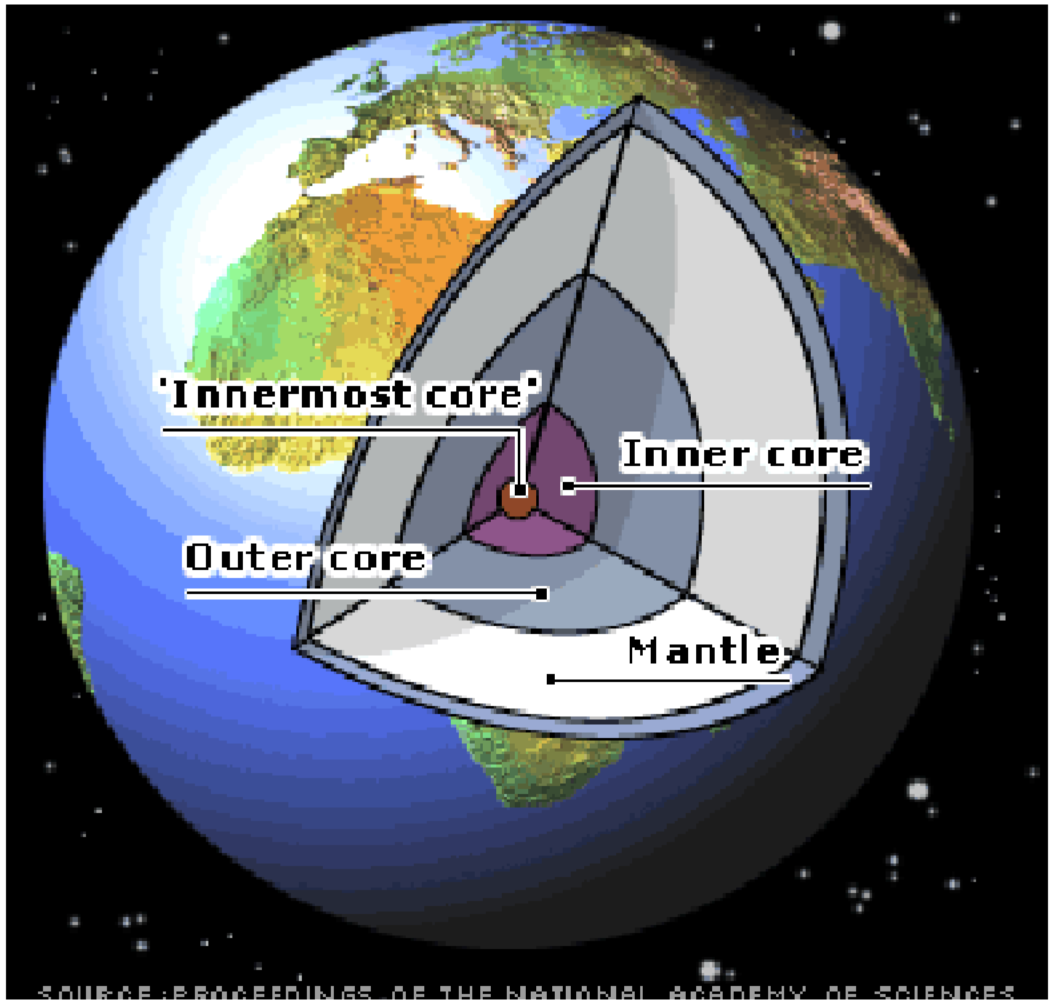
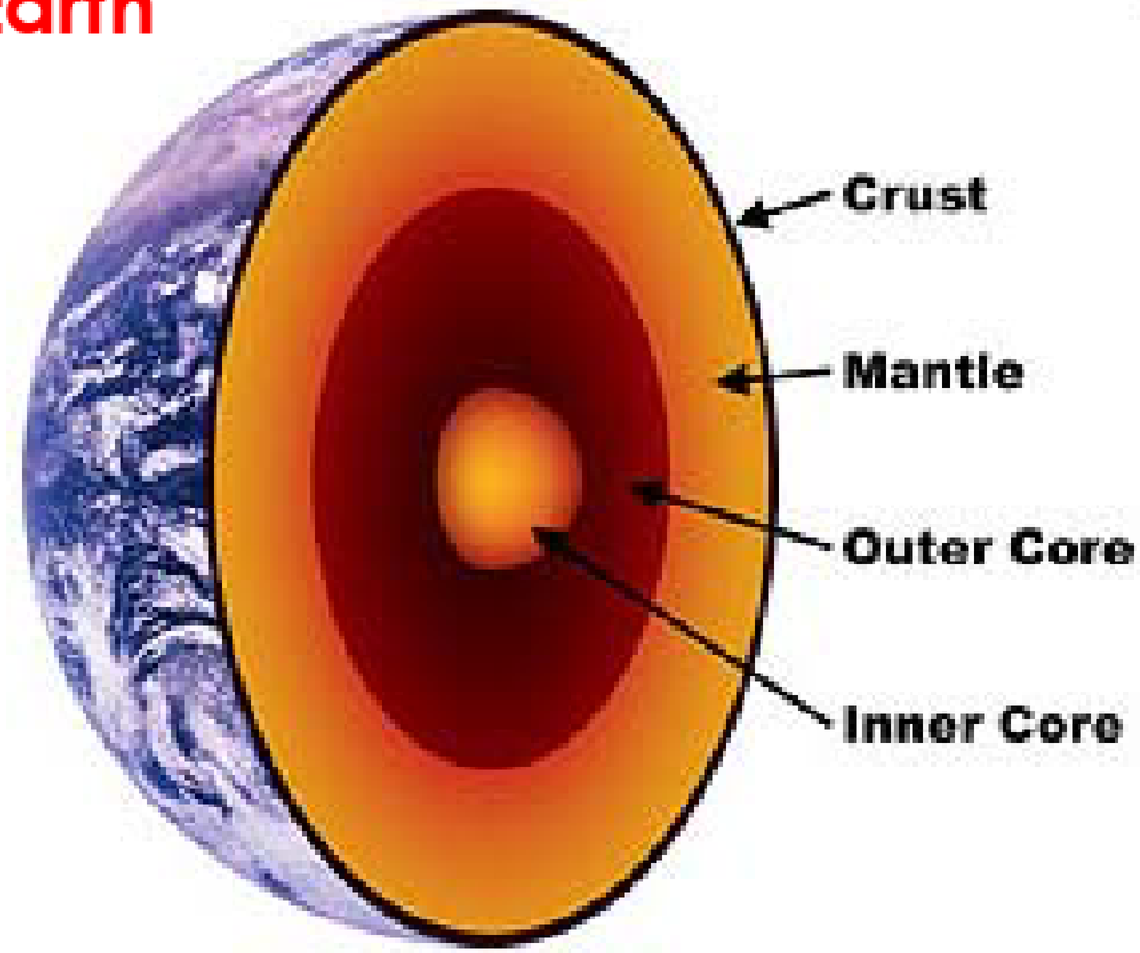
Element to Rock

Geology 1

G. Bertotti

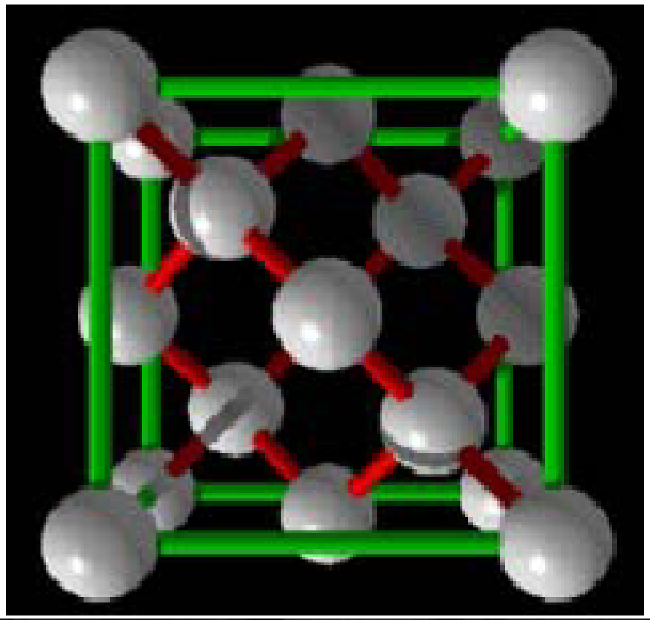


The Earth



- very little information on elements and minerals (will come in 3rd part, M. van Tooren)
- minerals and rocks forming the Earth (particularly its outer part)

The basic components: elements, minerals and rocks



Elements

the most fundamental substances into which matter can be separated by chemical means

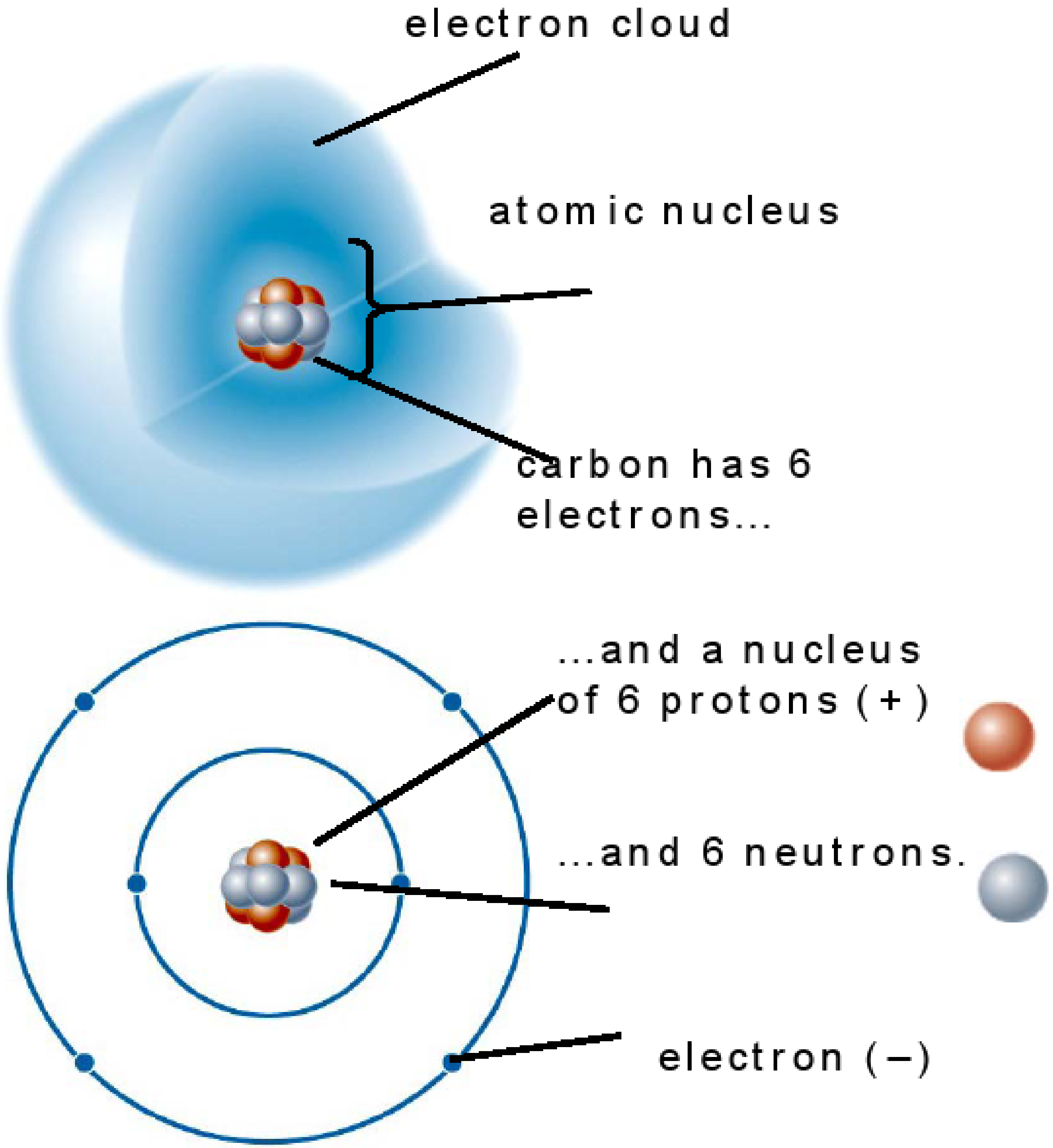
Minerals

Naturally formed, inorganic, solid material with a specific chemical composition and a characteristic crystalline structure.

Rocks

Naturally formed, coherent mass of one or more minerals, sometimes including organic debris.

