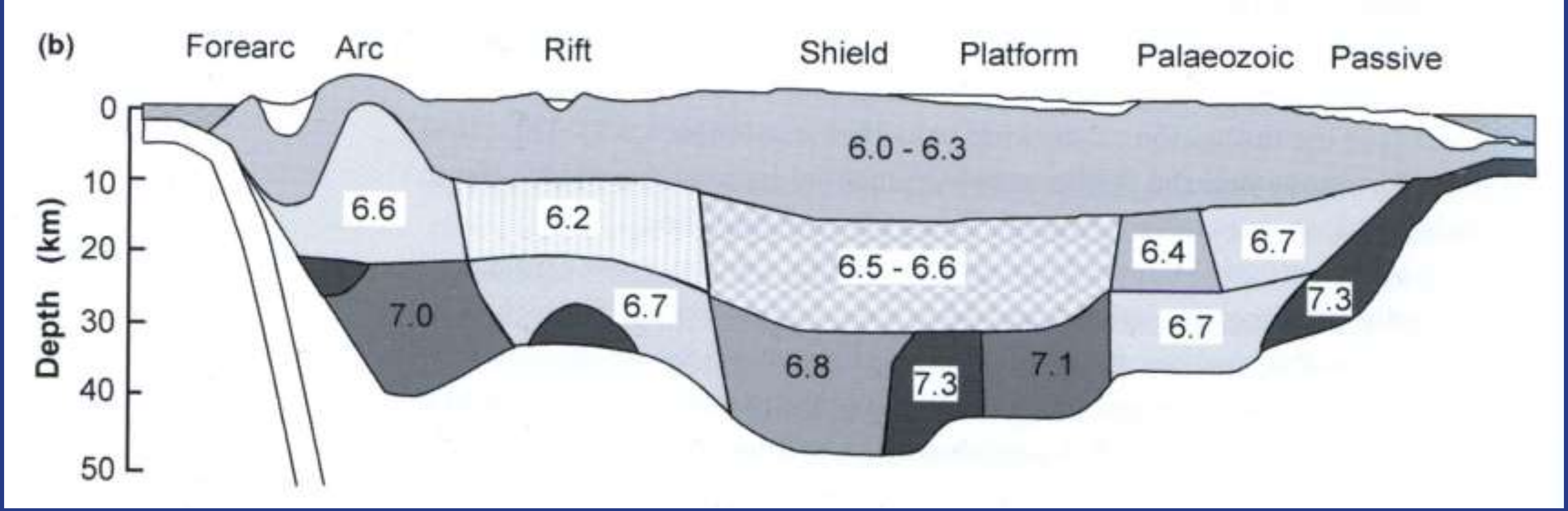


Distribution of velocities of longitudinal body waves (P waves) in an "ideal" continental crust. The numbers have the unit kilometre/second (km/s).

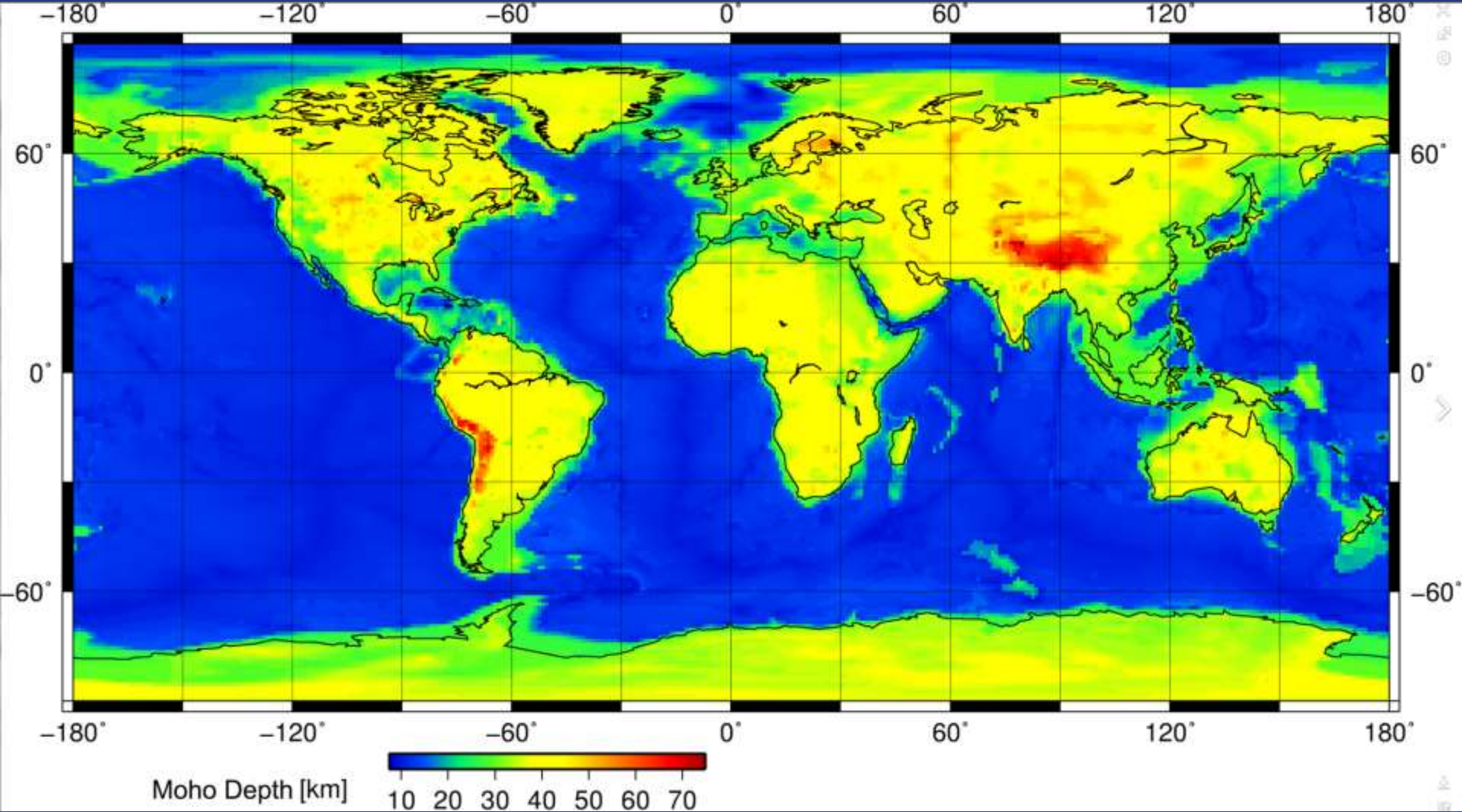
These velocities are related to the density of the rock in which the waves travel through the following equation:

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

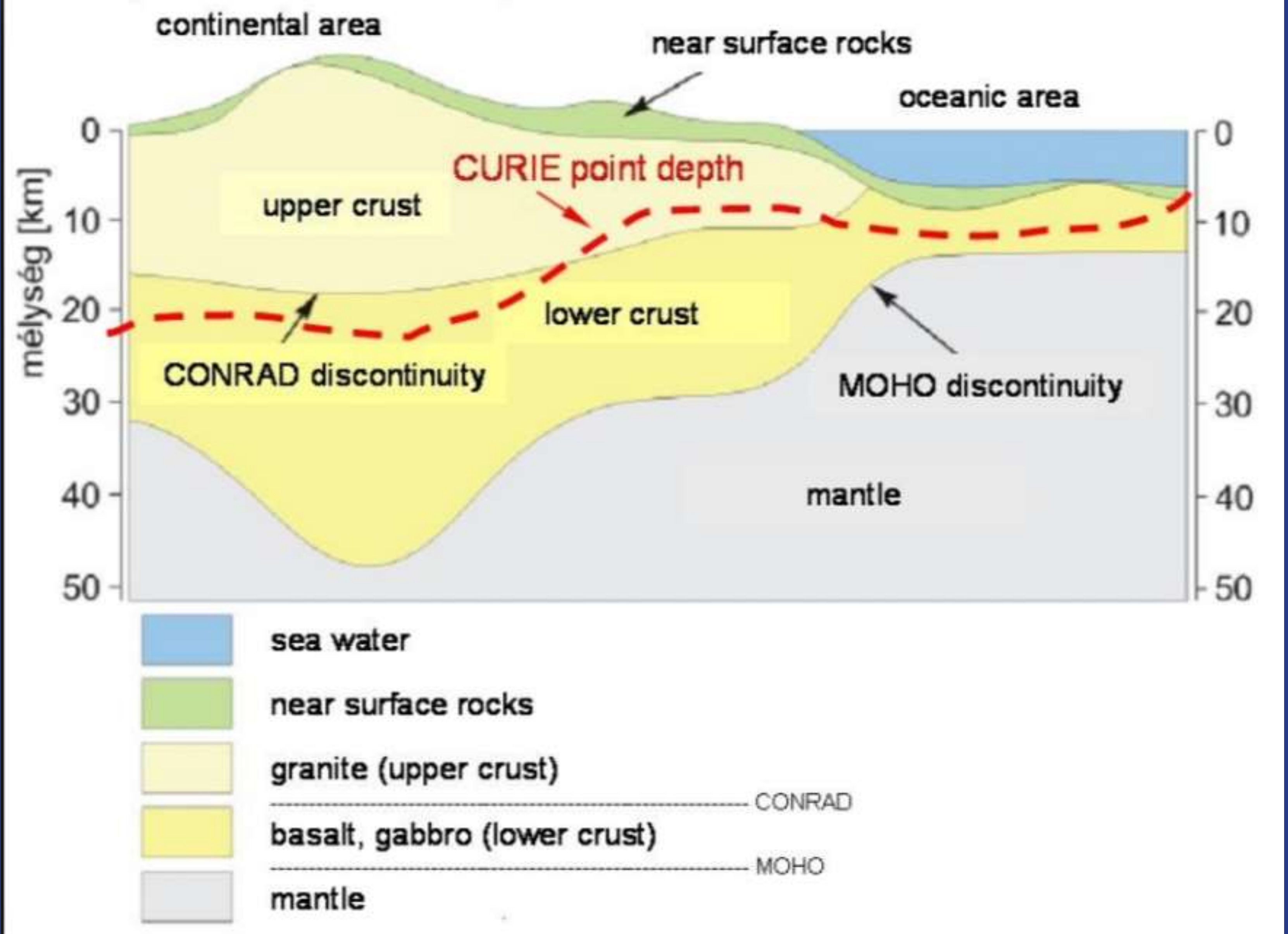
Where k is the modulus of incompressibility, μ is the shear modulus and ρ is density

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

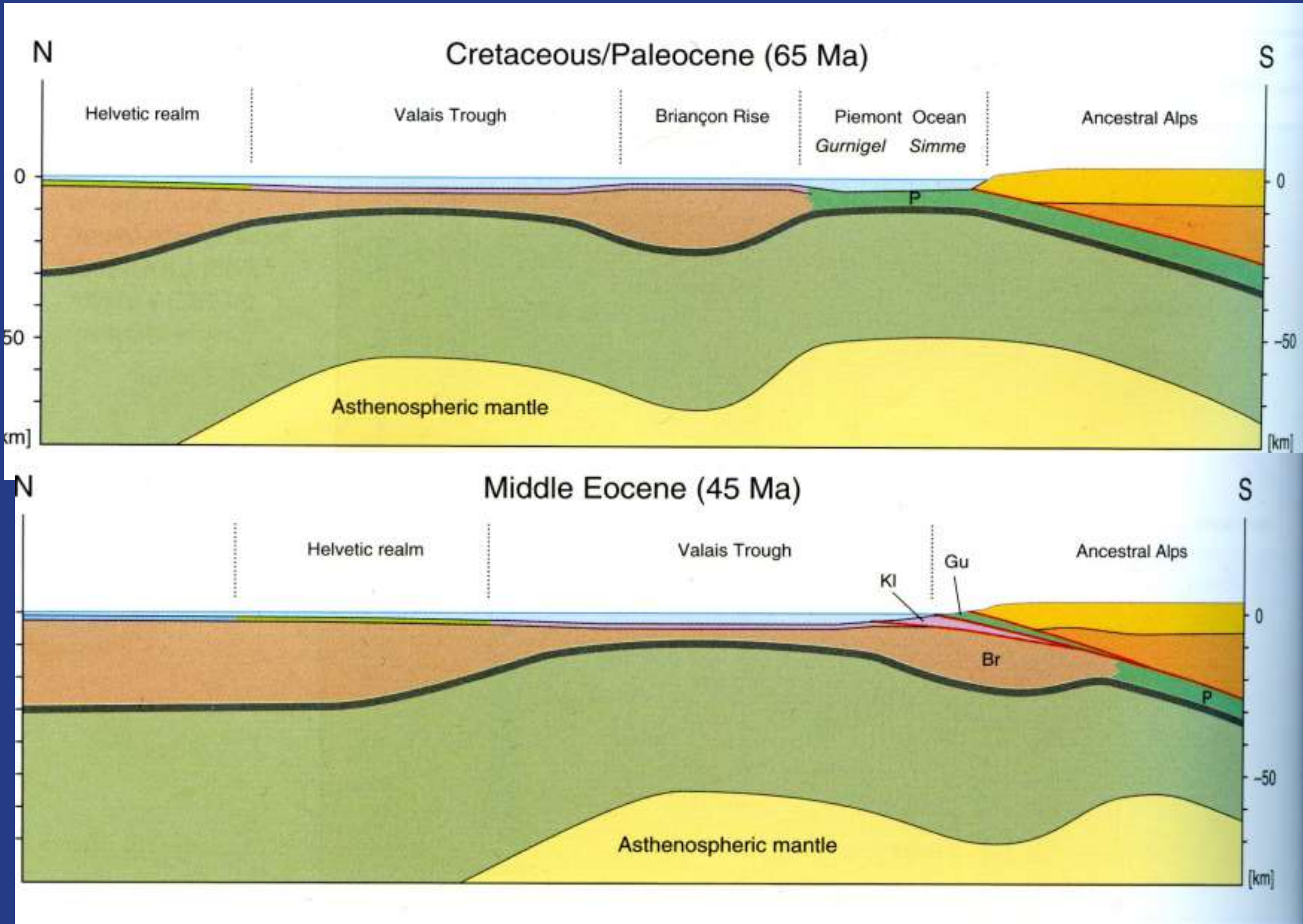


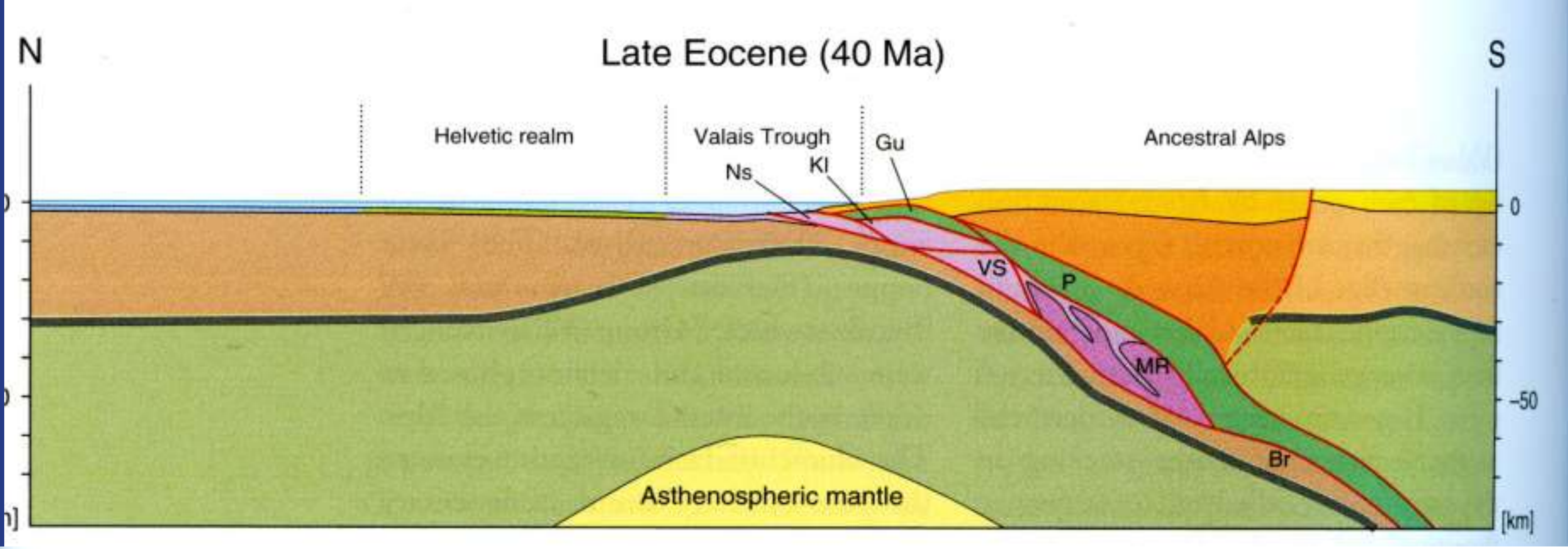
Map showing the Moho depth on earth. The Moho discontinuity marks the bottom of the earth's crust (both in the continents and in the oceans. Above it the seismic velocities reach values as high as 6.7 to 7.2 (basalt and gabbro) and immediately below it they reach 7.6 to 8.6 (peridotite). Since peridotites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

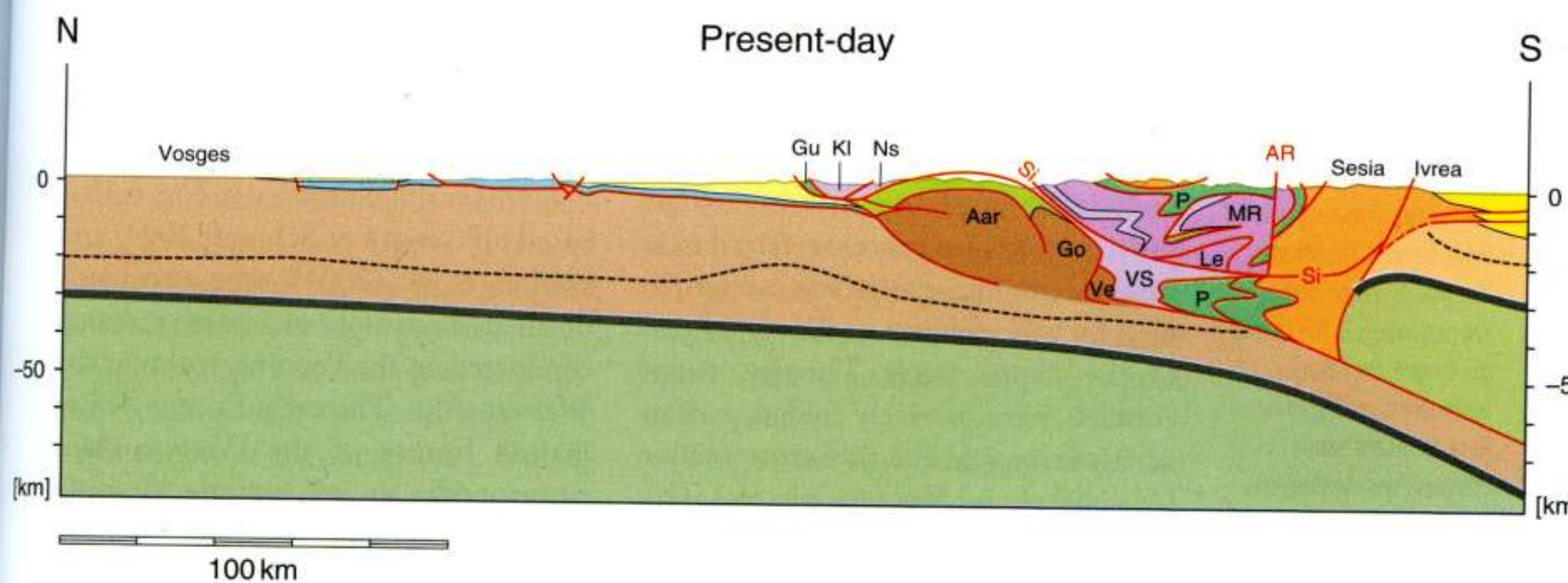


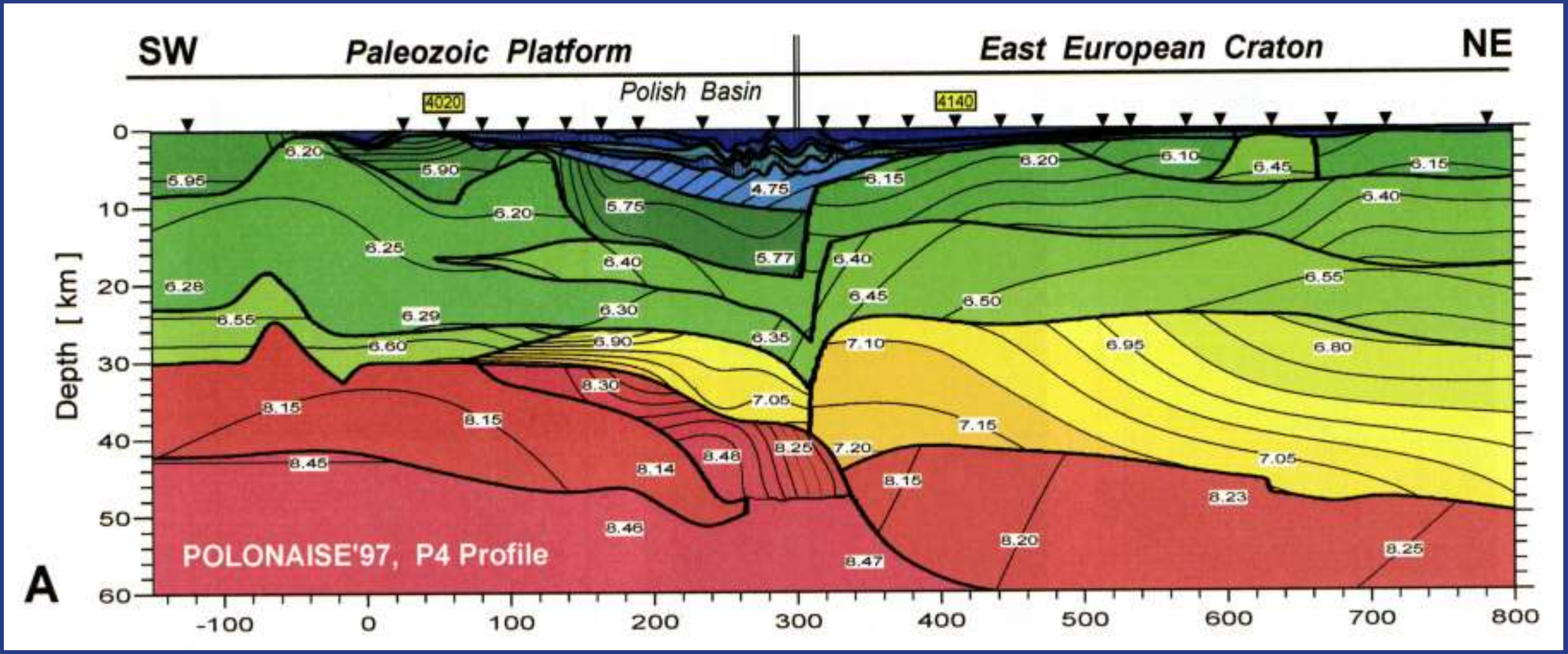
Schematic cross-section showing the Conrad discontinuity, across which the seismic velocities increase from “granite” velocities to “basalt” velocities.

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:

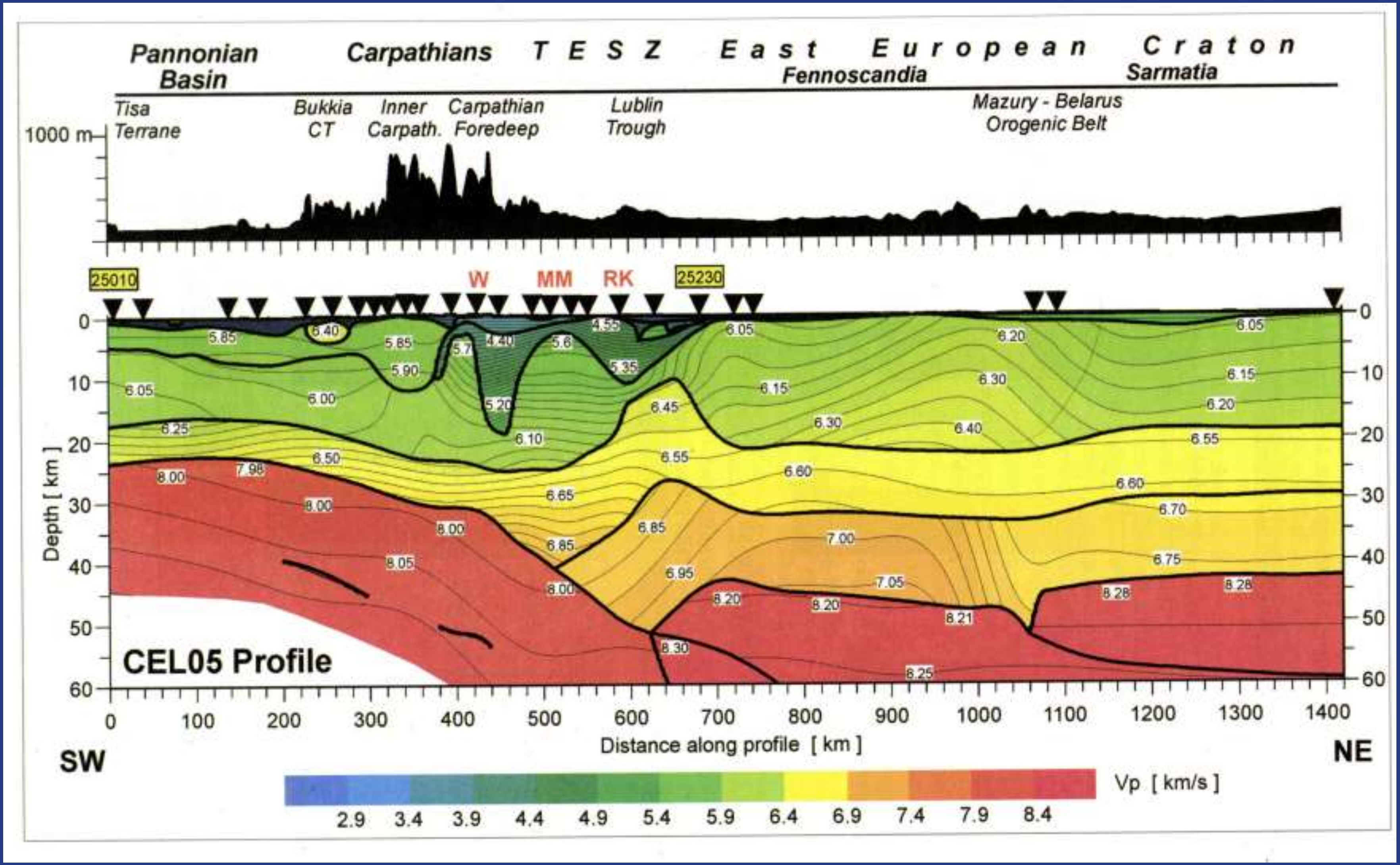



N
Late Eocene (40 Ma)
S
Helvetic realm
Valais Trough
Gu
Ancestral Alps
Ns
Kl
VS
P
MR
Br
Asthenospheric mantle
0
-50
[km]


N
Present-day
S
Vosges
Gu
Kl
Ns
Si
AR
Sesia
Ivrea
Aar
Go
Ve
VS
P
MR
Le
Si
0
-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

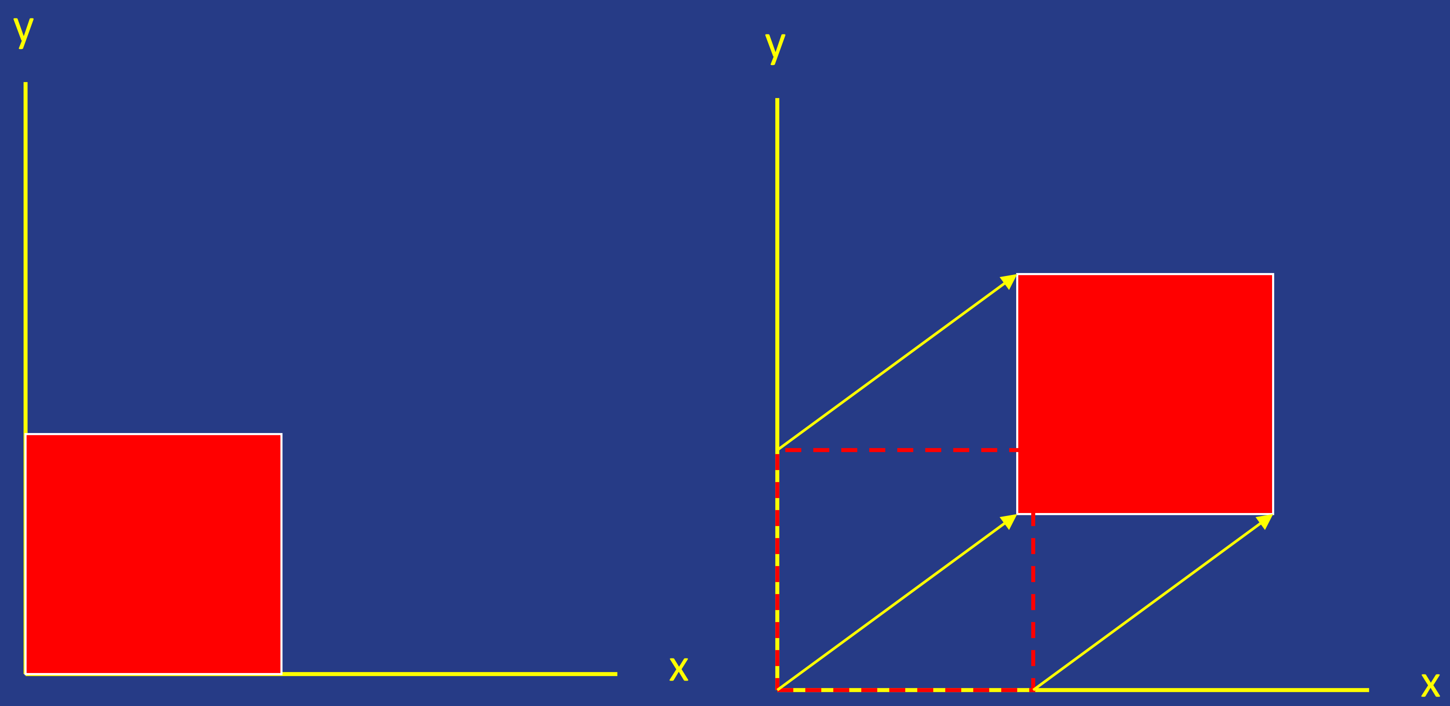
The mechanical behaviour of the continental crust, i.e. its reaction to forces deforming it, is a function of its rheology.

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).

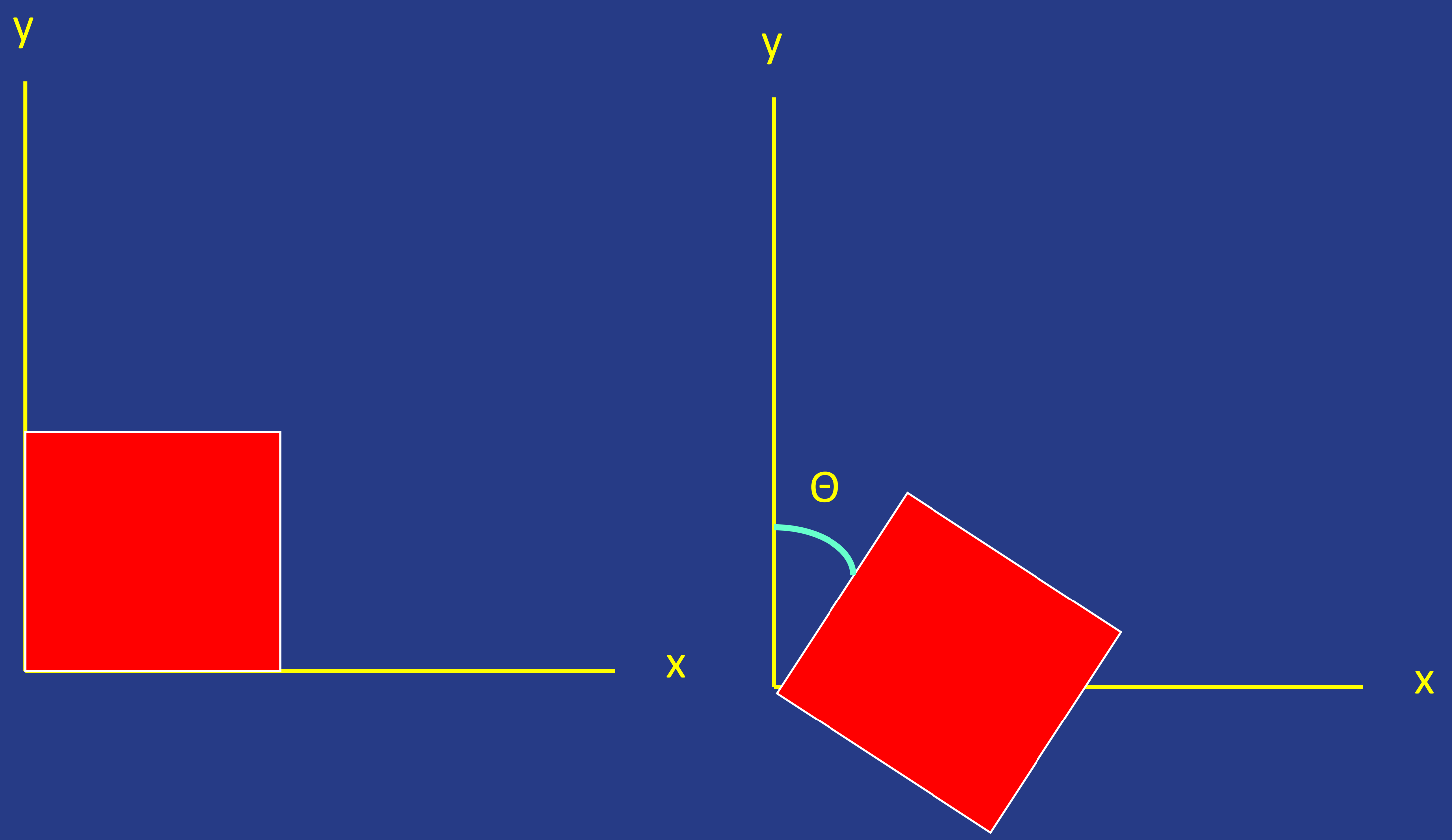
The substances change their location, orientation and shape under applied forces. Those changes are collectively called deformation. Deformation has three components:

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

Change of location involves translation on a plane surface

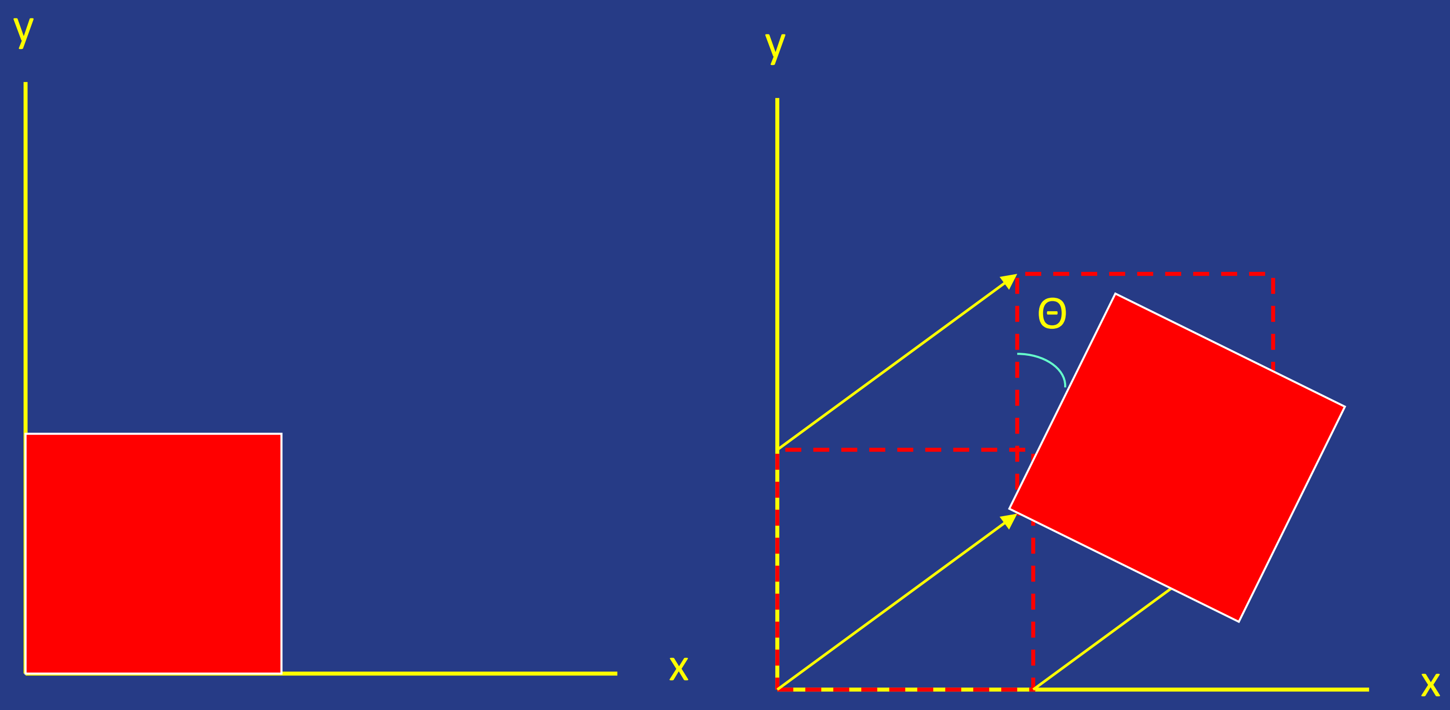


Both change of orientation and location must be measured against an external reference frame:



Change in orientation: Rotation around an angle Θ

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



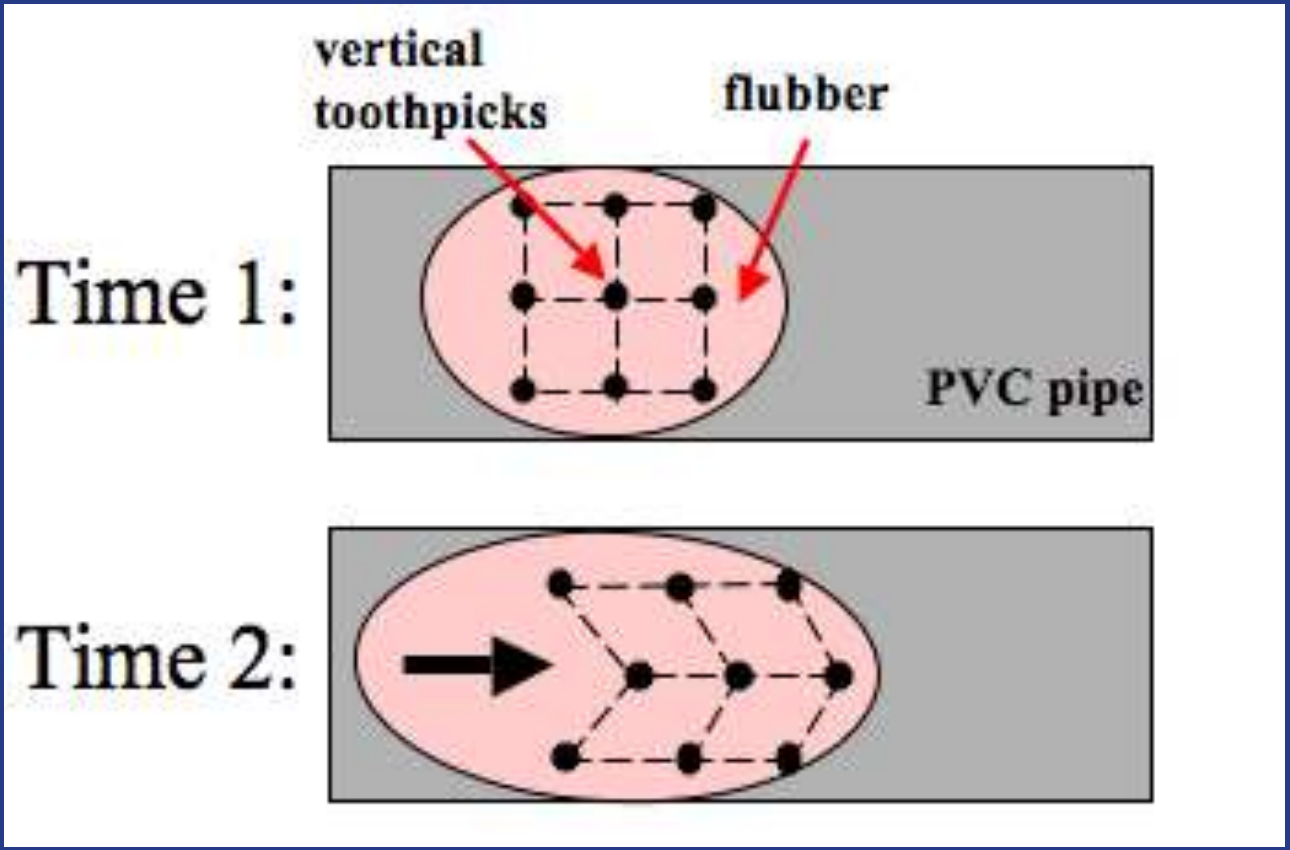
Homework:

Answer the questions:

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

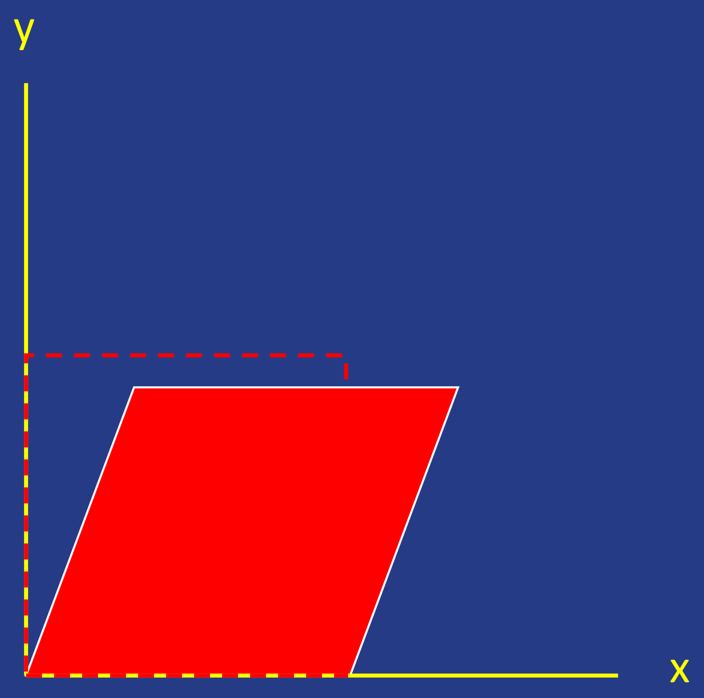
2. How would you describe it mathematically?

