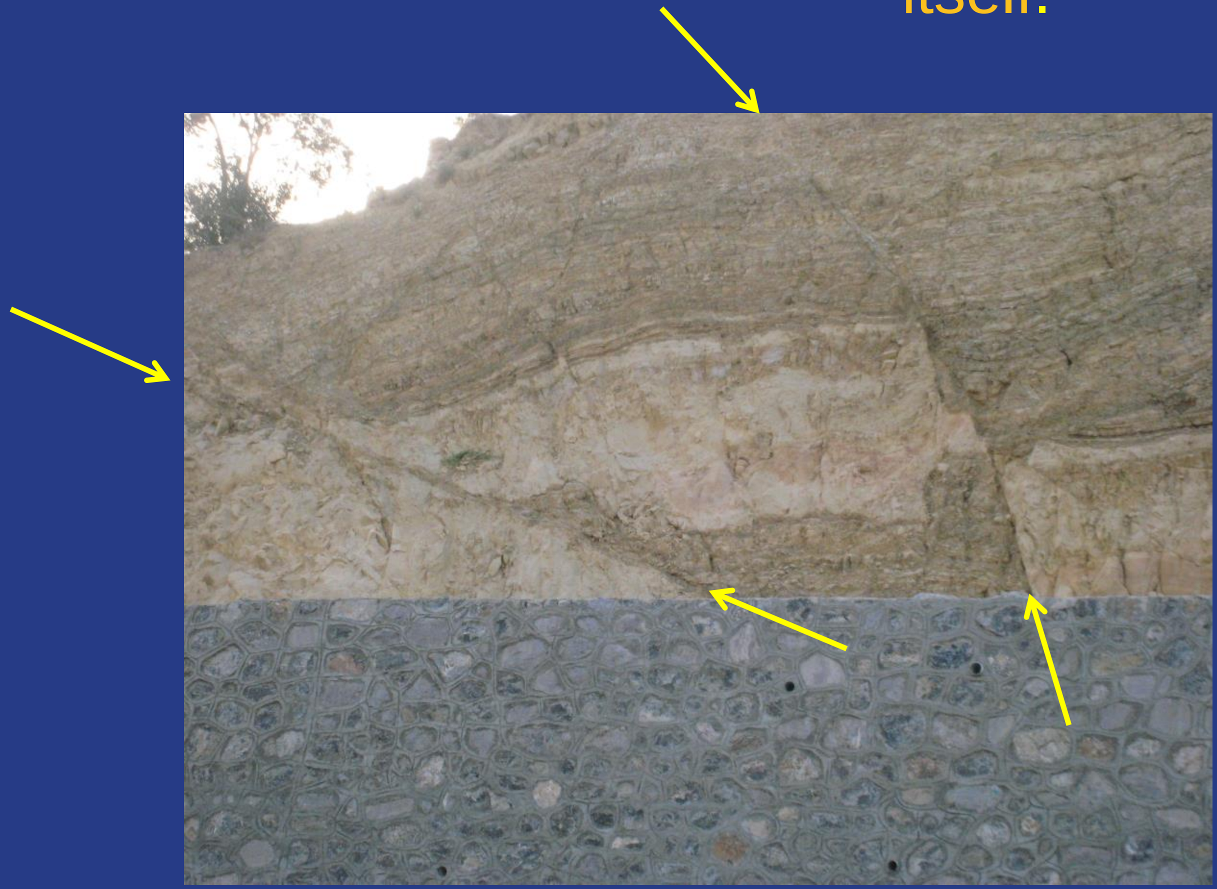
The name dacite comes from the ancient Roman province of Dacia, now western Romania, and was proposed in 1863 by the Austrian geologists Franz Ritter von Hauer and Guido Stache on p. 72 in their book on the geology of Transylvania (=Siebenbürgen)



Black dacite, locality unknown (from https://liftingshadows.wordpress.com/2008/03/)

Dacite porphyry with phenocrysts of gray plagioclase. It also contains small to medium size black hornblende crystals. The matrix consists chiefly of a very fine-grained quartz-feldspar intergrowth and scattered patches of wispy biotite. This sample is about 9 cm across

A fault is any planar or curviplanar break in rocks along which movement has happened parallel with the break itself.