The atom, where everything starts



the C atom (an example)

Atomic number: the number of protons in the nucleus

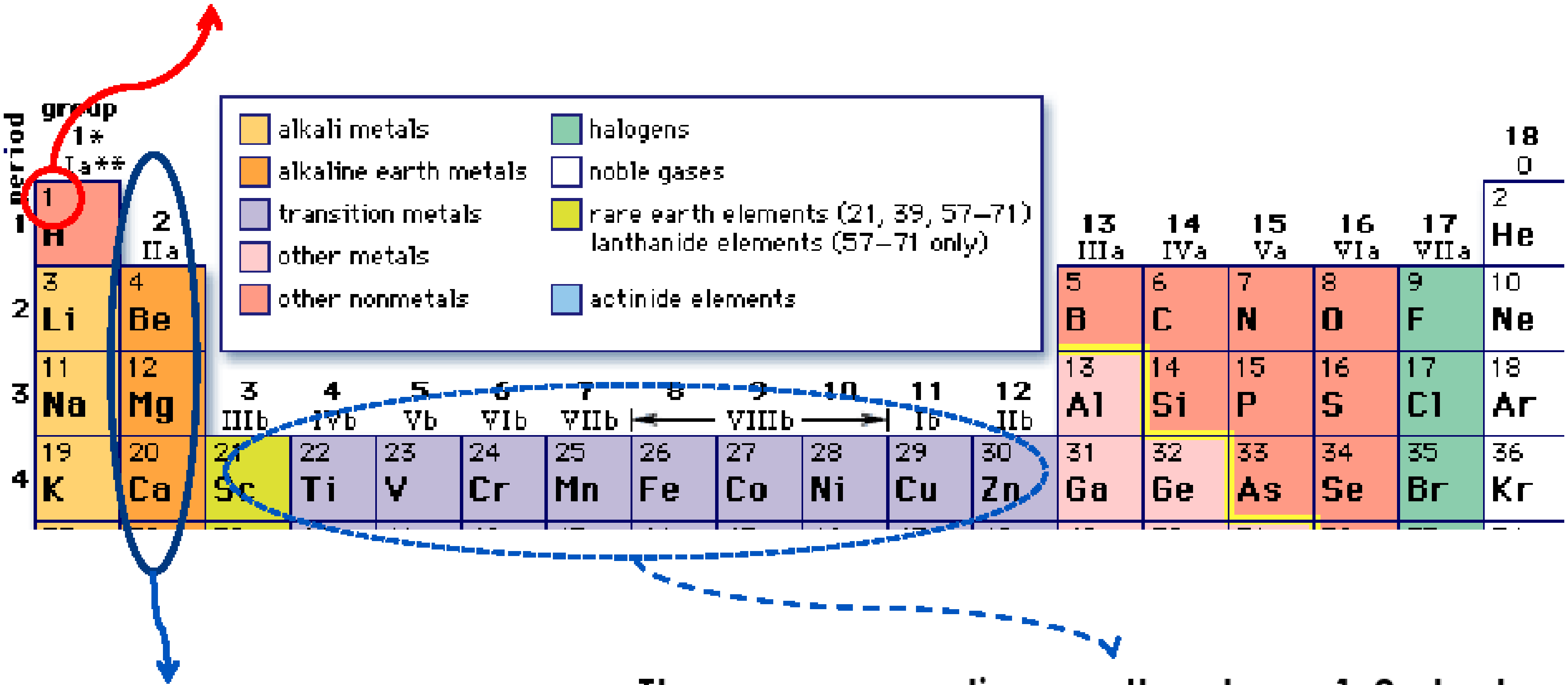
Atomic mass: mass of the neutrons + mass of the protons.

Electrons organized in shells. The electrons in the outer shell give the valence which controls interactions

Atoms with the same number of protons but different number of neutrons are called isotopes.

The table of elements

Atomic number
(number of protons)

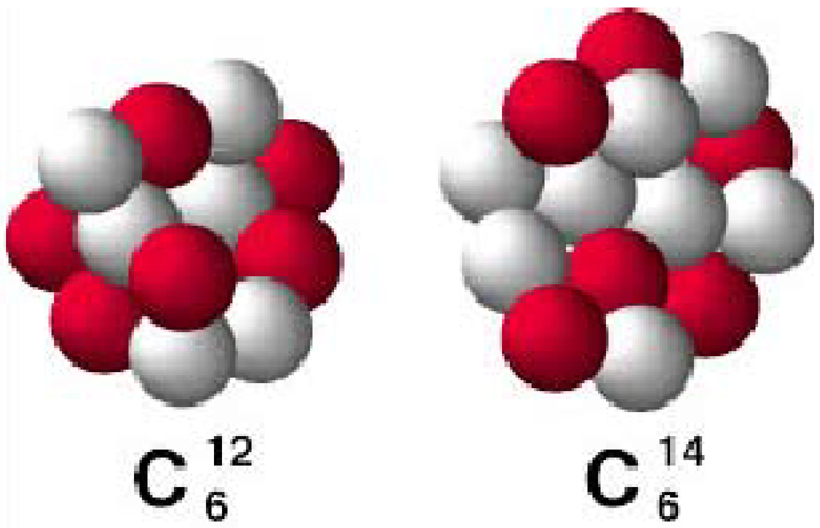


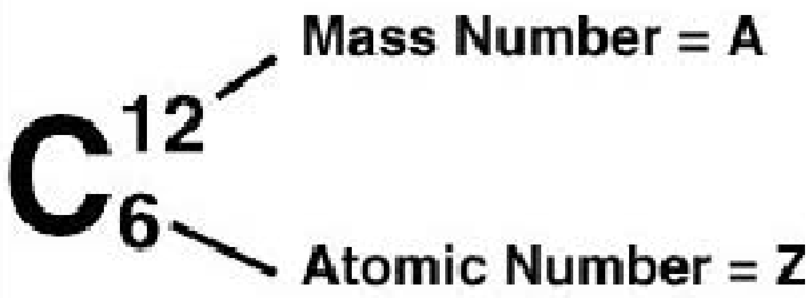
have the same number of electrons in the outside shell

These are exceptions as they have 1-2 electrons in the outer shell (they fill internal shells before the outer one is full)

Isotopes

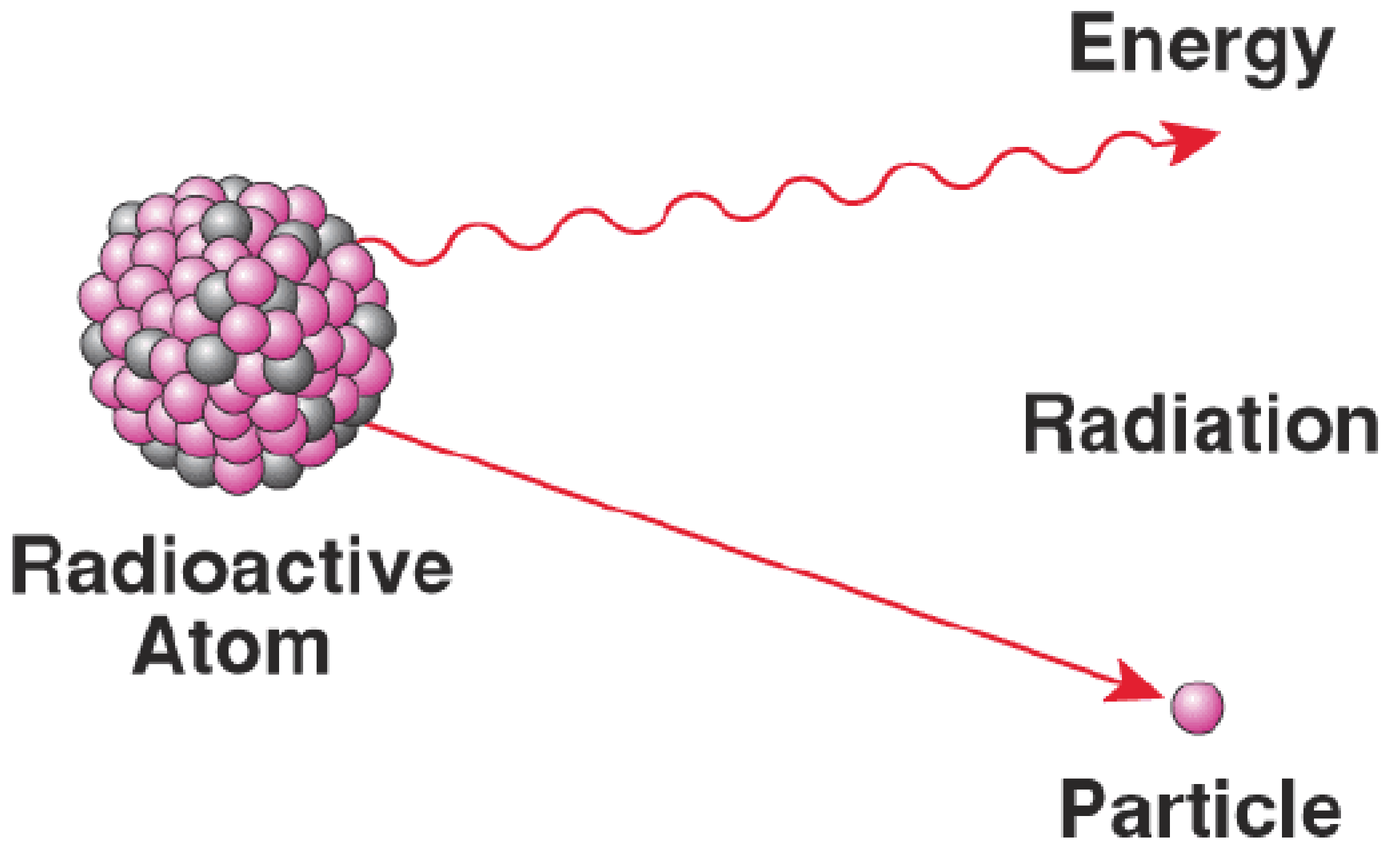
Atoms of the same elements always have the same number of protons but can have different number of neutrons leading to isotopes which are characterized by their different mass number





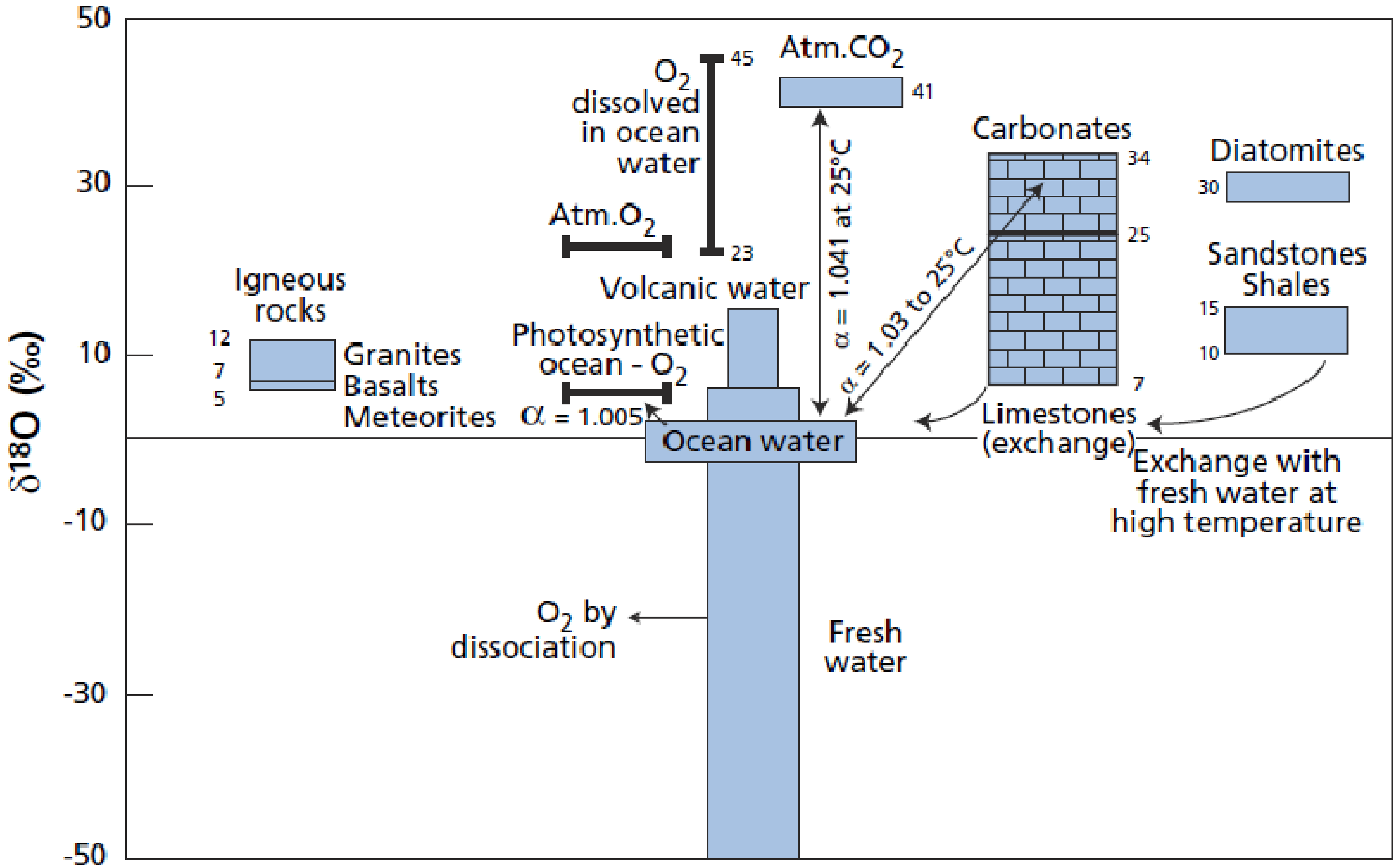
Carbon has three stable isotopes, C^{12}, C^{13} and C^{14}

Some isotopes are unstable and decay at variable rates radiating energy and particles