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

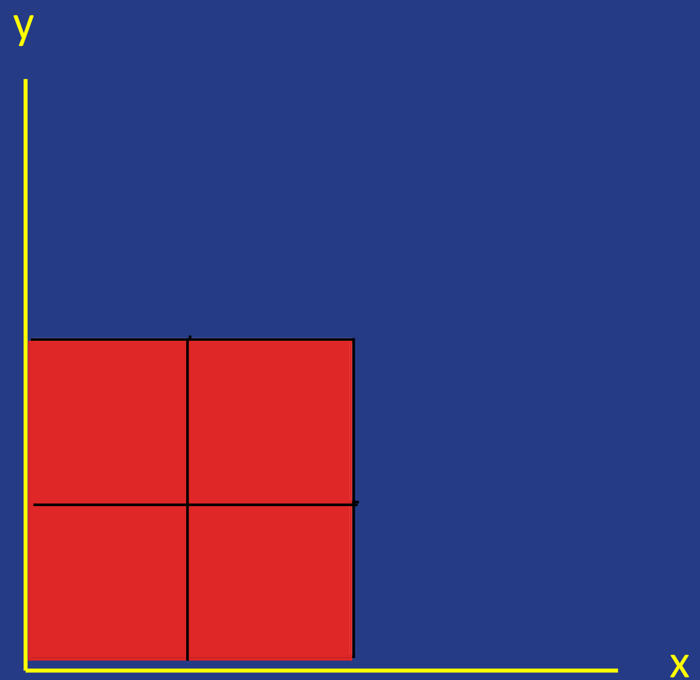


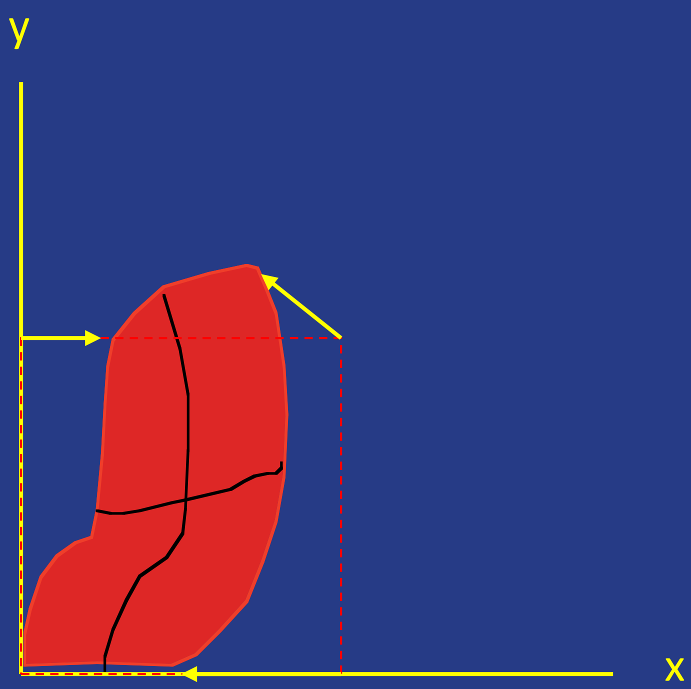
The toothpicks here form an internal reference frame. In time 2, the toothpicks have moved with respect to those of time 1

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.

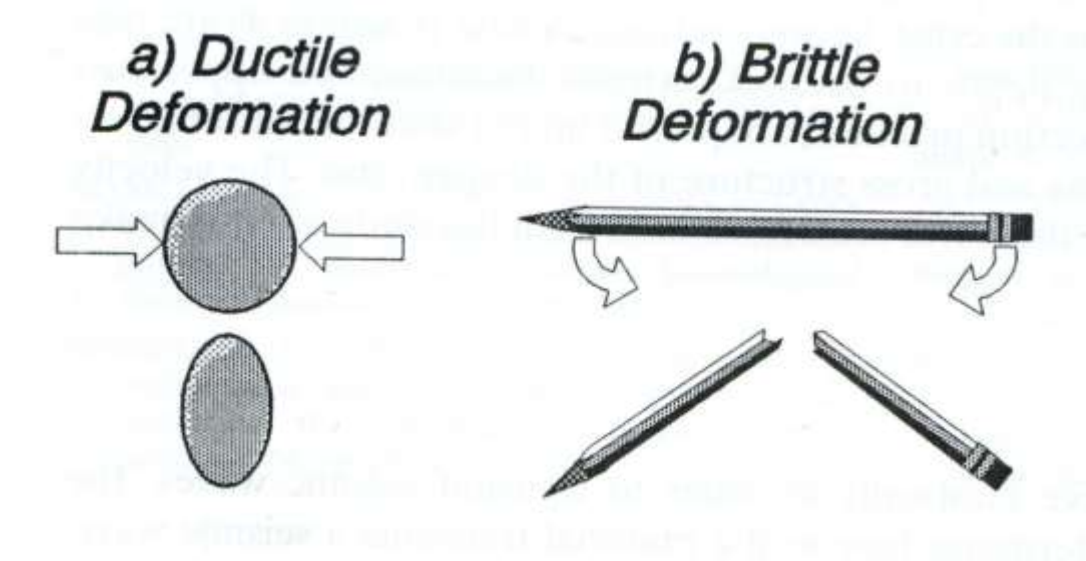
Solids my respond to forces either by breaking (brittle deformation) or by flowing (ductile deformation).

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

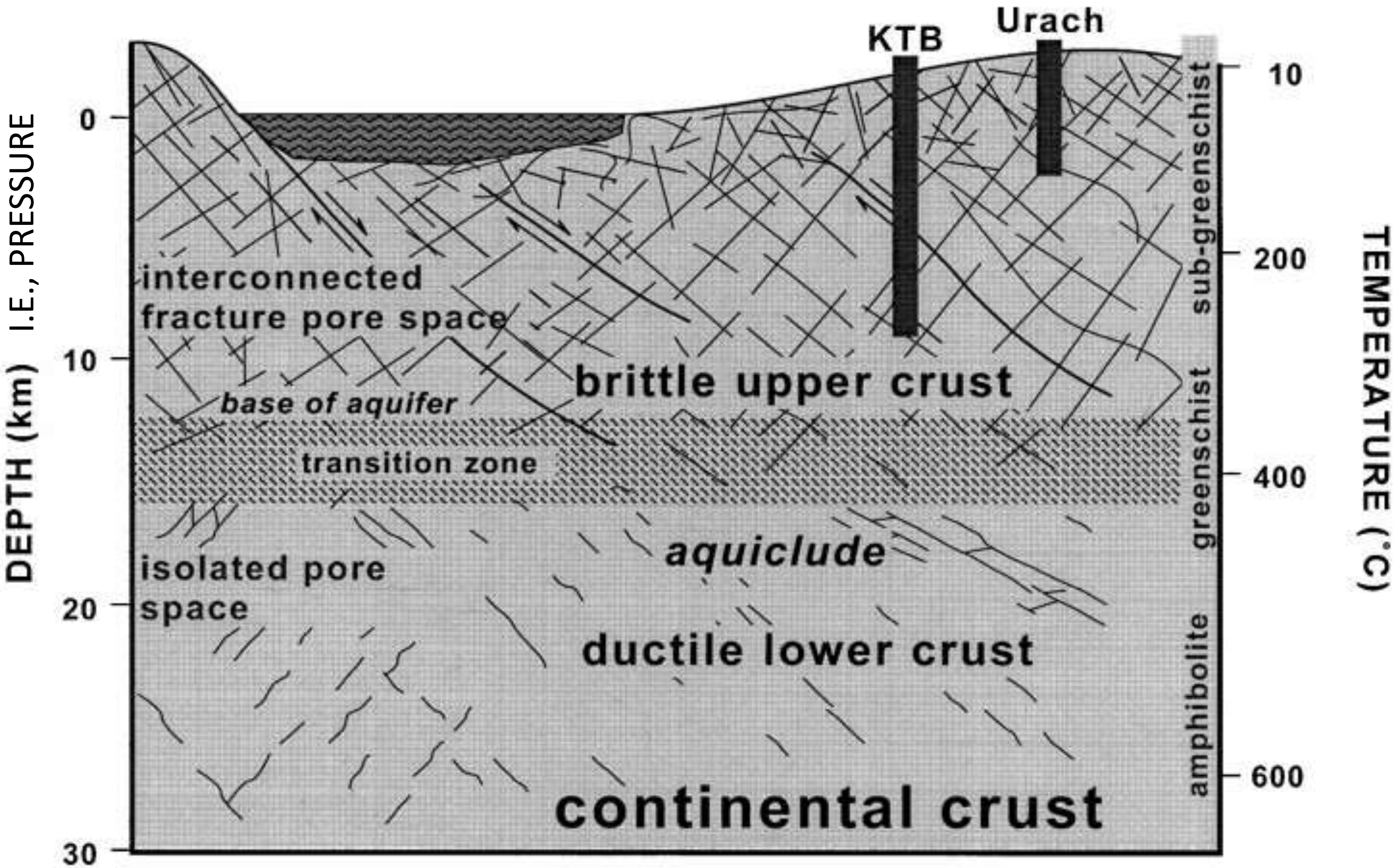
1. Composition

2. Temperature

3. Pressure



4. Strain rate (how fast the deformation occurs)



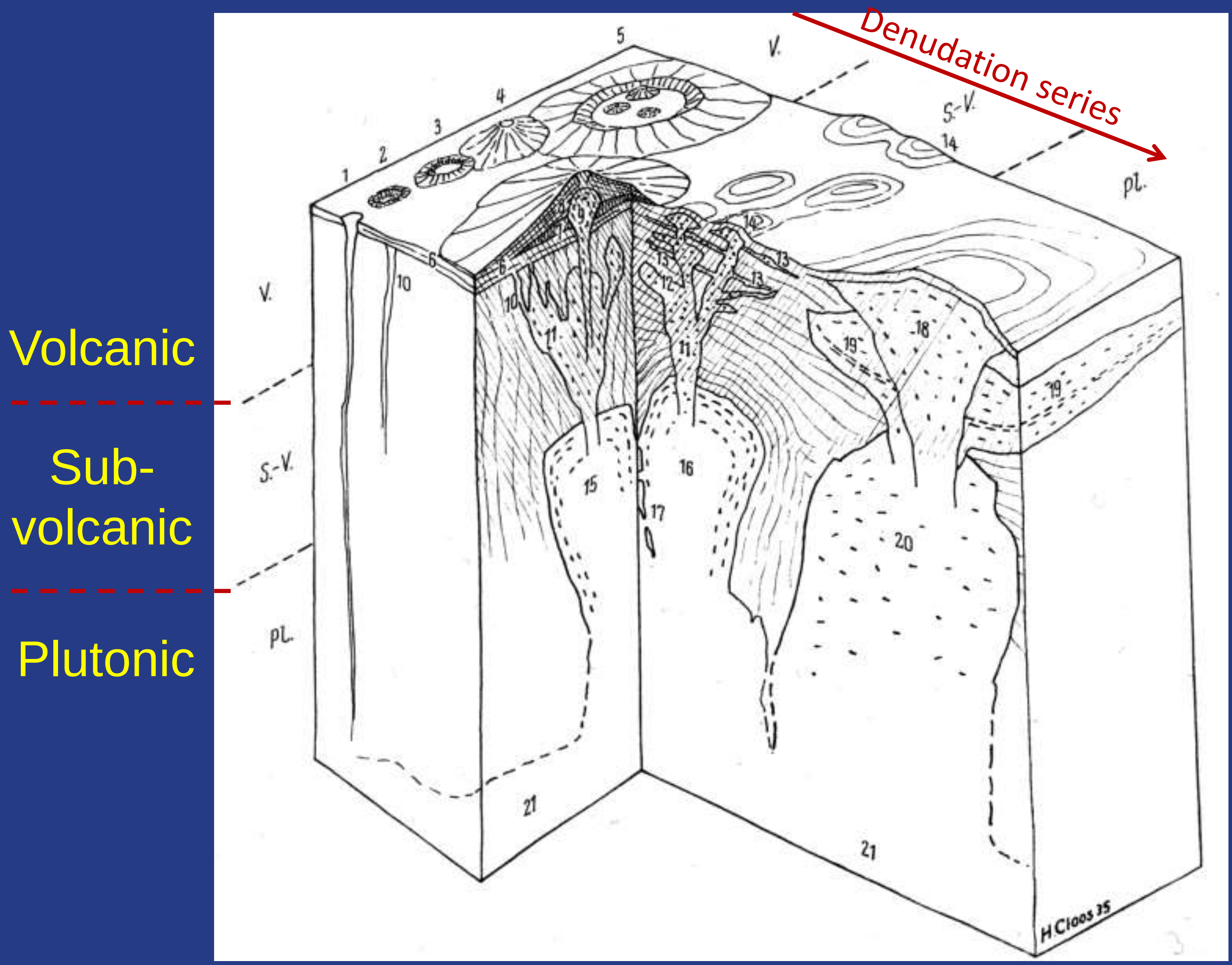
Rheological layering of the continental crust

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

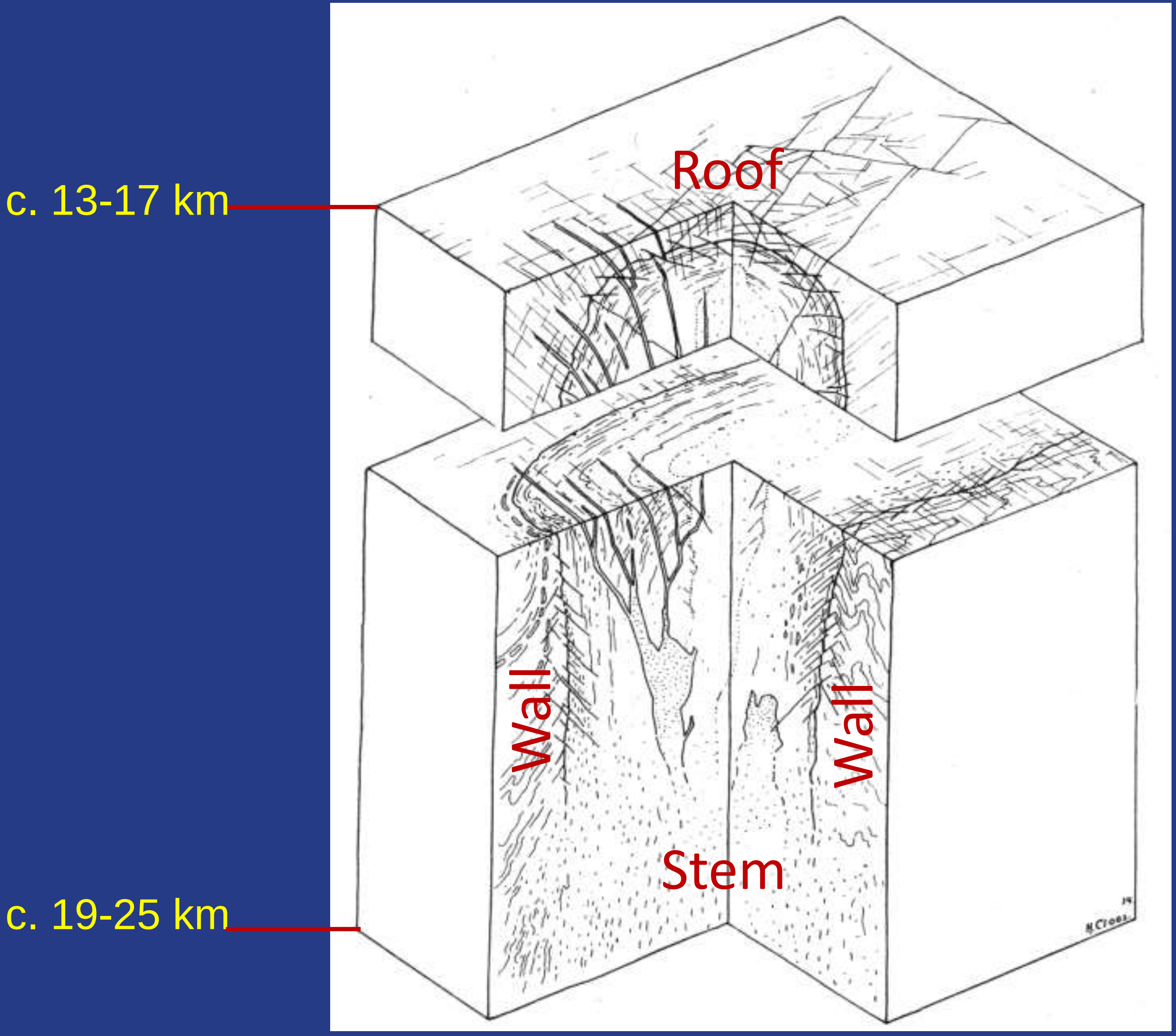
1. Surface igneous rocks (volcanic rocks)

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*).



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

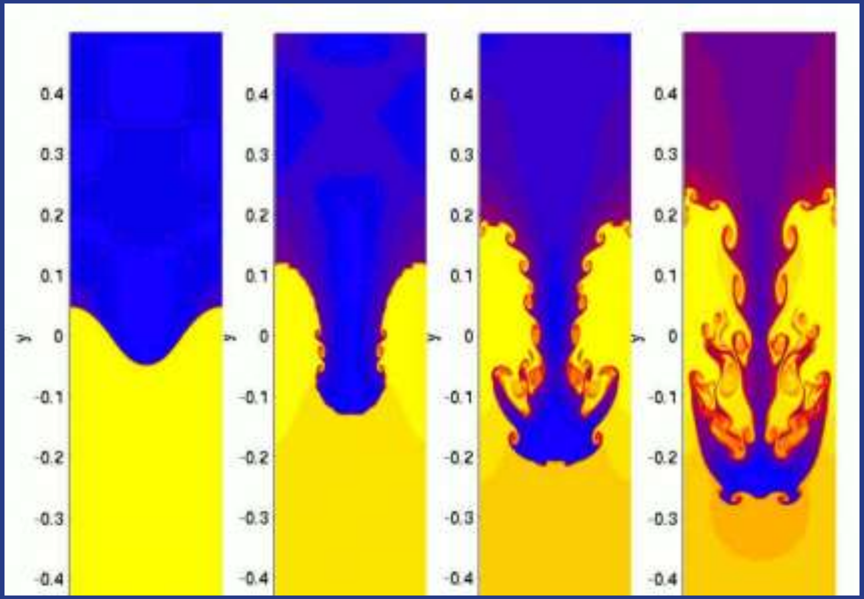


A schematic view of a pluton. Notice the increasingly more brittle nature of the structure as one ascends in the crust. From Cloos 1936.

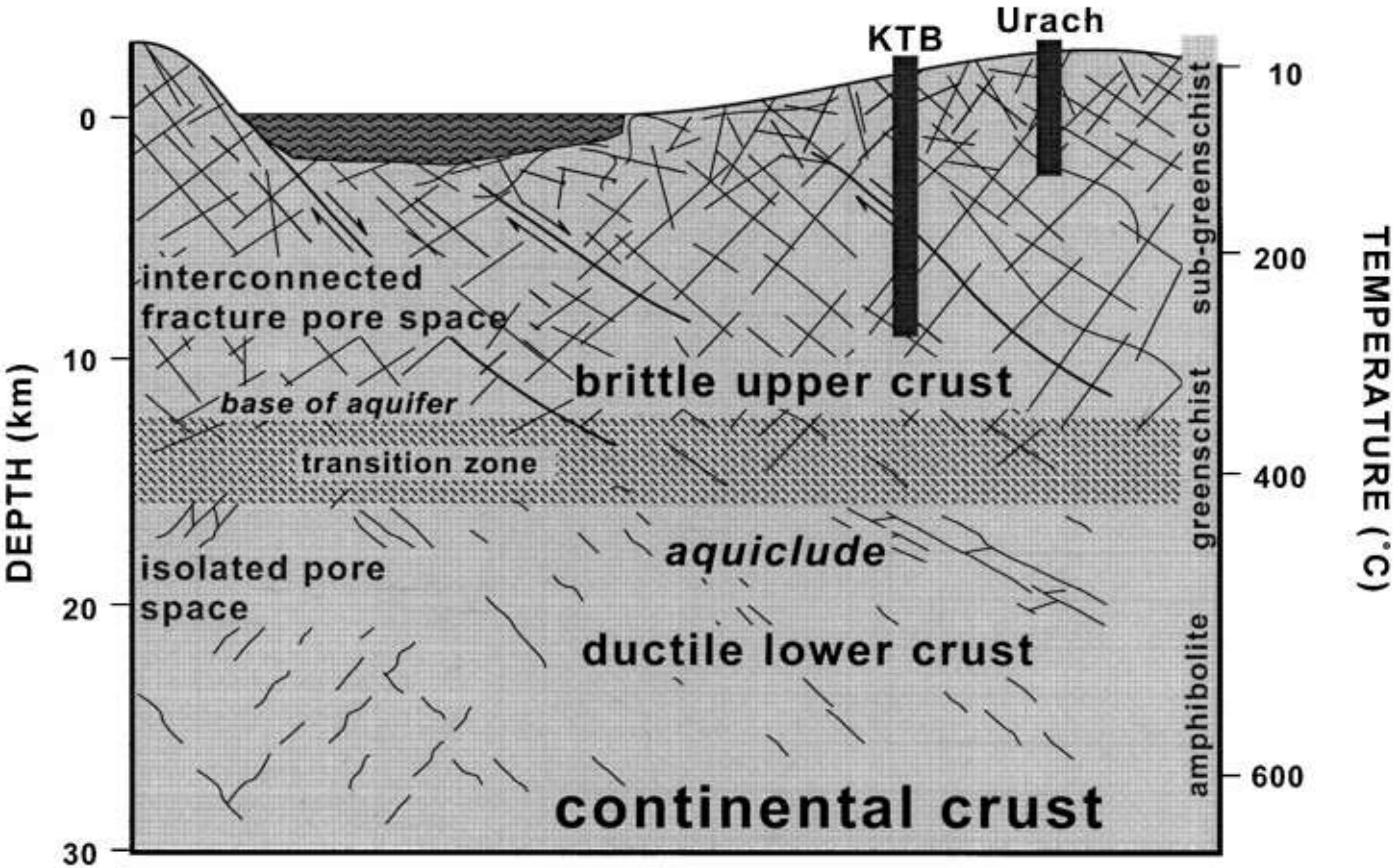
Most plutons rise as diapirs.

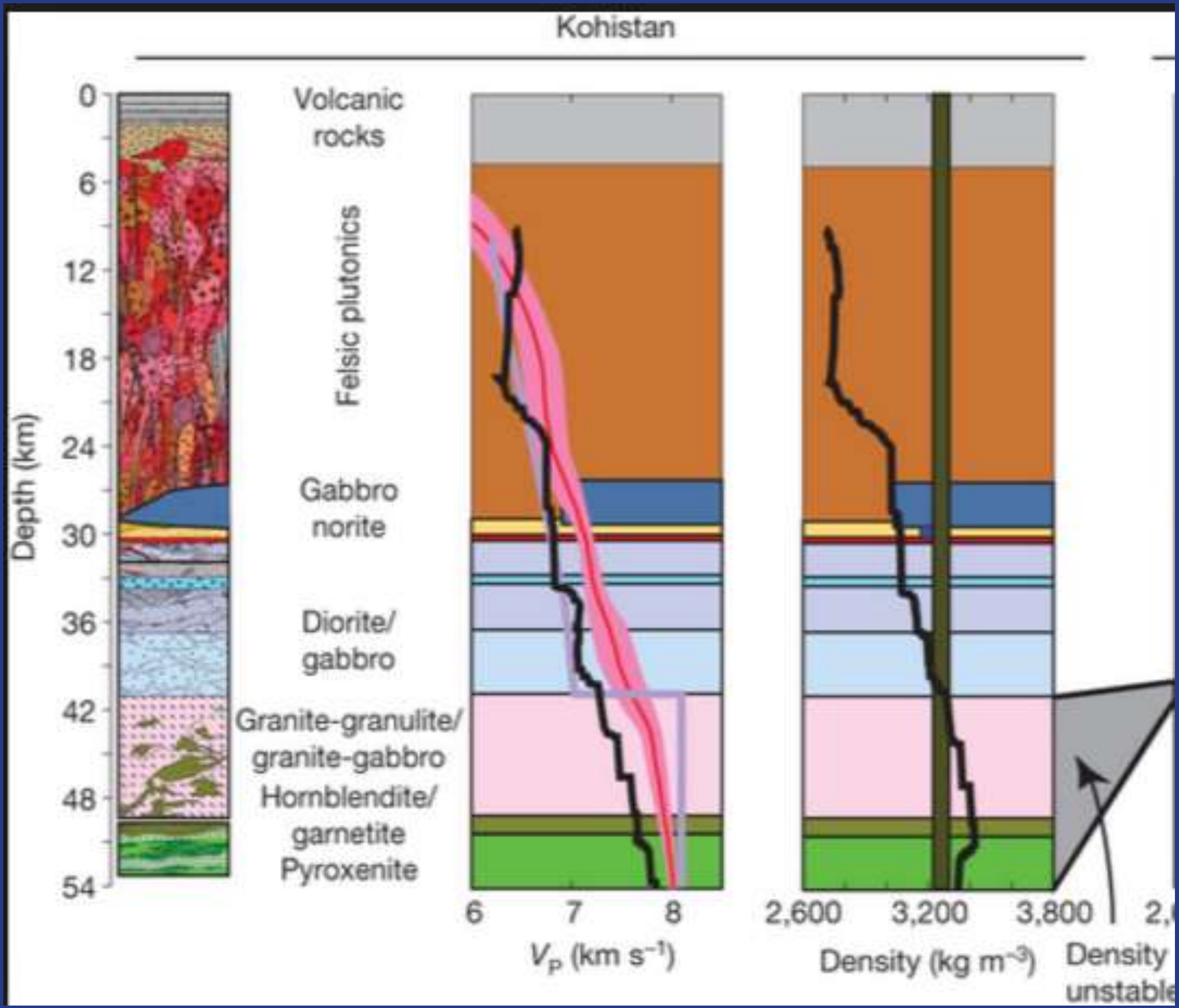
What is a diapir?

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)

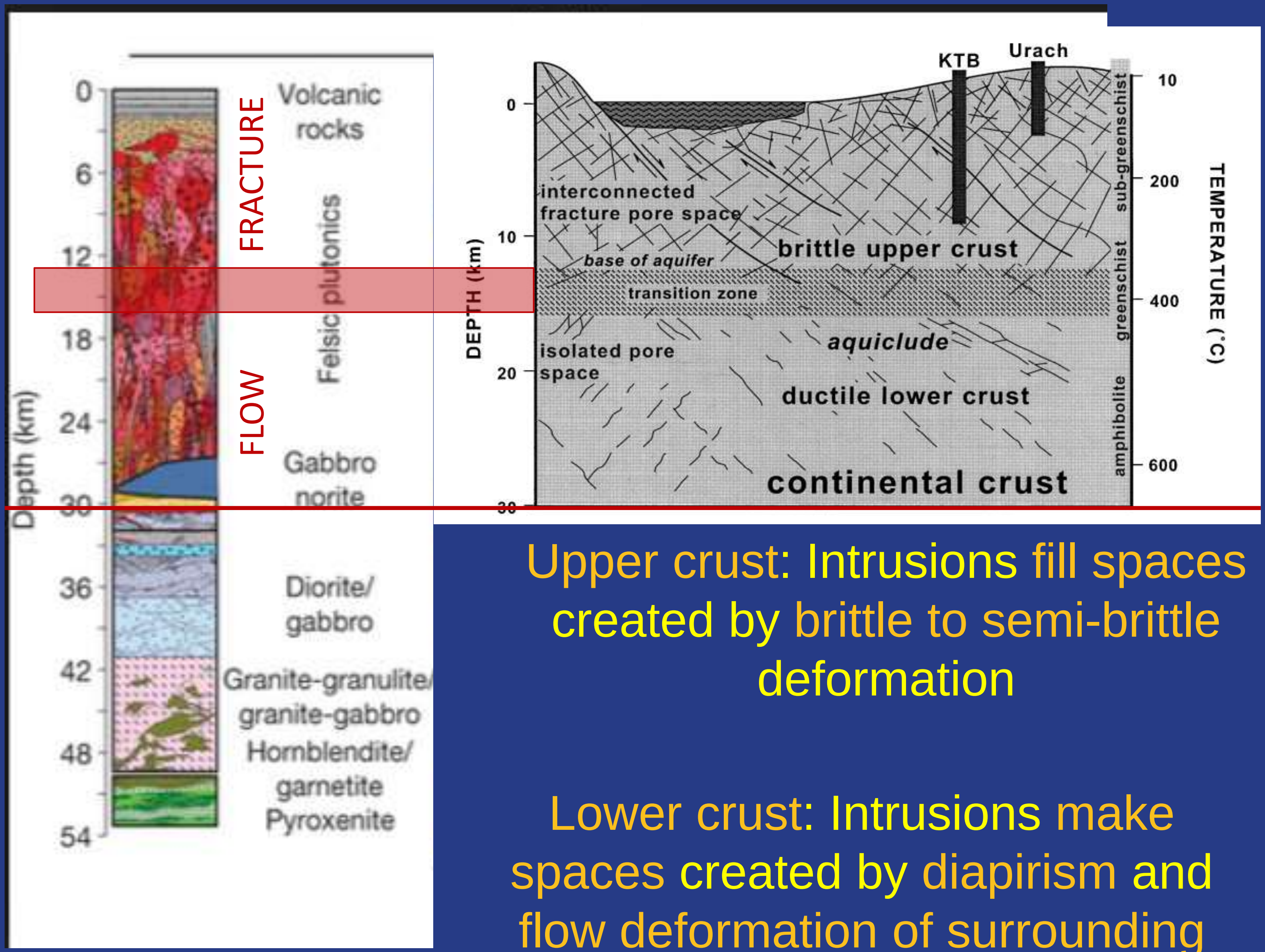


Raleigh-Taylor instability


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



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

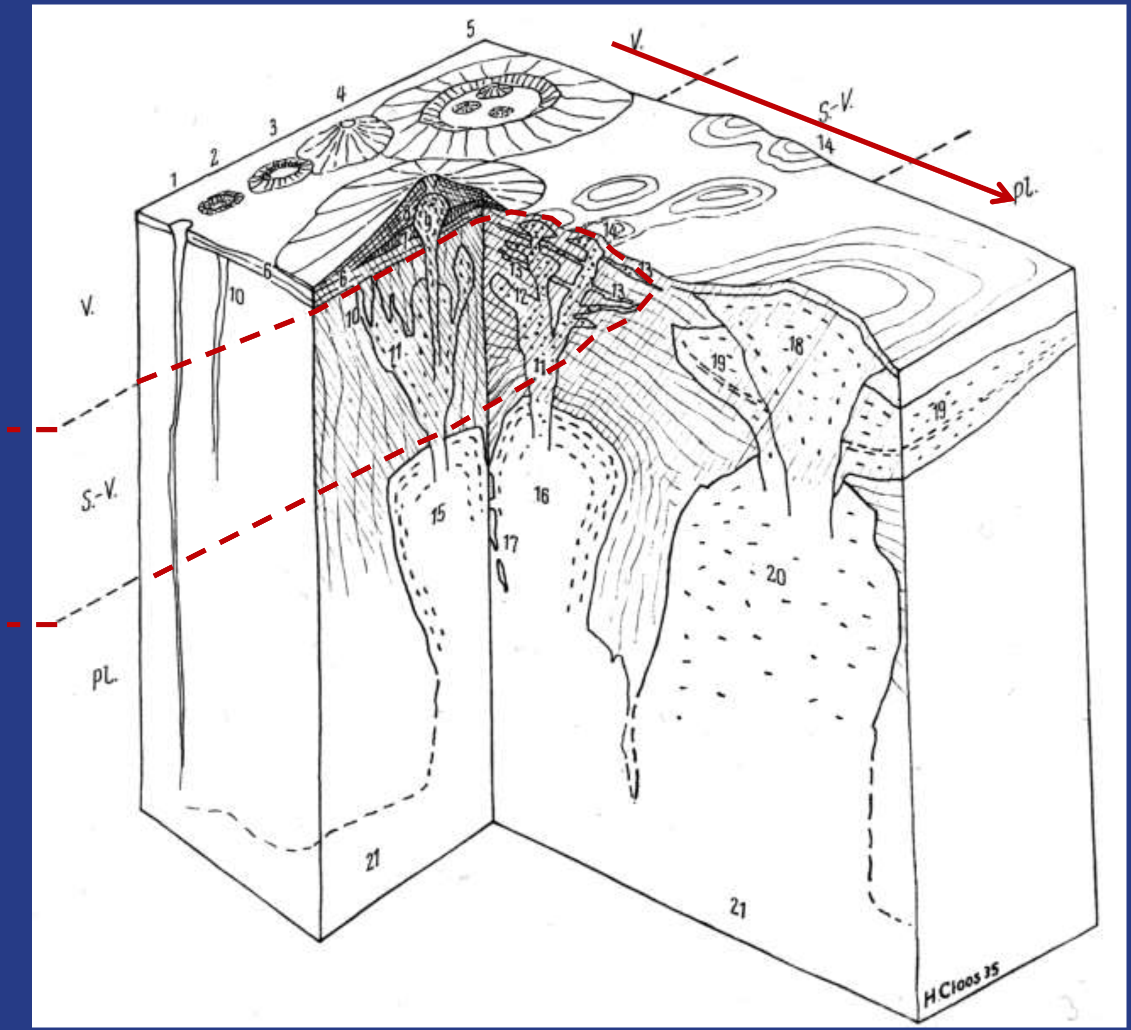
2. Intermediate depth igneous rocks (subvolcanic rocks)

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.



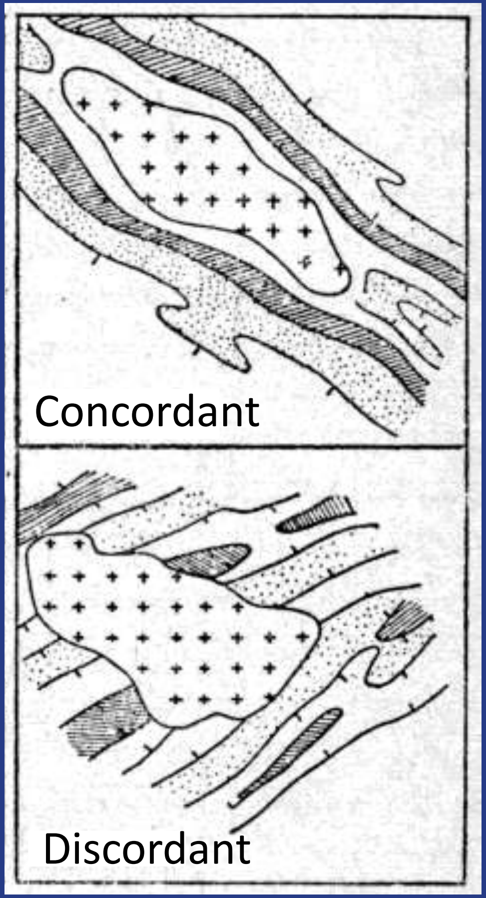
Intermediate depth or subvolcanic igneous rock bodies are the following:

Dyke (dike in American and old British spelling)
Sill
Phacolith (=Harpolith)
Akmolith
Bysmalith
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).

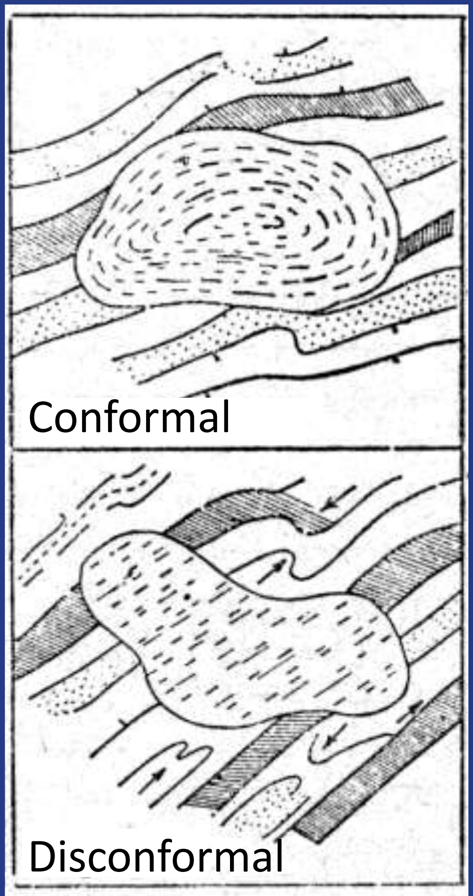
The boundaries of a discordant intrusive body truncates (or “cuts”) the fabric and texture of the surrounding country rock.



Intrusive bodies may be conformal or disconformal.

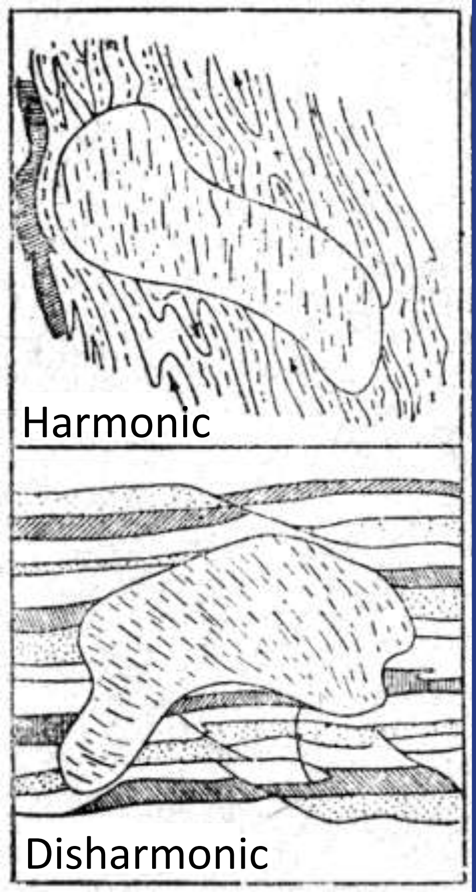
An intrusive body is called conformal if its internal fabric is parallel with its boundaries.

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.

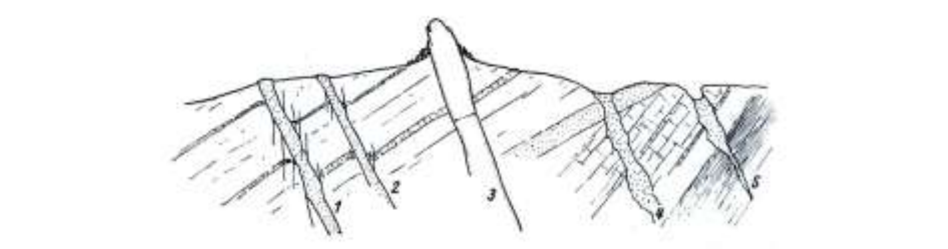
An intrusive body is said to be harmonic when its internal fabric is parallel with that of its country rock.