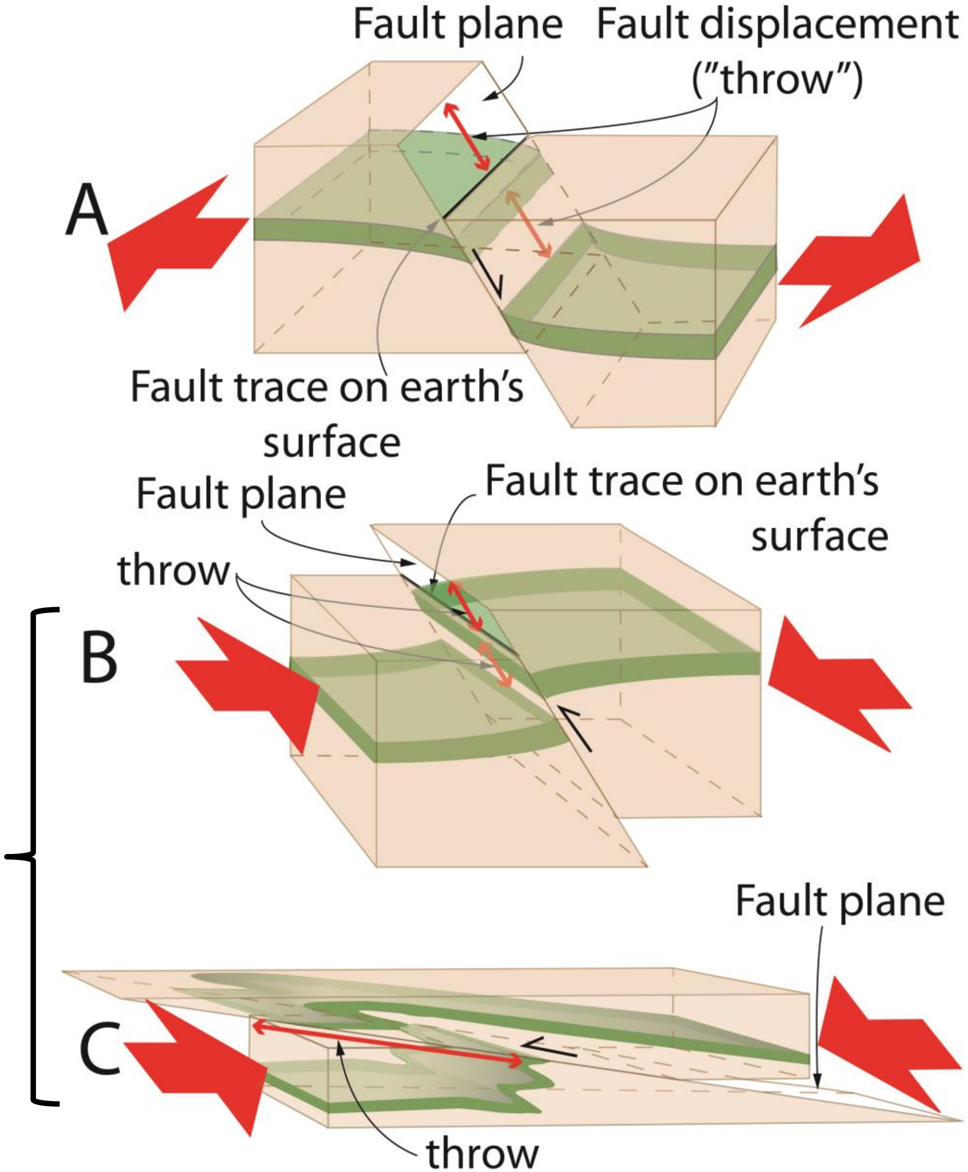


Mesoscopic scale faults near Burhaniye, western Turkey

The Owens Valley earthquake fault, 1872, California, USA

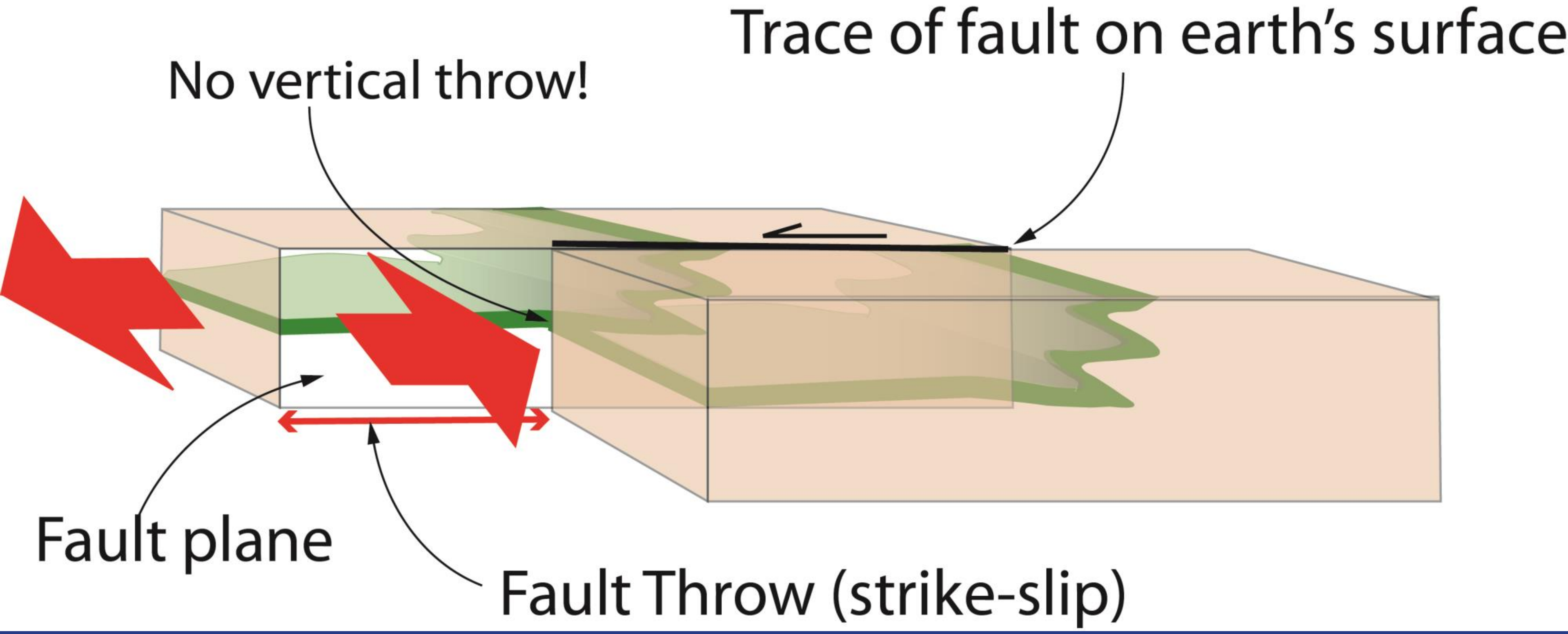
The famous Glarus thrust fault, Switzerland