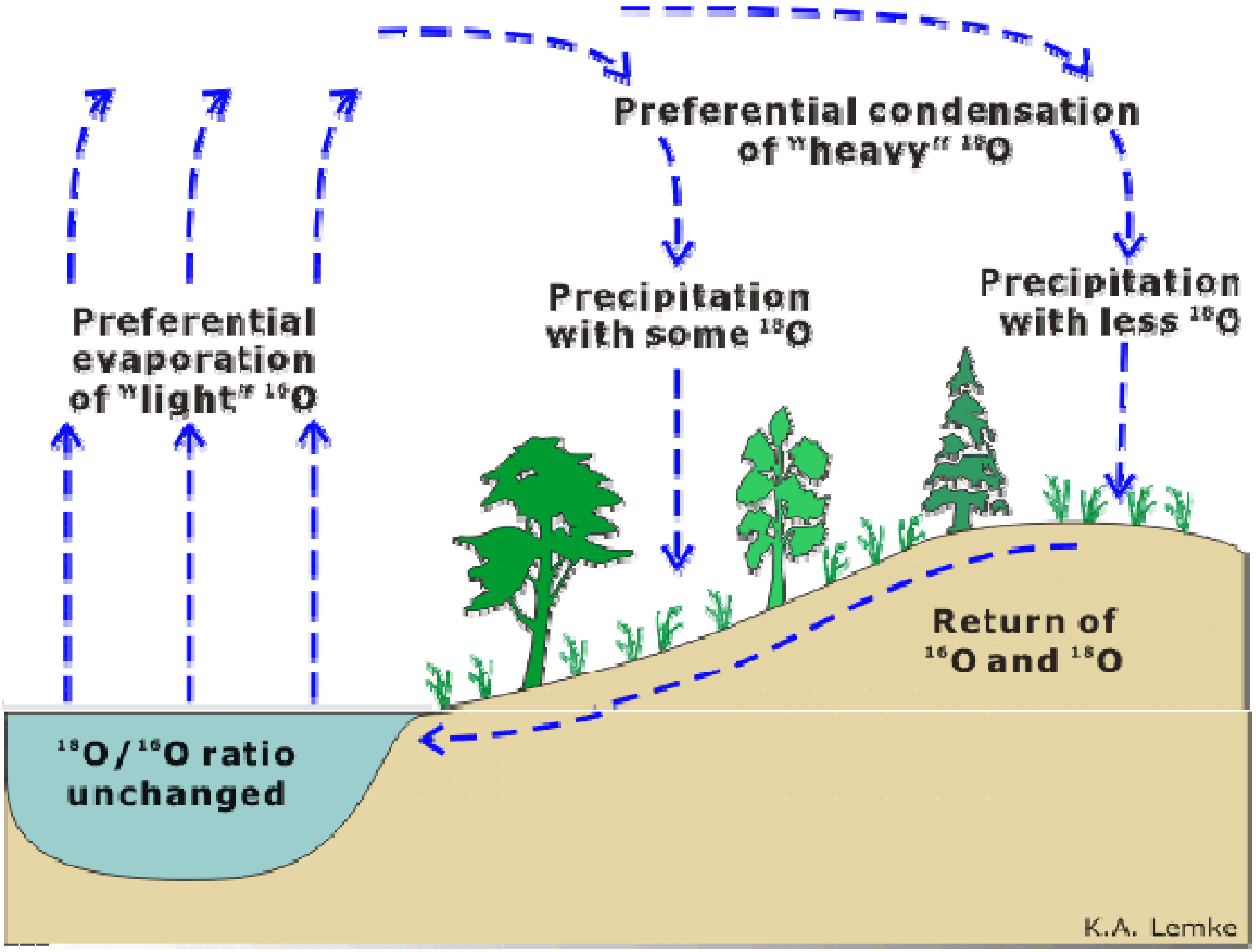


Because of their slightly different mass, isotopes have slightly different behaviour and can fractionate. Isotopes are fundamental tracers of numerous natural processes

The example of oxygen isotopes: large variations!



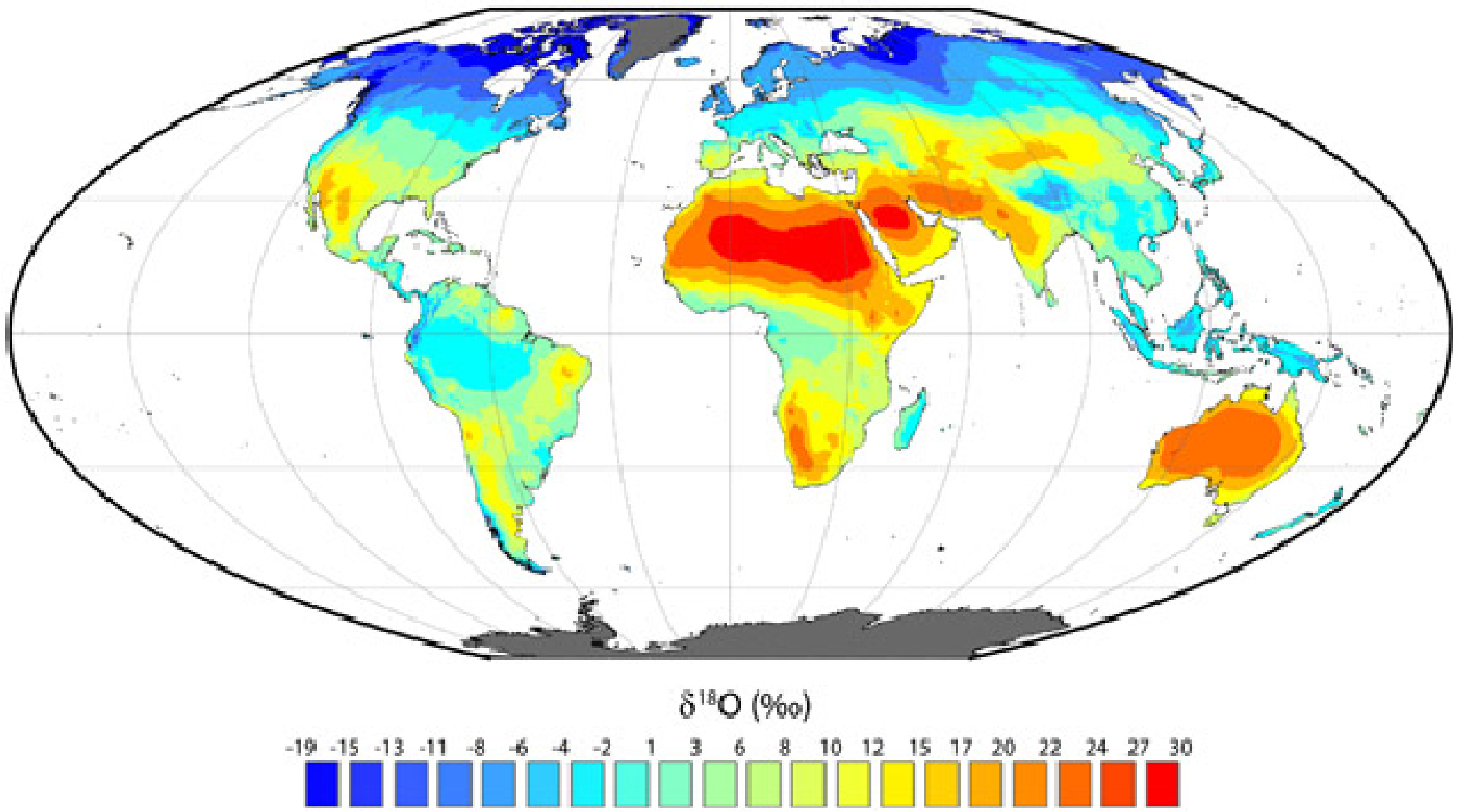
A typical agent of fractionation: evaporation and precipitation



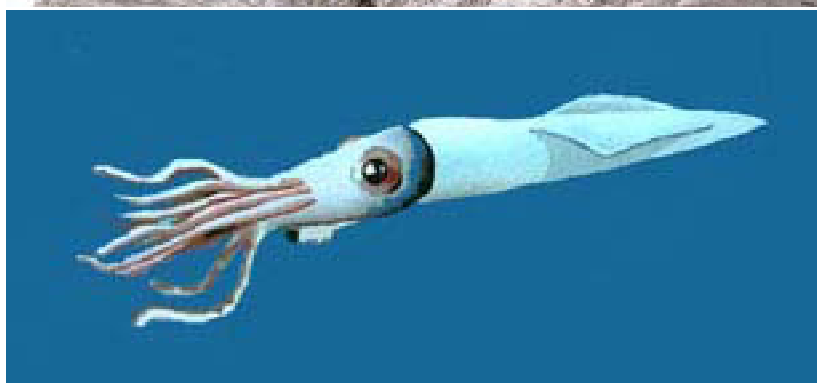
The isotope ratios depend on temperature!

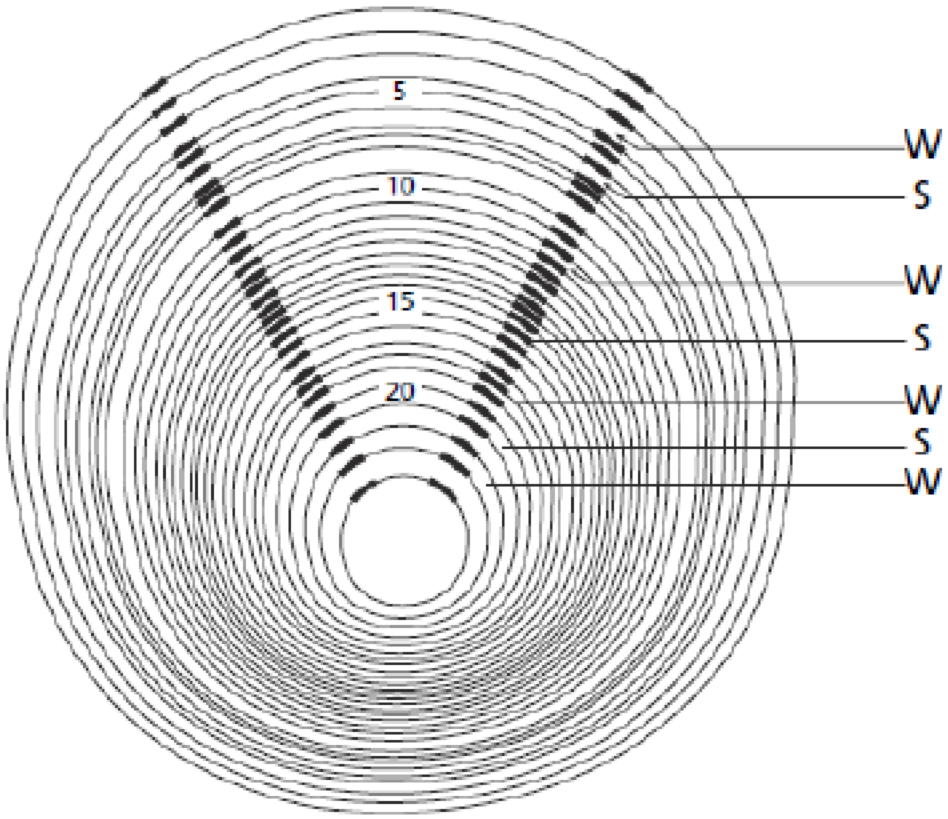
Isotopes become tracers and geo-thermometer

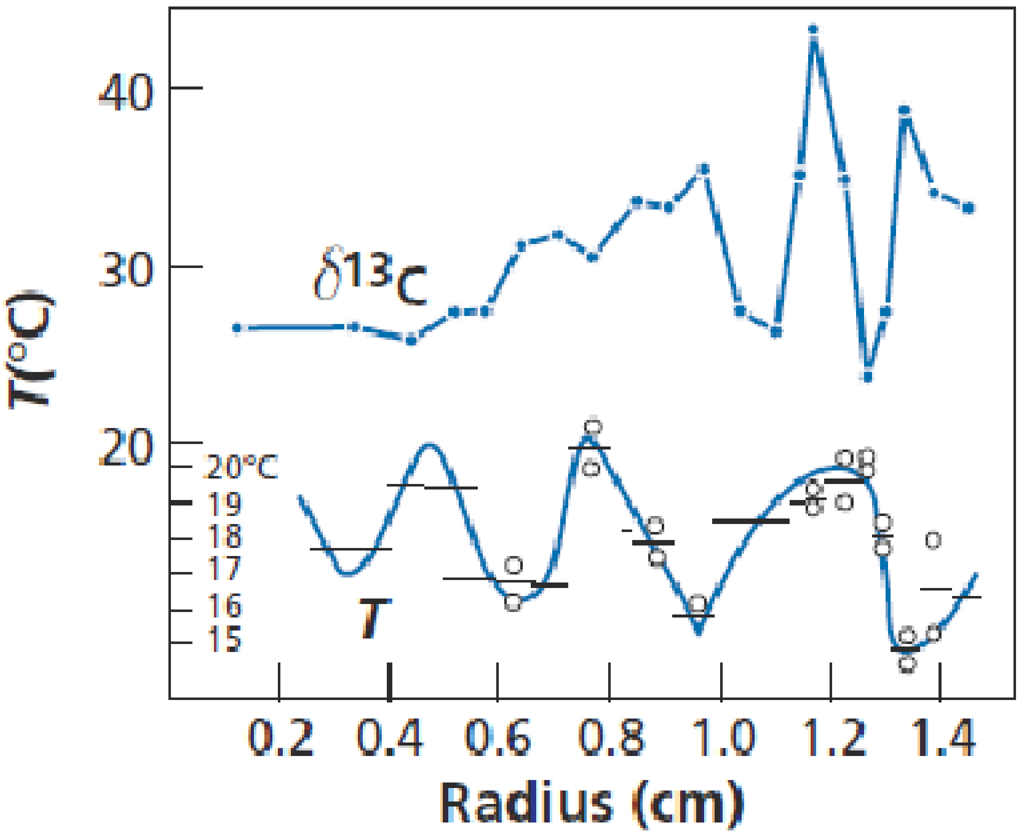
Rain in different parts of the world have different isotopic ratios