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

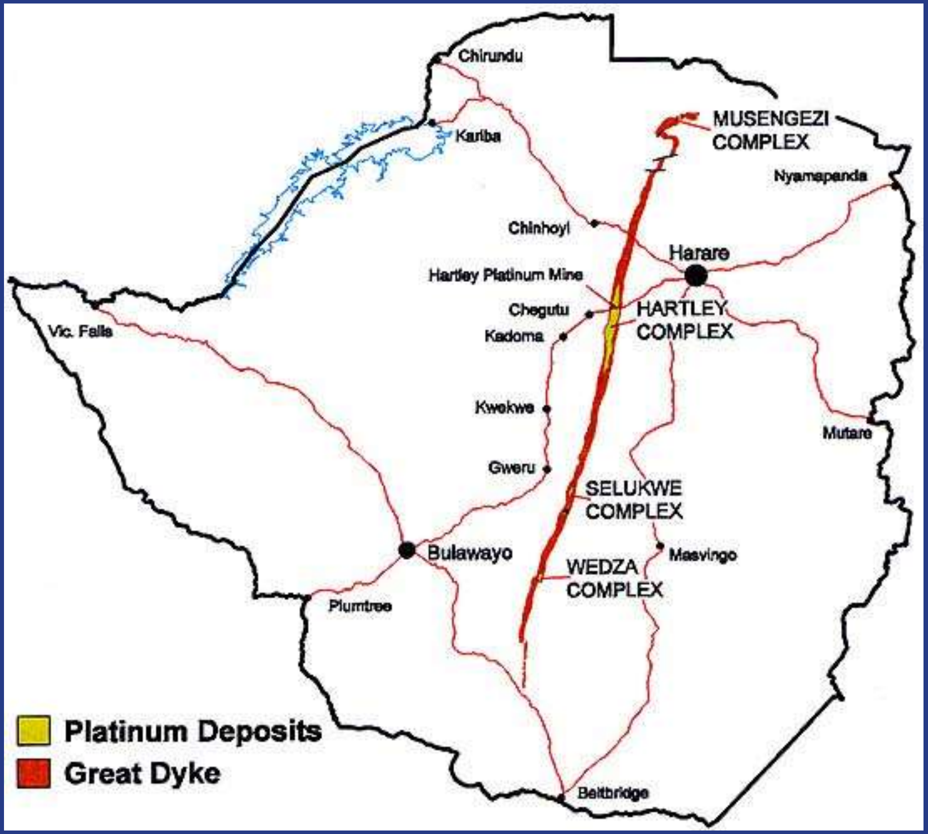
Dykes on the Island of Mull, Scotland, UK

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

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

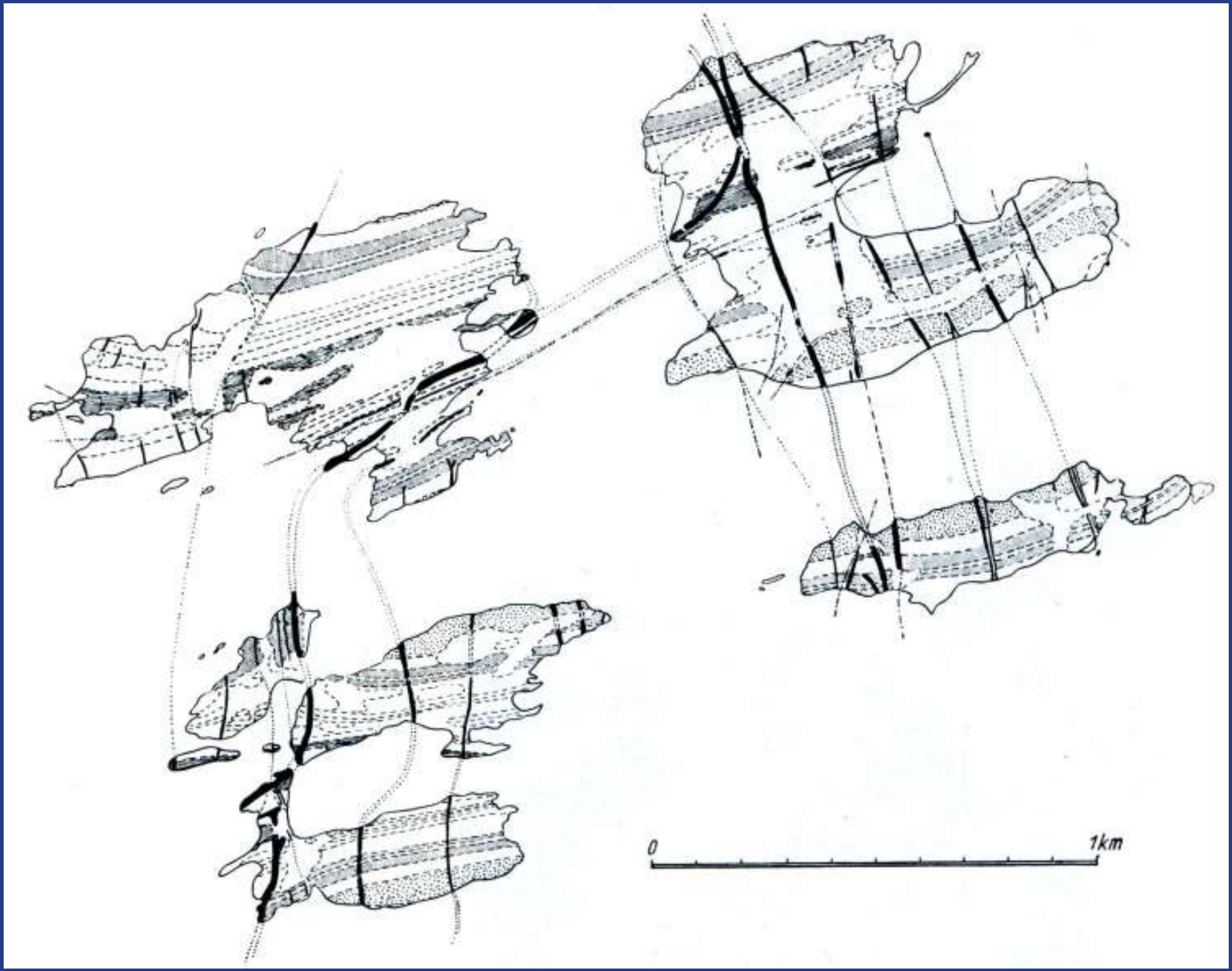
A huge Precambrian basaltic dyke in South Africa

The word's largest known dyke

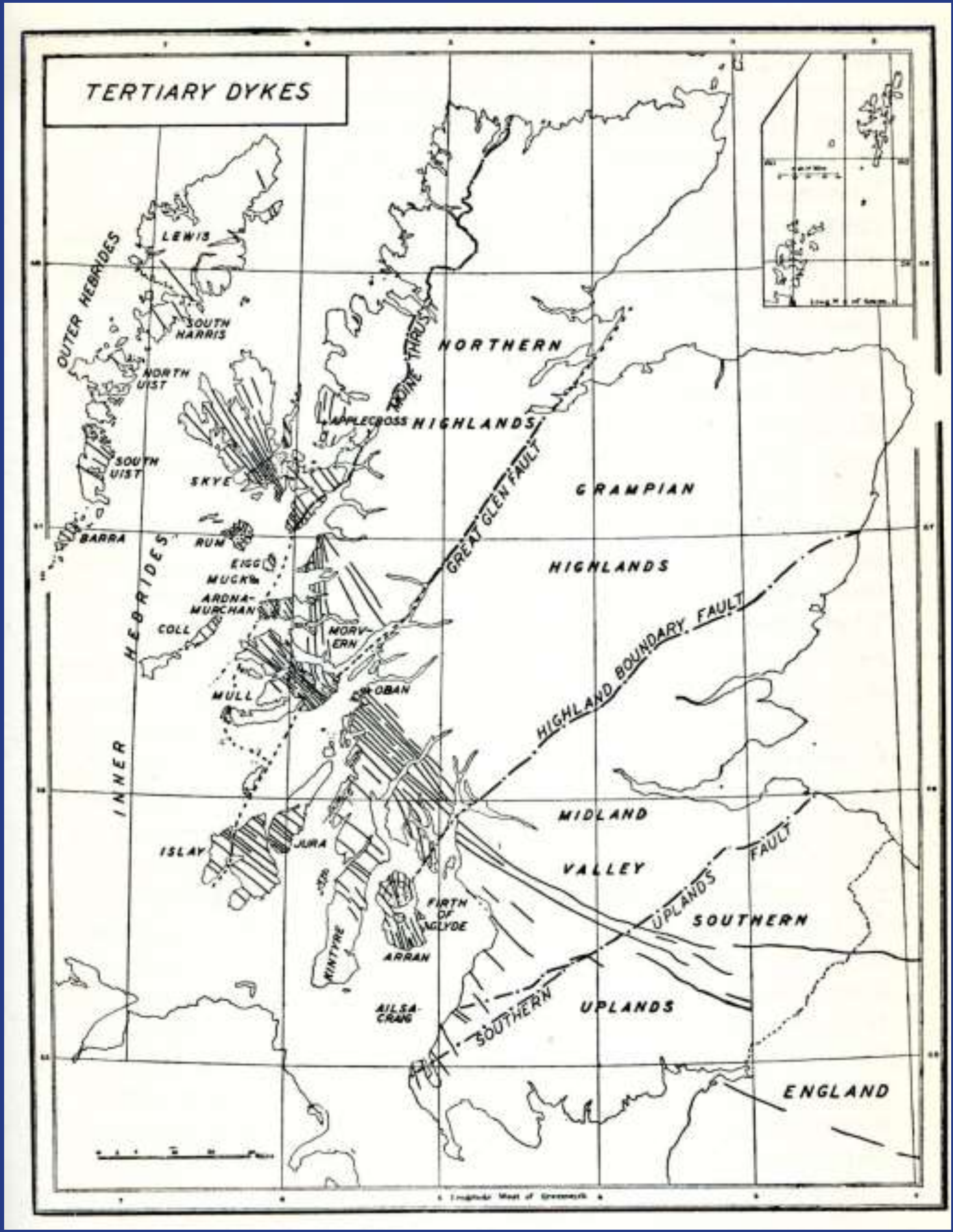


The *Great Dyke* of Zimbabwe. It is about 550 km long and at its widest spans a width of some 12 km. It is 2.575 billion years old.

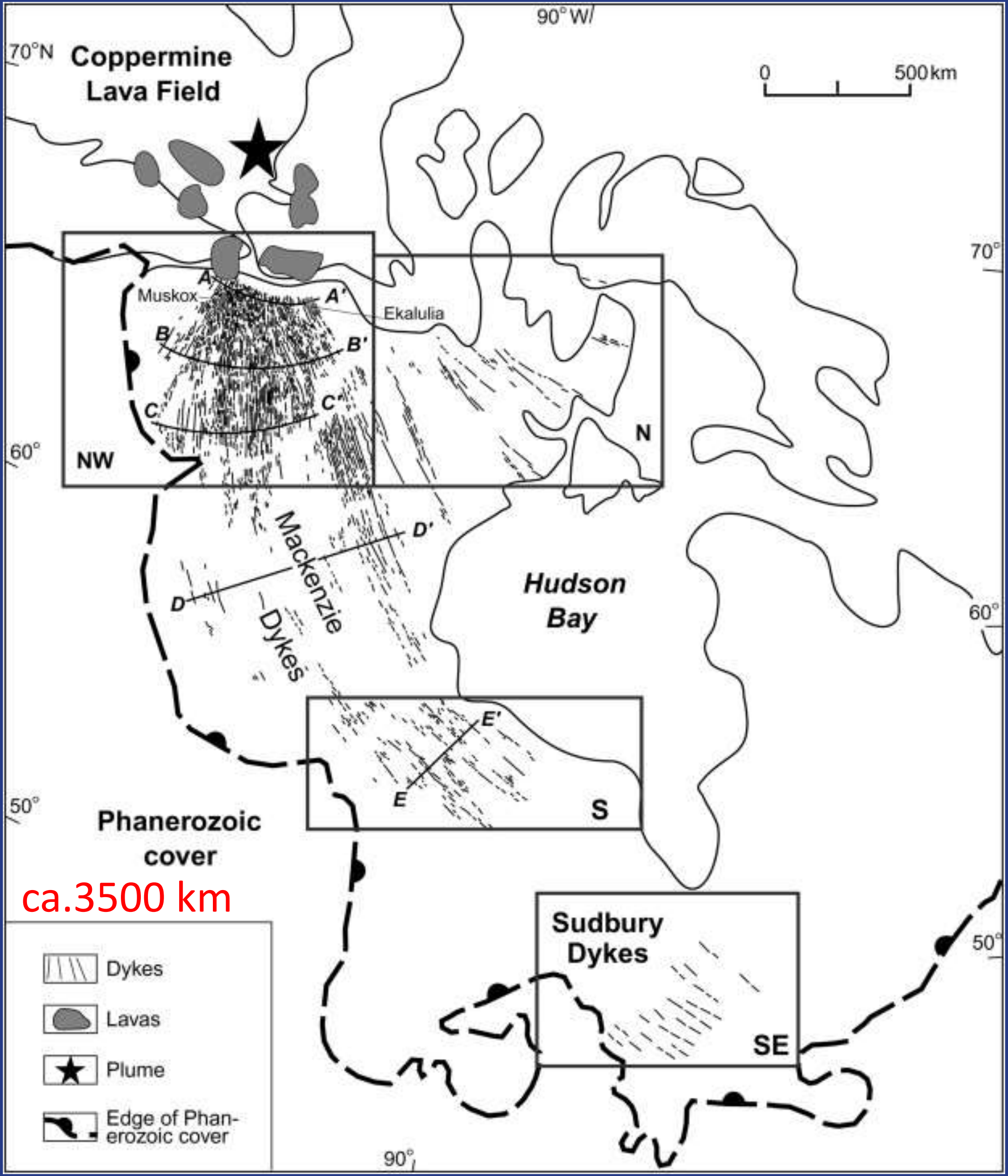
Satellite picture of the Great Dyke in Zimbabwe. The dyke is some 10 to 12 km wide in this picture. The age of the Great Dyke is 2500 million years.



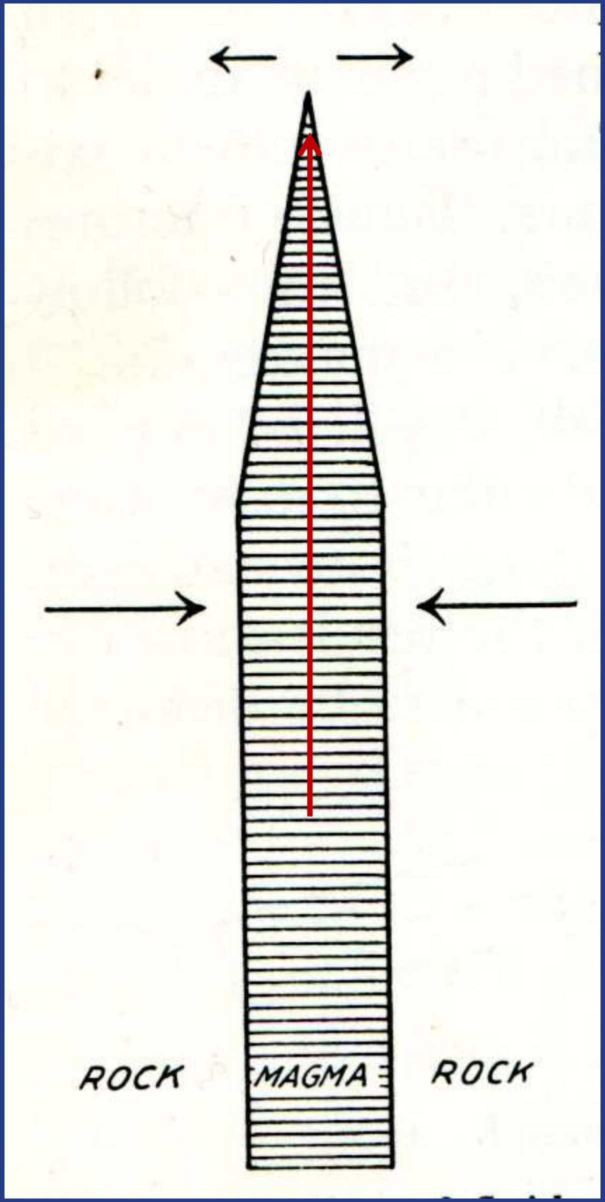
Dykes cutting through folded Silurian sedimentary rocks, Fjord Islands near Oslo, Norway (from Hans Cloos, 1937). As seen in this map dykes usually occur in groups called “swarms”



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:

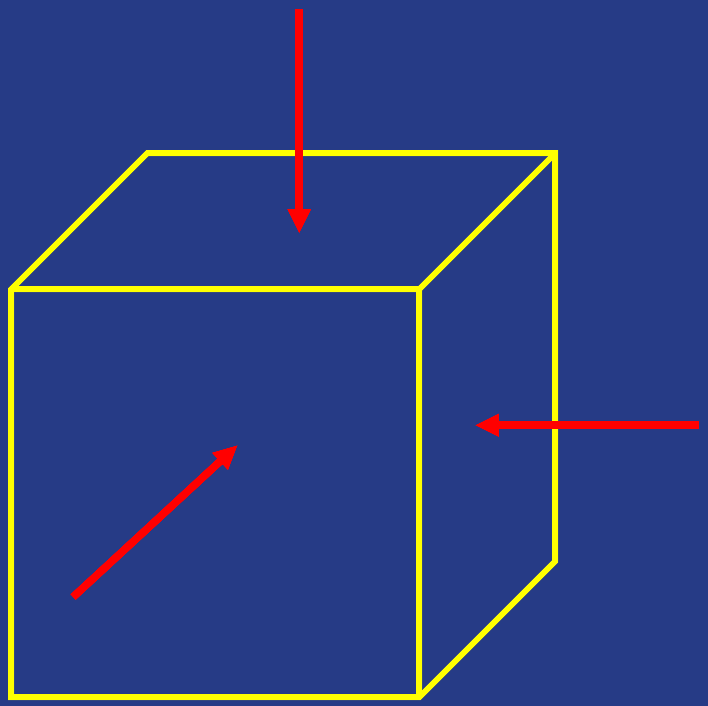
$\rho = F/A$

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.

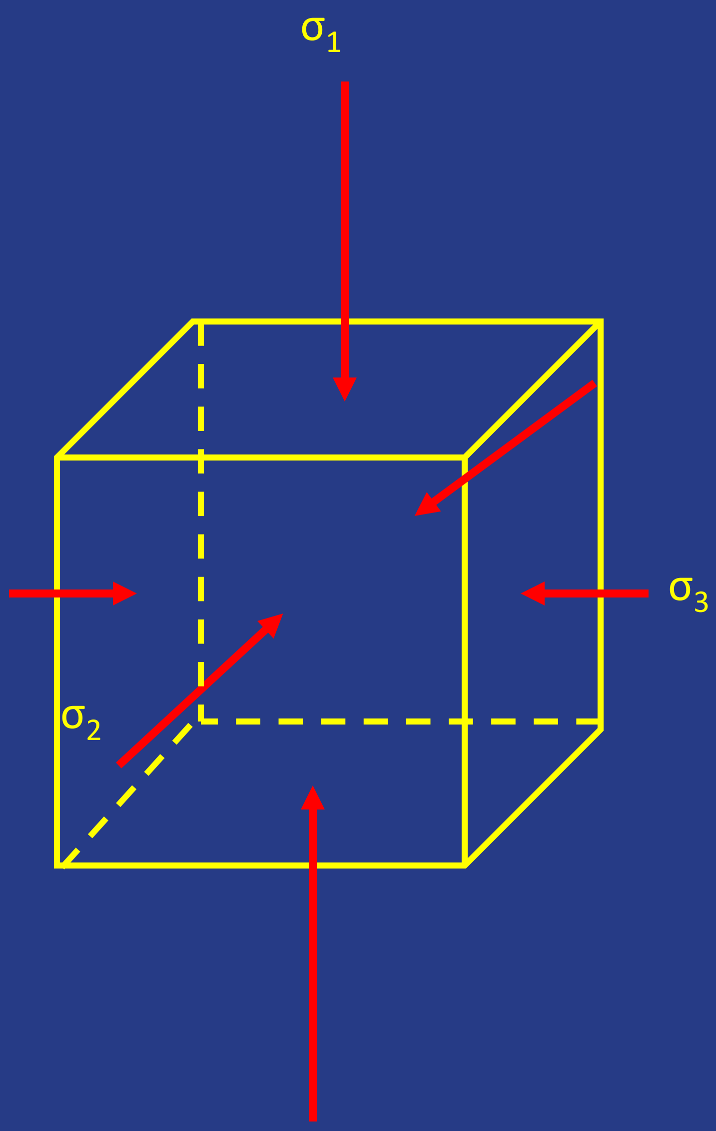
Normal stresses act perpendicularly on a surface, whereas shear stresses act parallel with the surface

Normal stresses: These stresses apply perpendicularly onto a surface

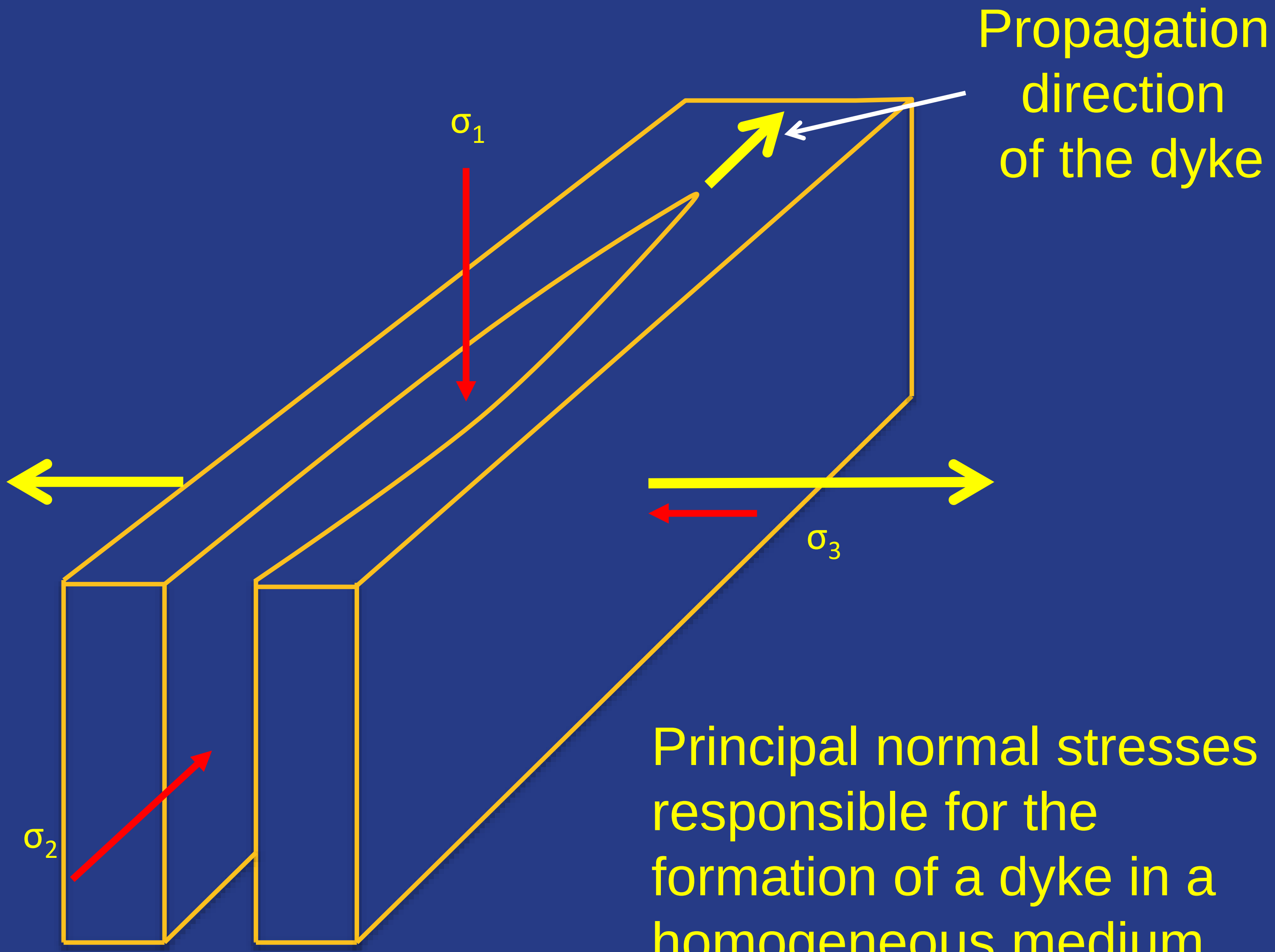


Because action=reaction, all stresses acting on a body come in opposite pairs. This is naturally also true for normal stresses.

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.

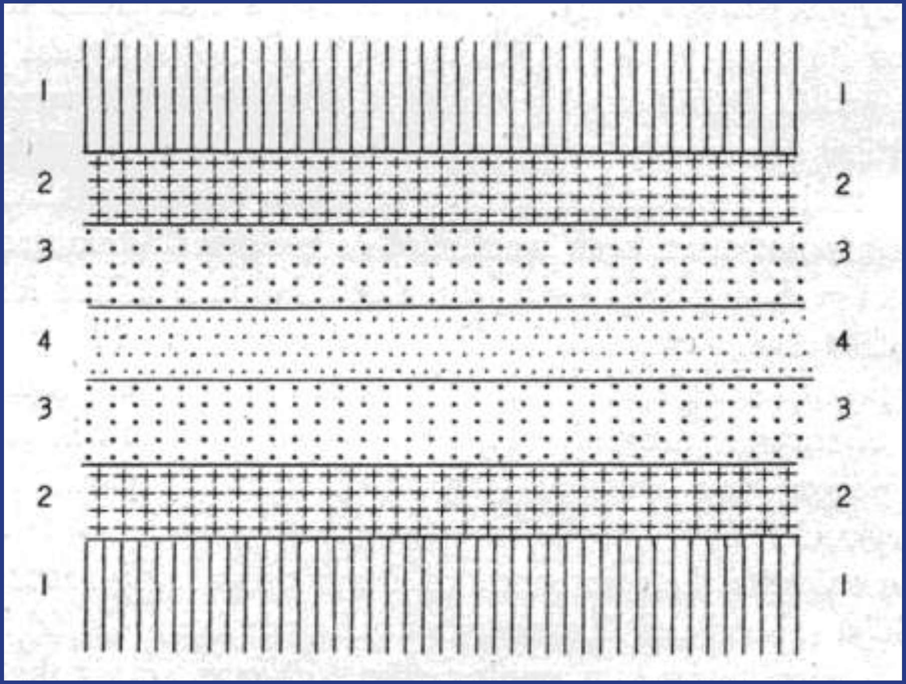


Principal normal stresses responsible for the formation of a dyke in a homogeneous medium according to Anderson's theory of dyke formation (1942, 1951)

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)

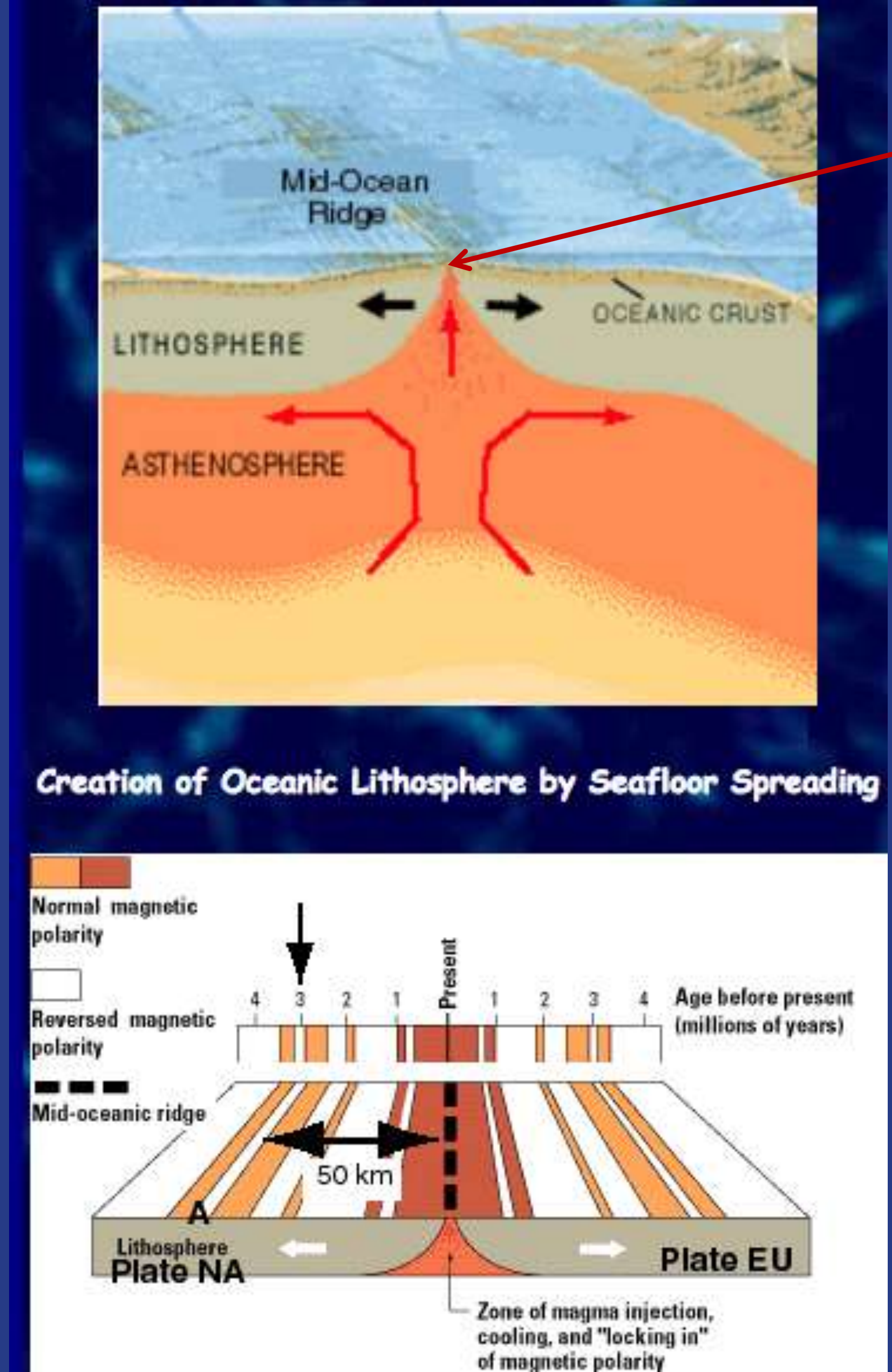
W. R. A. "Bob" Baragar (1926-)

Sheeted dykes, Troodos ophiolite, Cyprus

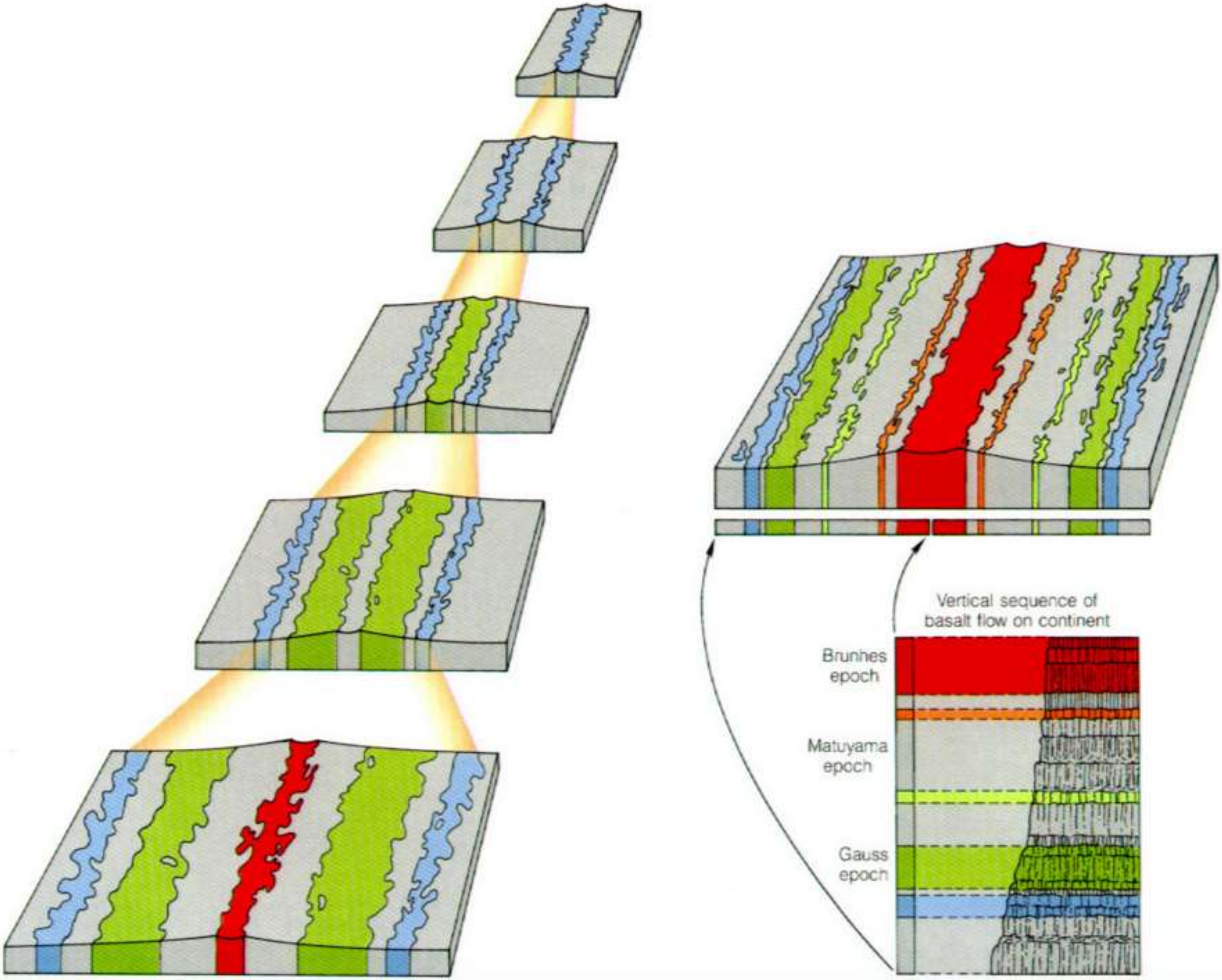
Sheeted dykes in the Kenai ophiolite,
Alaska, USA

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 fl

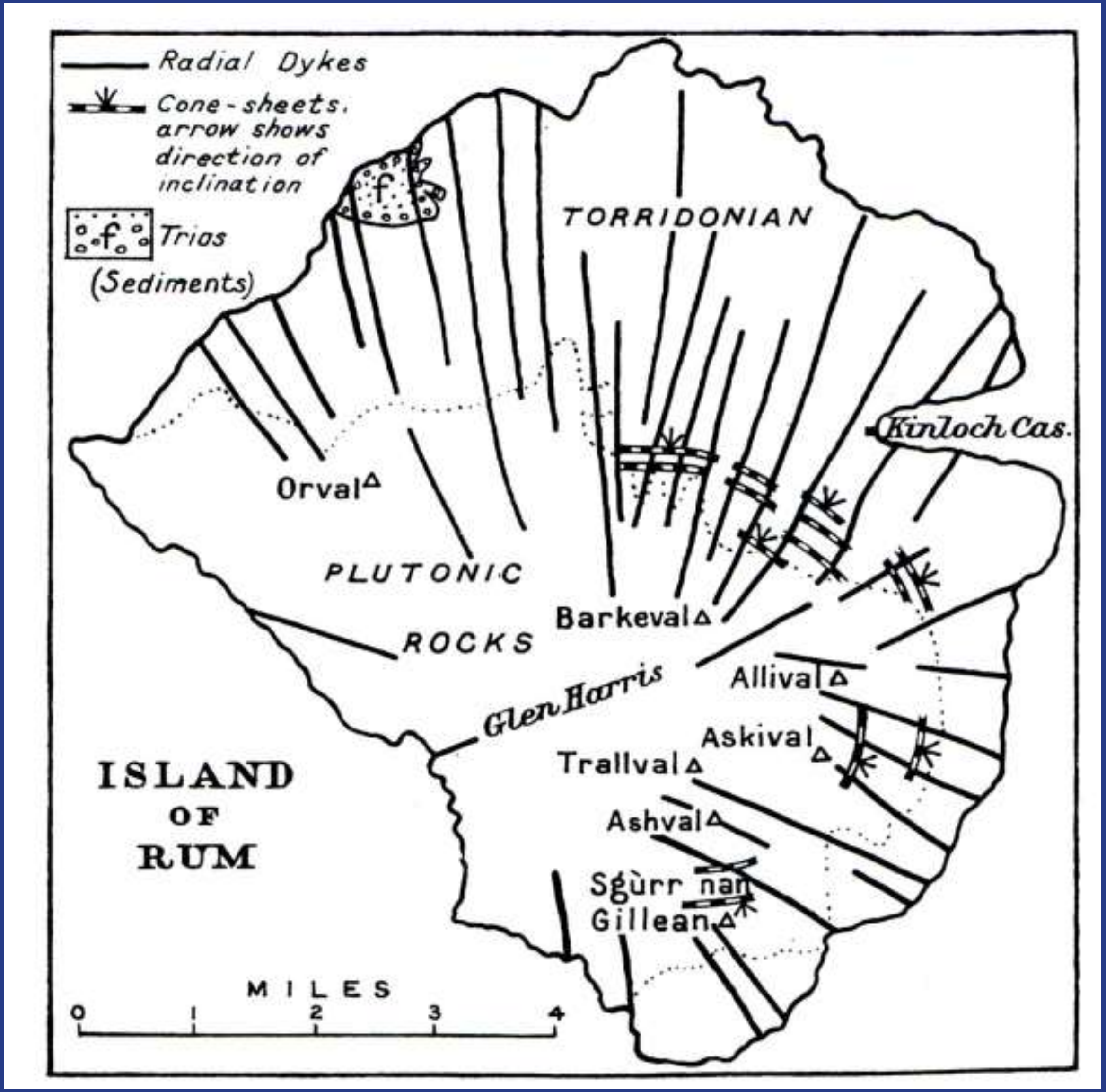


This is where sheeted dyke injection happens

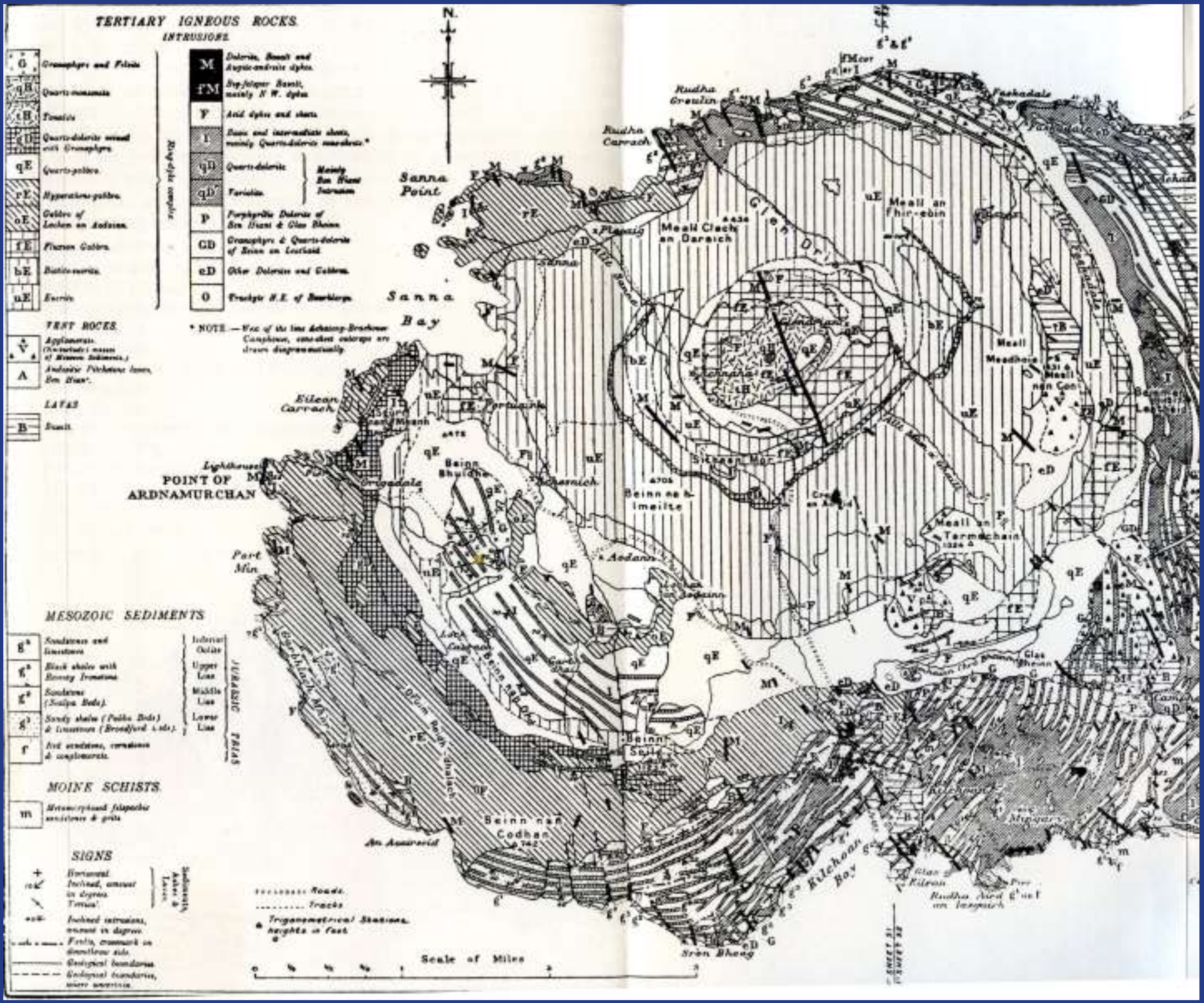


Vertical sequence of basalt flow on continent
Brunhes epoch
Matuyama epoch
Gauss epoch

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

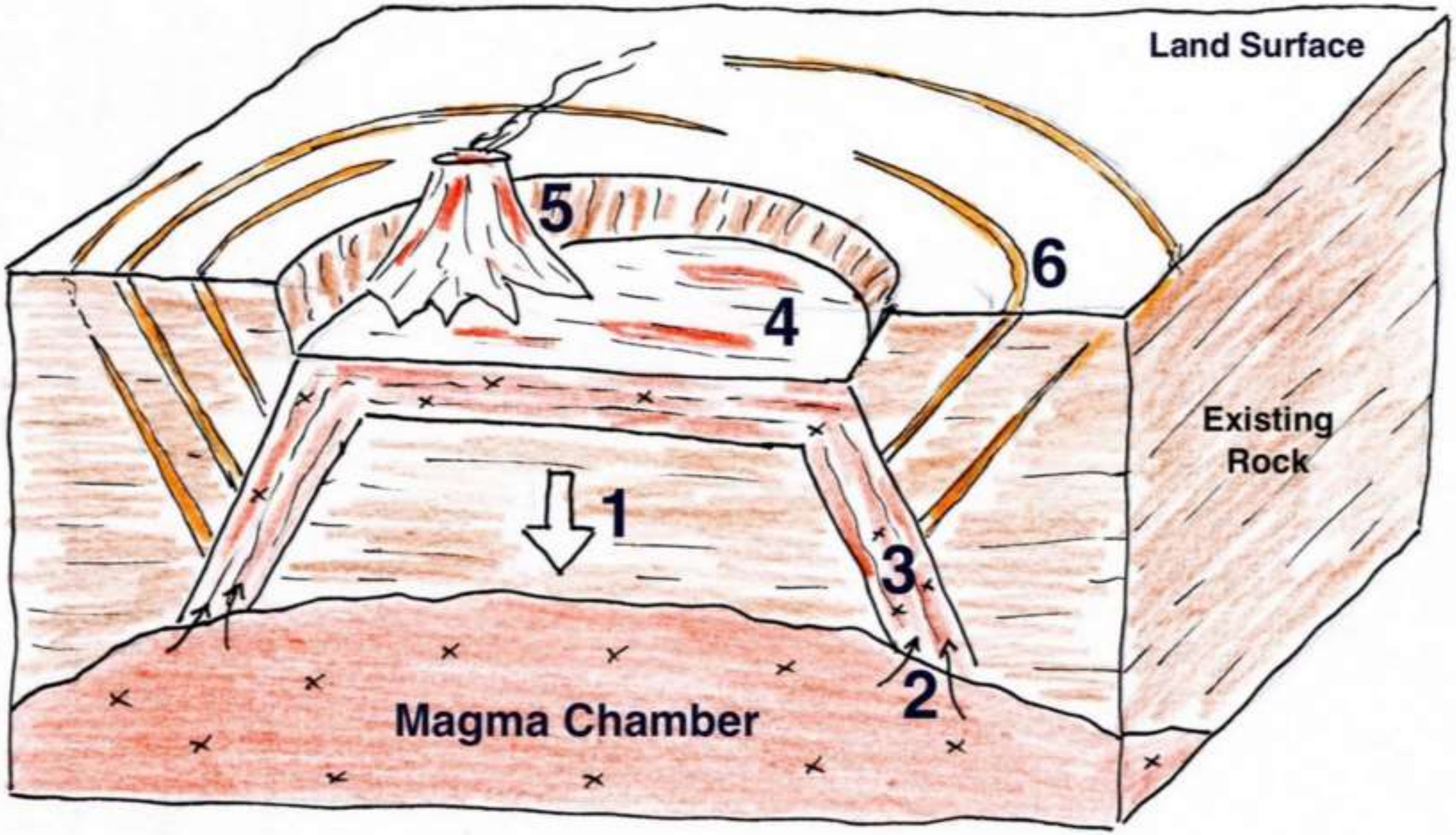


Radial and concentric (=ring) dykes of the Island of Rum.