Normal dip-slip fault



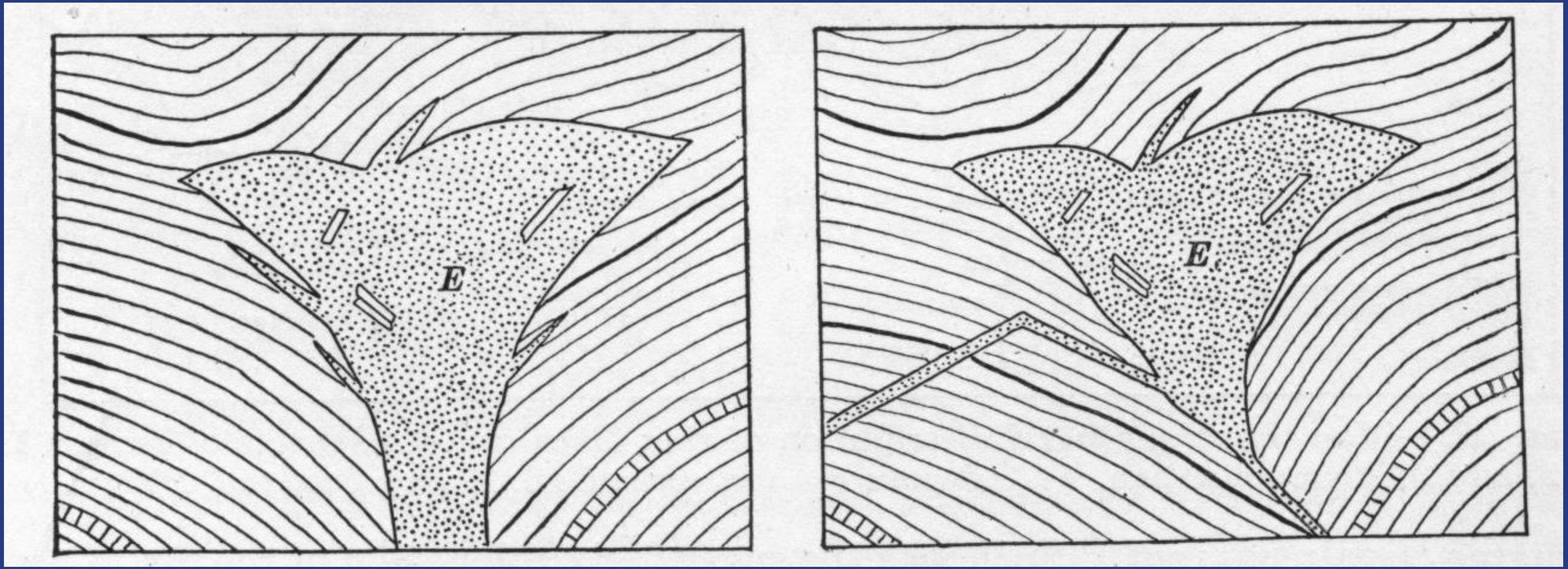
Reverse dip-slip fault

Kinds of dip-slip faults

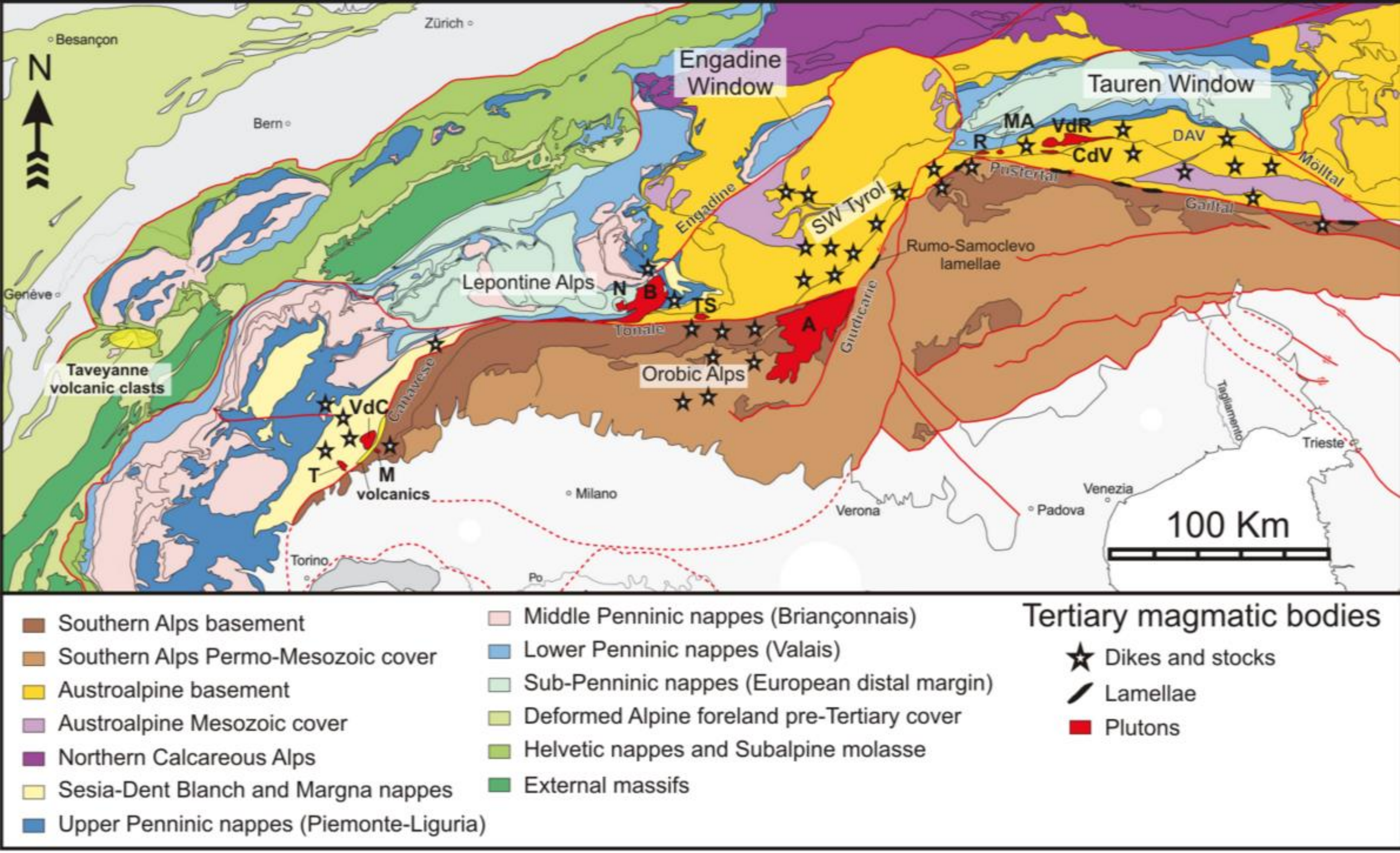


Strike-slip fault

Etmolith: Ethmolith is a funnel-shaped discordant intrusion . The term comes from the Greek ἠθμός (*ethmos*=strainer) and was proposed for the large Adamello intrusion in the Southern Alps by Wilhelm Salomon in 1903.



Ethmolith as proposed by Salomon in 1903 with two variants of its possible stem geometry.



A is the Adamello ethmolith

Monte Adamello, Southern Alps, northern Italy

Outcrops of the Adamello granite (=adamellite) ethmolith, southern Alps, northern Italy

Granite, Baveno, Italy.