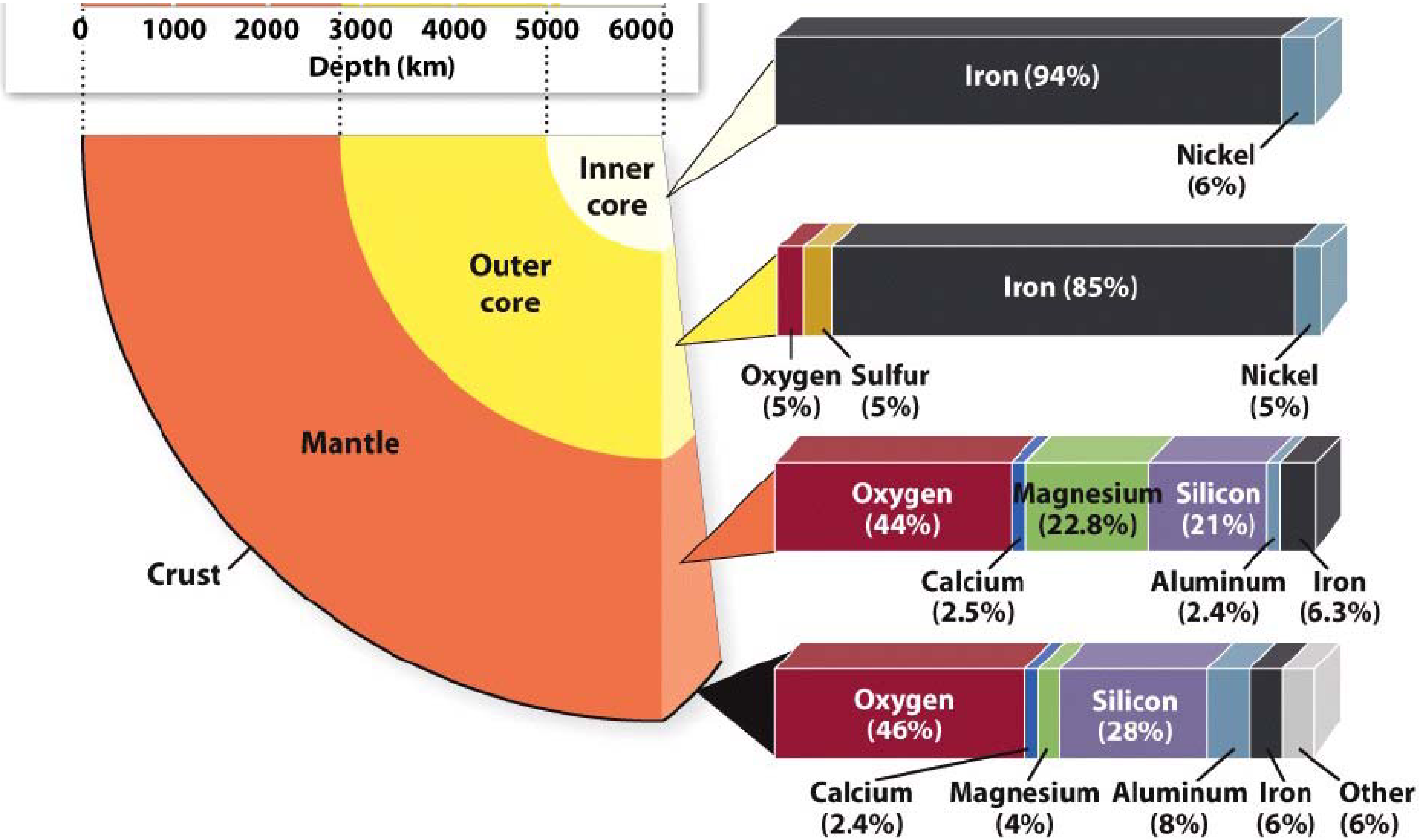
Temperatures 180Million years ago







Distribution of elements in the Earth



Apparently large changes (we will come back to this)

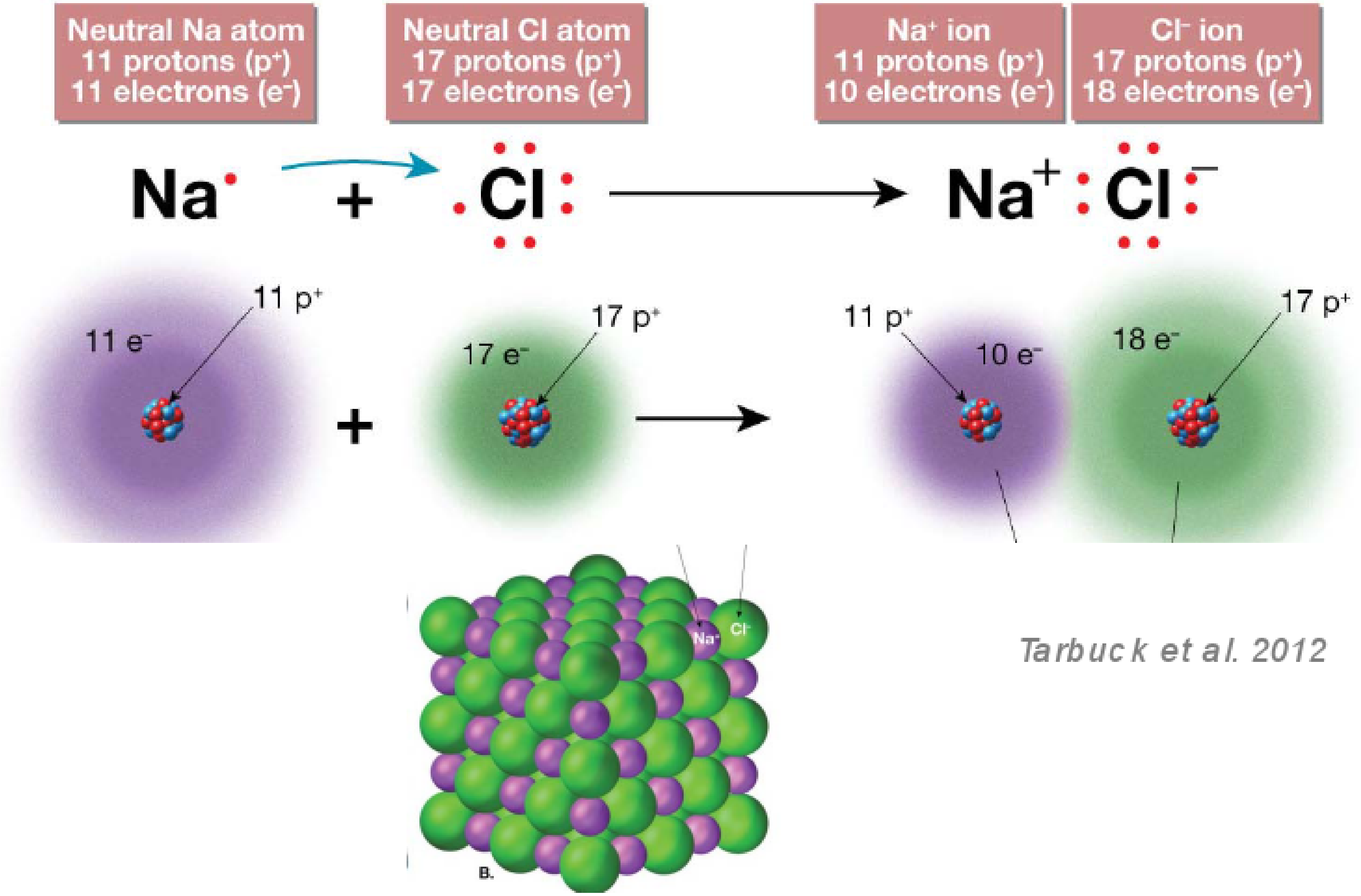
Chemical reactions

With the exception of noble gases, elements combine generally following the octet rule:

Atoms tend to gain loose or share electrons until they are surrounded by eight valence electrons

Ionic bonds

One atom gives up 1 or more of the valence electrons to another atom forming anions and cations which are then attracted to each other and form a compound