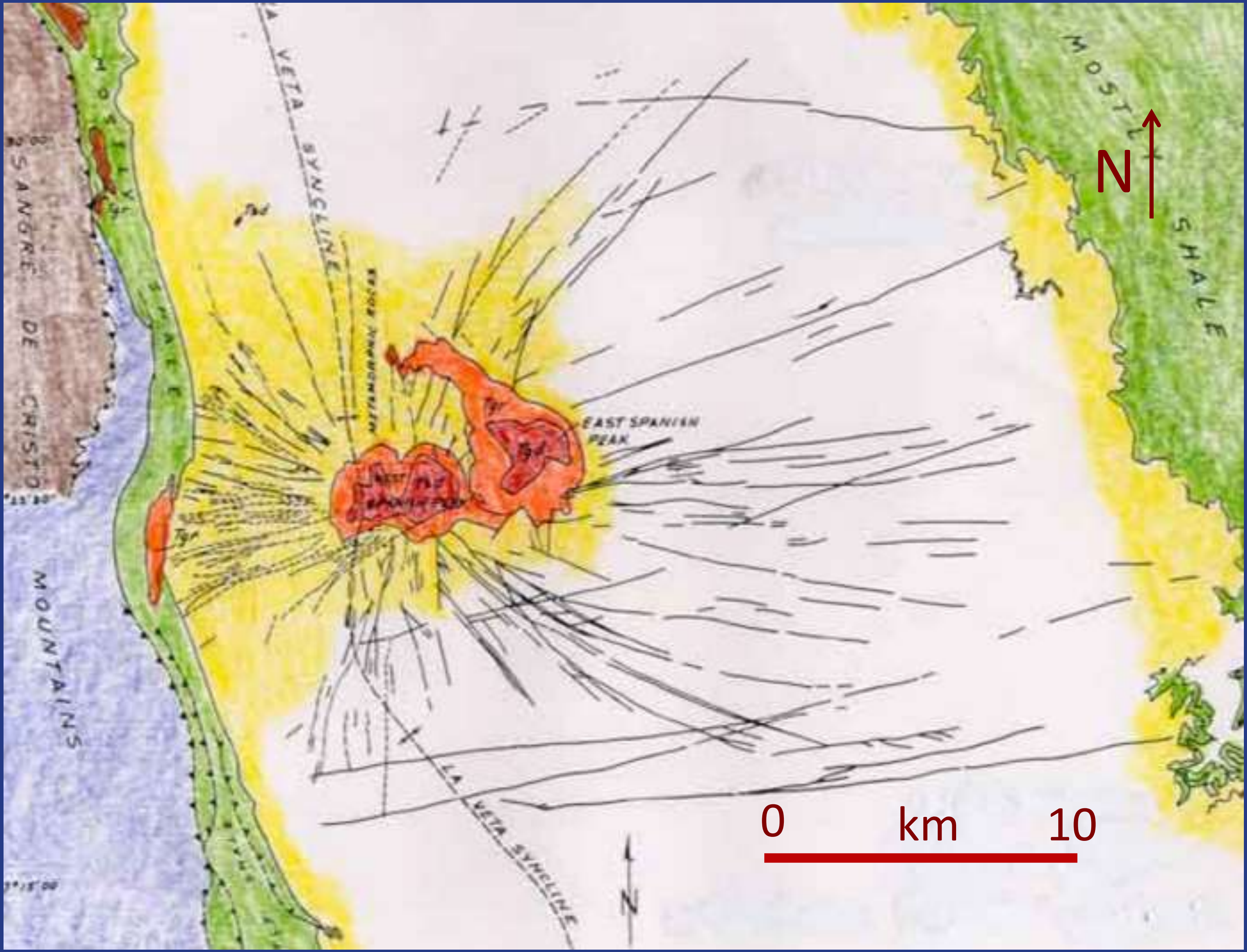


Radial and concentric dykes of Ardnamurchan

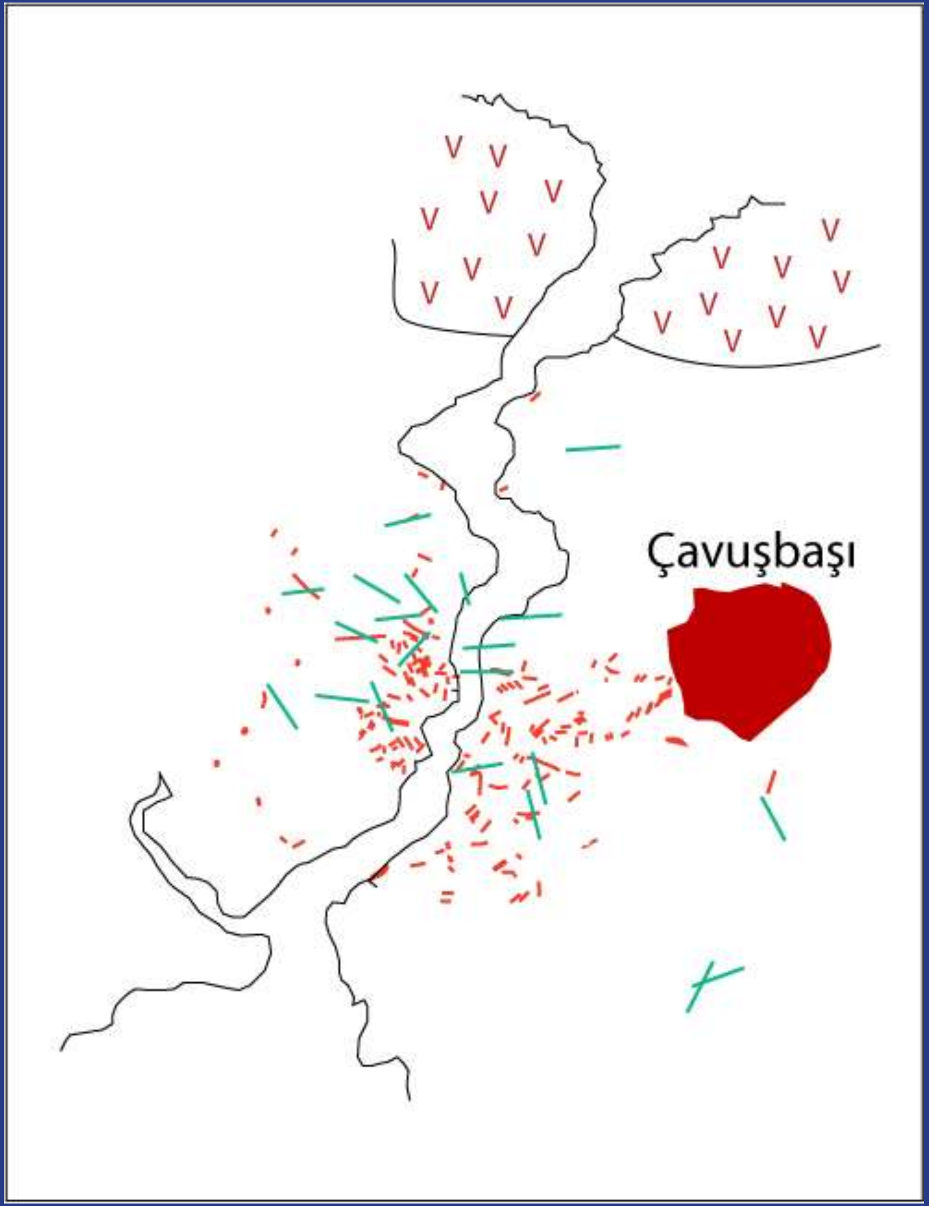
Volcanic Ring Complex, Ardnamurchan



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

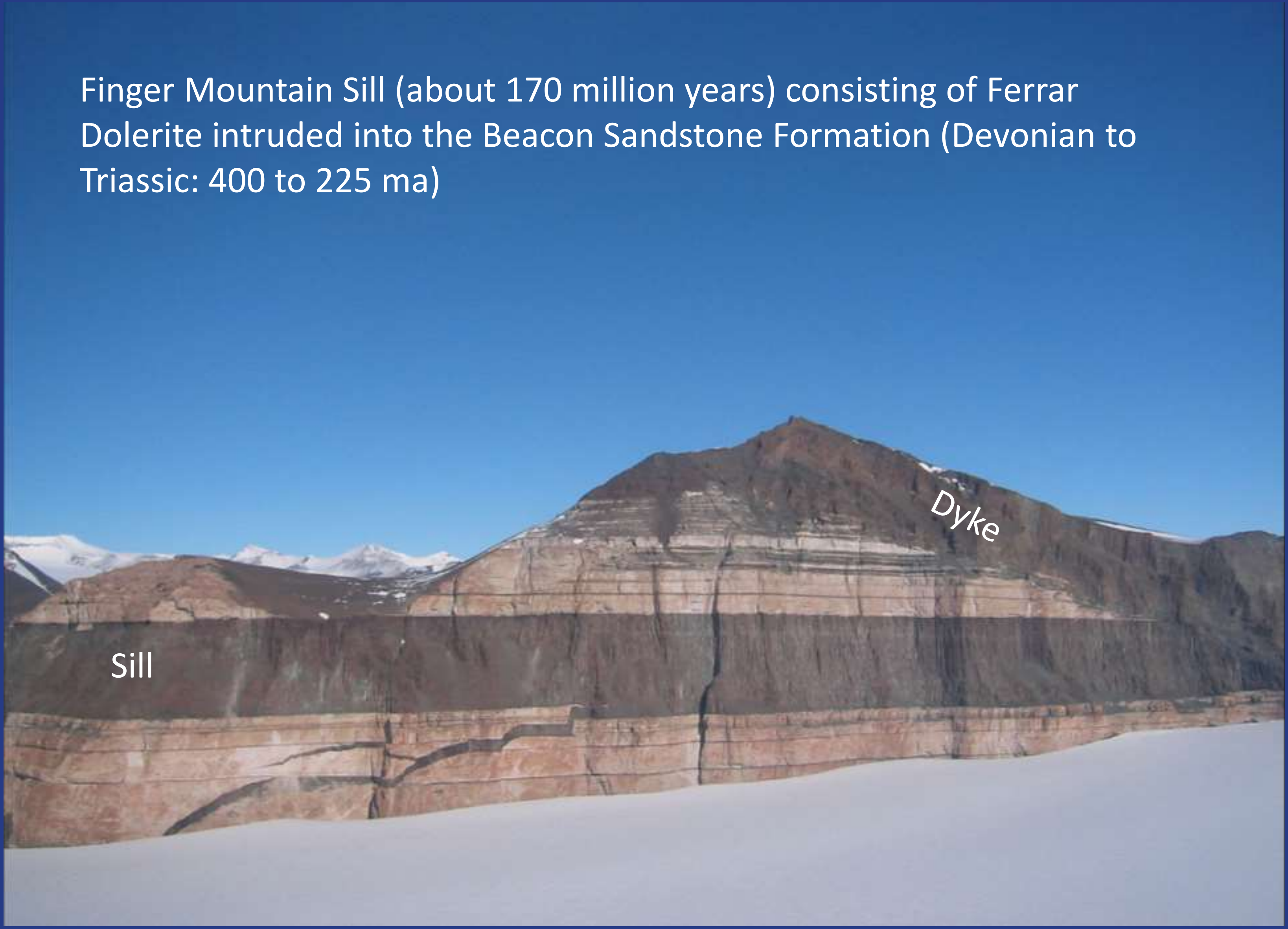


Spanish Peaks, Colorado, USA. Red is augite-granite-porphyry, orange is granite porphyry. Black lines are the dykes.



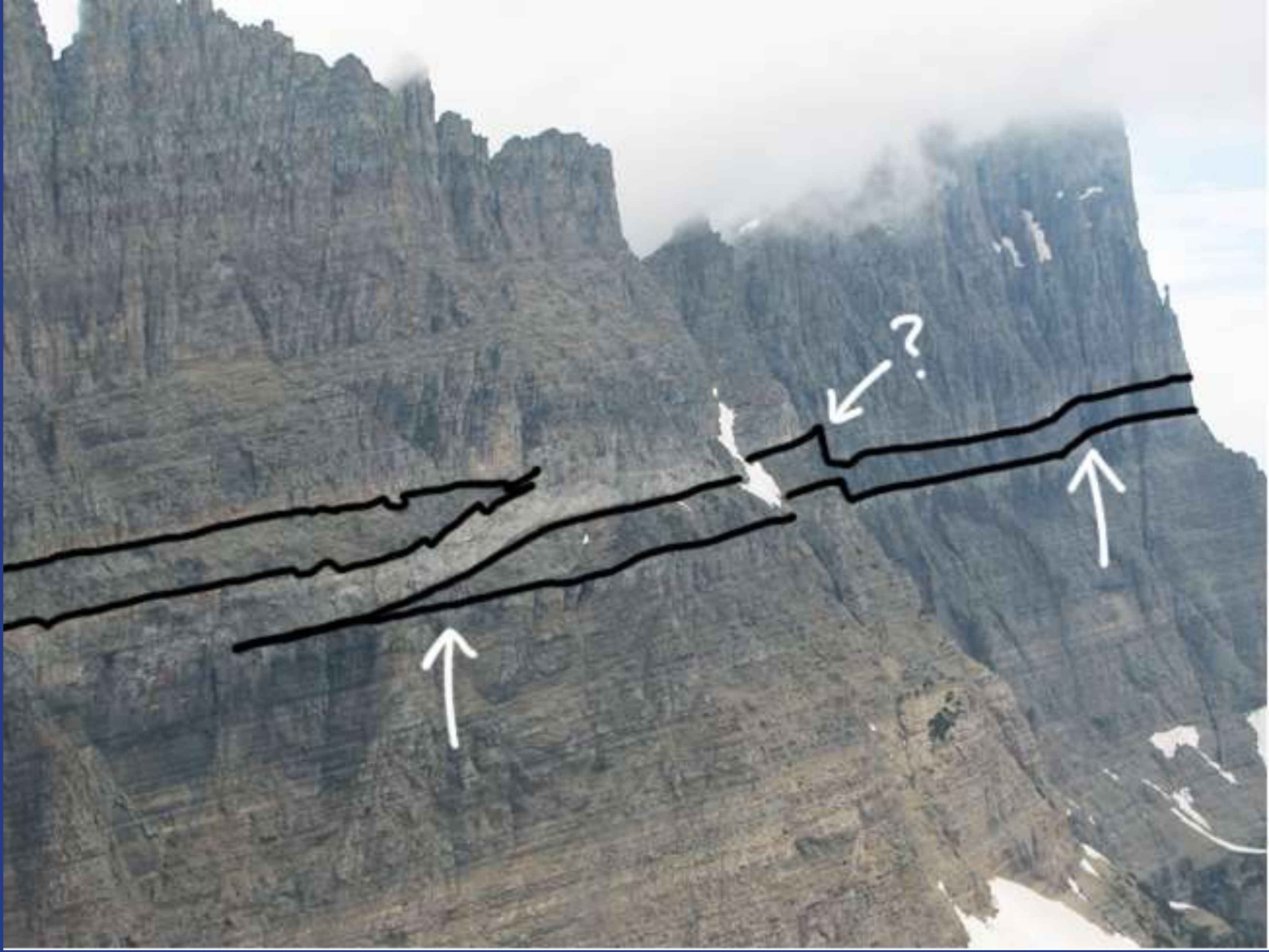
Radial dykes emanating from the Çavuşbaşı Granodiorite in İstanbul, which was a part of a volcanic magma chamber of about 65 millions of years of age.

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.



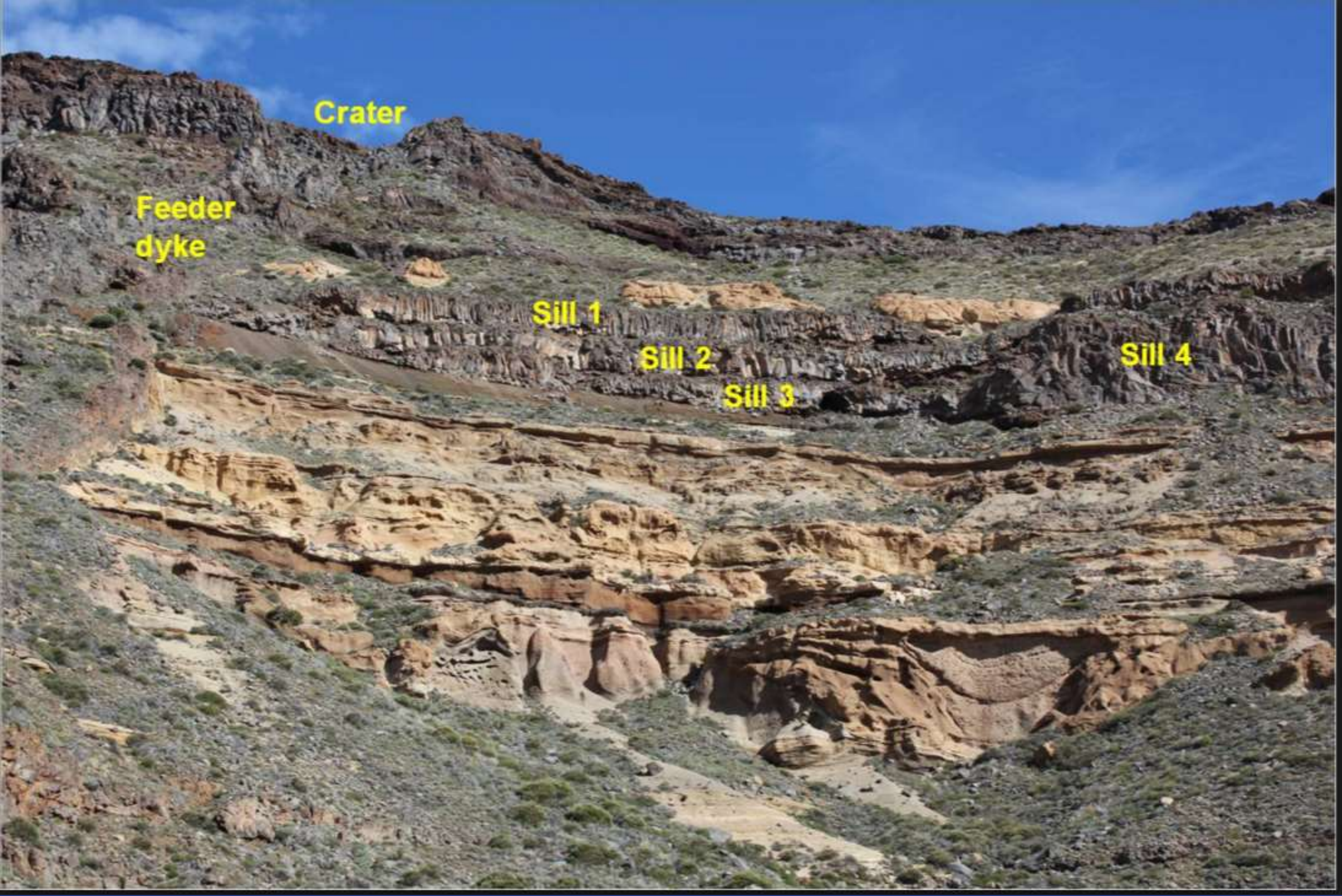
A granite sill used in a threshold in a home.

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



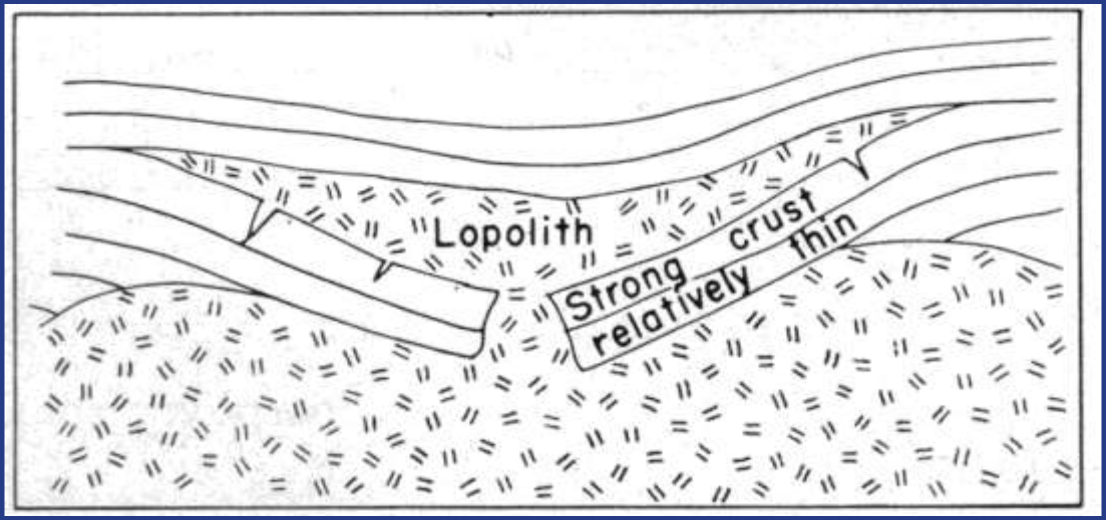
The Purcell Sill highlighted.

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

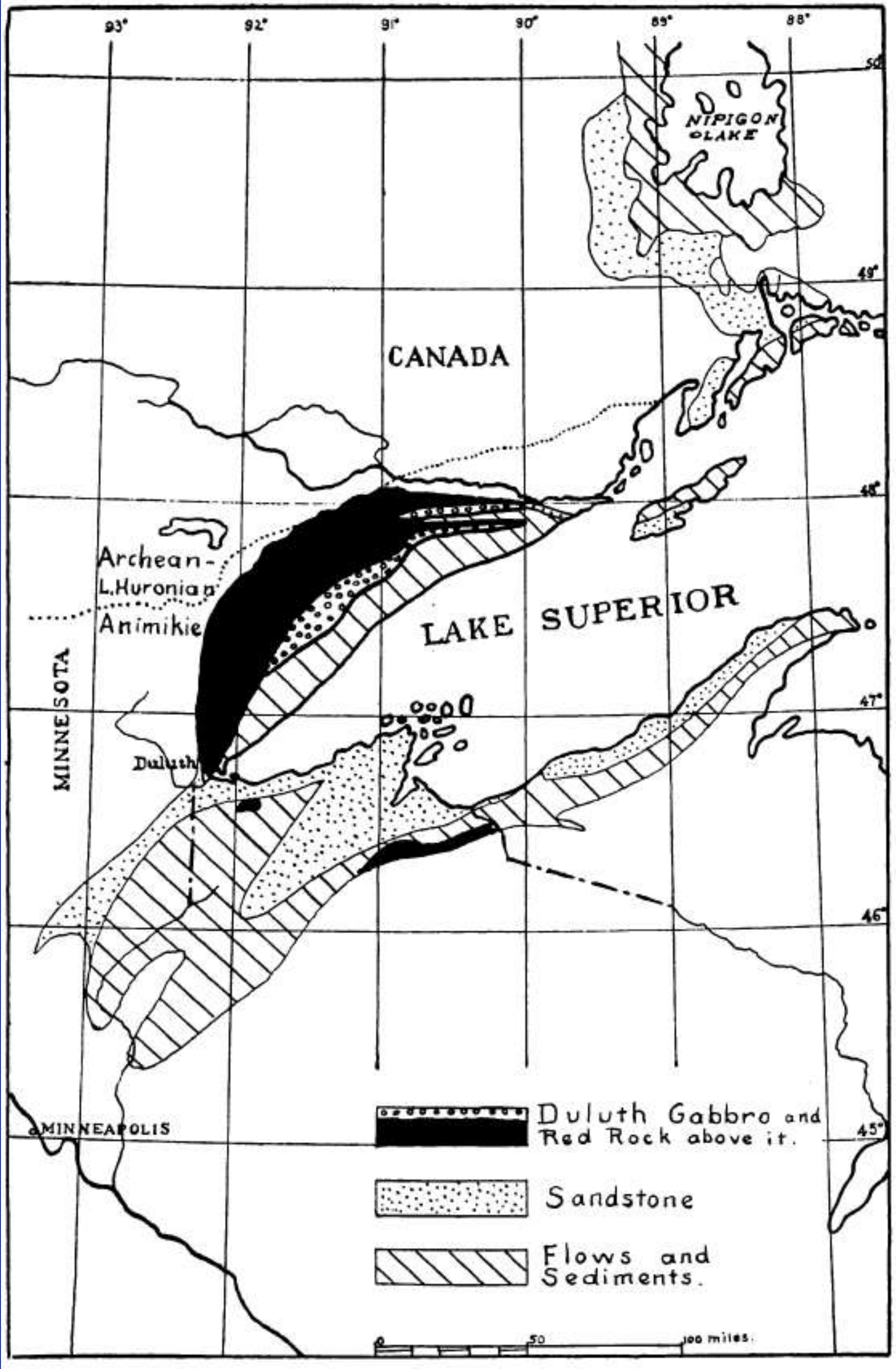


Sills and a feeder dyke, Tenerife, Canary Islands.

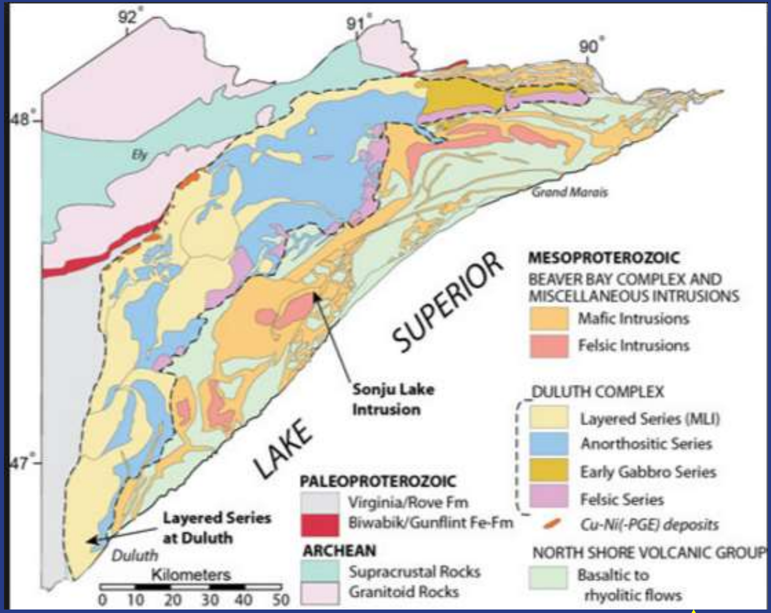
Lopolith: is defined as a lenticular, centrally sunken, generally concordant, intrusive mass, with its thickness approximately one-tenth to one-twentieth of its width or diameter. It was introduced in 1918 by the American geologist Frank Fitch Grout to describe the Duluth Gabbro and associated intrusions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



A schematic cross-section of a lopolith, redrawn by Hunt et al. (1953) from Grout's 1918 paper.



Grout's original map of the type lopolith, the Duluth Gabbro.



A modern geological map of the Duluth lopolith

An outcrop of the Duluth gabbro

Here is a new rock term again: gabbro. Gabbro is a phaneritic plutonic rock consisting of up to 90 % plagioclase, and about 30 to 10 % pyroxene, 95% of which are monoclinic pyroxenes (therefore mostly calcium- and iron-rich varieties: augite). The plagioclases range from bytownite to labradorite. If plagioclases be anorthite, the term eucrite has been used for gabbros containing them. Gabbros contain ilmenite, magnetite and spinel as accessory minerals.

The term gabbro was introduced into the geological terminology by the Great German geologist Baron Leopold von Buch in 1810. He took the term from the stonemasons and artists of Tuscany in Italy, where the term had been current since the middle of the 18th century.

Chemically and mineralogically gabbro is equivalent to basalt. It is only in grain size that it differs from it. Basalt is aphanitic, whereas gabbro is phaneritic.

Basalt occurs as lava; gabbro occurs as plutonic rock. So we call gabbros the deep-seated equialents of basat. The intermediate grain-sized igneous magmatic rock having the same composition as basalt and gabbro is called a dolerite (Americans and continental Europeans call it diabase. In the United Kingdom, diabase is only used for altered dolerite). Dolerite mostly occurs in subvolcanic intrusive masses such as dykes and sills.

The term dolerite was introduced by the great French mineralogist René Just Haüy in 1822. Diabase has priority: it was introduced in 1813 by another great French geologist, Alexandre Brongniart, as equivalent to *Werner's Grünstein*.

Gabbro from an unknown locality

There are two kinds of gabbros:

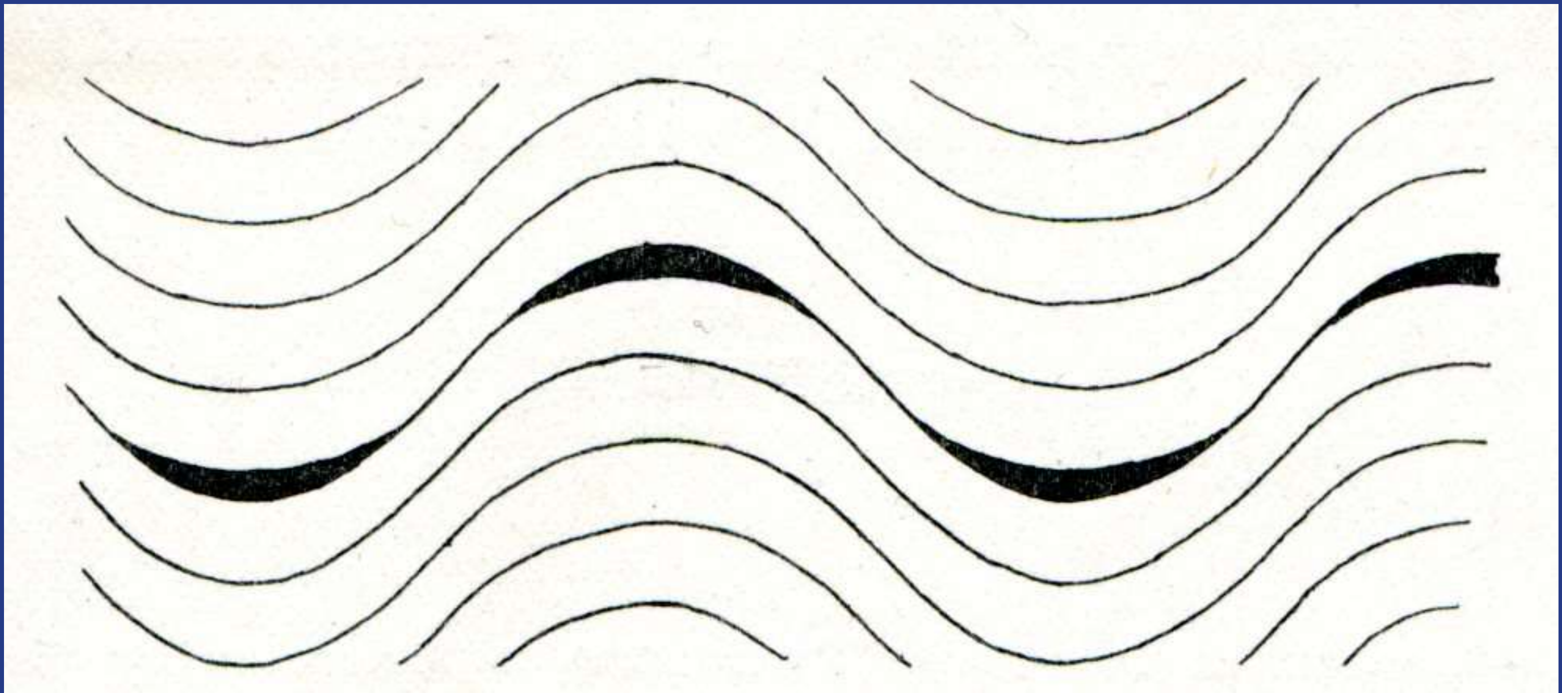
1. Melanogabbro meaning “dark gabbro” The melanogabbros are rich in pyroxenes. The prefix melano- comes from the Greek μέλᾰν (*melan*=black pigment, ink)

2. Leucogabbro meaning “light gabbro”. Leucogabbros are poorer in pyroxenes. The prefix leuco- comes from the Greek word λευκόν (*leukon*=white).

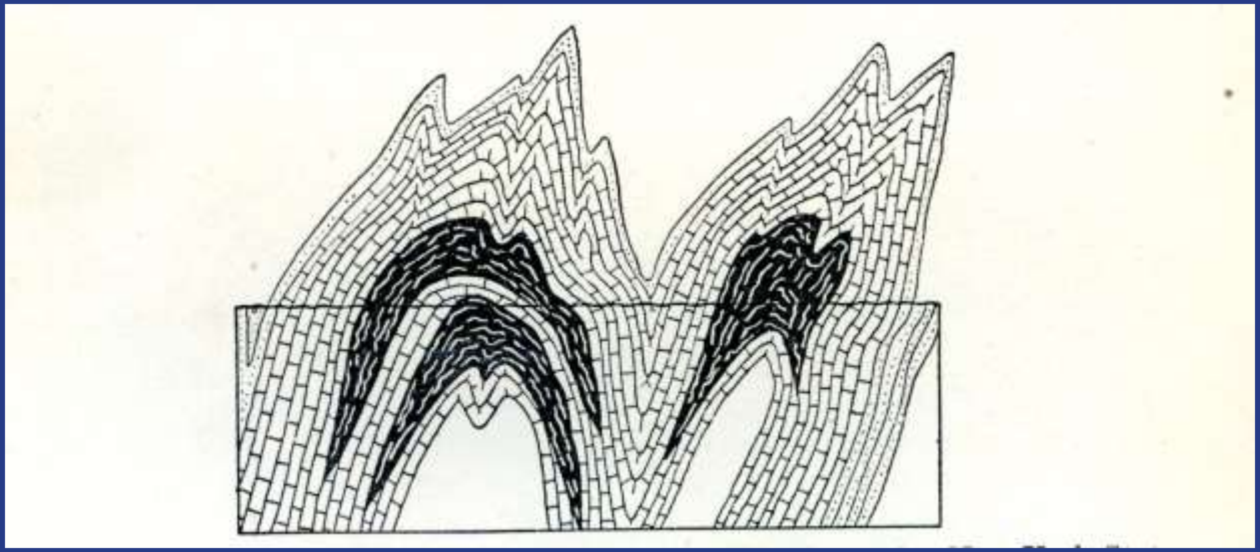
Let us also remember that some geologists have started calling dolerites “microgabbros”, a usage I would not recommend.

A leucogabbro from the Semail ophiolite nappe, Oman

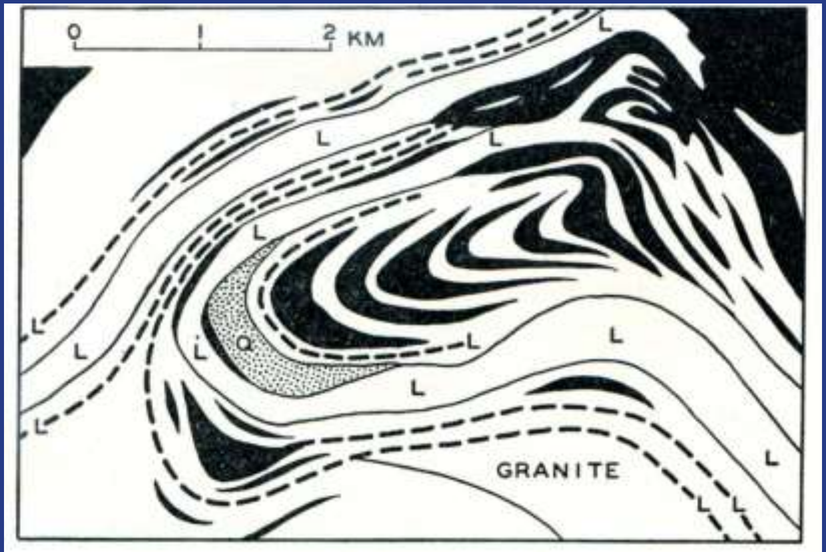
A melanogabbro of unknown locality



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)

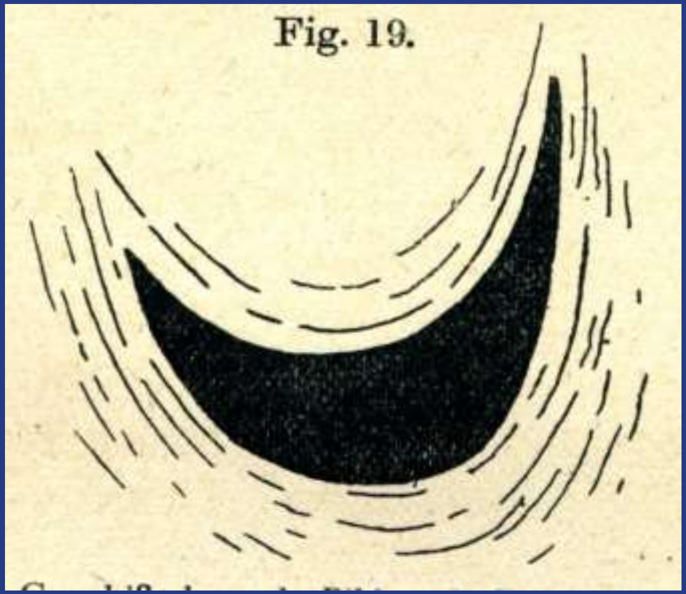


Precambrian phacoliths, South Africa (from Daly, 1914, p. 89).

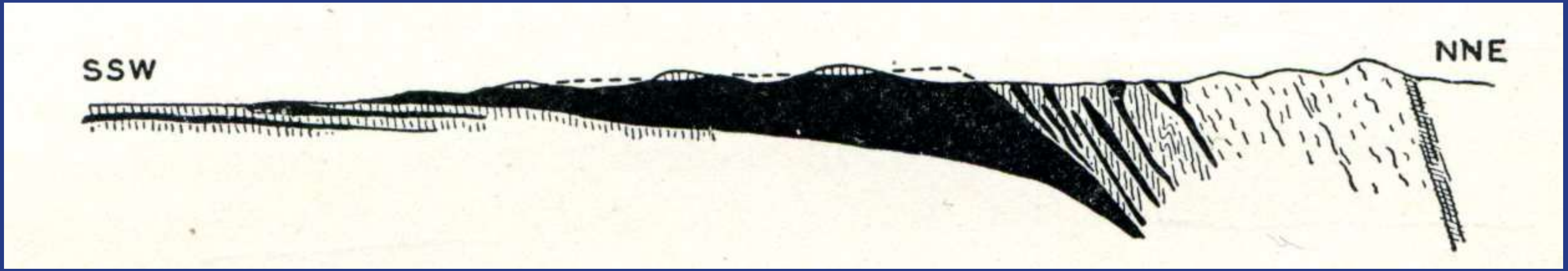
Rising Wolf Mountain dolerite phacolith,
Glacier National Park, Montana, USA

Rising Wolf Mountain
Phacolith at a distance.

In 1921 the great German geologist Hans Cloos proposed the term harpolith for “sicle-shaped intrusions”. The term was derived from the Greek ἅρπη (*arpe*=sicle). Cloos though that the harpoliths were formed concurrently with the folding process and became intruded into the crests and troughs of the folds which formed during the folding. *But this is precisely the definition of Harker’s phacolith*. By the rules priority, Cloos’s term harpolith must fall and make way to Harker’s phacolith.

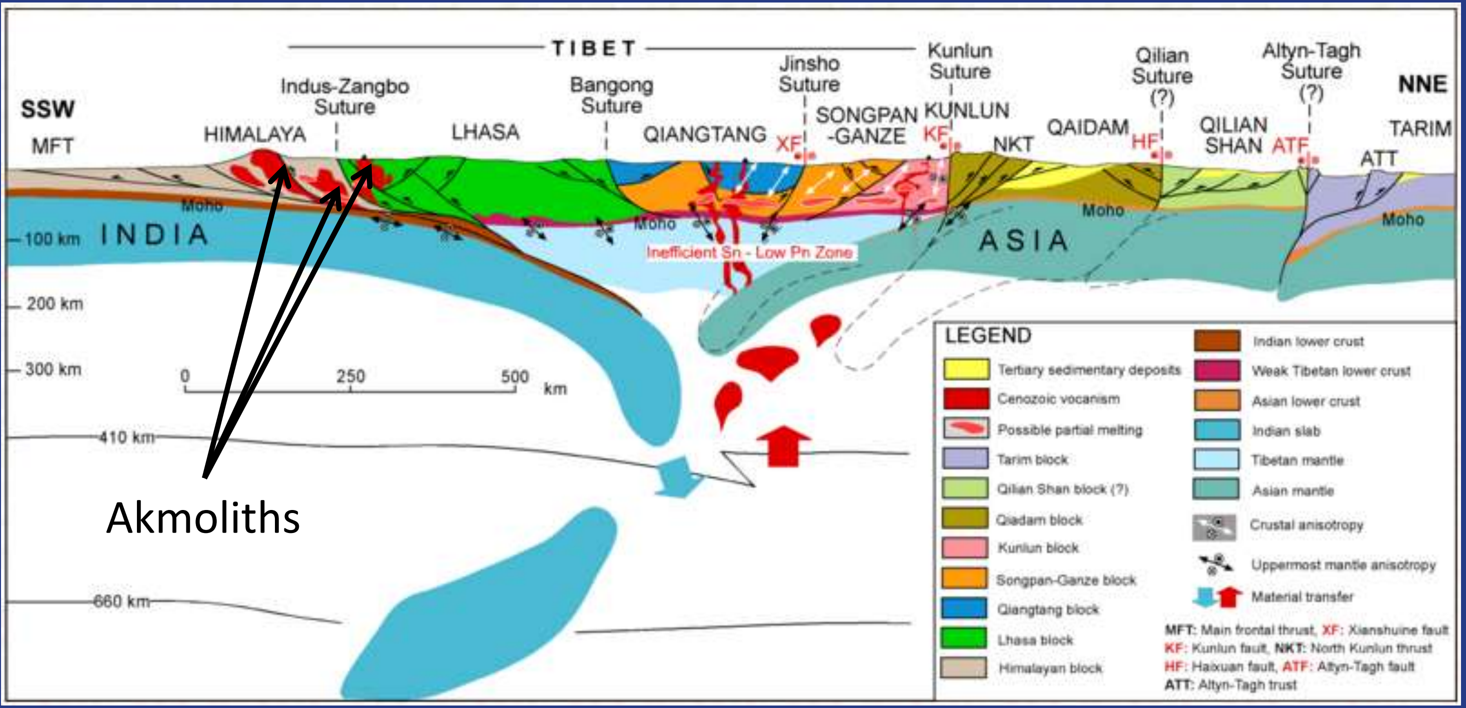


Cloos’ figure for his harpolith. Compare this with Harker’s phacolith.