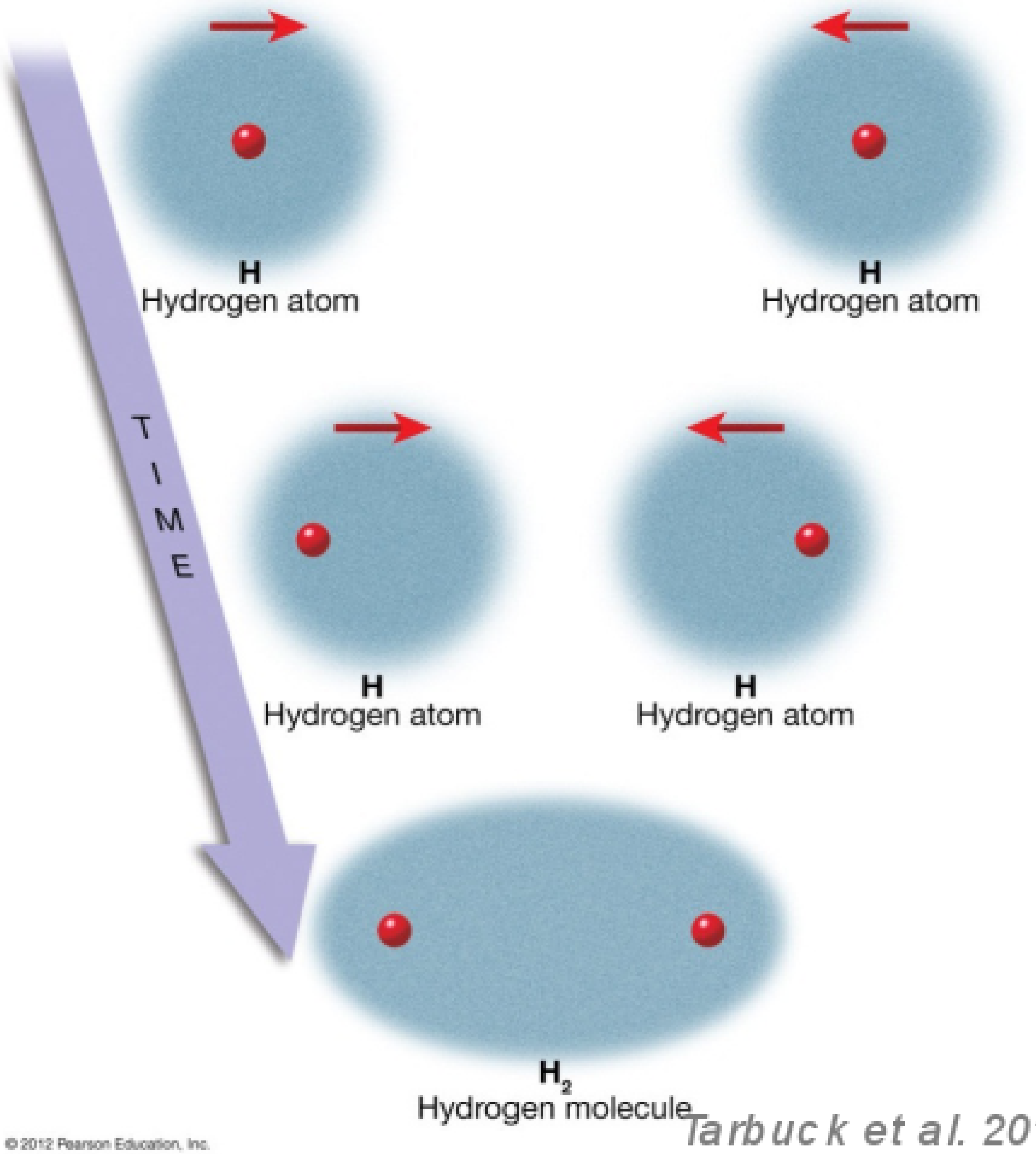
Tarbuck et al. 2012

Covalent bonds

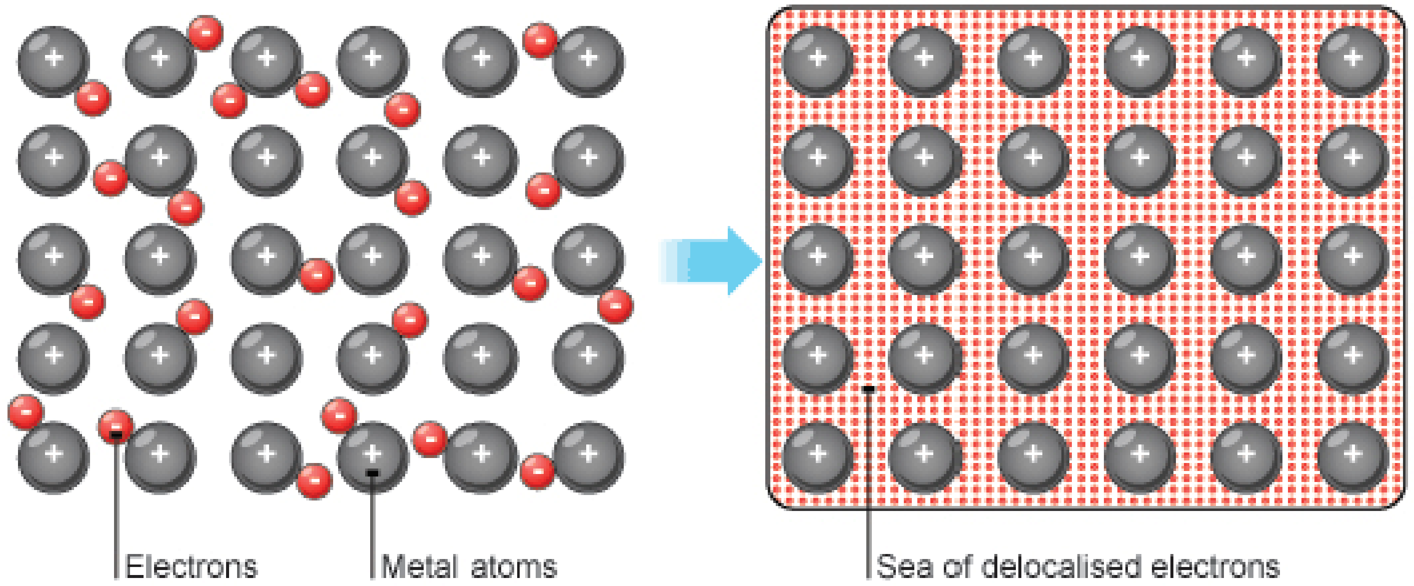
When forces holding atoms together are too strong they share a pair of electrons and form a covalent bond.

The attraction between protons of one atom and the electrons of the other keeps them together

$$H\cdot + H\cdot \rightarrow H:H$$



Tarbuck et al. 2012



Metallic bonds

Valence electrons move freely between atoms

Very strong bonds leading to high conductivity, strength etc

Minerals

Minerals

A mineral is a naturally occurring solid chemical substance that :

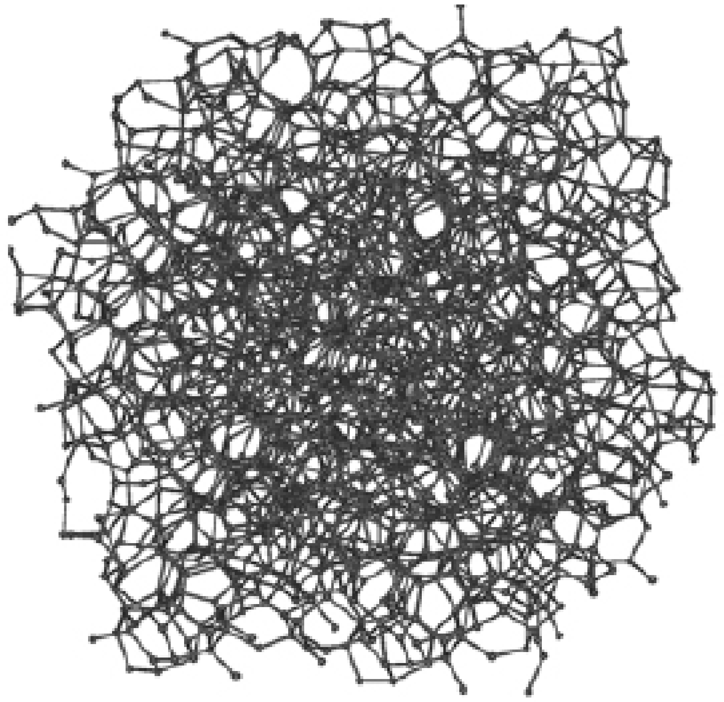
- **is formed through geological processes**
- **has a highly ordered atomic structure**
- **has a characteristic chemical composition**
- **has specific physical properties.**

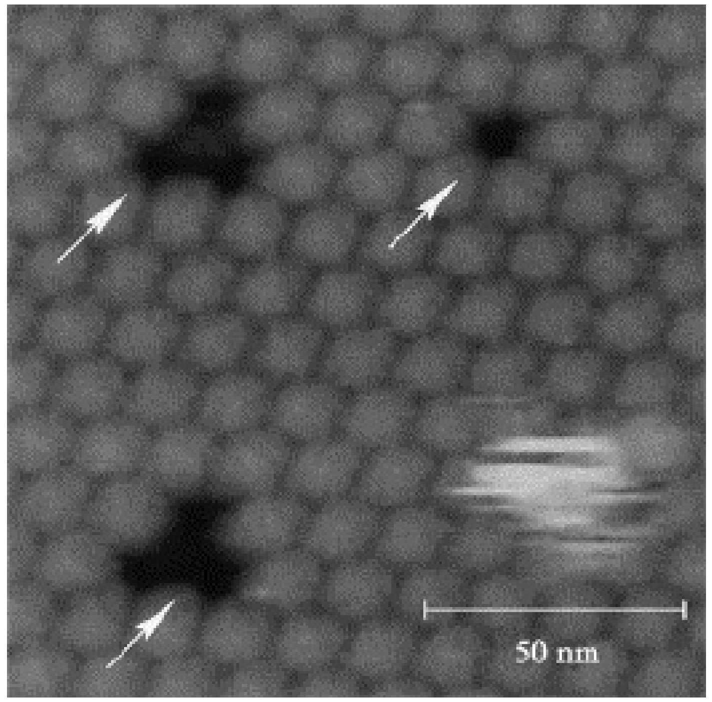
NB minerals can be formed by 1 element or more elements

Birth and growth of a crystal

Crystal are mostly born in a liquid solution. Slowly, small nuclei form around which the crystal grows.

If sufficient time is available the crystal will grow developing a perfect structure.
If not atom organization will be poor to non-existent

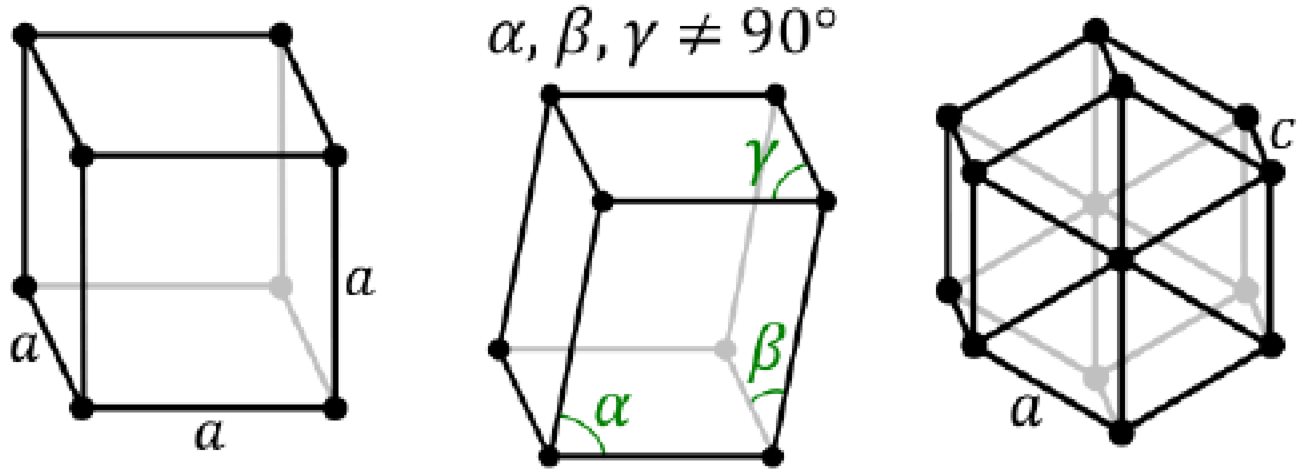




If the crystal can grow freely its crystal habit will be nicely displayed
If not, the crystallographic structure is visible only inside the crystal (x-rays)

Crystal structure and composition

Crystallography. A crystal is composed of unit cells stacked in 3D in an orderly way. The unit cell is a tiny box containing one or more atoms, a spatial arrangement of atoms. Different classes are defined on the basis of lattice parameters, (length and angle of cell edges, distances etc).



The way elements are arranged bears consequences on the physical properties of the mineral

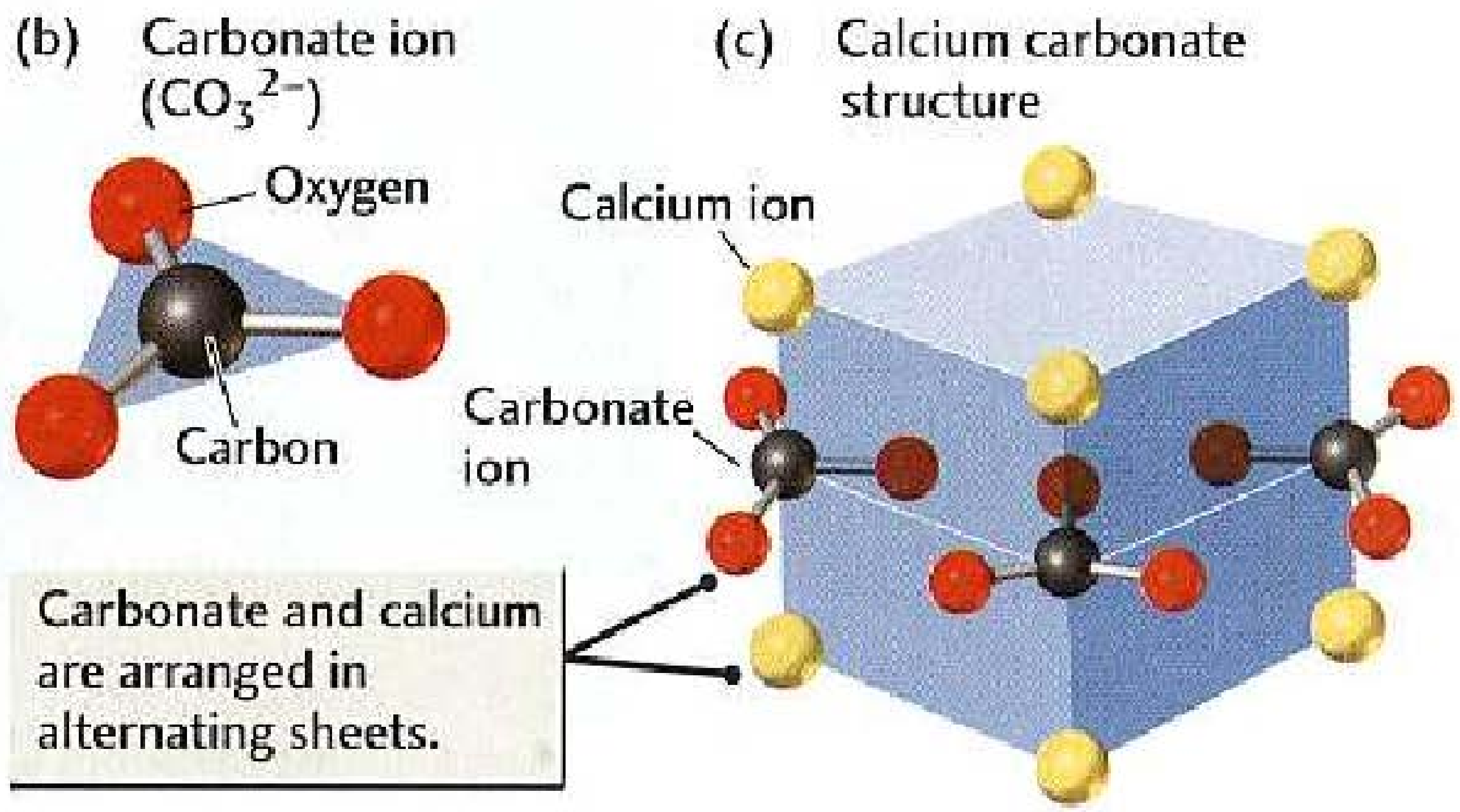
Mineral classification on the base of composition

Silicates
Carbonates
Sulfates
Halides

Oxides
Sulfides
Phosphates
Elemental minerals
Organic minerals

Carbonates $(CO_3)^{2-}$

Carbonate minerals constructed around the carbonate anion, $(CO_3)^{2-}$ with Ca between the sheet-like layers

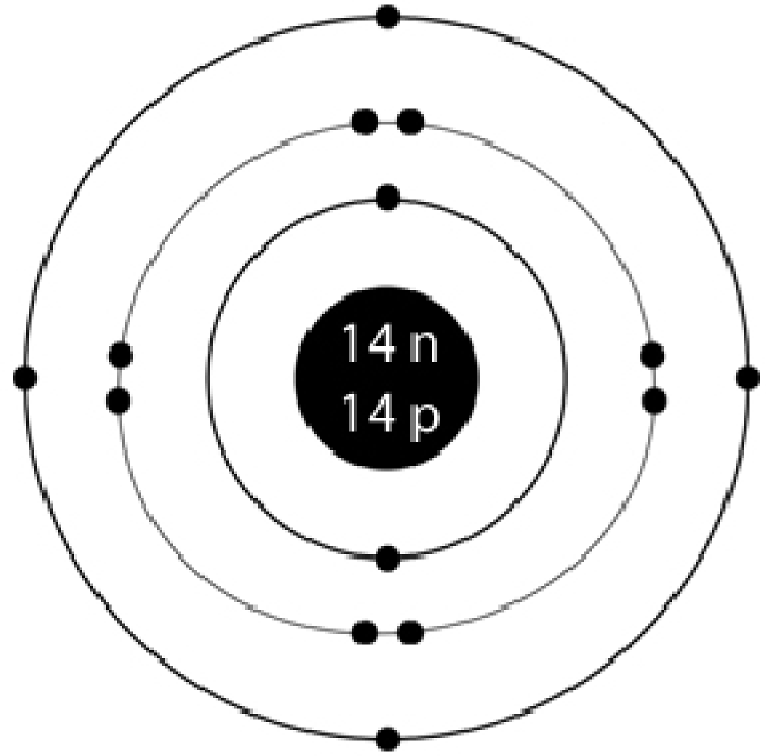


- Calcite-Aragonite, $CaCO_3$
- Dolomite, $CaMg(CO_3)_2$

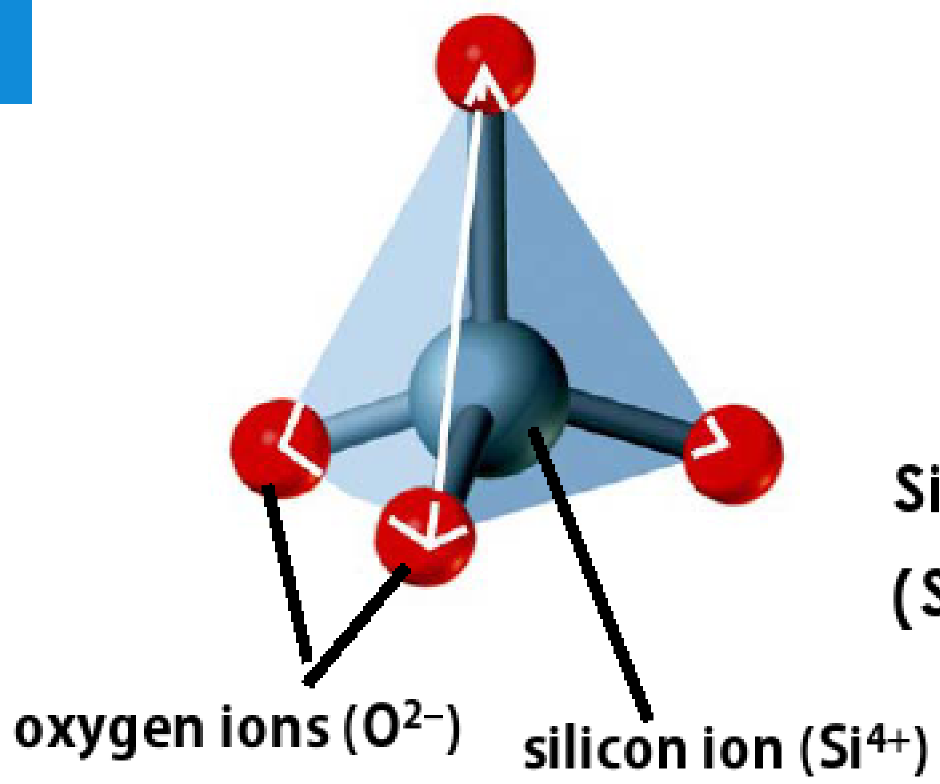
One of the most important minerals created by living organisms!

Silicate minerals

The most abundant minerals in Earth's crust



Si: 4 electrons in the outer shell



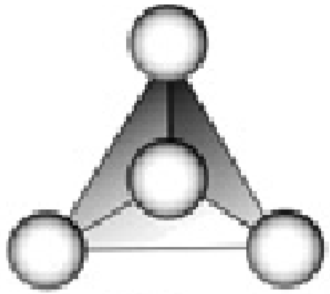
Silicon ties with O to form the very stable $(SiO_4)^{4-}$ tertrahedra

The tetrahedra can be linked in many different ways giving rise to very complicated structures

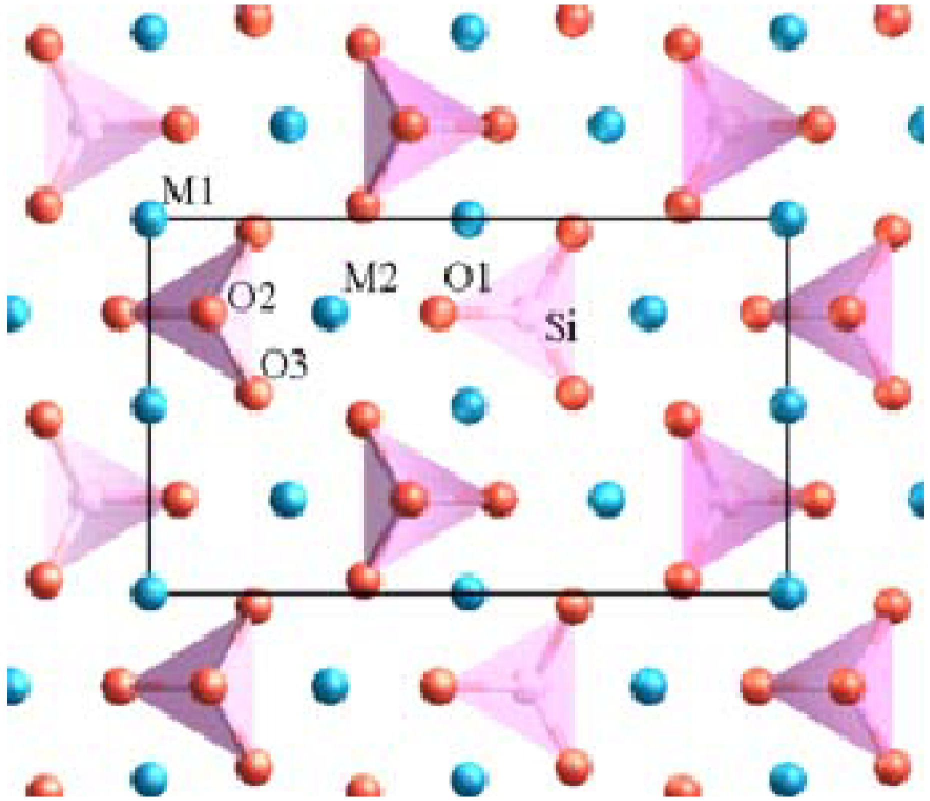
Other elements such as Al, Mg, Fe, Na, K and Ca commonly enter the structure

Isolated tetrahedra

A Si tetrahedron surrounded by cations (mainly Fe2+ and Mg2+)



Isolated Tetrahedron
$(SiO_4)^{4-}$



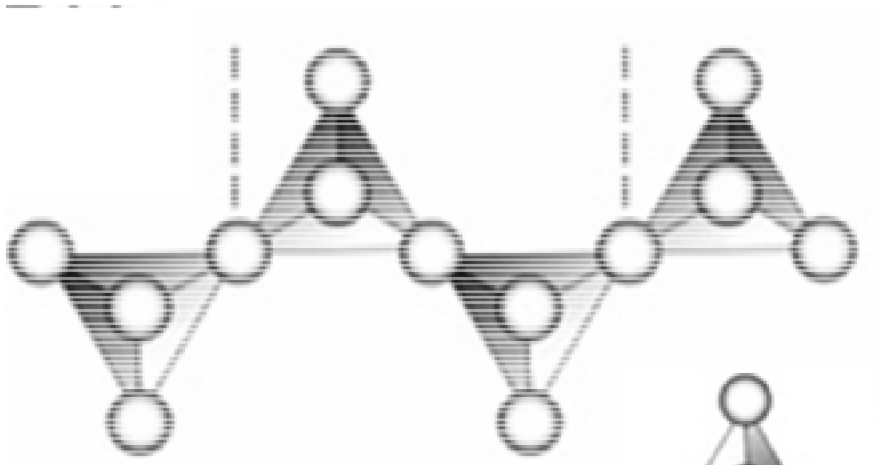
Olivine $(Mg,Fe)_2SiO_4$ (the most important component of the Earth' mantle)

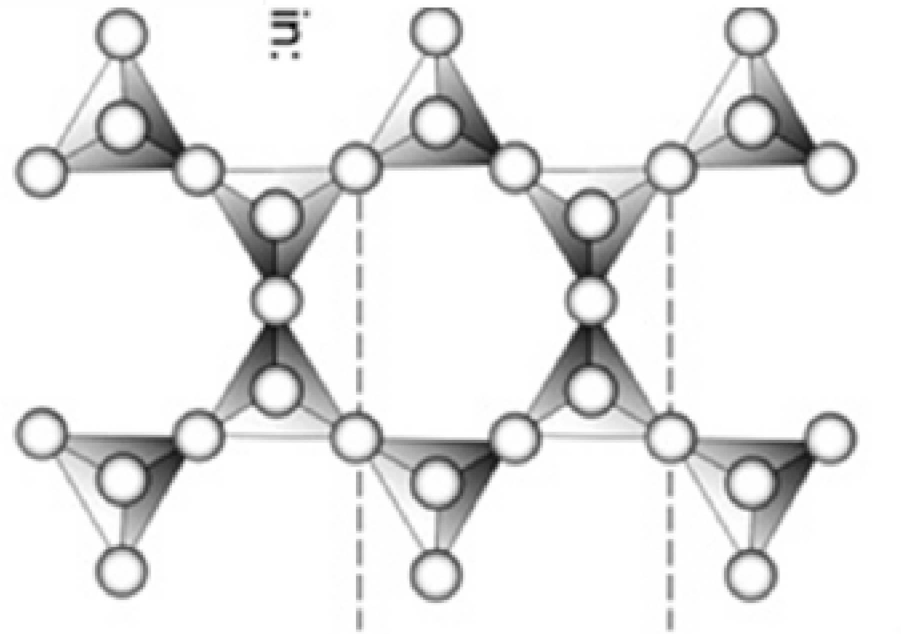
Elements such as Mg and Fe find their place between tetrahedra (blue spots)

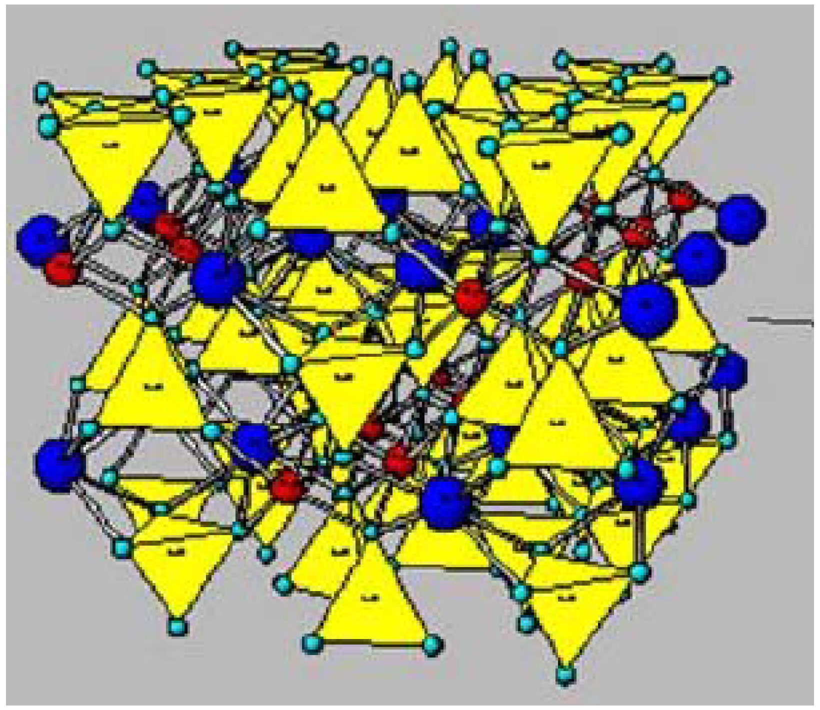
Chain silicates (inosilicates)

Adjoining tetrahedron share 1 oxygen forming chains. Remaining negative charges are compensated by cations. The loose structure allows many different mineral types