Hans Cloos’ interpretation of the Bavarian intrusion, Southern Germany, as a harpolith. We must now call it a phacolith, not because the interpretation has changed, but because the term harpolith must now be abandoned because of the rules of priority.

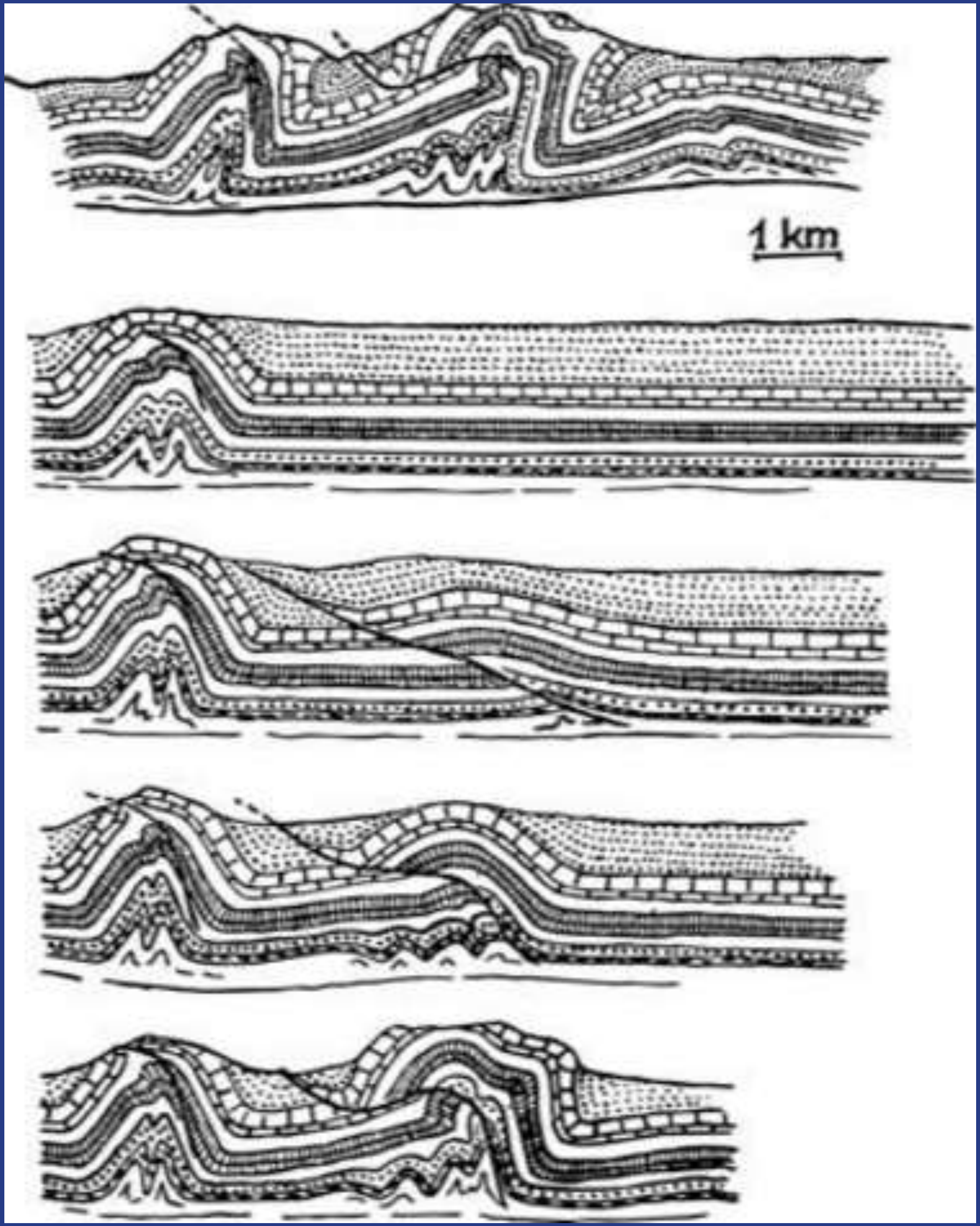
Akmolith (also spelled acmolith): An igneous body intruded along a décollement, i.e., detachment, surface with or without tongue-like intrusions into thrust surfaces dipping into the décollement. This term was proposed by the German geologist Otto Heinrich Erdmannsdörffer in 1924 from the Greek ἀκμή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



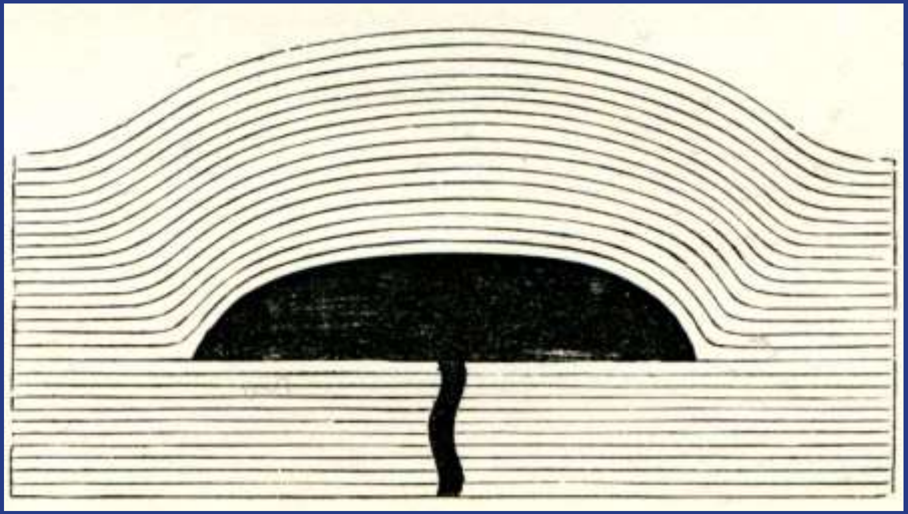
Folding over a décollement surface in the Jura Mountains, Switzerland

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).

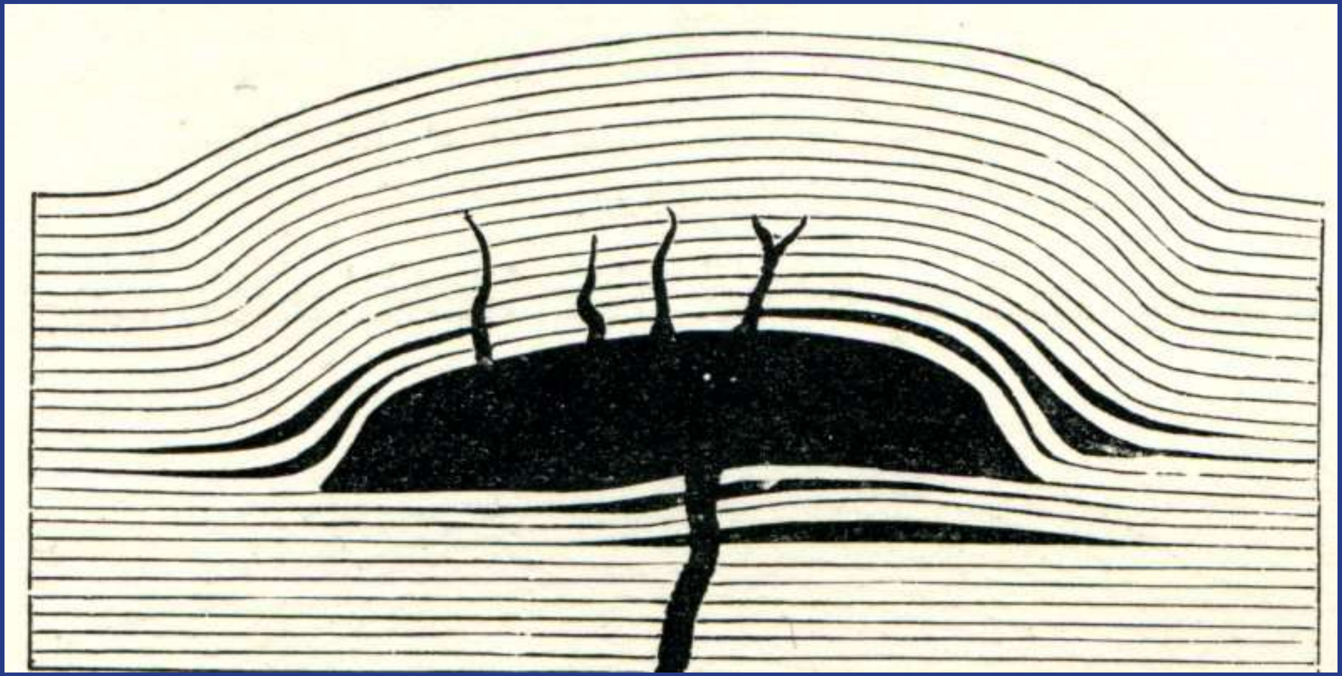
Griggs regrettably provided no figure for this feature.

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.

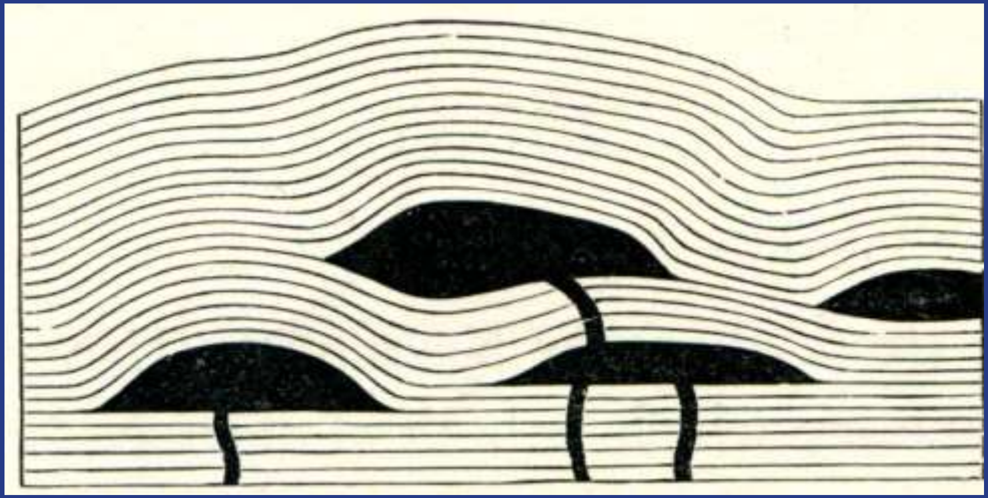
Gilbert derived the term laccolite from the Greek λάκκος (*lakkos*=cistern) and λίθος (*lithos*=stone)



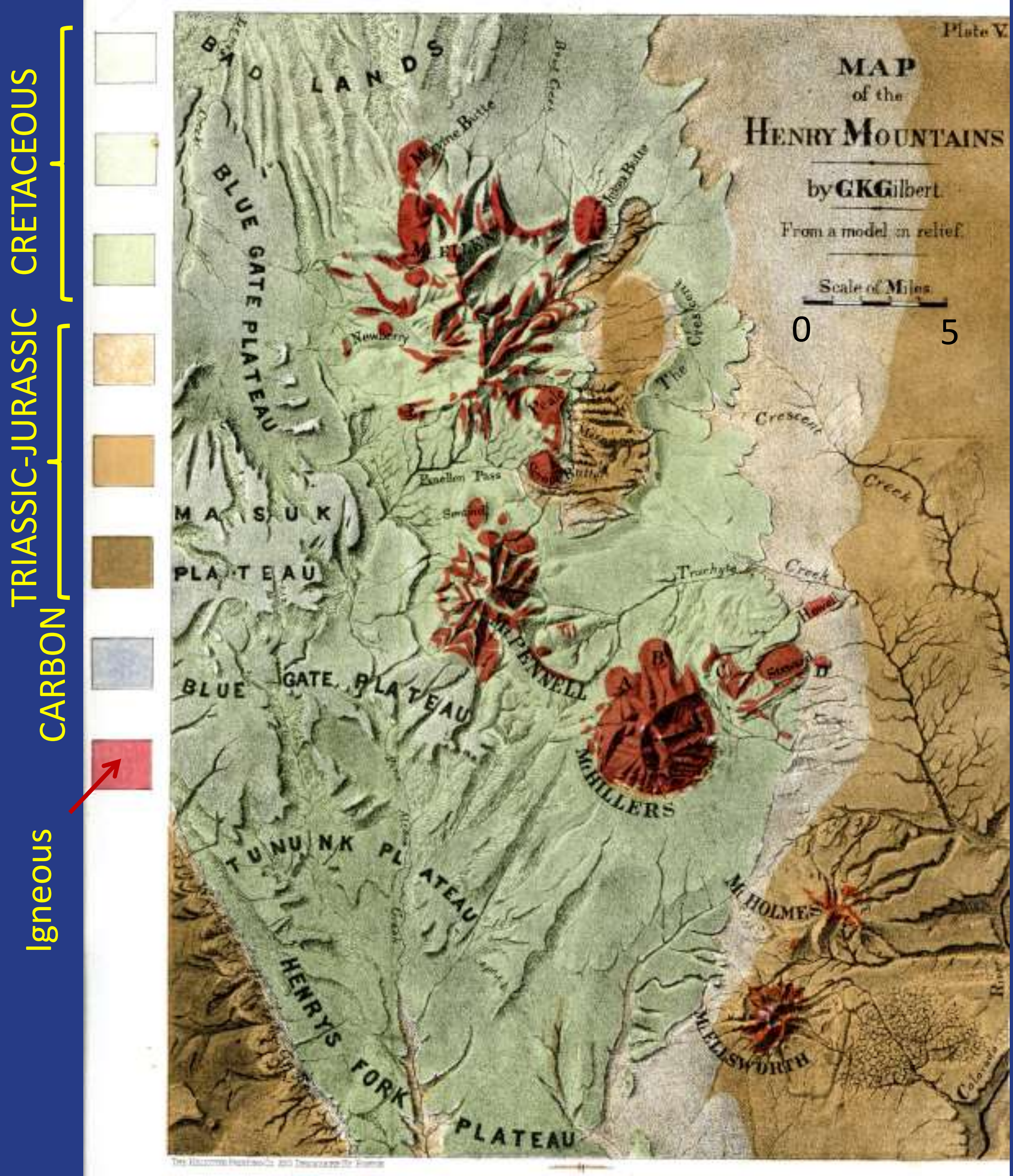
A schematic cross-section of a laccolith (from Gilbert 1877)



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

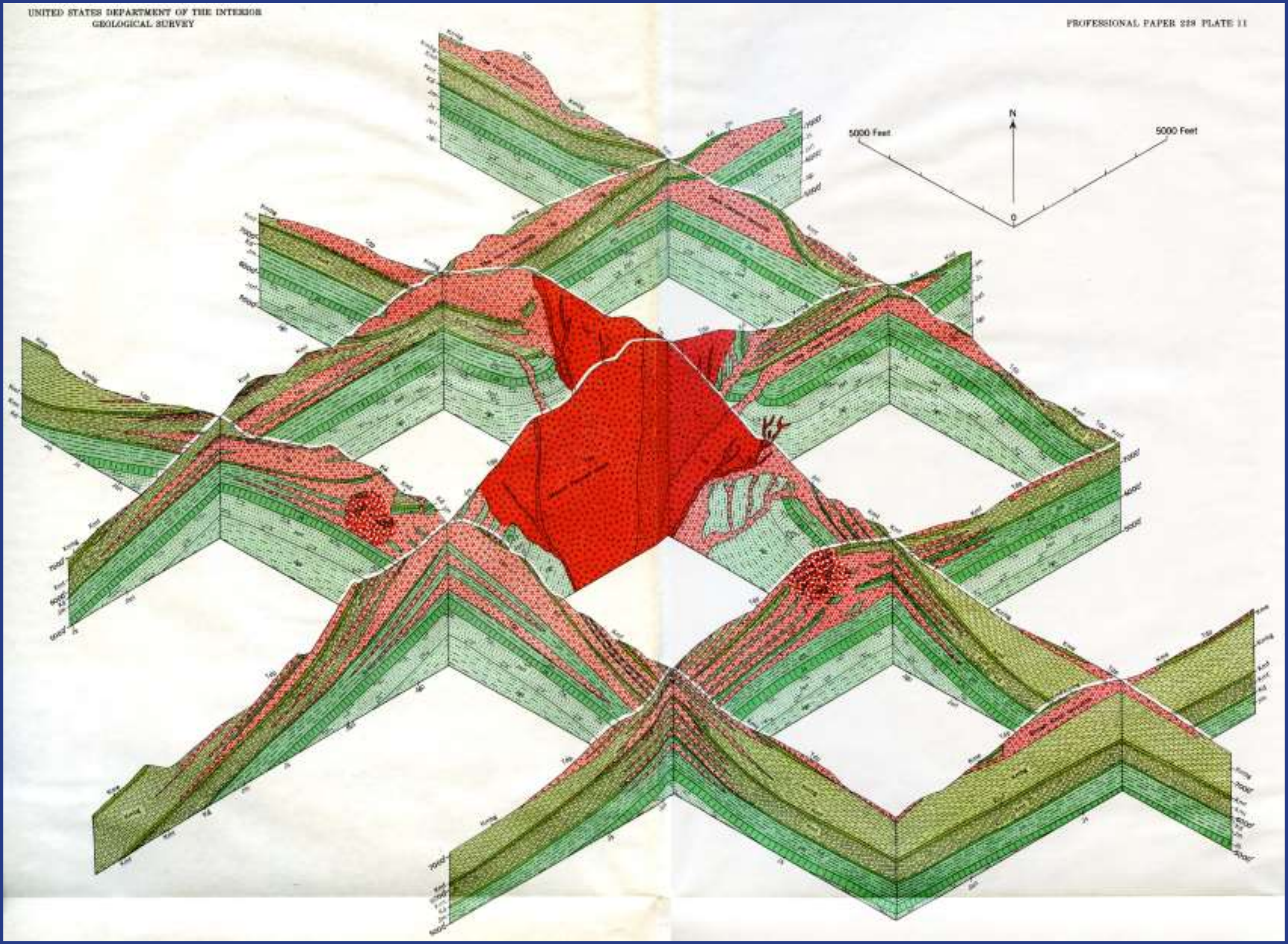


Ideal cross-section of grouped laccoliths (from Gilbert 1877)

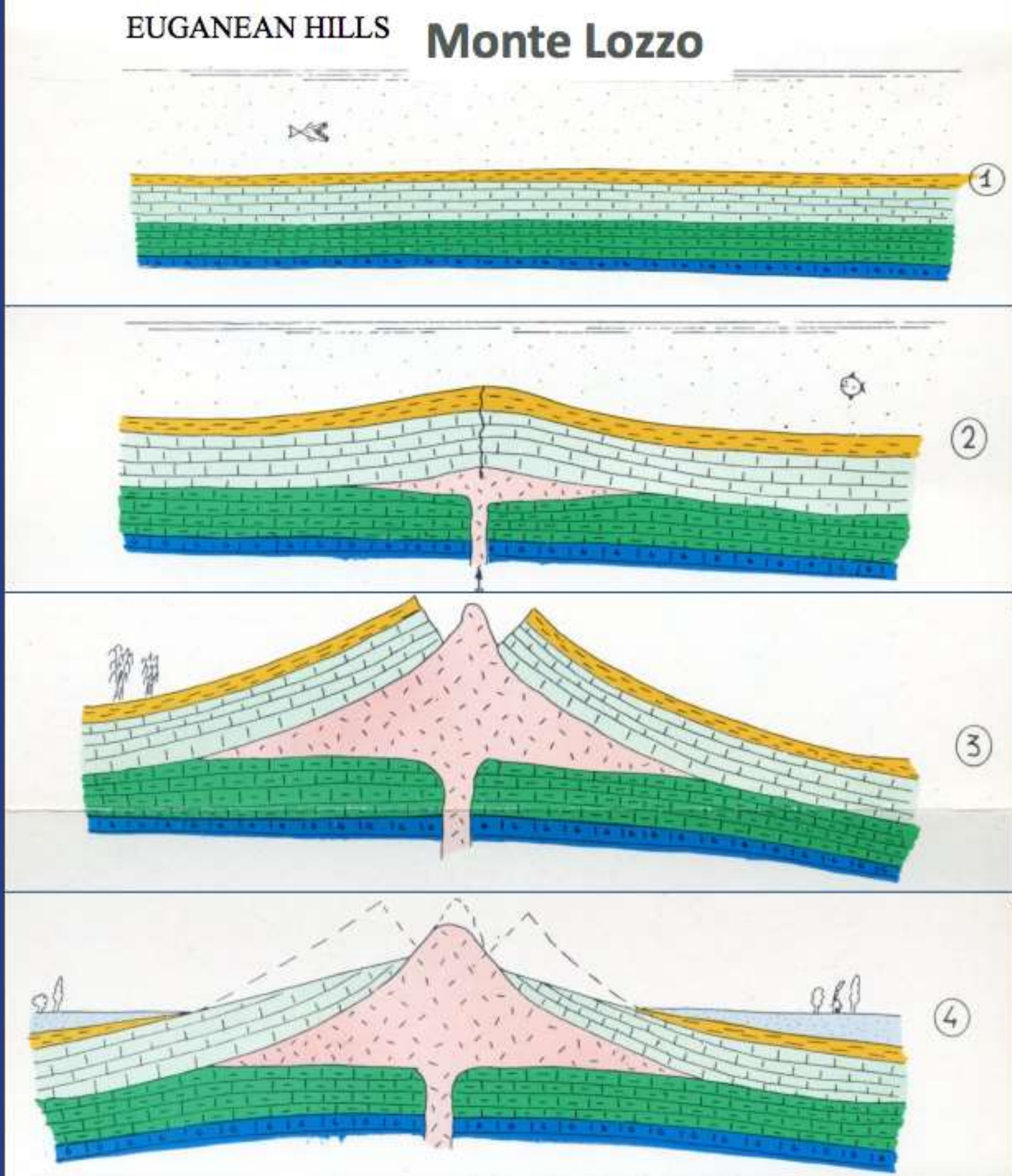


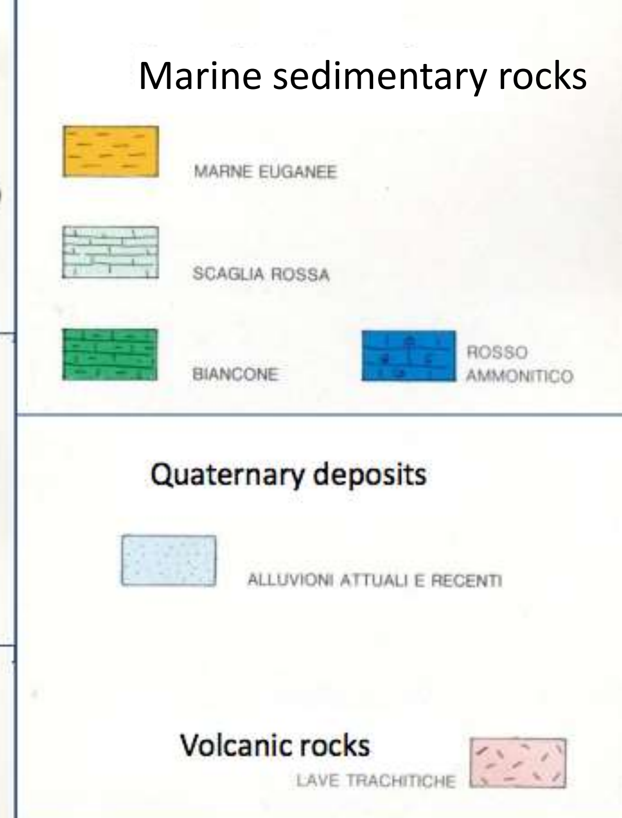
Geological map of the Henry Mountains region, Utah, showing the laccoliths (in red)

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)





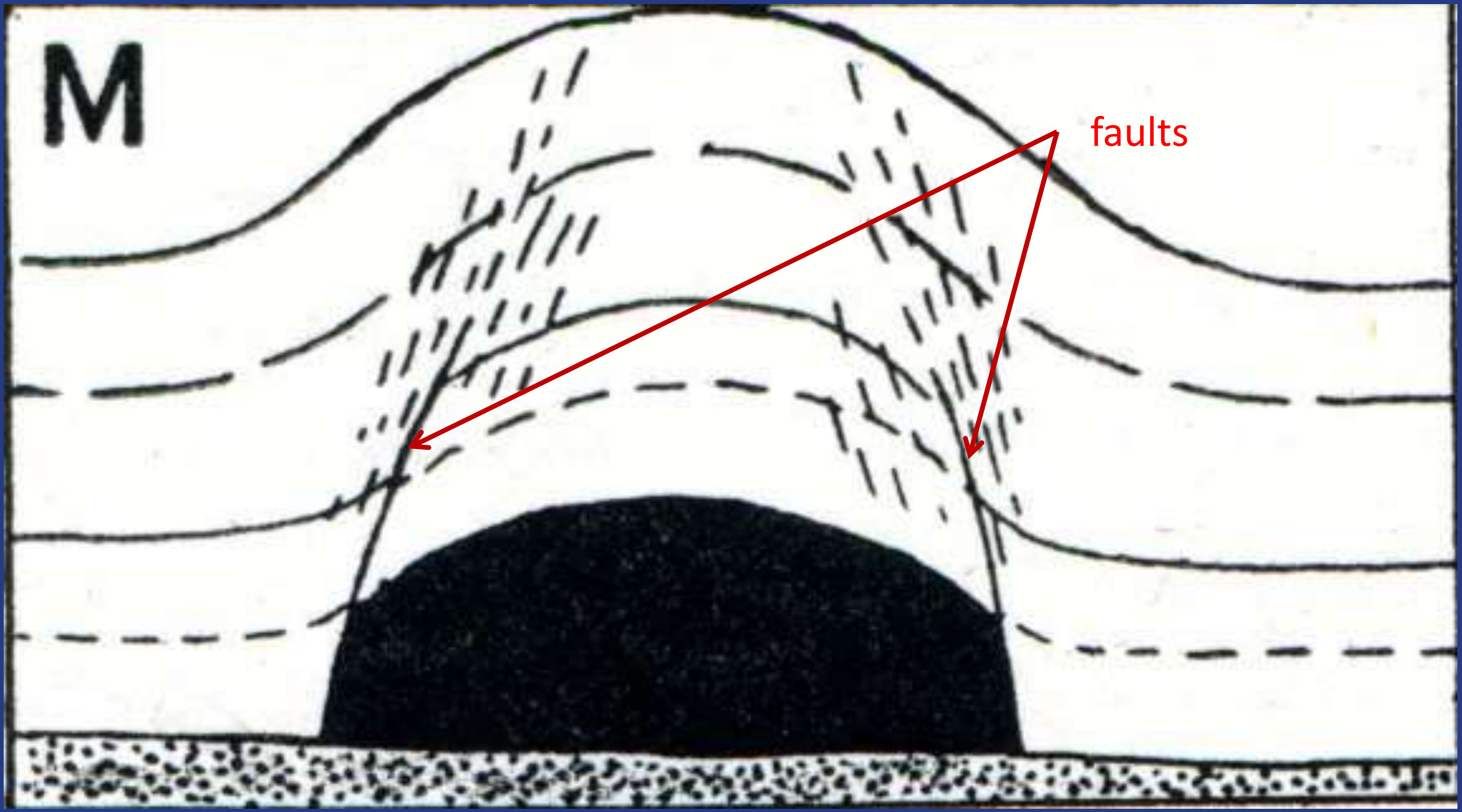
Lava pushed up the roof of older sedimentary rocks (2).
Than broke them (3)
The sedimentary cover has been eroded by atmospheric elements (4)

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

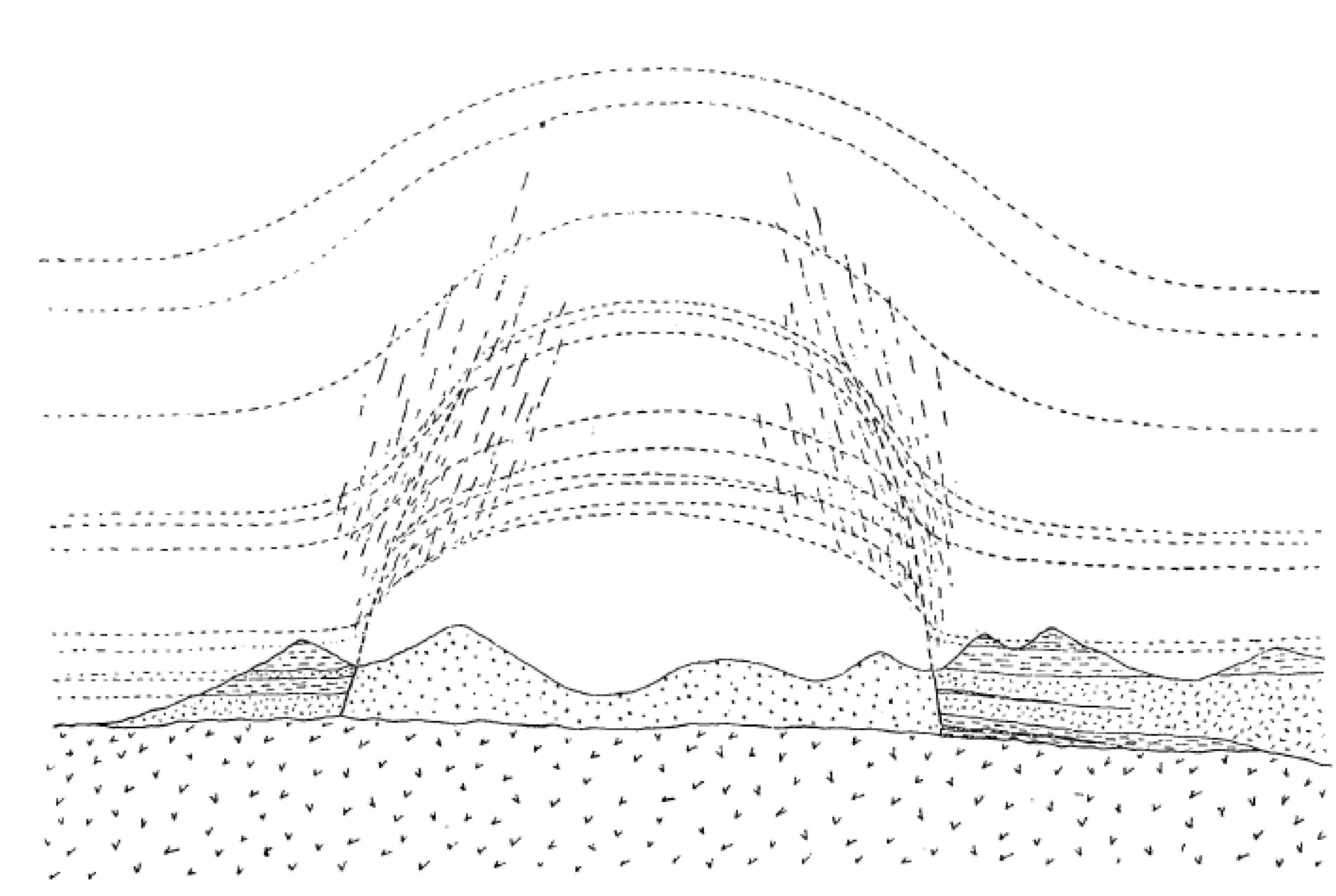
Monte Lozzo in the Euganean Hills, northern Italy

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

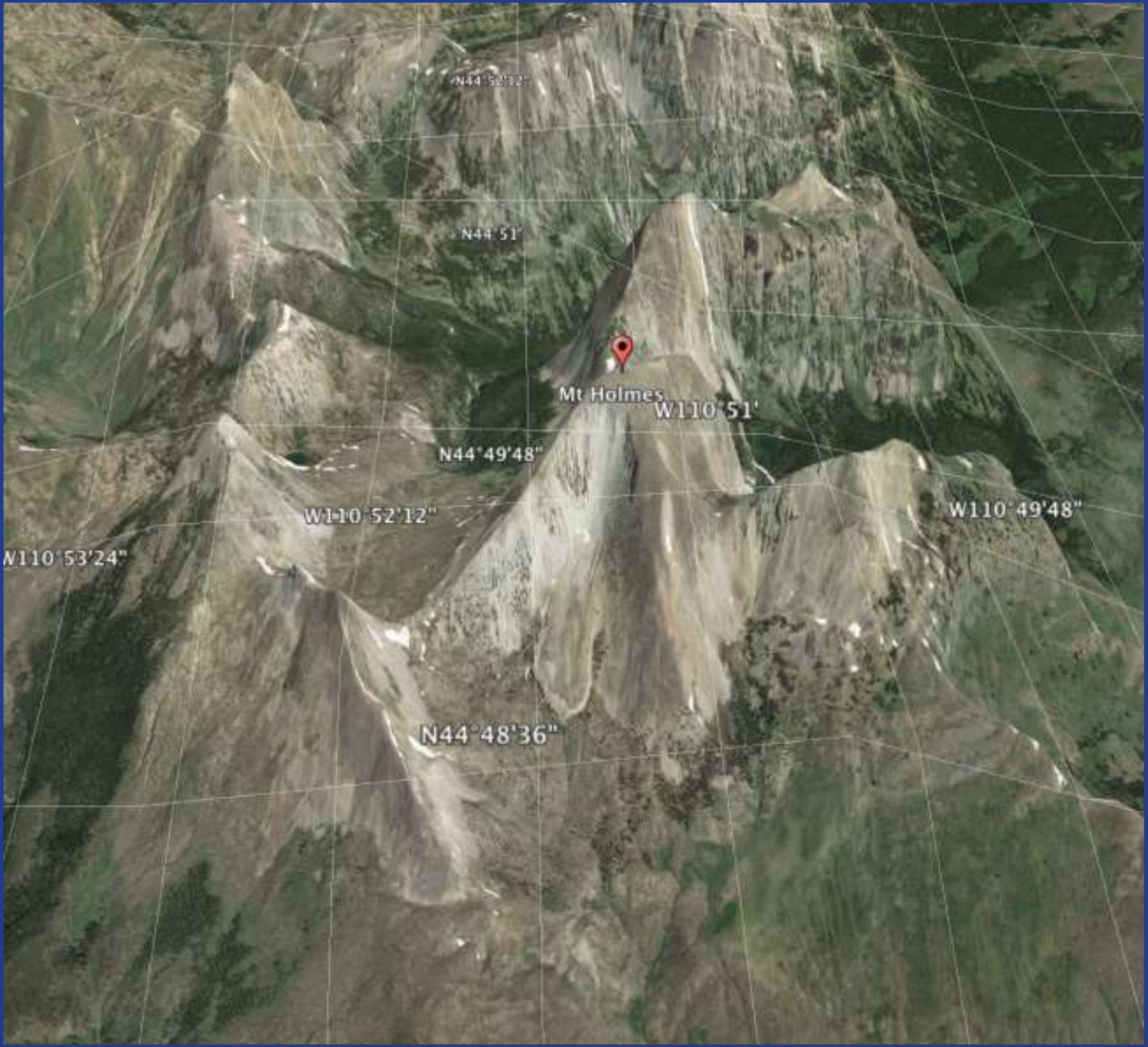
Traprain Law, seen from the north.



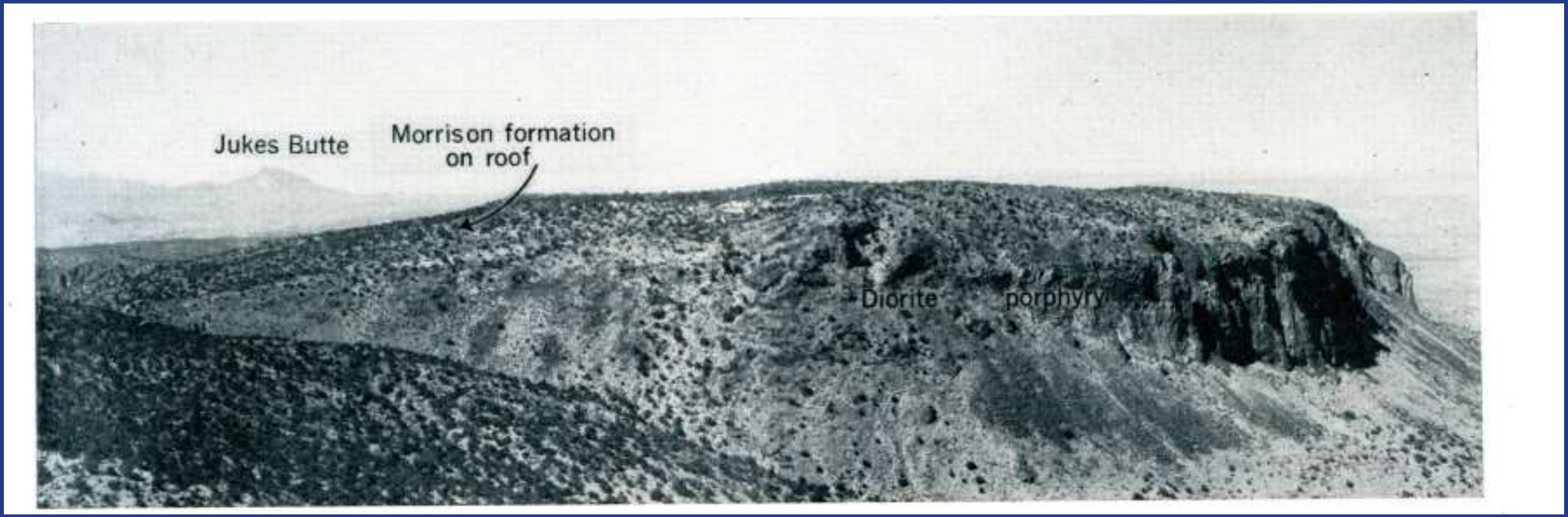
The term bysmalith was proposed by Iddings in 1898 for a more-or-less cylindrical body of igneous rock that forcefully injected and pushed like a piston the overlying rock carapace. It was derived from the Greek βύσμα (*bysma*=plug) and λίθος (*lithos*=stone). Bysmaliths are also called “bell-jar intrusions”



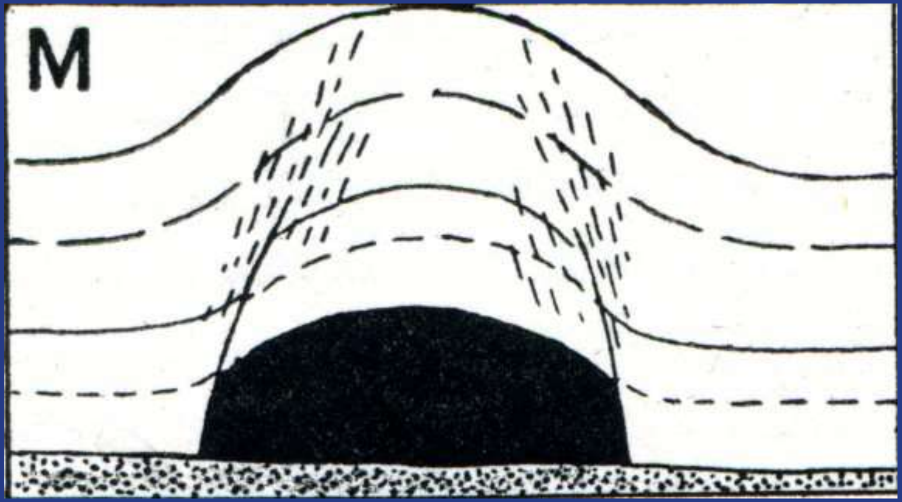
The Mt. Holmes dacite porphyry bysmalith
according to Iddings 1898.



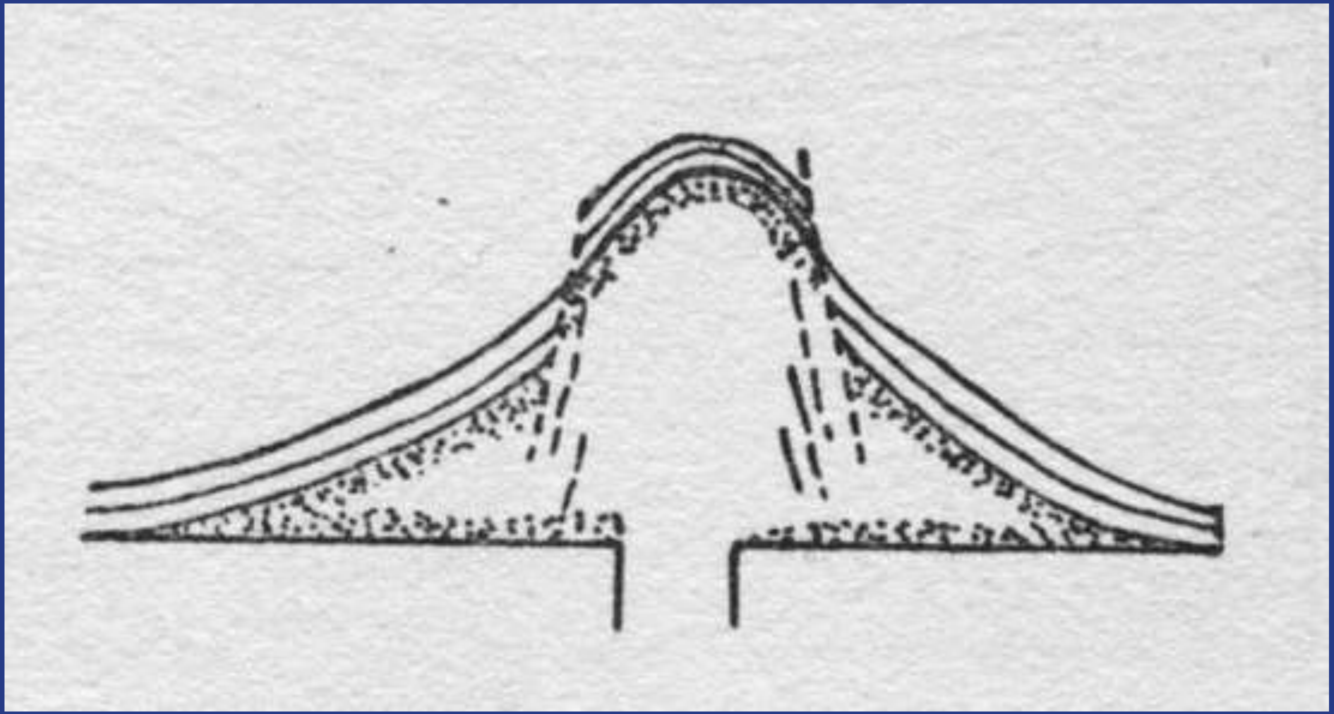
The Mt. Holmes dacite porphyry bysmalith, Yellowstone National Park, Wyoming, USA



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.

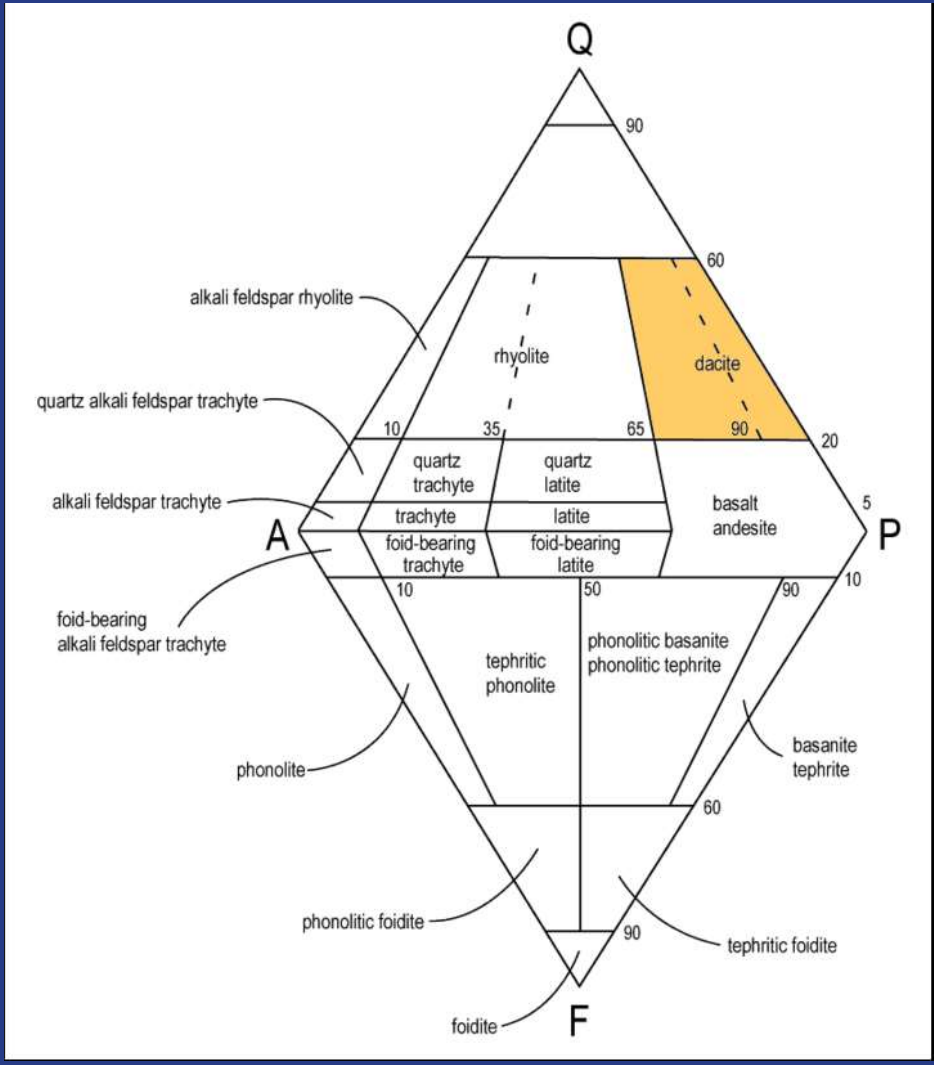
This schematic section is from Tyrell 1929.

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.

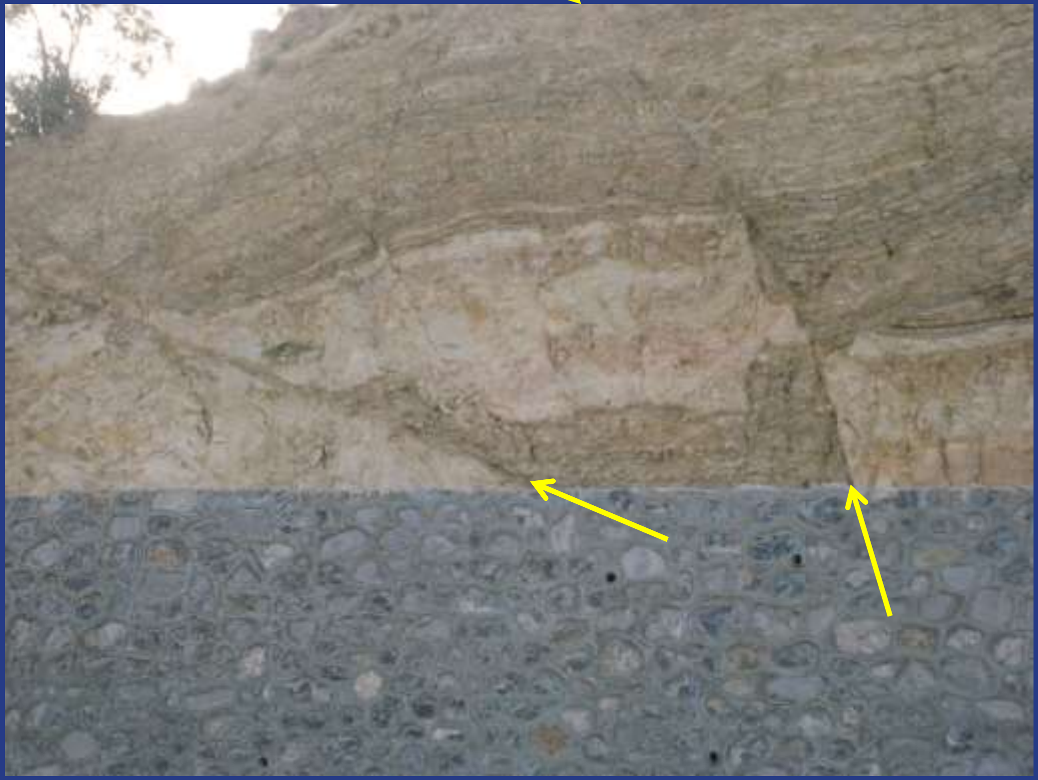
The name dacite comes from the ancient Roman province of Dacia, now western Romania, and was proposed in 1863 by the Austrian geologists Franz Ritter von Hauer and Guido Stache on p. 72 in their book on the geology of Transylvania (=Siebenbürgen)



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.



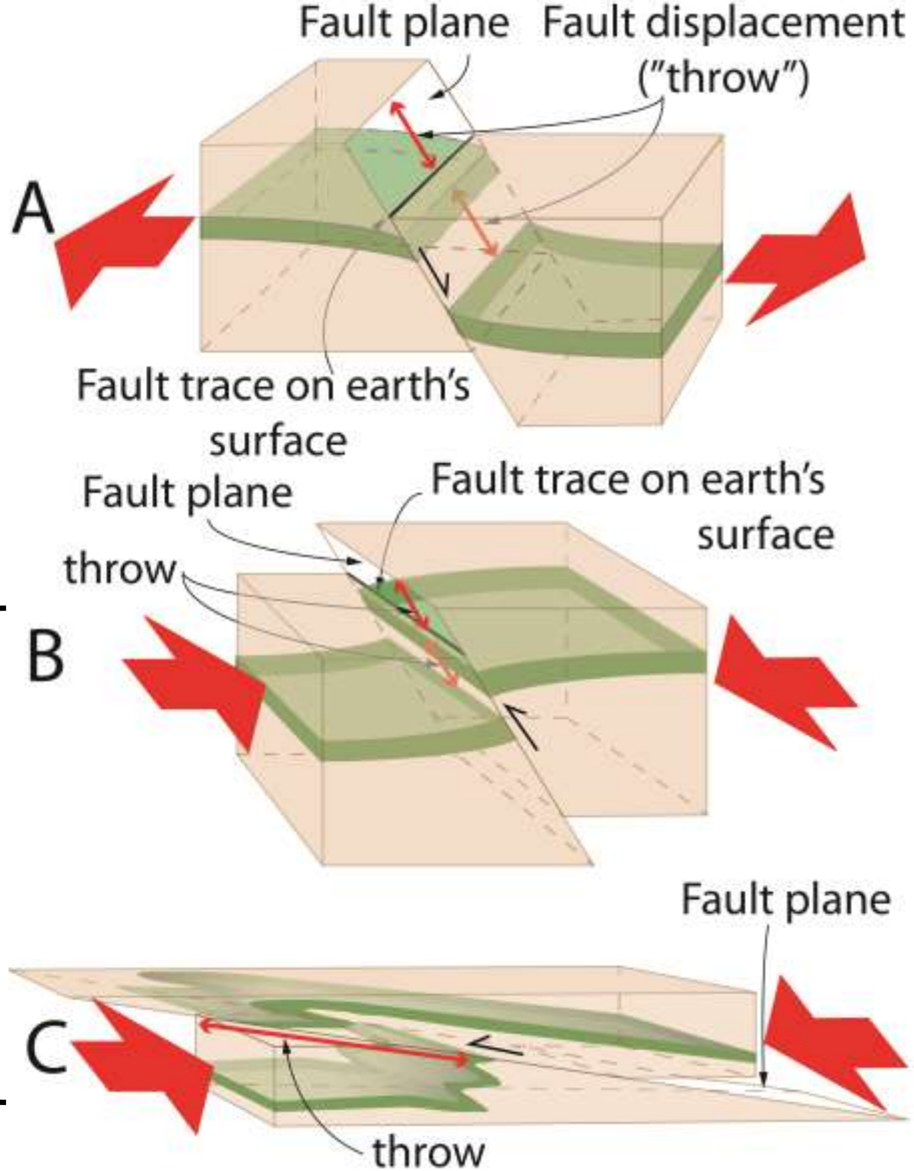
Mesoscopic scale faults near Burhaniye, western Turkey

The Owens Valley earthquake fault, 1872, California, USA

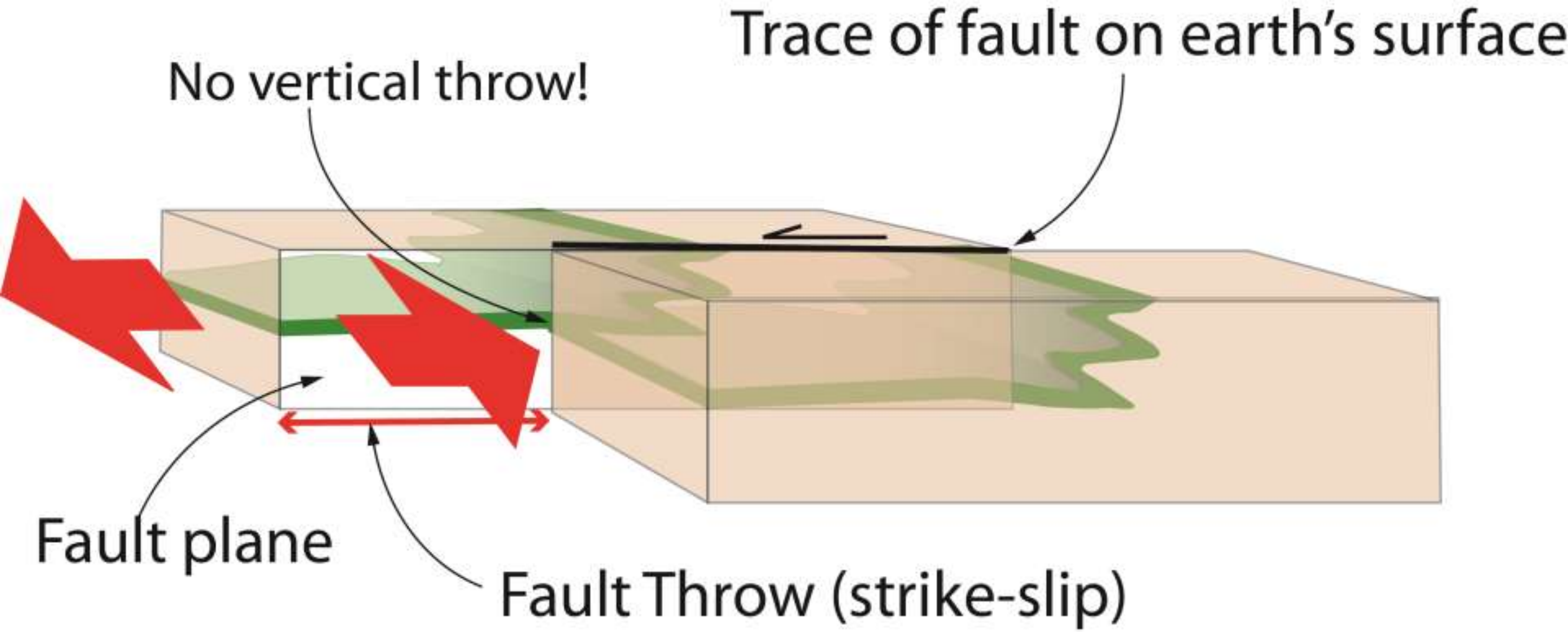
The famous Glarus thrust fault, Switzerland

Normal dip-slip fault

Reverse dip-slip fault



Kinds of dip-slip faults

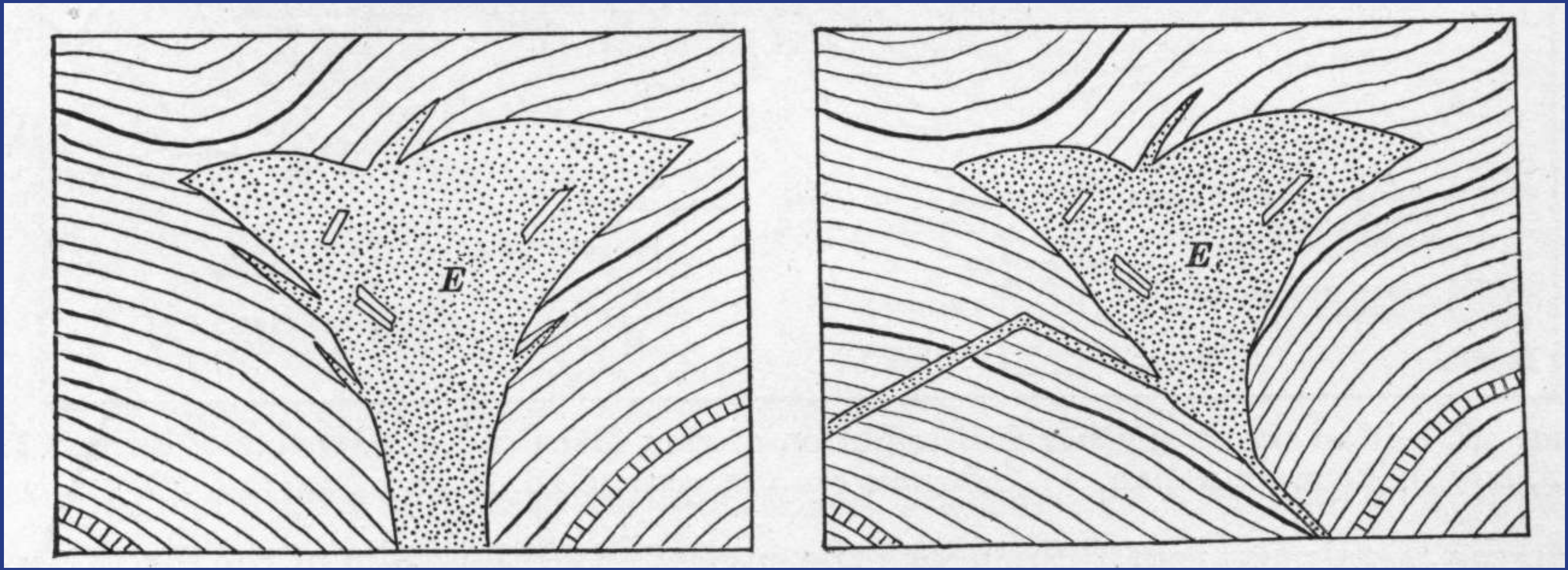


Strike-slip fault

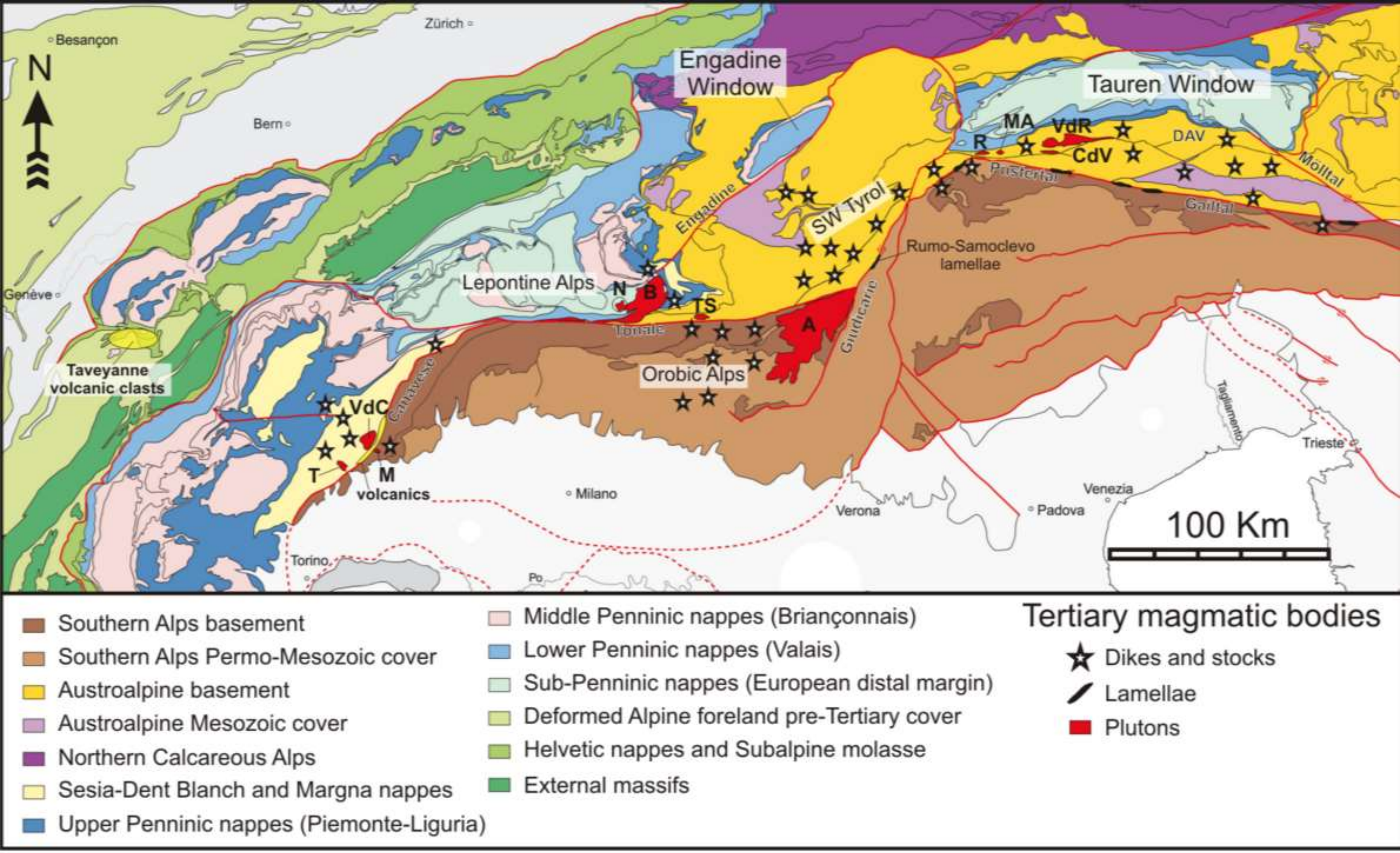
Sphenolith: Sphenolith is a wedge-shaped intrusion, partly concordant and partly discordant, whereby its end may consist of a number of wedges presenting a saw-tooth appearance. It was proposed by the Swiss geologist Carl Burkhardt in 1906 for the dacitic intrusion of Las Parroquias in Mexico. The term is derived from the Greek σφήν (*sphen*=wedge).

The type sphenolith: The diorite of las Parroquias, Mexico. From Burkhardt, 1906

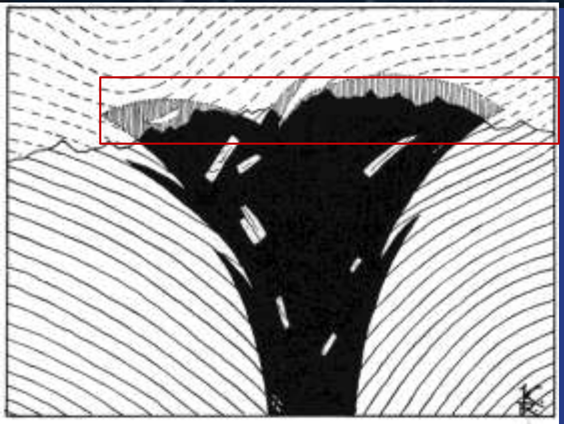
Etmolith: Ethmolith is a funnel-shaped discordant intrusion . The term comes from the Greek ἠθμός (*ethmos*=strainer) and was proposed for the large Adamello intrusion in the Southern Alps by Wilhelm Salomon in 1903.



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

Deep-seated plutonic rocks.

Deep seated plutonic rocks usually occur in batholiths.

The term batholith was introduced by Eduard Suess, perhaps the greatest geologist who ever lived, in 1883 in the first part of the first volume of his great classic *Das Antlitz der Erde* (The Face of the Earth), p. 219. The term is derived from the Greek βάθος (*bathos*= depth or height) and λίθος (*lithos*=stone).

There Suess imagined a batholith to be a lens-shaped intrusion formed by granitic magma filling the empty spaces created by tectonic motions.

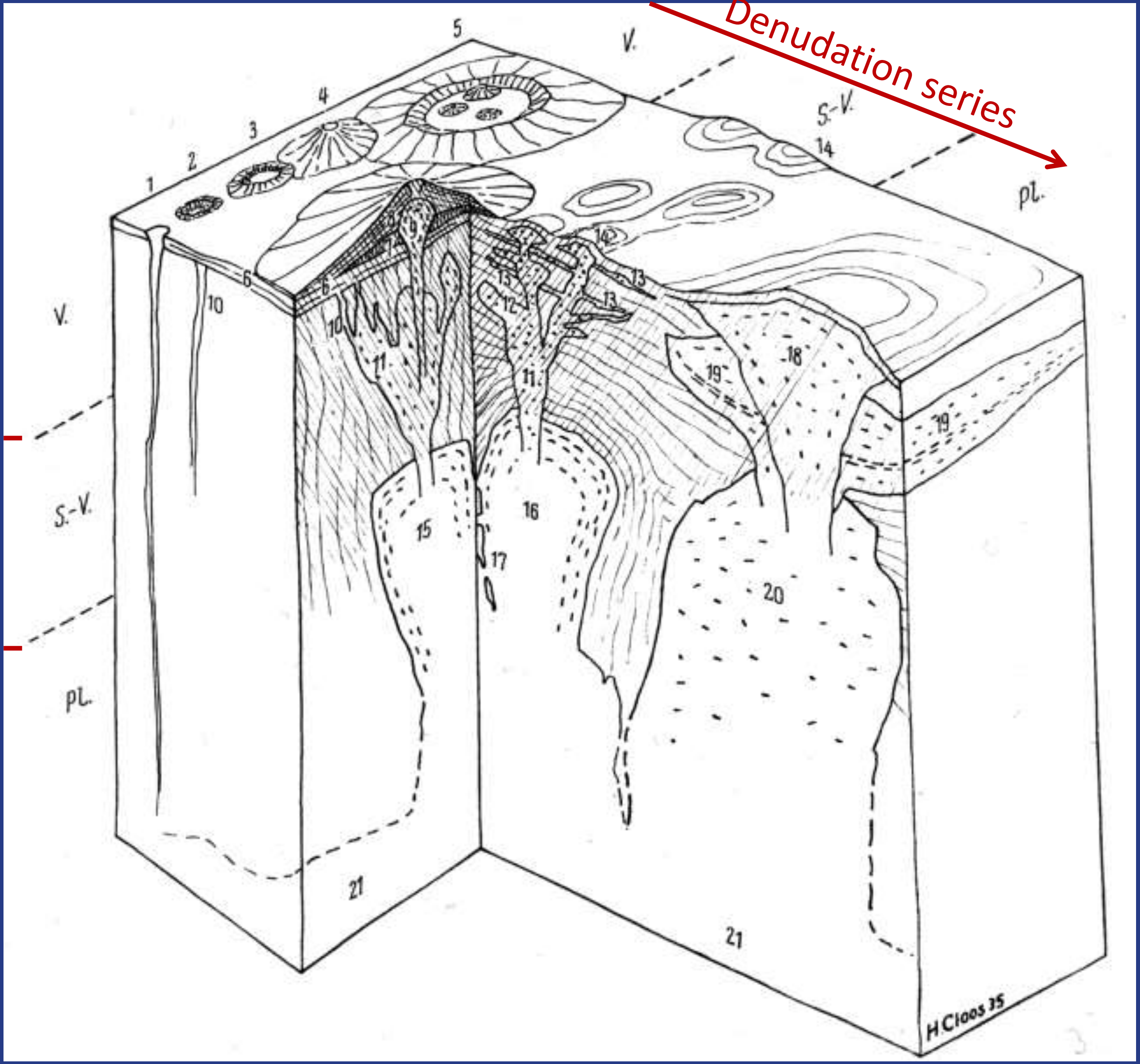
Later Suess becase convinced that the granite batholiths make their own space by melting and incorporating their country rocks piece-meal into themselves (Suess 1909, pp 633 ff). He cited Dalys's idea of overhead stoping, i.e. the collapse of parts of the roof of the batholith into itself.

Diapiric rise of the batholiths have been considered seriously first by the American geologist Frank Grout in 1945, although many geologists before hat noted that batholiths behaved like salt domes. The problem they had was that the cause of the rise of salt domes had remained highly contested.

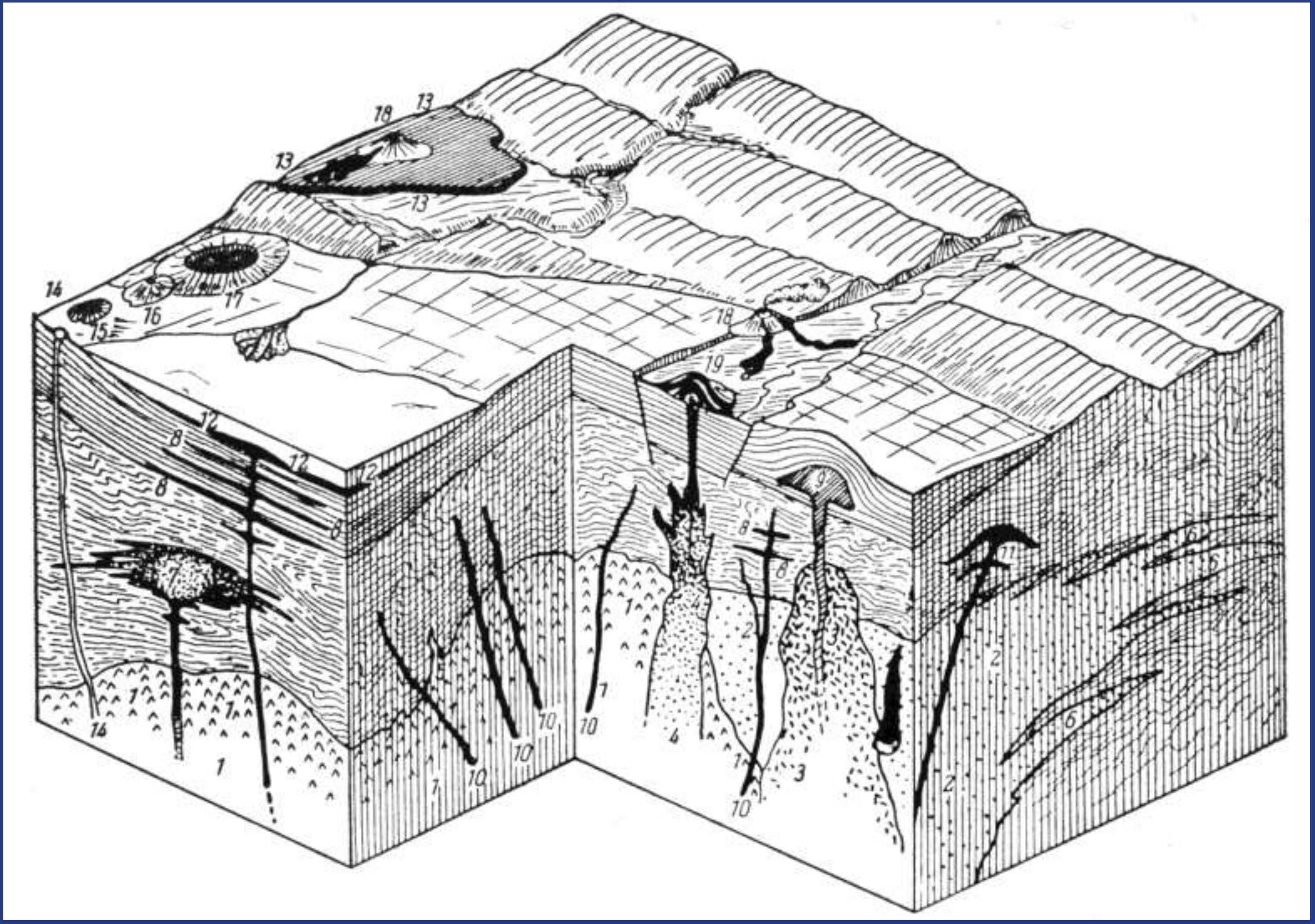
Volcanic

Sub-volcanic

Plutonic

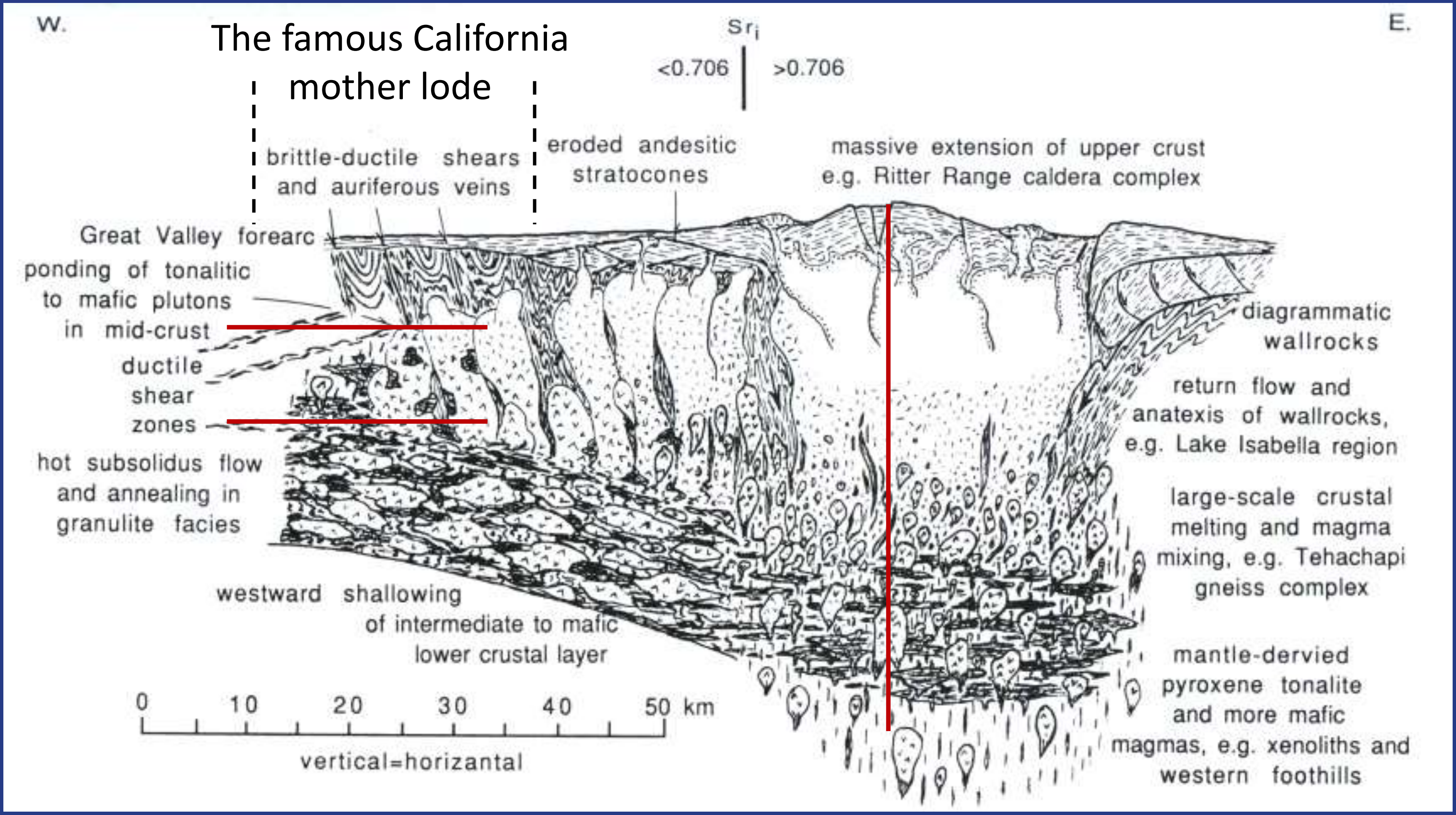


Places of origin of magmatic rocks (after Hans Cloos, 1936).



Places of origin of magmatic rocks (after Radim Kettner, 1936).

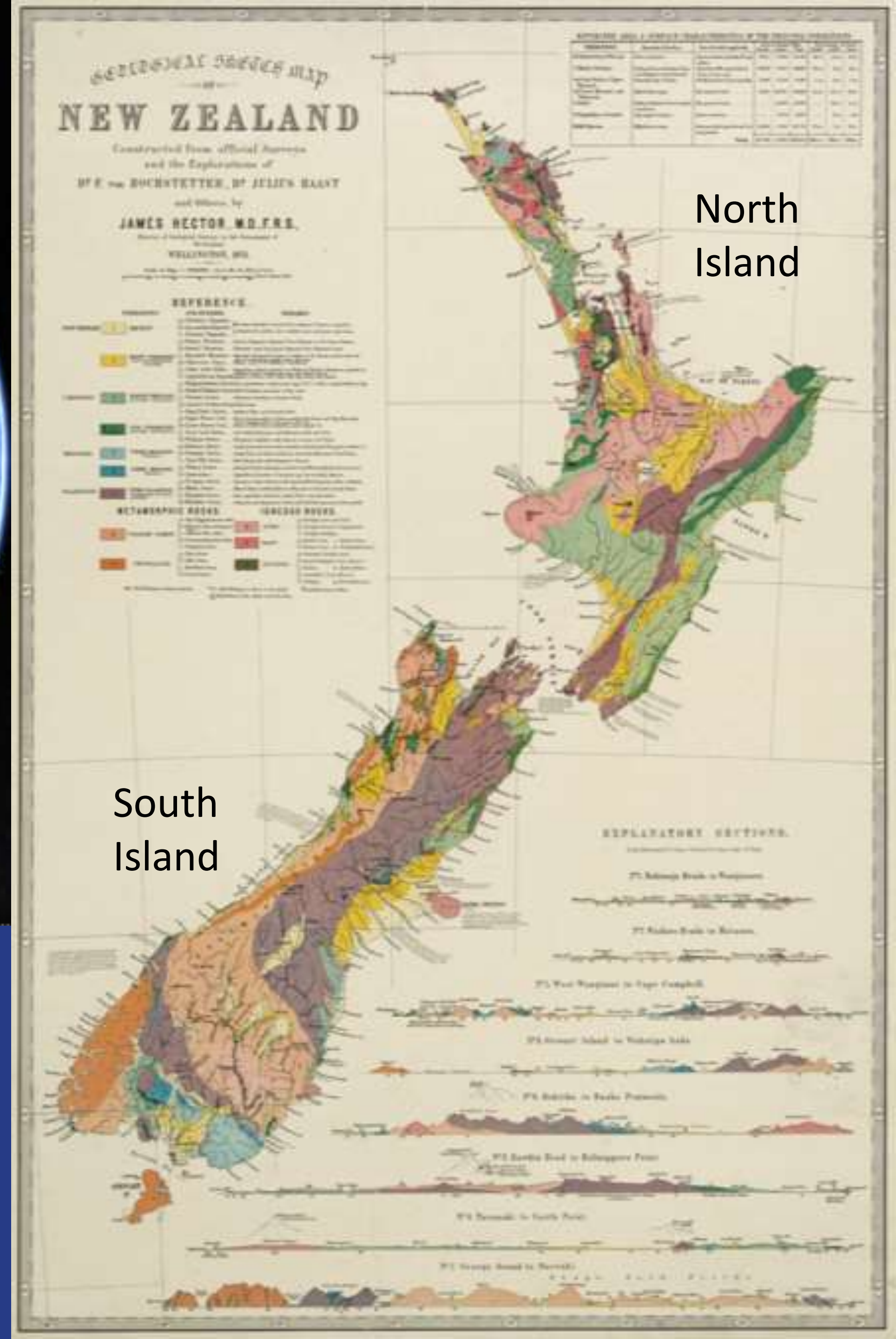
Location of the Sierra Nevada batholith, California, western United States



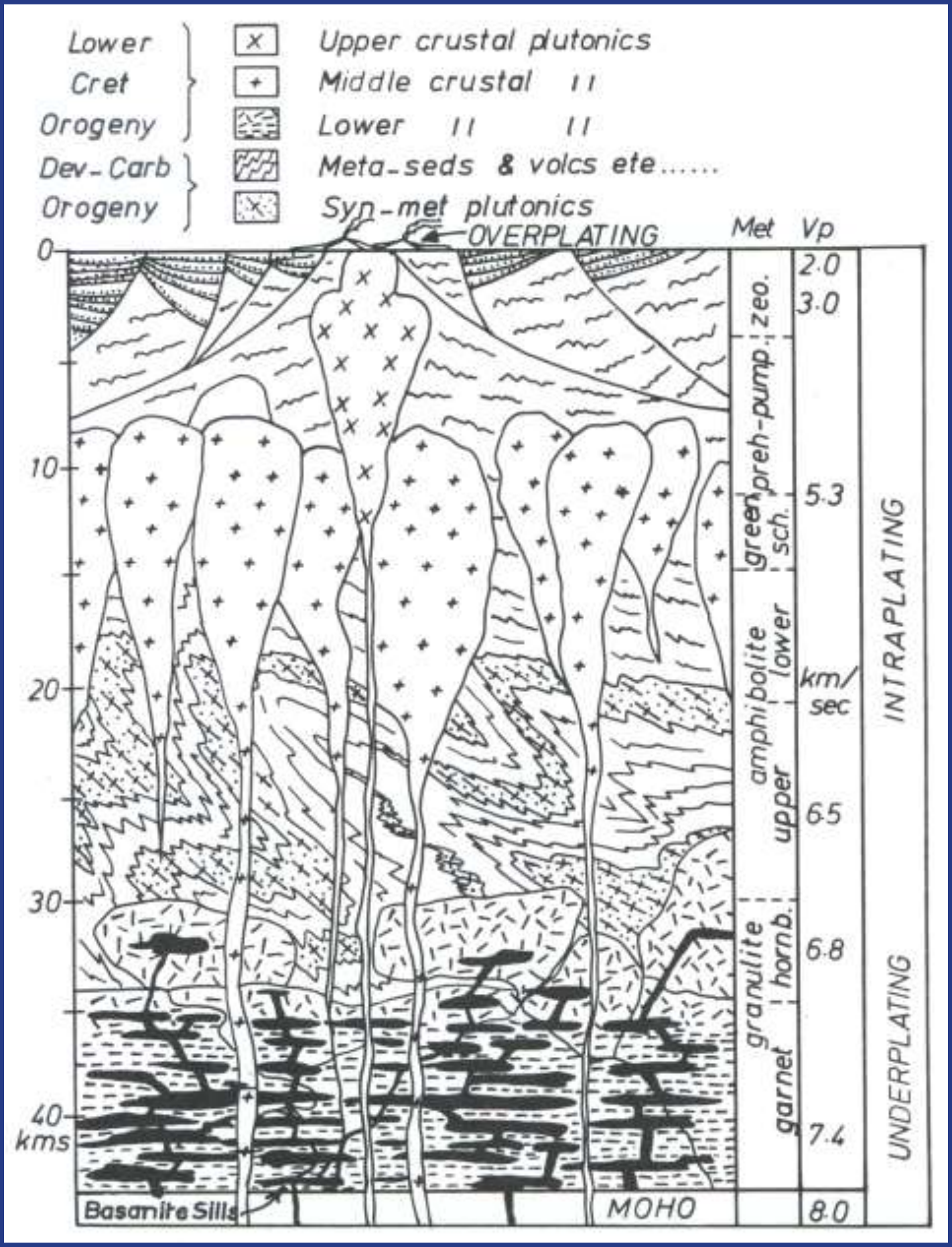
A cross-section of the Sierra Nevada batholith in California, western USA from Saleeby, 1990

People panning for gold near the mother lode in California during the 1849 California gold rush

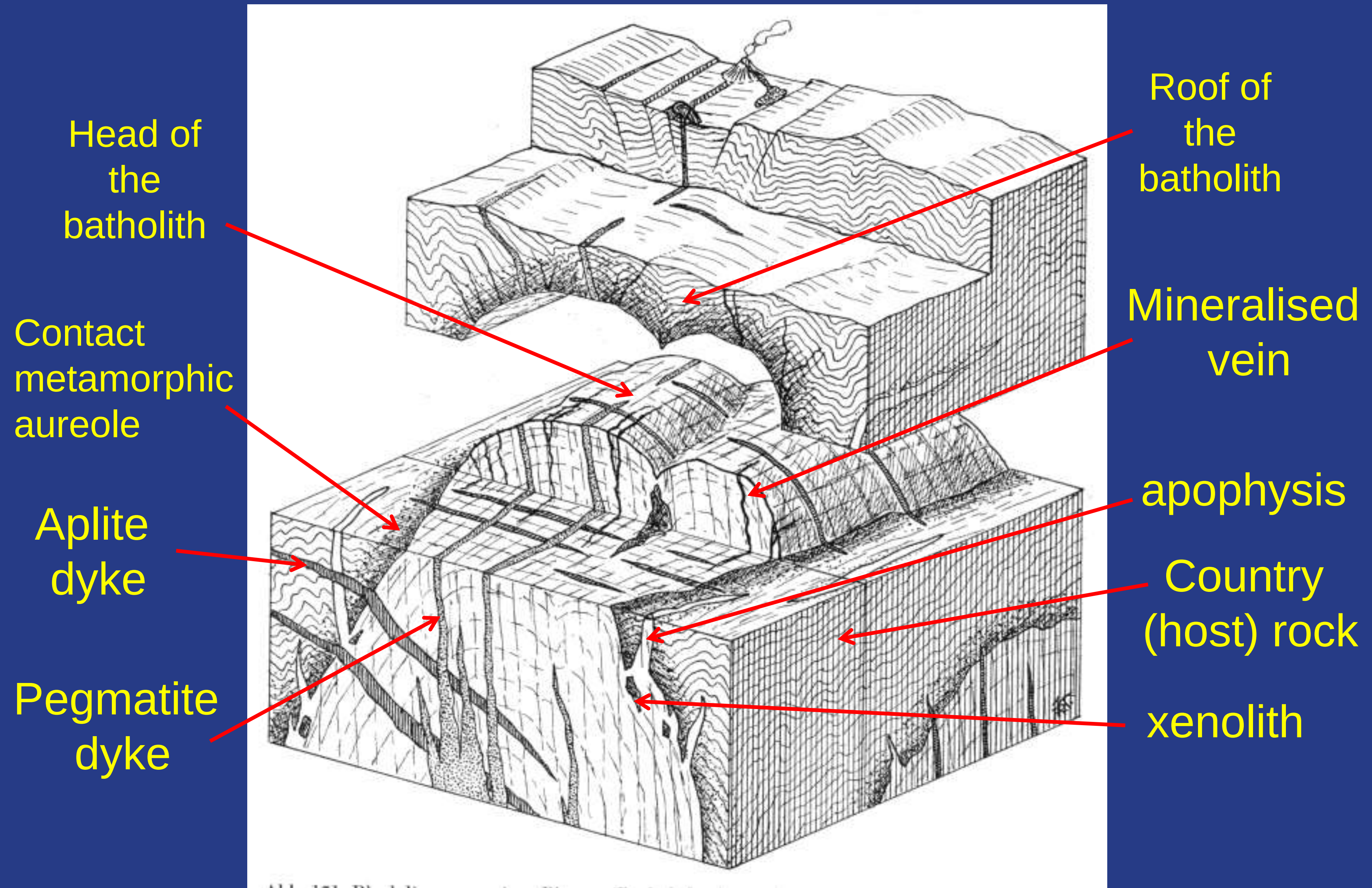
USA postal stamp of 1999 commemorating the sesquicentennial of the 1849 gold rush in California



Location and geological map of New Zealand



Inferred crustal model for the western part of the South Island, New Zealand (from Oliver, 1990)



Mesoscopic and makroscopic structures of a batholith (from Kettner, 1936)

There are two new terms here:

Xenolith: Xenolith is a piece of rock, either from the country rock or from an earlier part of the intrusion, that is caught up within the intrusion. It comes from the Greek words ξένος (*xenos*=friendly stranger, guest) and λίθος (*lithos*=stone). It was introduced into the geological terminology in 1894 by the English geologist William Johnson Sollas.