Single or double chains exist



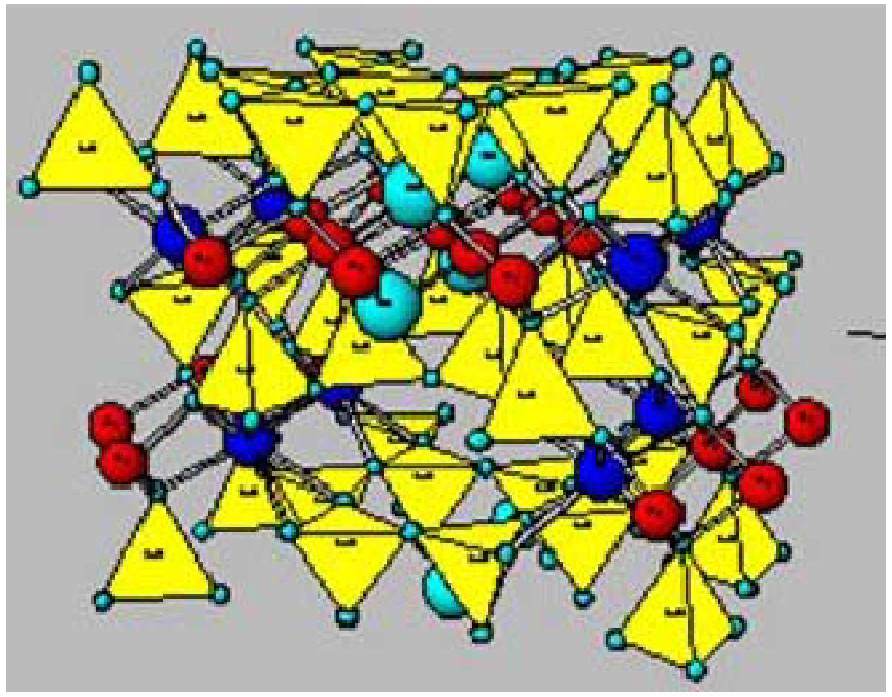




Pyroxene group

(Ca,Na)(Mg,Fe,Al){$(Si,Al)_2O_6$}

Important in the mantle and elsewhere

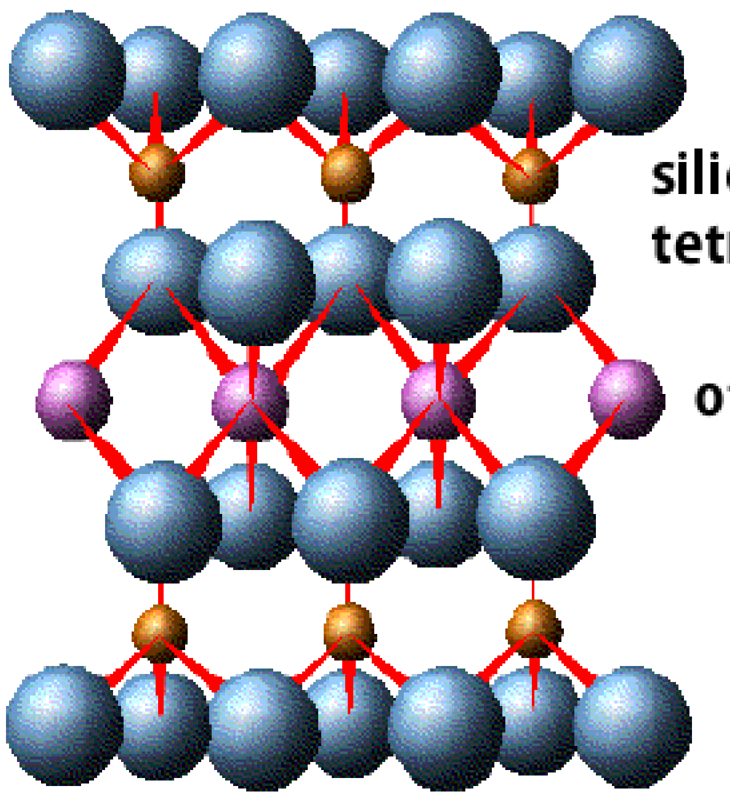


Amphiboles

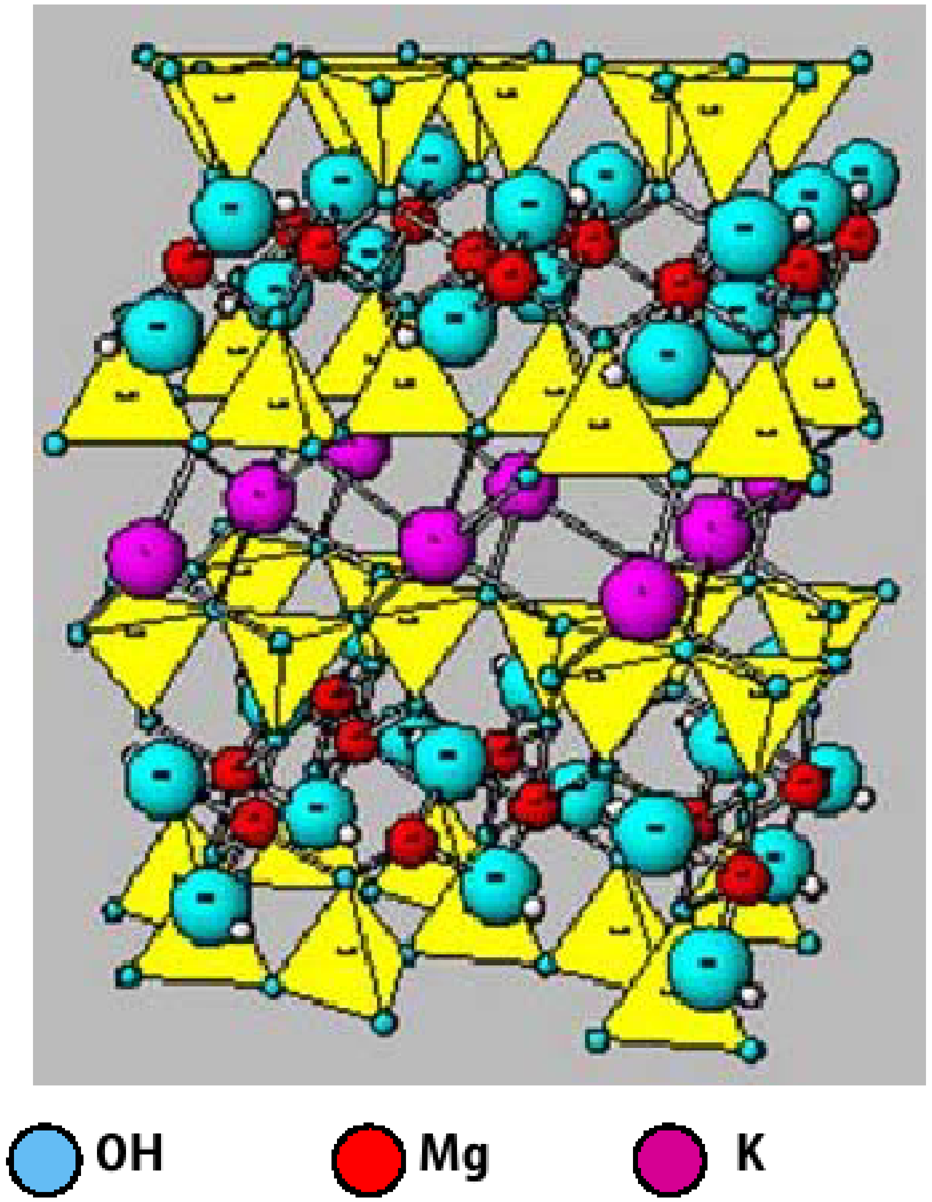
$(Na,Ca)_{2-3}(Mg,Fe,Al)_5${$(Si,Al)_8O_22$)$(OH)_2$

Note the presence of the (OH) oxydrile: it means water!

Sheet silicates (phyllosilicates)



Si tetrahedrons are linked 2 dimensionally into sheets. Between two planes of Si tetrahdrons is an octahedral layer (either filled with Al (as one end member) or with some divalent cation (Fe^{+2}, Mg^{+2}) at another extreme).

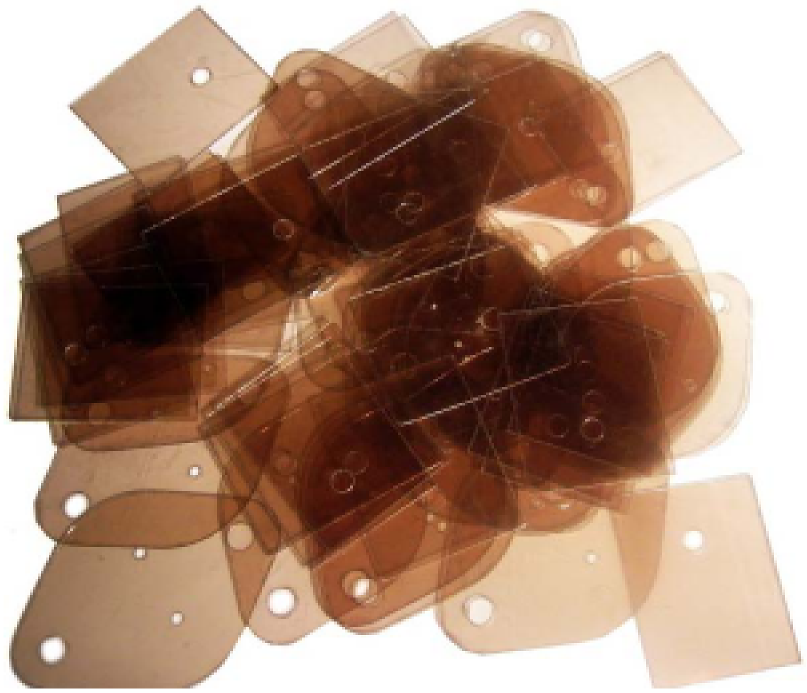


Micas

(e.g. muscovite and biotite)

$(K,Na,Ca)_2(Al, Mg,Fe)_{4-6}Si_8O_{20}(OH)_4$

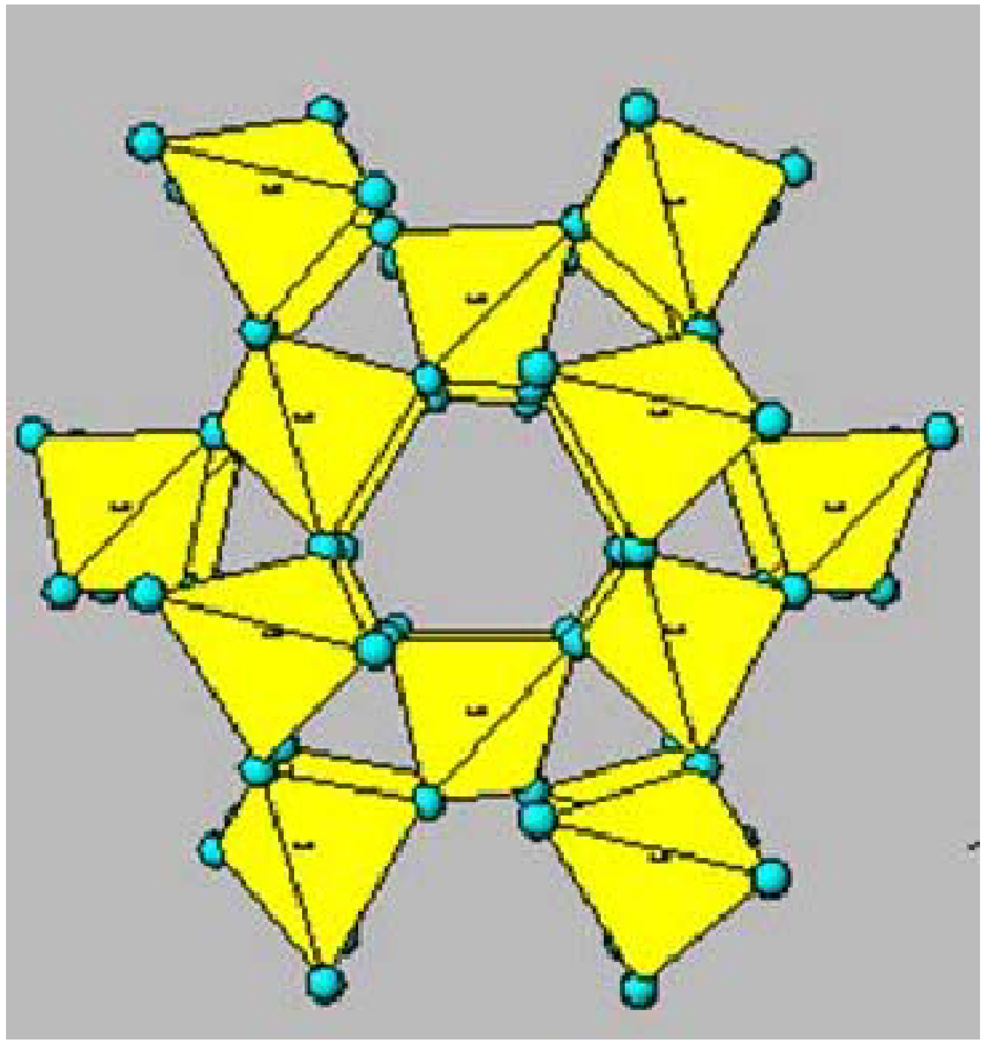
Have a very important basal cleavage



Framework (tecto) silicates

Are the most complex form of Si tetrahedral linkages: a 3D sharing of O.

quartz (SiO_2), a 3D linkage of O which results in a completely neutral charge, no need for counterbalancing cations, and a very strong resistance to chemical weathering.