A porphyritic xenolith in the Sierra Nevada granodiorite pluton, California, USA.

Xenoliths picked up from the country rock by a granite. Unknown locality.

If the xenolith consists of a single crystal it is termed a xenocryst.

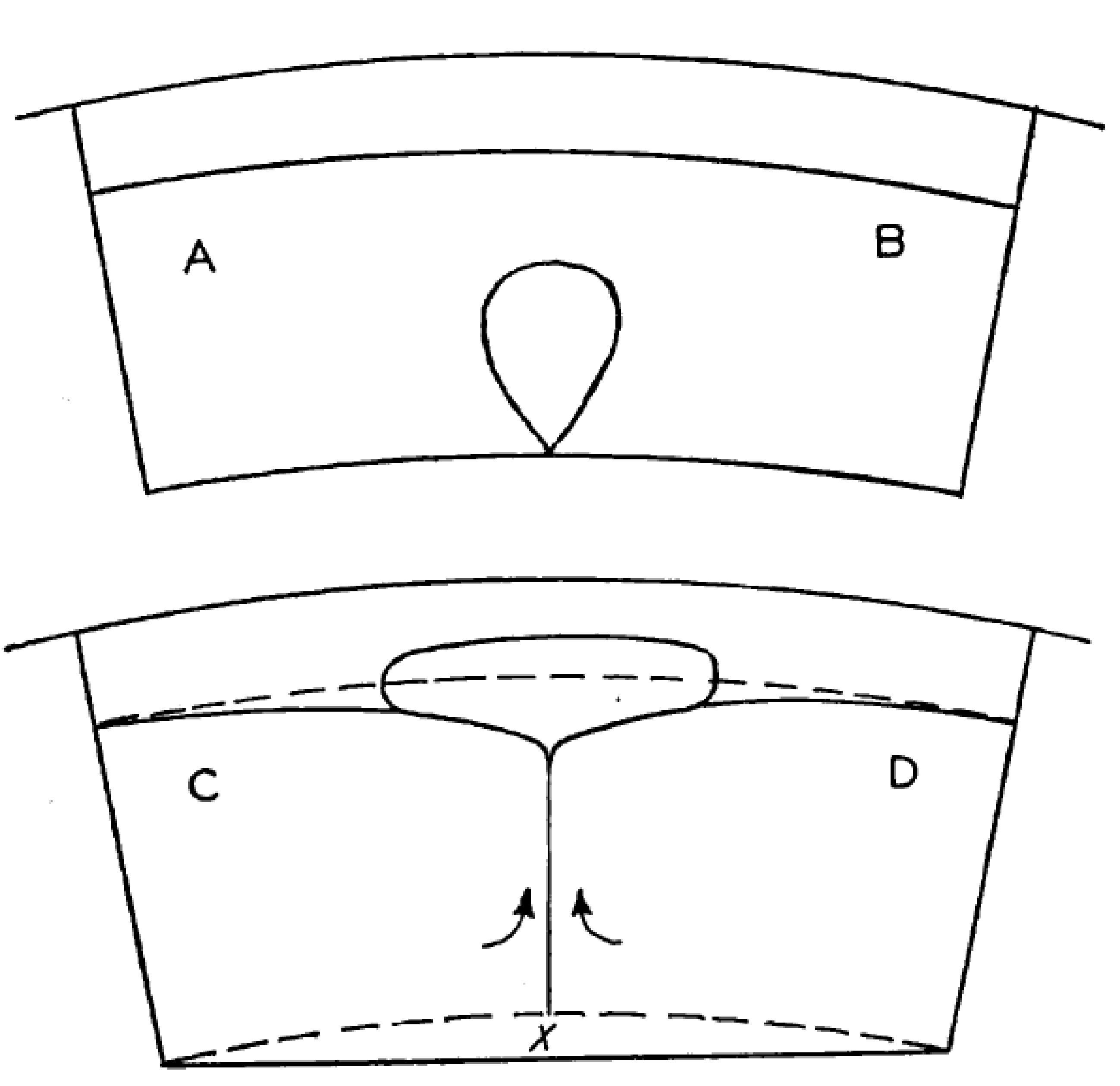
Clinopyroxene xenocrysts in a kimberlite

Apophysis (also apophyse): an apophysis is a vein, tongue or a small dyke that can be directly traced to a larger intrusion, of which it is an offshoot. It comes from the Greek ἀπό (*apo*=away from) and φύσις (*physis*= form, stature). It plural form is apophyses.

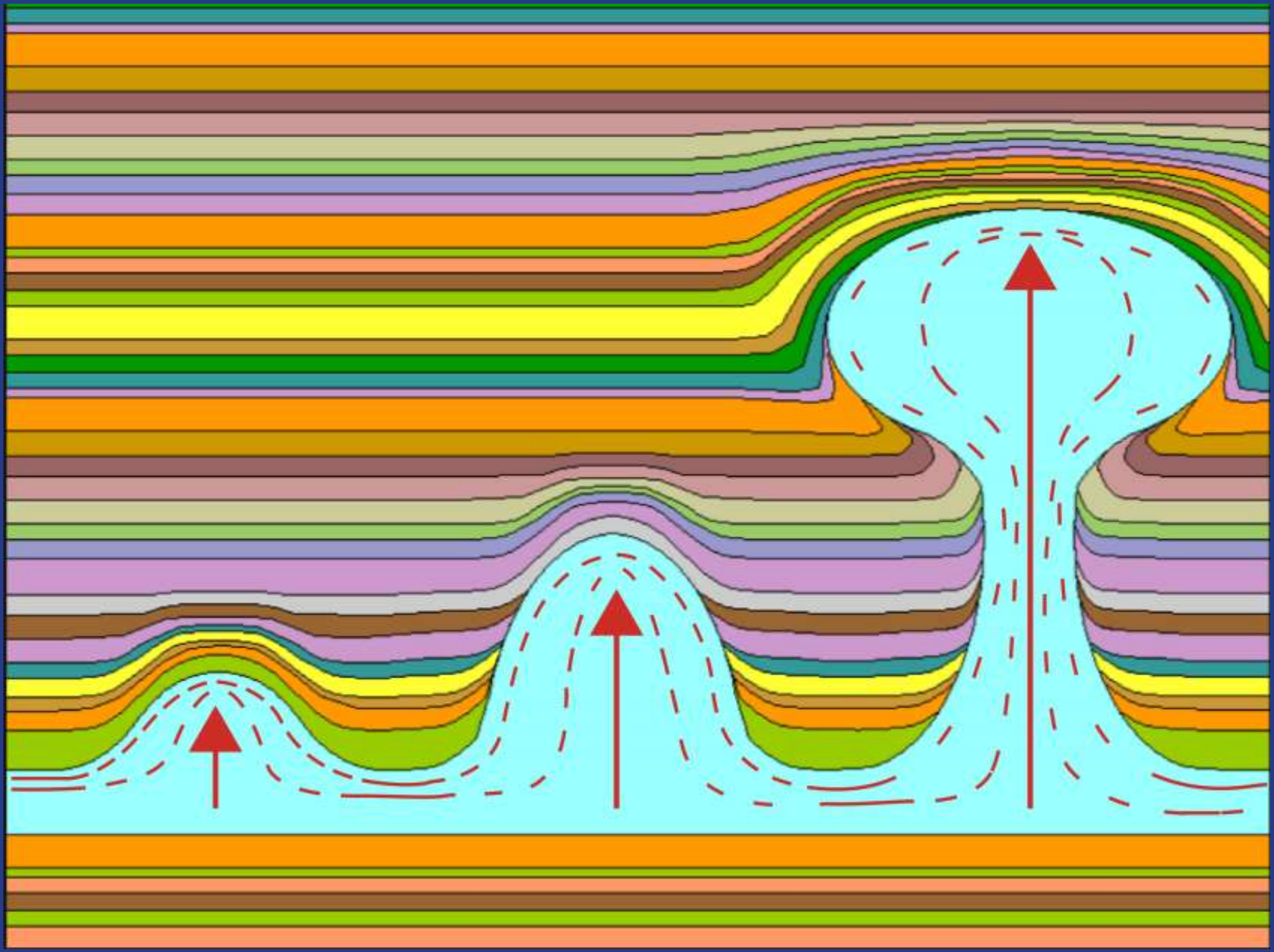
An epiphysis is an unattached vein or tongue or dyke somehow related to the intrusion. From the Greek ἔπί (*epi*=upon, on).

American Geological Institute (AGI) *Glossary of Geology* considers apophysis and epipysis equivalent, which is wrong.

Roof of a granite batholith with its apophyses and epiphyses. Ivory Coast, Africa.



Diapiric rise and spreading of a batholith at a density discontinuity in the crust (after Grout, 1945)



Generation of internal fabric in diapirs

All batholiths emplaced at lower or middle crustal levels have an internal architecture characterised by flow structures. Towards the centre of the batholith the granite is usually undeformed. Maximum deformation is seen along the sides and the top of the pluton and along its stem.

The top is characterised by pure flattening or what is called vertical shortening.

The stem exhibits constriction texture which is lengthening and all sided constriction

The sides exhibit simple shear strains.

Because of these deformations, near the sides the igneous rocks within a batholith display gneissic texture.

In is very important not to confuse the batholith-margin-gneisses with the gneisses formed by regional deformation and metamorphism of granites and pelitic rocks. This latter category we shall see later in the course.

Here again we have a new term: gneiss

Gneiss is a textural term. It designates a phaneritic rock with a strong foliation that usually has a wavy aspect. This wavy aspect is commonly the result of the presence of less deformed mineral crystals along the foliation planes.

The word gneiss may come from the Middle High German noun *ganeist* (also *gneist*) meaning a spark. It came into geology via the German miners. The Grimm dictionary says, however, that its origin is uncertain.

What is foliation?

Foliation is the ability of a piece of rock to split along foliae that are the result of deformation. It comes from the Latin word *folium* meaning a leaf.

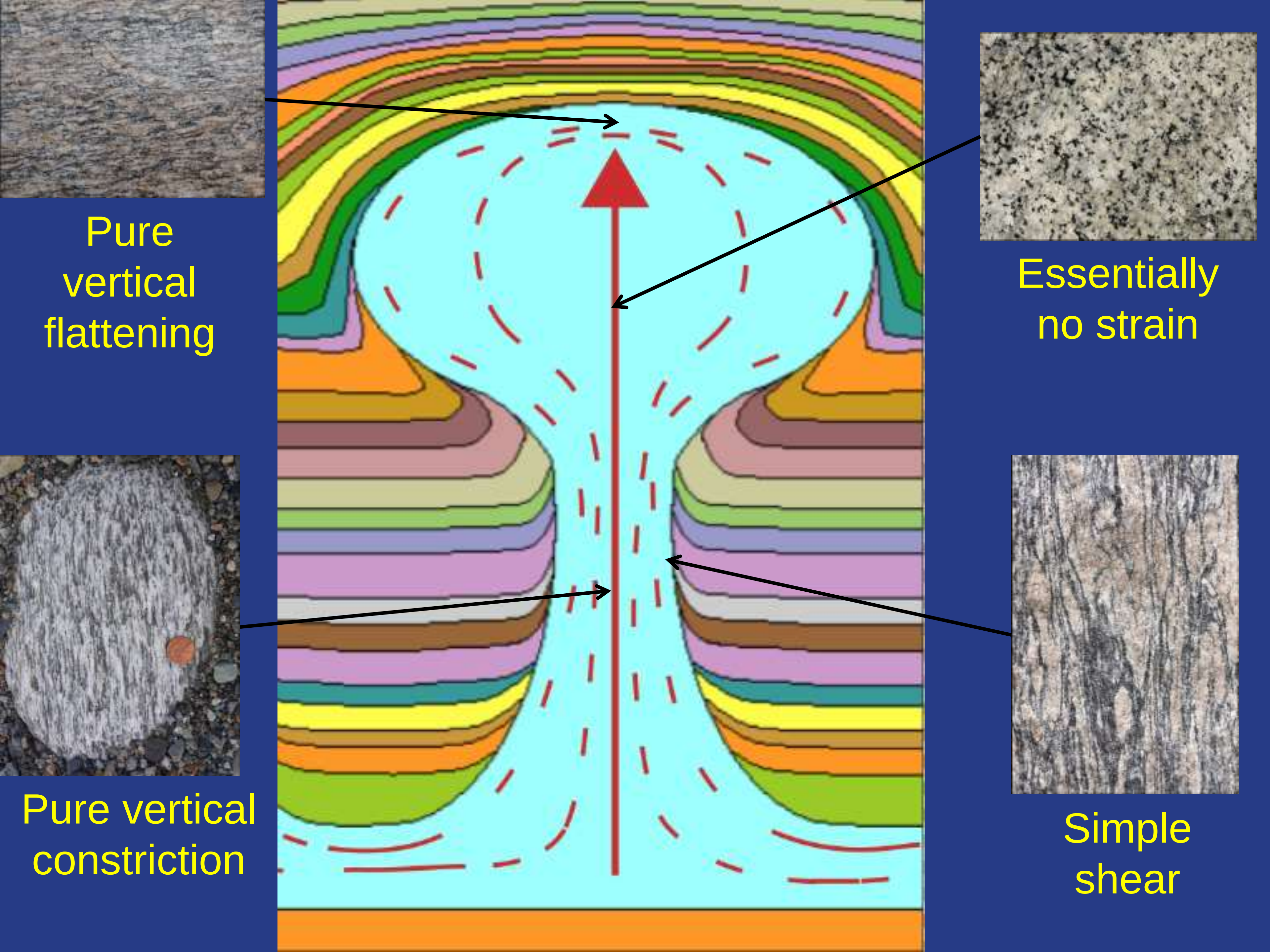
A gneiss of unknown locality.

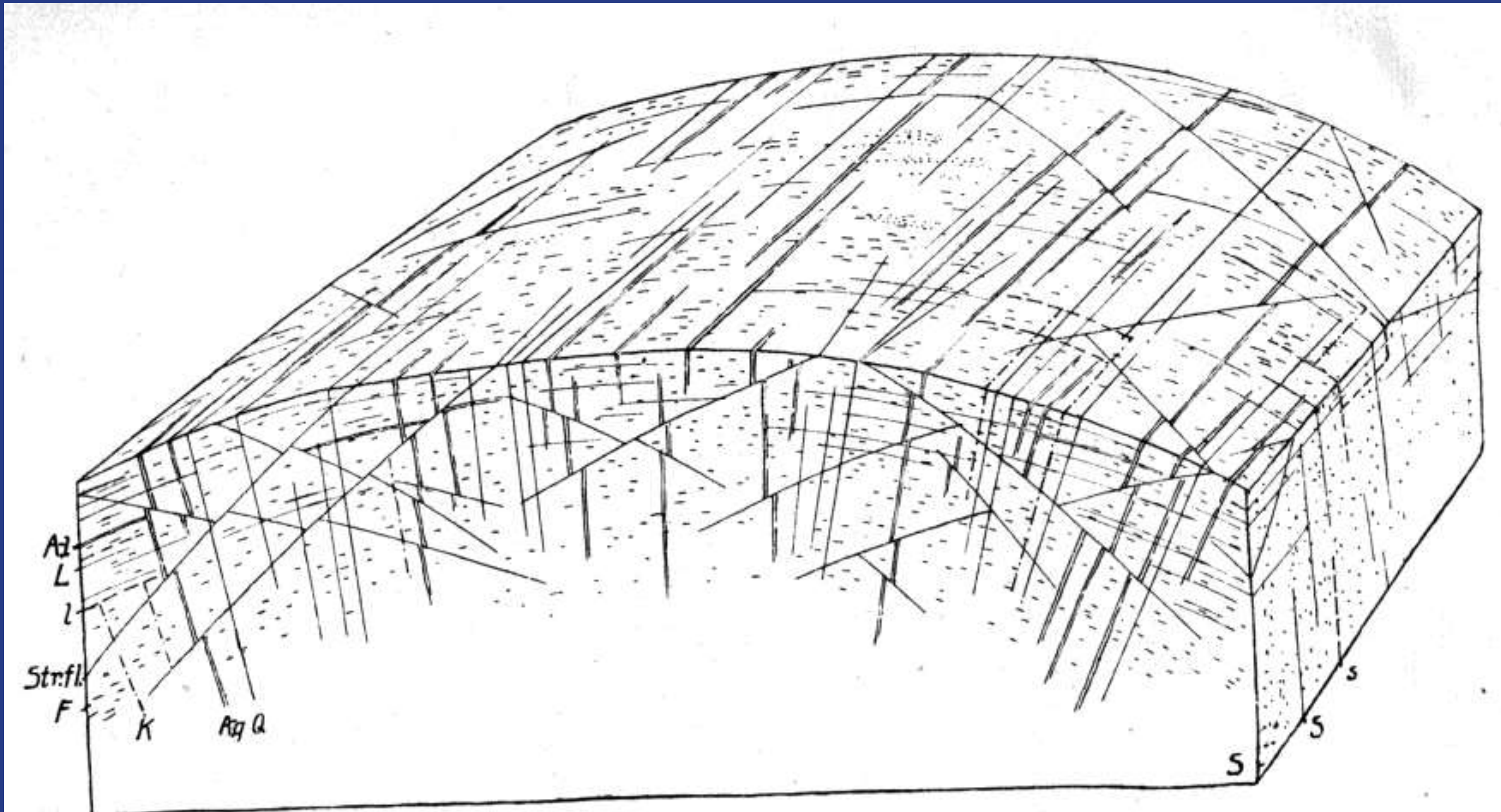
Another example of gneiss (locality unknown)

Another example of a gneiss
(locality unknown)

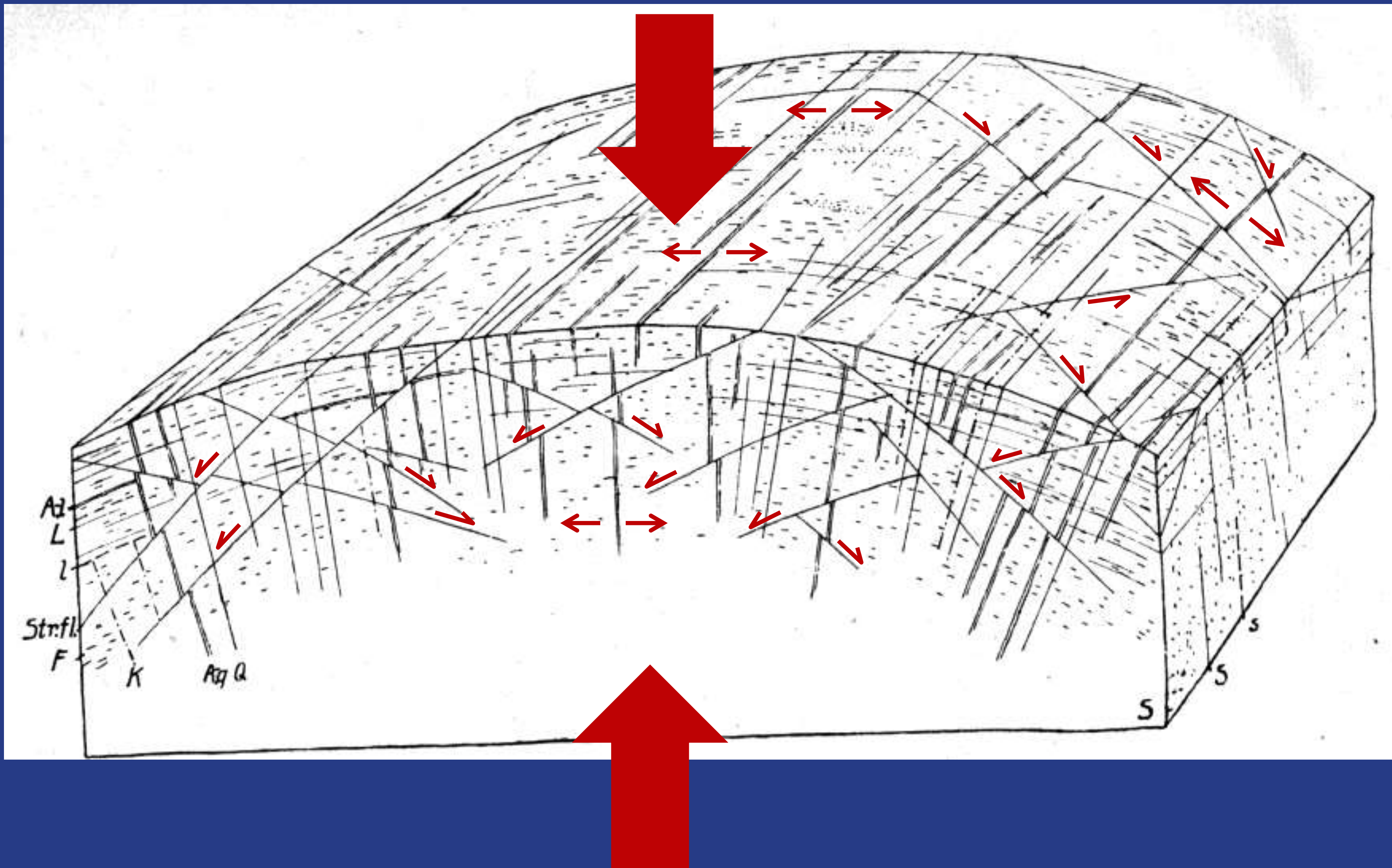
A mafic gneiss (locality unknown, but most likely Scandinavia)

The Morton Gneiss, Minnesota, USA.


Pure vertical flattening
Essentially no strain
Pure vertical constriction
Simple shear

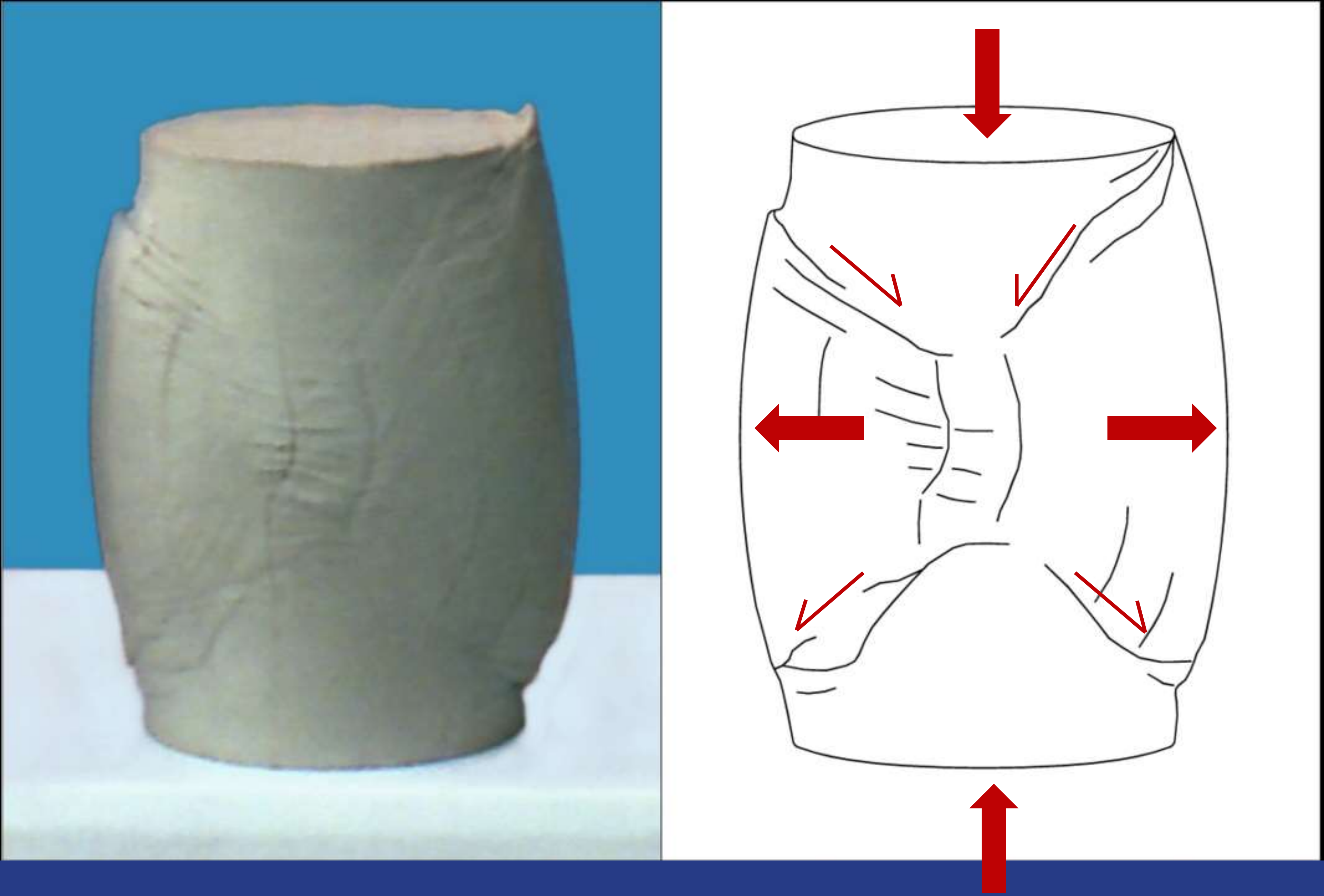


Internal structure of a batholith as seen at the surface (from Cloos, 1922)



A granite batholith subjected to brittle deformation after it was emplaced and uplifted into shallower crustal levels.

Shortening and extension during a rock mechanics experiment test

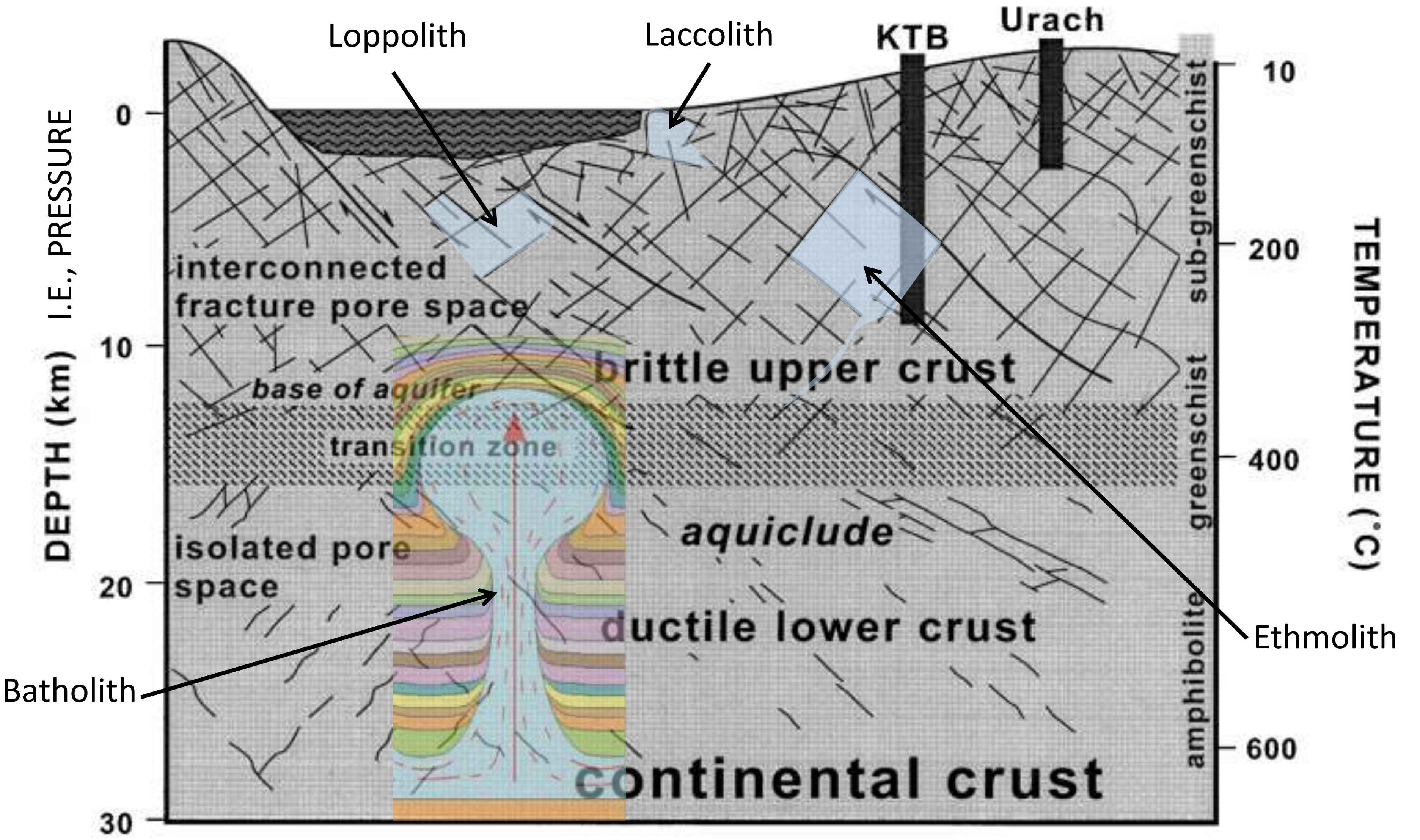


Conjugate shears that formed in a shortening rock cylinder

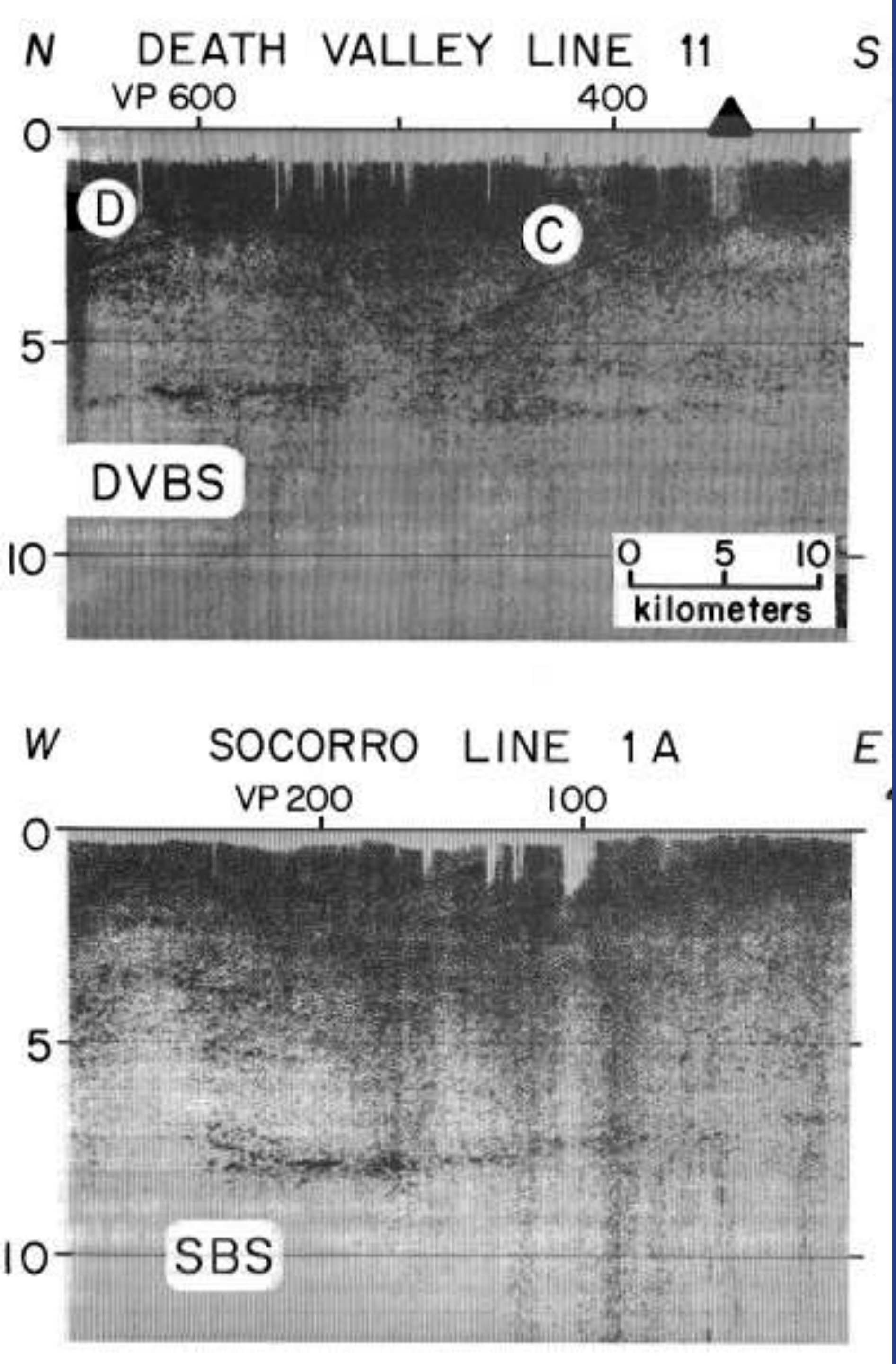
Unloading fractures in the granites of the Krokonoše Mountains (formerly Riesengebirge) in the Czech Republic (formerly Silesia, Germany) forming what is called “tor topography”

Unloading fractures in the Altay Mountains, Siberia, Russia, forming a tor topography.

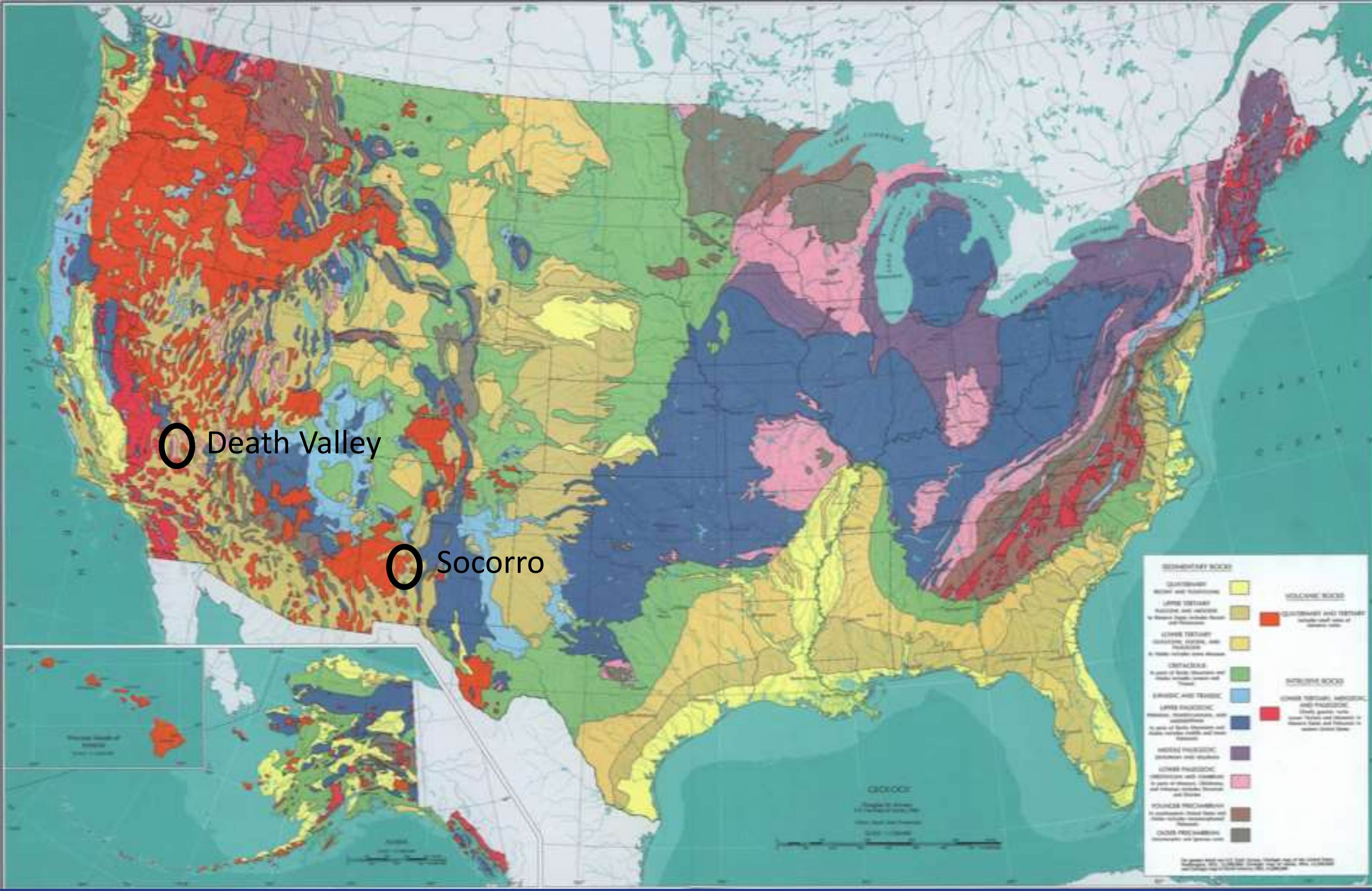
Exfoliation seen in the Sierra Nevada batholith in the Yosemite National Park, California, USA

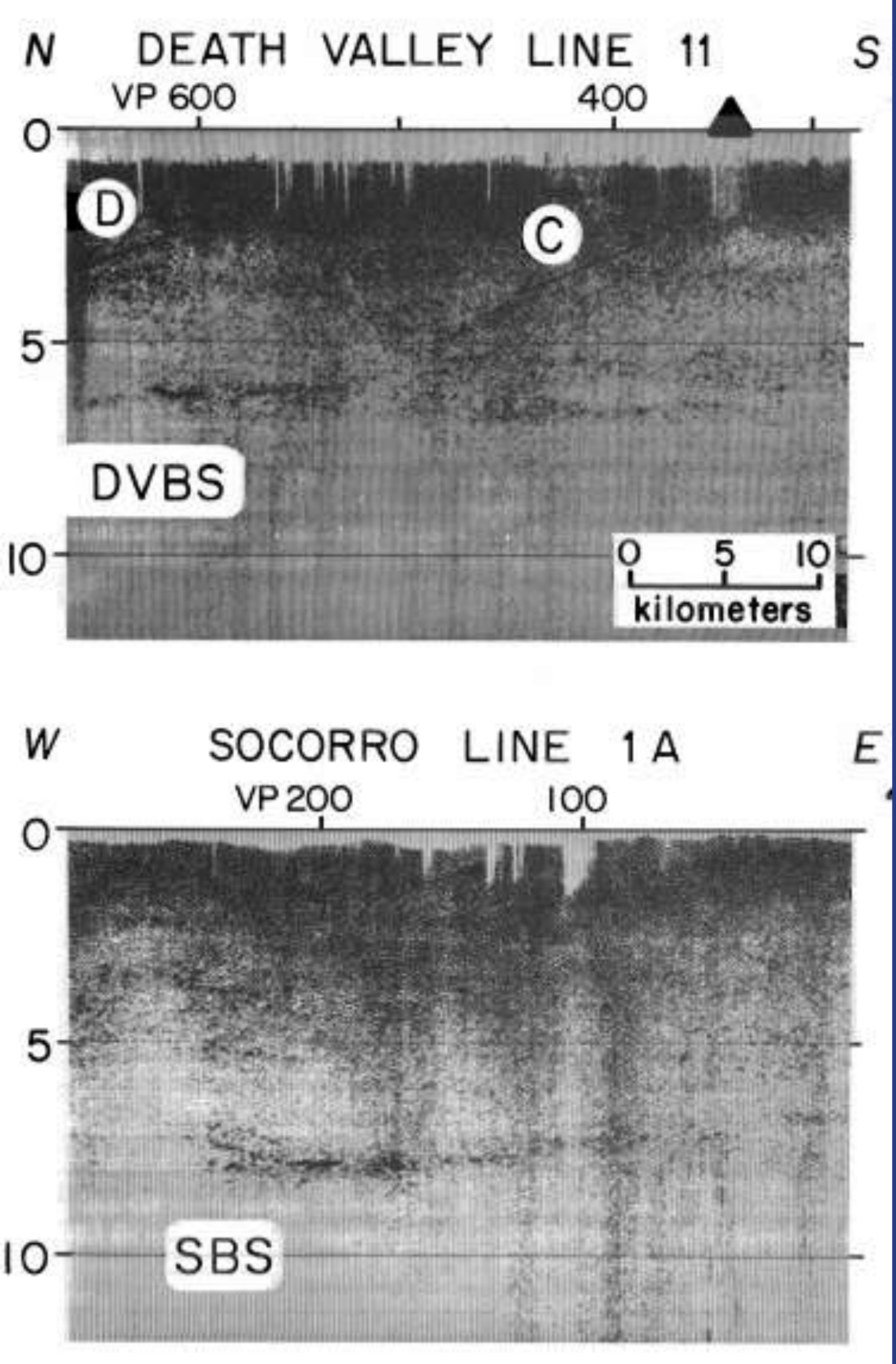


Place of various plutons in the density and rheological laylering of the continental crust



These two seismic reflexion profiles show two brightspots under two rift valleys: the Death Valley in California and the Rio Grande in New Mexico. They are thought to correspond to lenticular magma chambers within the brittle-ductile transition area that is shallower than usual under the rifts.


Death Valley
Socorro



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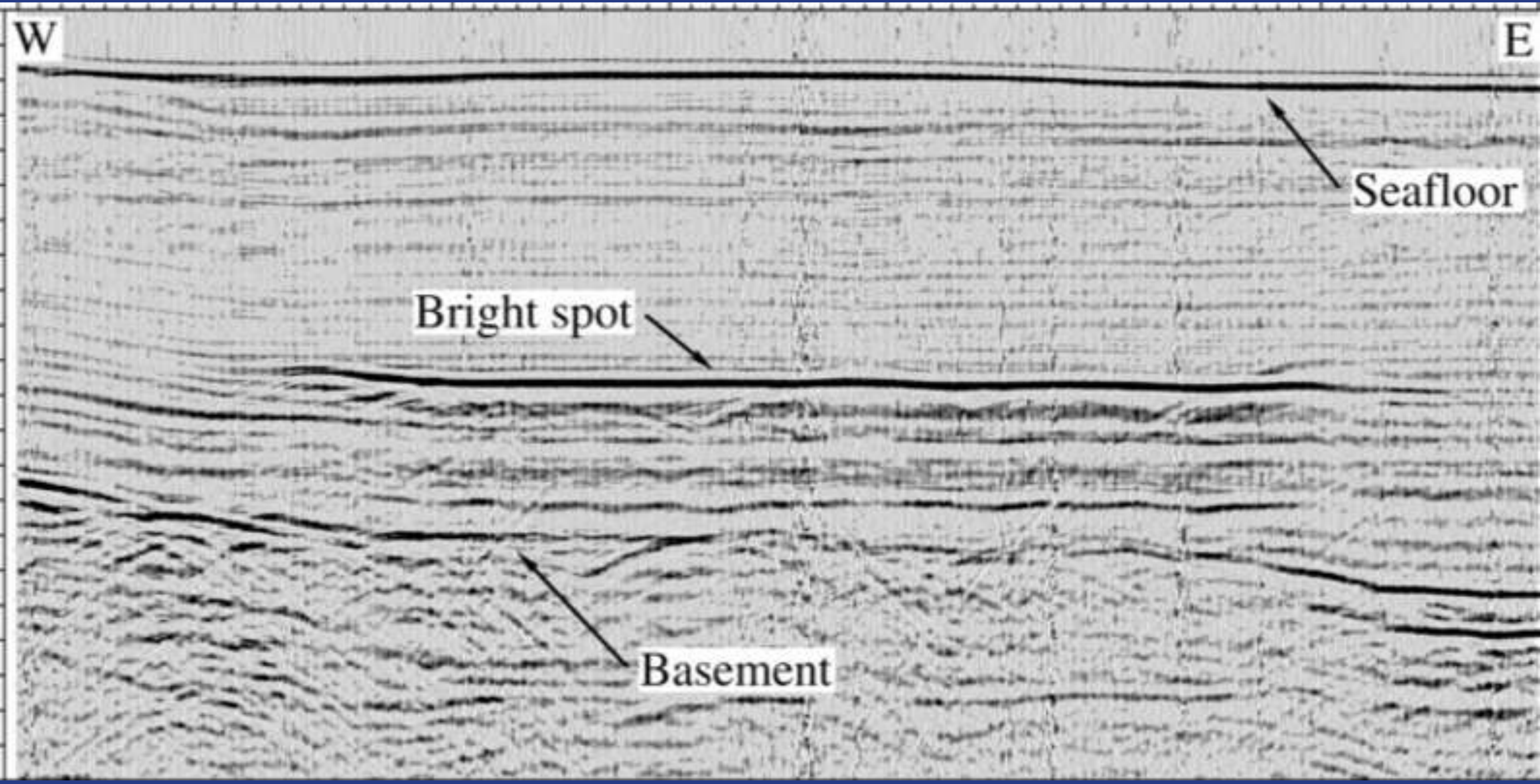
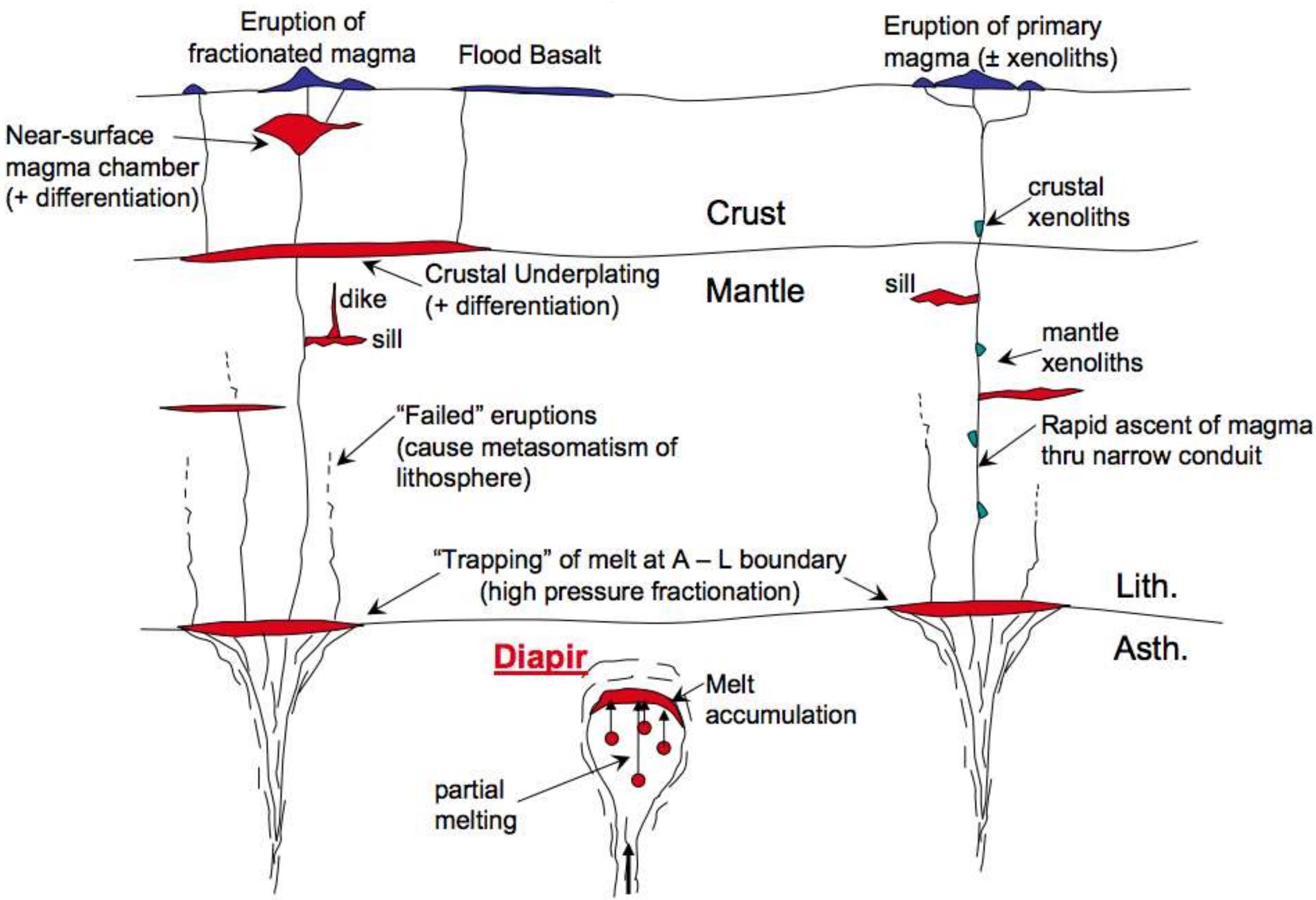


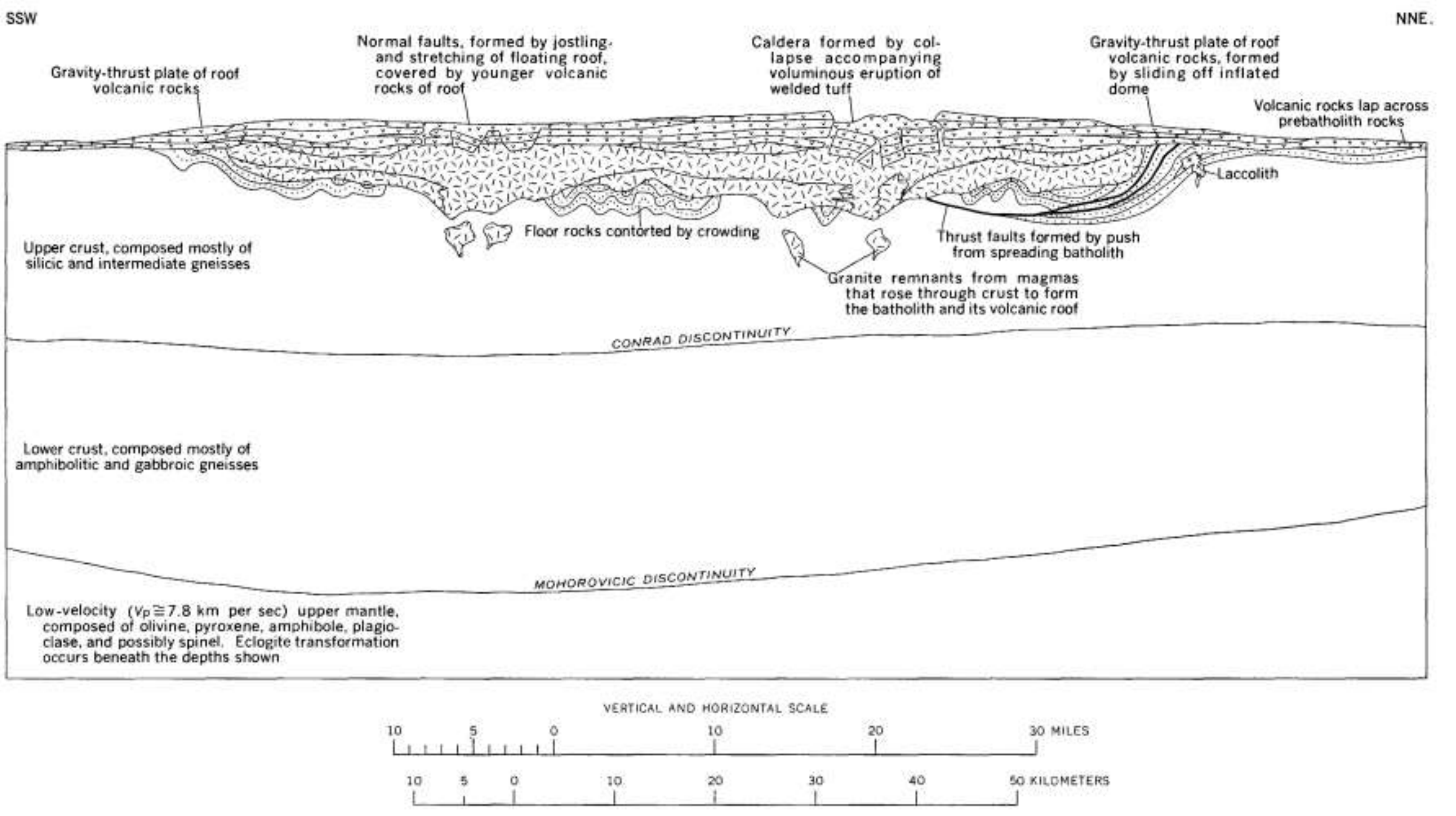
A typical bright spot in a sedimentary section. Brightspots result from a high impedance contrast.

Schematic view of some processes in basalt formation



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

Surprisingly, some large granite batholiths reach almost to the earth's surface and are emplaced under their volcanic carapace. How does that happen?



Cross section of the Boulder Batholith, Montana, USA (from Hamilton and Myers, 1966)

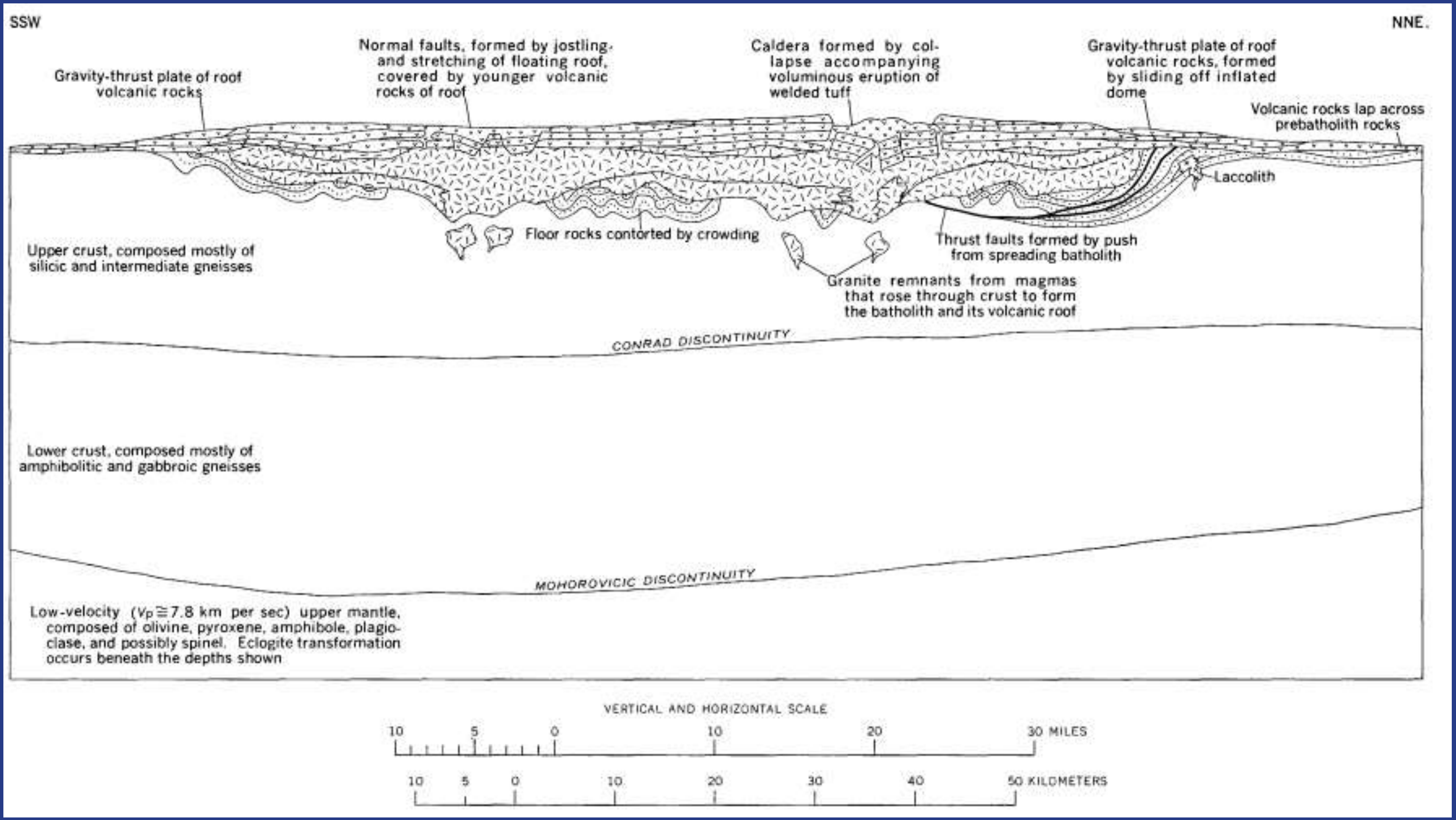
Pumice
(lava froth)

Rhyolite tuff
(pyroclastic
deposit)

Granite
(Magma intruding into
its own pyroclastic roof)

Lava froth

Granitic magma under its own froth



Cross section of the Boulder Batholith, Montana, USA (from Hamilton and Myers, 1966), buried under and in part intruding its own ash and pumice carapace.

The batholithic rocks

The batholithic rocks are those magmatic rocks that are phaneritic, i.e. those that cooled at depth slowly. Almost every batholithic or intermediate intrusive rock has a surface, i.e. volcanic equivalent. The main batholithic rock types and their volcanic equivalents are the following:

Granite, Baveno, Italy.

Granite from an unknown locality

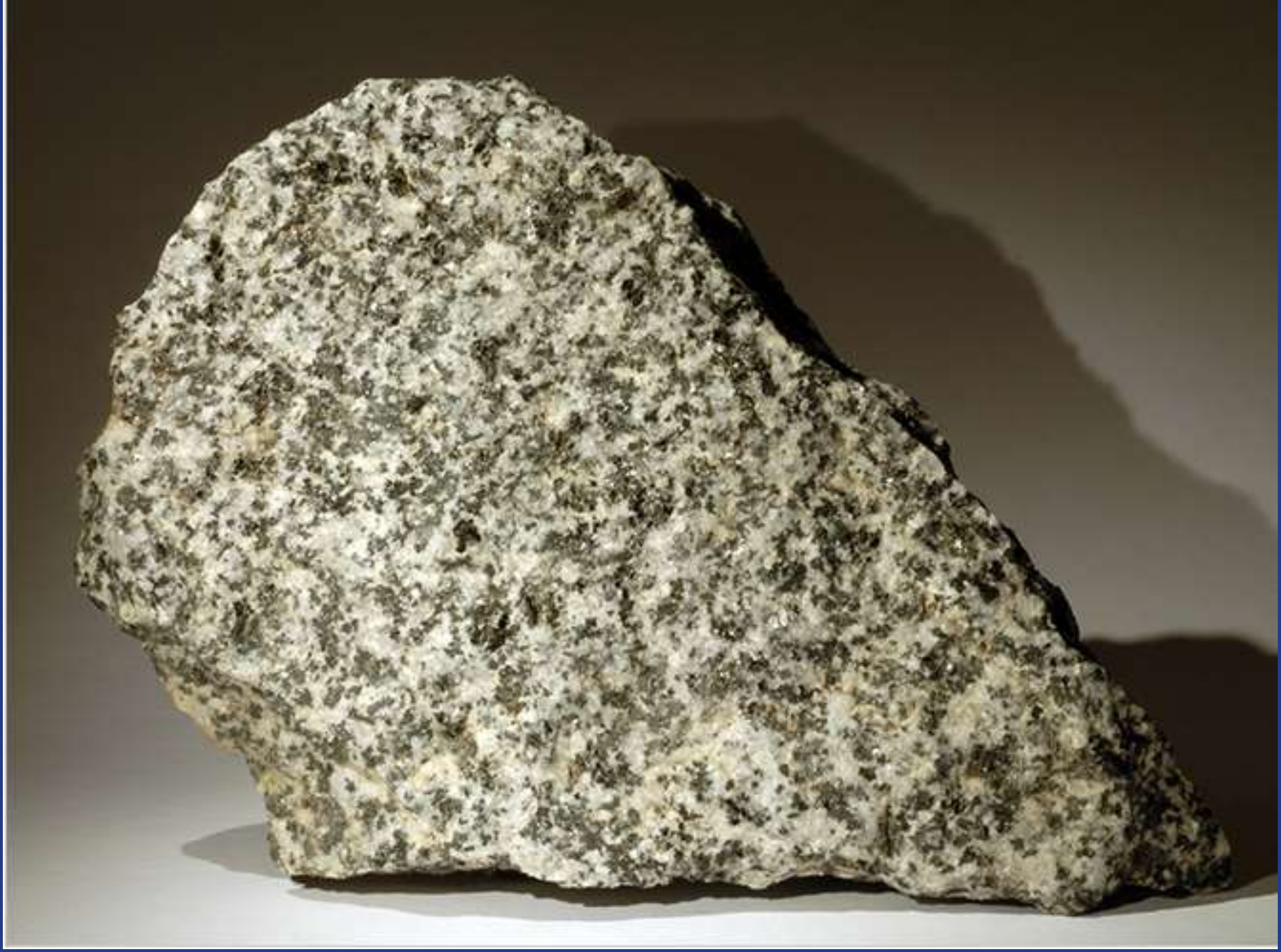
Typical granite landscape in a temperate climate: western USA

Typical granite landscape in a temperate climate: western USA

Granite outcrops in Saudi Arabia: semi-desert environment here

Diorite is a term introduced in 1822 by the great French mineralogist René Just Haüy from the Greek διοριω (*diorio*= to separate, to drow a boundary through) in reference to its distinct mafic and felsic components.

Diorite from an unknown locality



Diorite from Gore Mountain, New York, USA

Diorite landscape. The diorite tower is on the Dunderberg trail, California, USA

Syenite is an old name going back to antiquity, but for a granite in Syena in Egypt.

The name is now used for a phaneritic rock consisting essentially of potassium feldspar with subordinate oligoclase or even andesine (they make up less than one-third of the feldspar). If more than 5 % quartz is present, the rock is called a quartz syenite. Apatite, sphene and ore minerals appear as usual accessories.

Syenite from an unknown locality

Syenite from an unknown locality

The term granodiorite was first proposed by the American geologist George Ferdinand Becker and was first published by the Swedish geologist Waldemar Lindgren in 1893. As originally proposed it covered all rock compositions between diorite and granite.

Granodiorite, Loch Doon, Scotland, UK

Granodiorite from the Sierra Nevada batholith with xenolith

Late magmatic products in batholiths: aplite and pegmatite dykes.

Let us start with the aplite dykes:

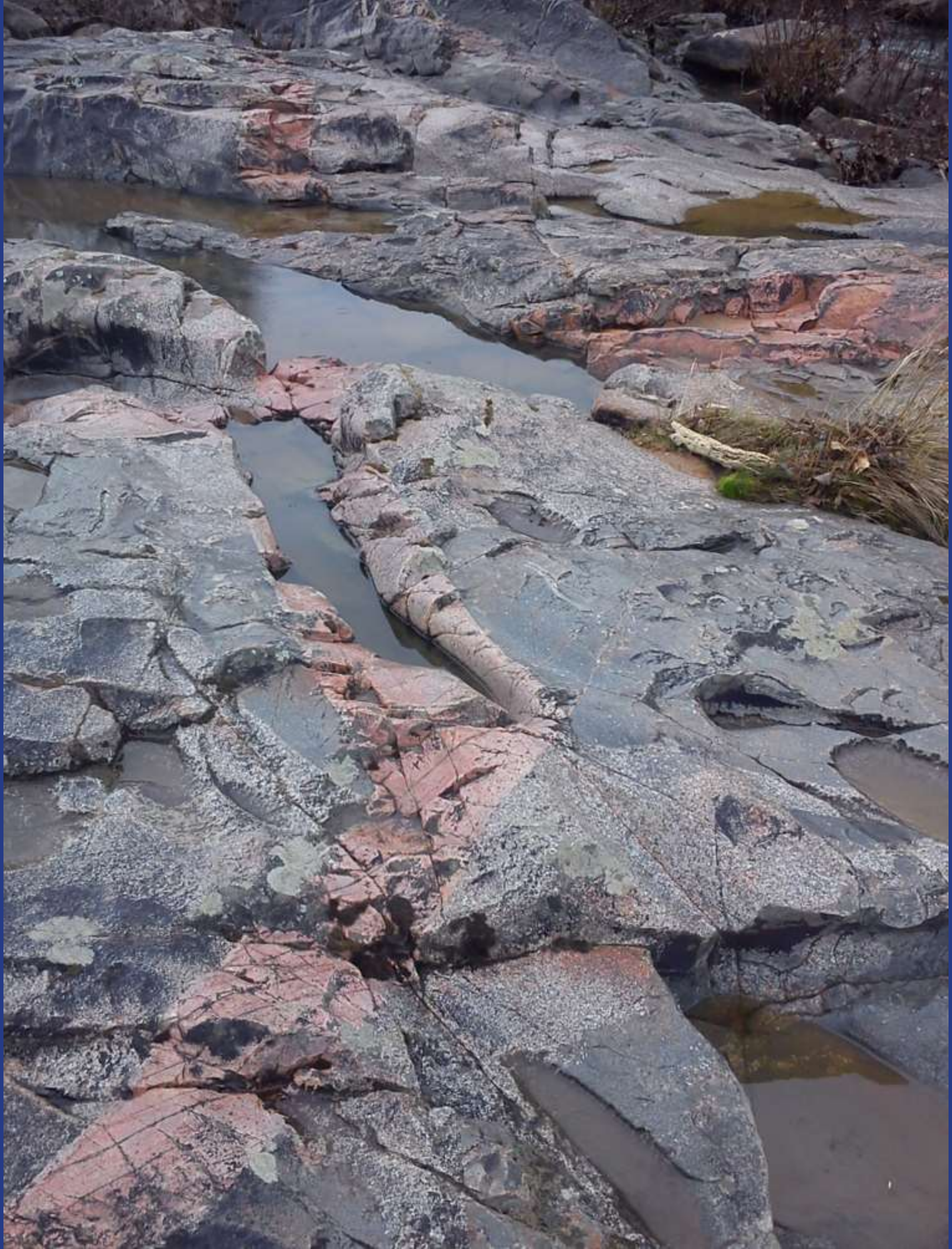
An aplite dyke is a fine-grained igneous dyke intruding a pluton and consisting commonly of the latest magmatic products of that pluton.

In granitic plutons, aplite dykes usually consist of potassium feldspars, muscovite and quartz.

A beautiful aplite dyke in the l'Eree granite in the Channel Islands, north of France. Photo by Jessica Winder.

Another aplite dyke from the l’Eree granite on the Channel islands. Photo by Jessica Winder

Aplite dyke in the Silvermine granite with xenoliths in Missouri, USA



Criss-crossing aplite dykes in the Silvermine granite in Missouri, USA.

Light-coloured aplite dyke cross-cutting granodiorite in the Yosemite National Park, California, USA

Close-up view of an aplite dyke in a granitoid. Locality unknown.

Pegmatite dyke is a late magmatic intrusion in plutons, similar to aplites in composition, but consists of very much larger crystal size, larger than those of the batholithic rock into which they intrude. Their large size results from the higher temperatures in which they crystallise compared with those in which aplites crystallise. That is why pegmatites are seen in intrusions of greenschist grade metamorphic conditions (i.e. ambient temperatures of 250 to 450°C).

Some of the most beautiful and rare crystal forms are usually collected from pegmatites.

A pegmatite dyke with feldspar crystals.
Photo by T. Praszkier

Pegmatite dykes intruding granites near Peach Springs Canyon, Arizona, USA

Pegmatite dyke intruding
granite in Nevada, USA

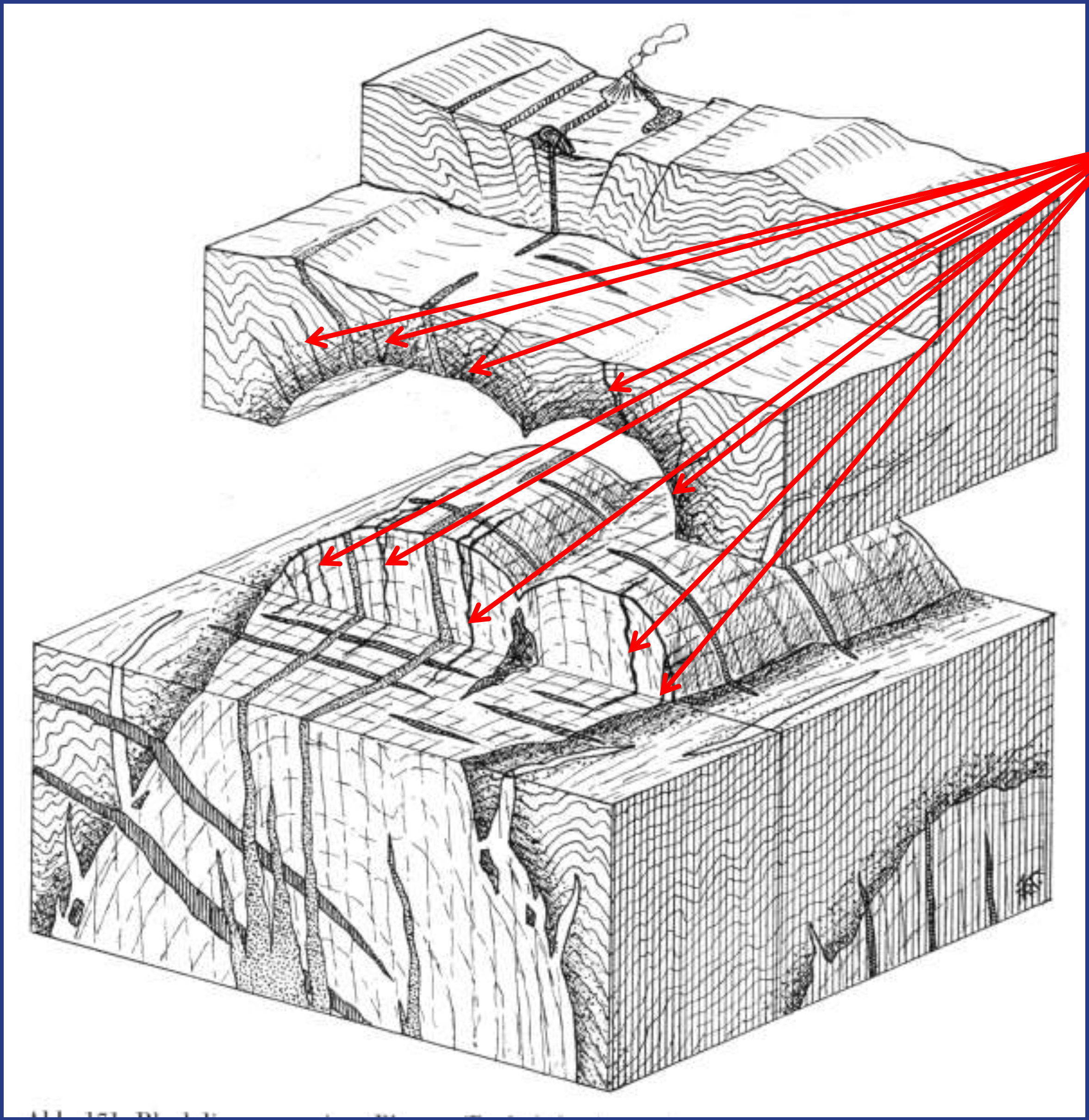
Another process commonly associated with the late phases of magmatic intrusion is metasomatism. The term was introduced by the great German geologist Carl Fiedrich Naumann in 1826 to designate replacement of one mineral by another in an open system, often by percolating fluids. The term comes from the Greek μετά (*meta*=after, next after) and σωμα (*soma*=body). This replacement happens by the presence of interstitial, chemically active pore fluids in capillary action. The replacement often occurs by not necessarily affecting the fabric.

Metasomatism is distinguished from other mineral replacement processes by its following features:

1. From the ion-by-ion replacement in minerals (e.g. in zeolites) by mechanisms in which dissolution of minerals occurs synchronously with the precipitation of new minerals thus maintaining a constant volume.

2. From the group of processes including the infilling of cavities and cracks, magma crystallisation and magma-rock interactions by the preservation of the rocks in solid state during replacement, because the volume of solution filling pores is negligible in comparison with the total rock volume being metasomatised.

3. From isochemical metamorphism by the substantial chemical changes it introduces by either addition or subtraction of major elements and molecules other than H_2O and CO_2.



Mineralised veins: these are the avenues for the metasomatising fluids rising from the batholith. The minerals are deposited by these veins.

Metasomatism is a vast subject that can only be properly treated once one knows enough igneous petrology, hydrogeology and geochemistry. It has two main mechanisms and a number of rock family types resulting from metasomatic activity.

The metasomatic rock types are the following:

Fenite

Skarn family → Magnesian skarn; → Calc-skarn

Rodingite family

Greisen family

Beresite family

Propylite family

Secondary (or hydrothermal) quartzite family

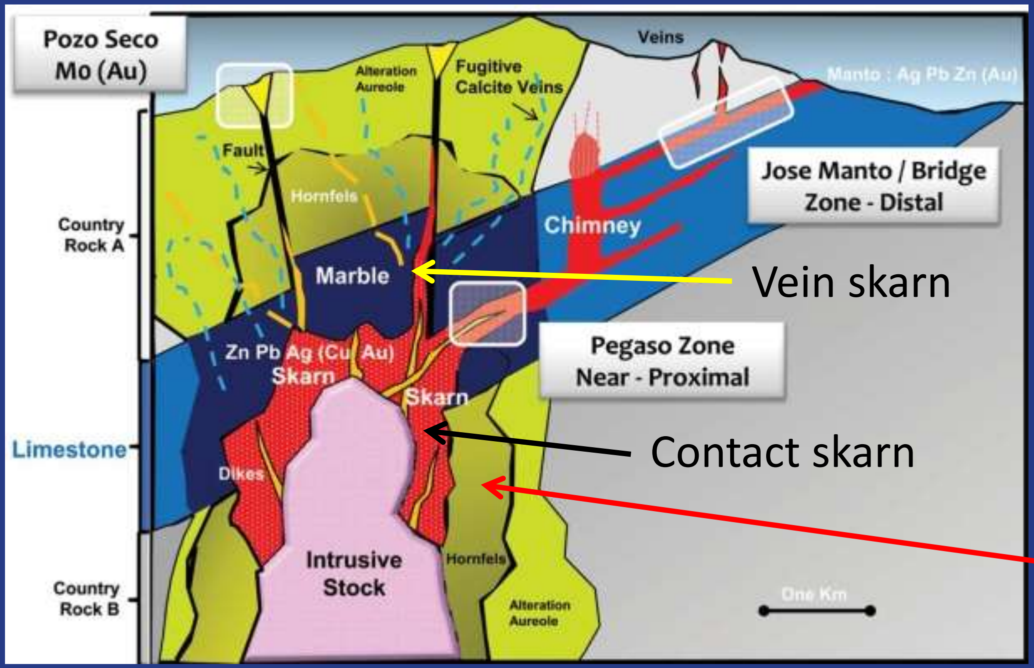
Gumbeite family

Aceite family

Argillisite family

Because of their importance in ore genesis and ophiolite geology I will here describe only the skarn and rodingite families. Anybody interested in the other families may ask Semih or Nalan for a PDF copy of the chapter 9 entitled metasomatism and metasomatic rocks of the *Recommendations of the International Union of Geological Sciences Subcommission On The Systematics Of Metamorphic Rocks* (Zharikov et al., 2007), which I used for the notes on metasomatism here.

Skarn (term proposed by the great German geologist Viktor Goldschmidt in 1911 from an old Swedish mining term describing a silicate rock around ores) is a metasomatic rock formed at the contact between an intrusive silicate igneous rock and a carbonate rock (usually sedimentary or metamorphic). It consists mainly of Ca-Mg-Fe-Mn silicates, which are free or poor in water.



The Pozo Seco molybdenum-gold deposit that formed in a skarn, Mexico.

Contact metamorphic aureole

Magnesian skarns are high temperature rocks containing forsterite, diopside, spinel, periclase, clinohumite, phlogopite, pargasite and form at the contacts of magmatic and calc-magnesian or magnesian carbonate rocks. Typically magnesian skarns may be host to ores of iron, base metals, copper, gold, iron-magnesium borates and phlogopite.

Calc-skarn is a high to medium temperature rock consisting mainly of granditic garnet, salite (to ferrosalite and/or johannsenite pyroxene, wollastonite or Mn-rich pyroxenoids. It forms at contacts of magmatic intrusive rocks with calcium carbonate rocks. It can replace former magnesian skarns (in hypabyssal or subvolcanic conditions). Typically calc-skarns may host ores of Fe, base metals, Cu, W, Mo, Be, B, U, REE.

Permian marbles hosting the calc-skarn of Uludağ, Turkey, in which the tungsten ore originated.

Batholiths and other kinds of plutons not only alter the rocks surrounding them by the fluids they release, but also by the heat they provide. This leads to what is called “contact metamorphism”.

The great Japanese geologist Akiho Miyashiro defines contact metamorphism as follows:

Contact metamorphism is recrystallisation of rocks in an aureole around an intrusive igneous body due to rise in temperature.

The width of the contact metamorphic aureoles varies but is in most cases in the range of several metres to several kilometres. The rise in temperature is partly because of conduction and partly because of convection of the interstitial liquids.

But what is metamorphism?

The great Scottish naturalist James Hutton, one of the founders of geology, is usually cited as the first person who had a sophisticated idea of what we today call metamorphism. His first example of metamorphosis under the effect of heat was the origin of anthracite which he wrote in his great classic in 1788.

In his *Description of the Western Islands of Scotland* (1819), the Scottish geologist John Macculloch interpreted amphibolitic schists as argillites modified by the effect of heat.

Extremely important is von Buch’s statement from 1818-1819:

“If the porphyry of the Puy de Dôme, of Sarcou, of Puy de Nugère originated from granite, so could also the beds of the Montdor owe their origin to the metamorphosis of the granite (not melting) and the basalt could be a fluid product of these rocks. But even the most enthusiastic vulcanists would not dare to view this result as a general one and to apply it to the German basalts.”

The first occurrence in the geological literature of the verb 'being metamorphosed' seems to be by the French-German geologist Ami Boué in 1823.

Today metamorphism is defined as the mineralogical change of rocks under changed temperature and/or pressure conditions without leading to melting. That change is called metamorphic recrystallisation.

Rocks that have been subjected to metamorphism are called metamorphic rocks.

METAMORPHISM

Contact metamorphism

Regional metamorphism

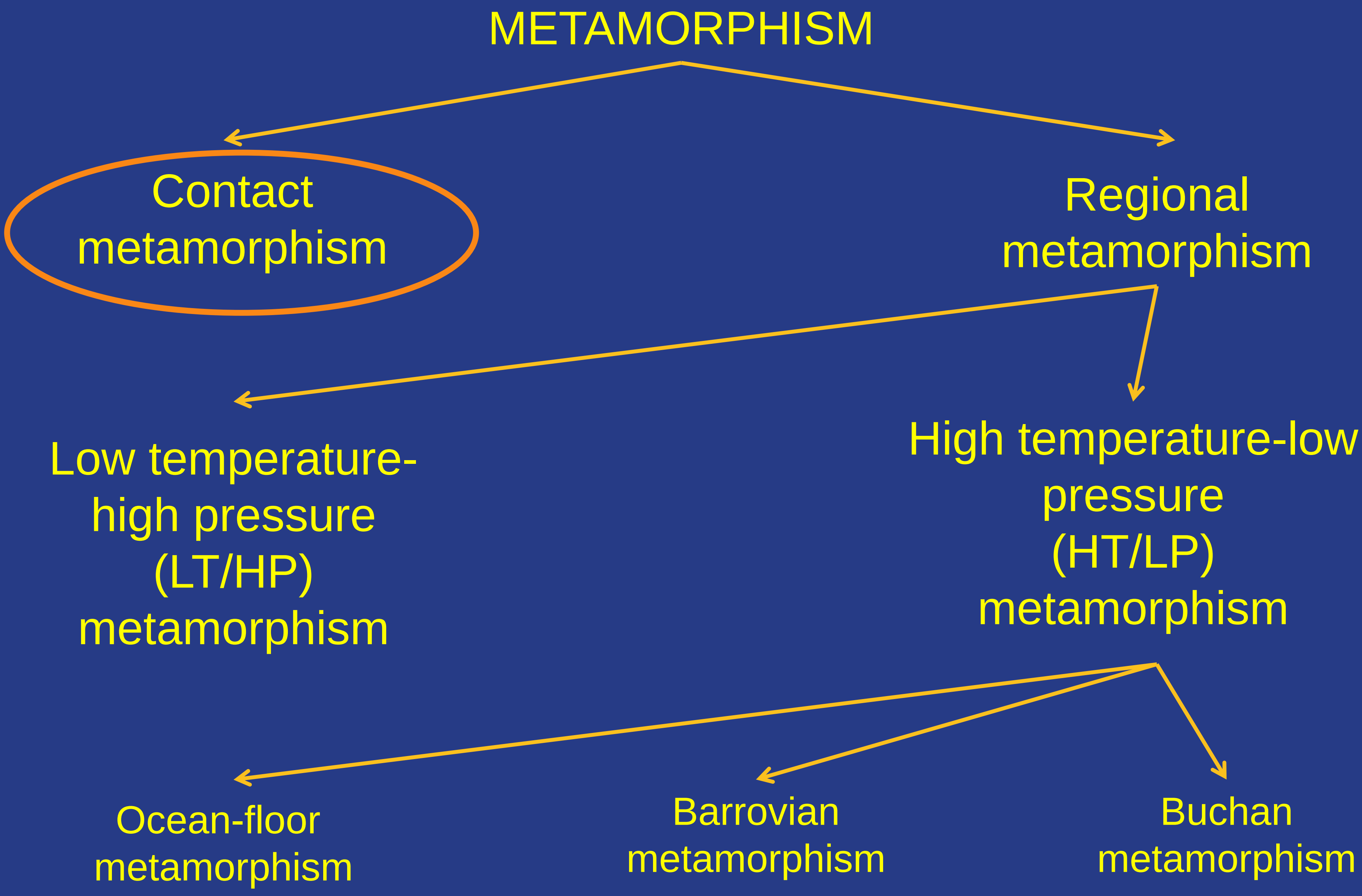
Low temperature-high pressure (LT/HP) metamorphism

High temperature-low pressure (HT/LP) metamorphism

Ocean-floor metamorphism

Barrovian metamorphism

Buchan metamorphism



METAMORPHISM
Contact metamorphism
Regional metamorphism
Low temperature-high pressure (LT/HP) metamorphism
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Buchan metamorphism

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