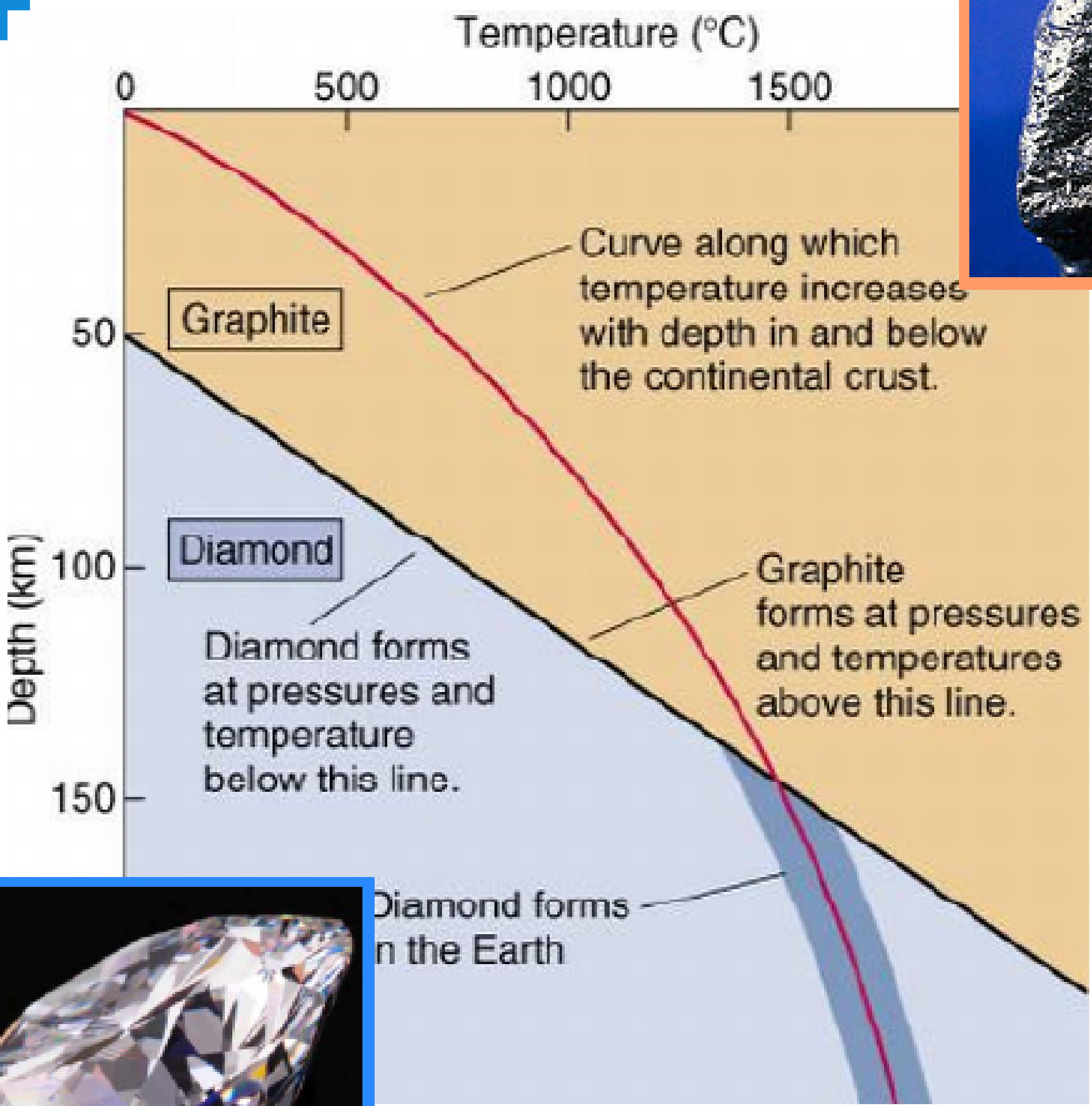
In nature, Al can easily substitute Si in the tetrahedral configuration (Al has about the same size and position on the periodic table).

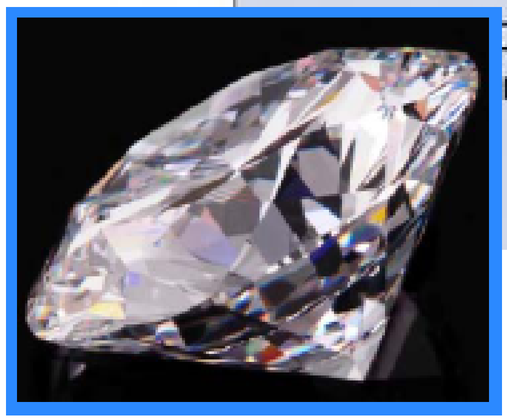
Because Al has one less positive charge than Si, the addition of Al in place of Si creates a net negative charge that must be counterbalanced by a cation.

Tectosilicates with Al are feldspars (alkali feldspars and plagioclases)

Stability fields of minerals: single minerals

The crystal structure can change with changing pressure and temperature





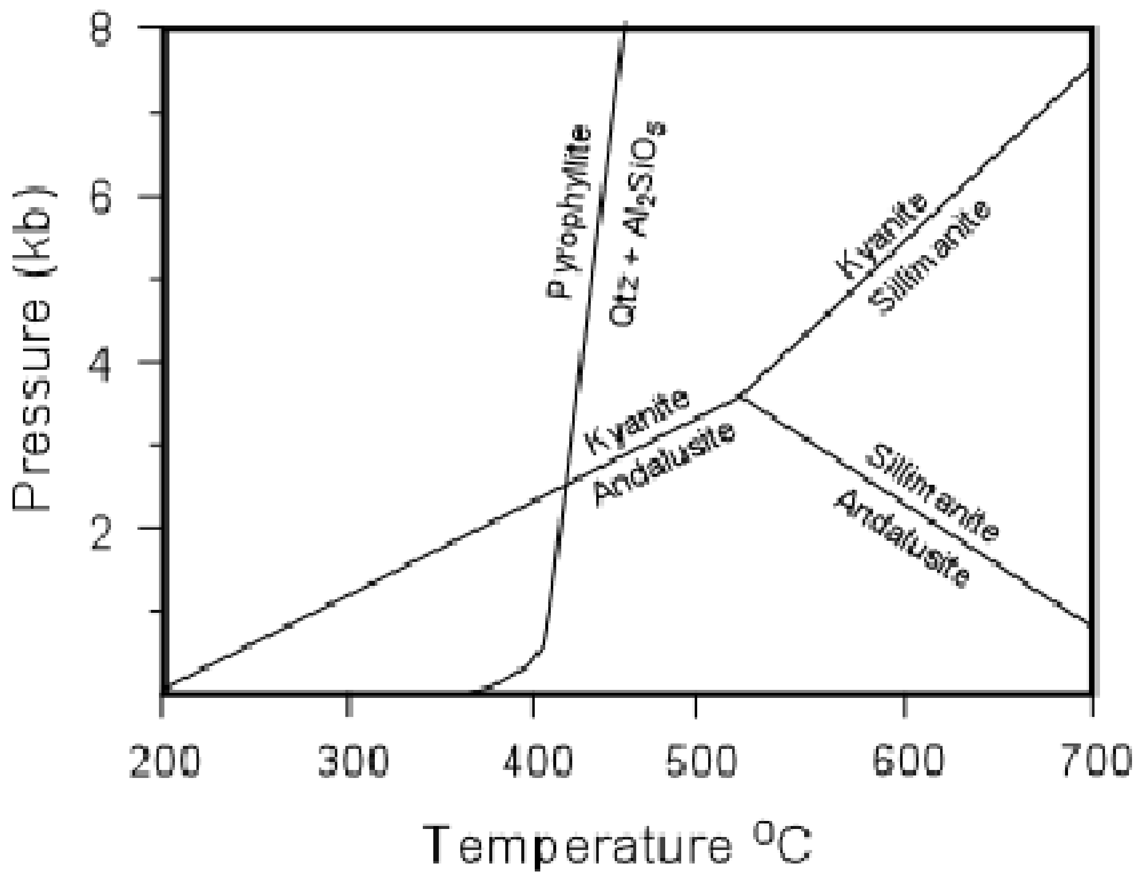
Polymorphism: Some elements and compounds form two or more different minerals depending on P,T conditions (same composition, different internal structure)

- C graphite, diamond
- $CaCO_3$ calcite, aragonite
- ....

very useful as minerals become indicative of specific T, p conditions

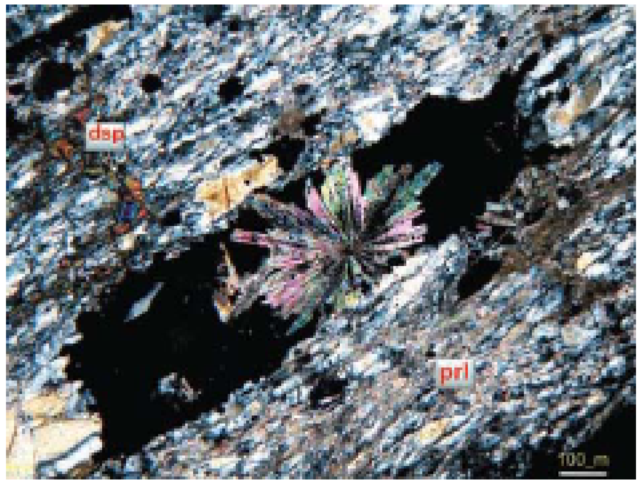
Stability fields: reactions

With changing pressure and temperature, minerals can even become unstable and produce other minerals



$$Al_2Si_4O_{10}(OH)_2 \iff Al_2SiO_5 + 3SiO_2 + H_2O$$

Pyrophyllite — Ky or Andal+Qtz+fluid



Pyrophyllite: mineral with many industrial applications (insecticides, thermal insulation …)

And now…… the rocks

Rocks: naturally occurring aggregates of (one or more) minerals

Igneous rocks

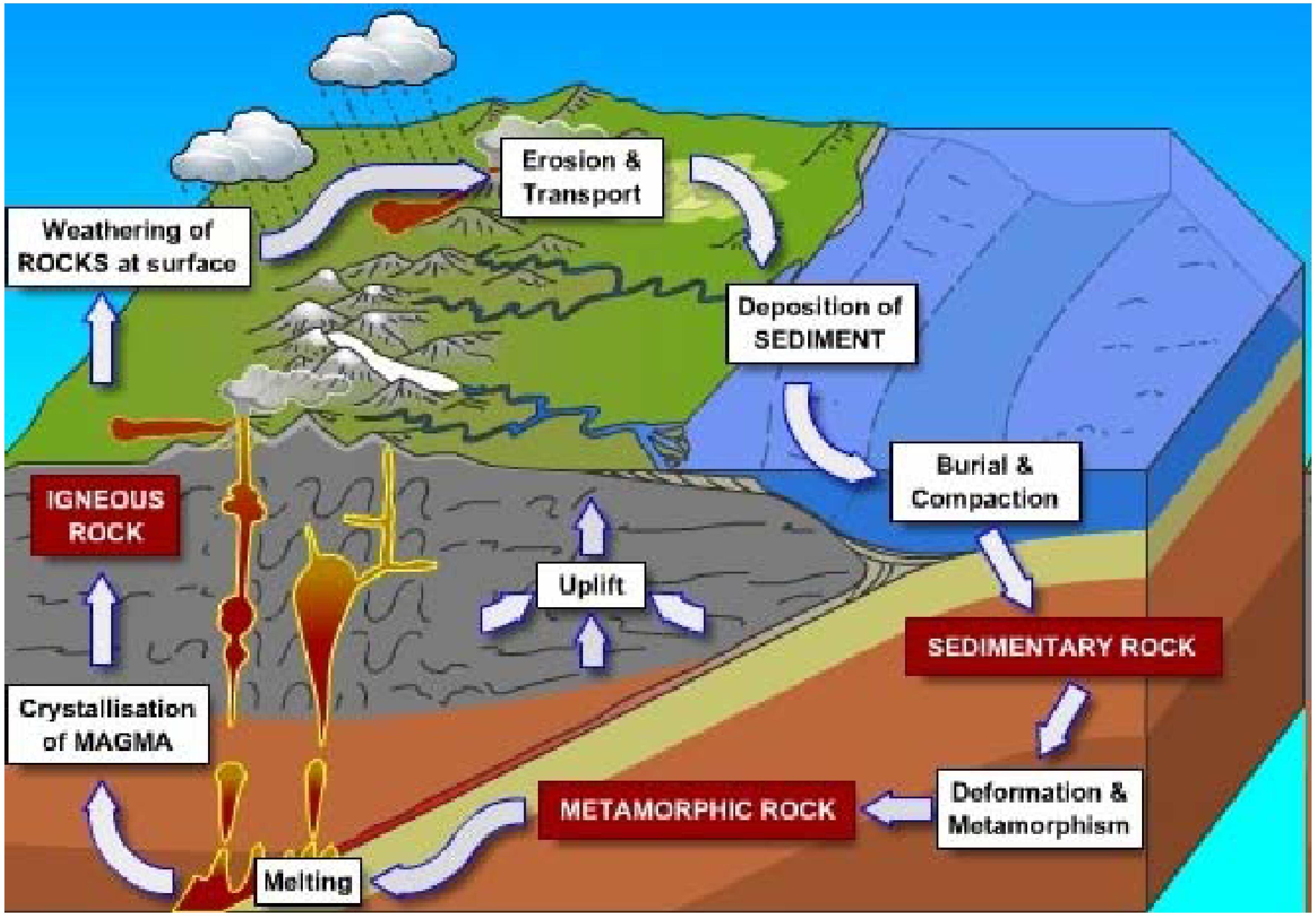
Formed by solidification of magma

Sedimentary rocks

Formed and deposited at the Earth's surface, by erosion of older rocks, biologic or chemical processes

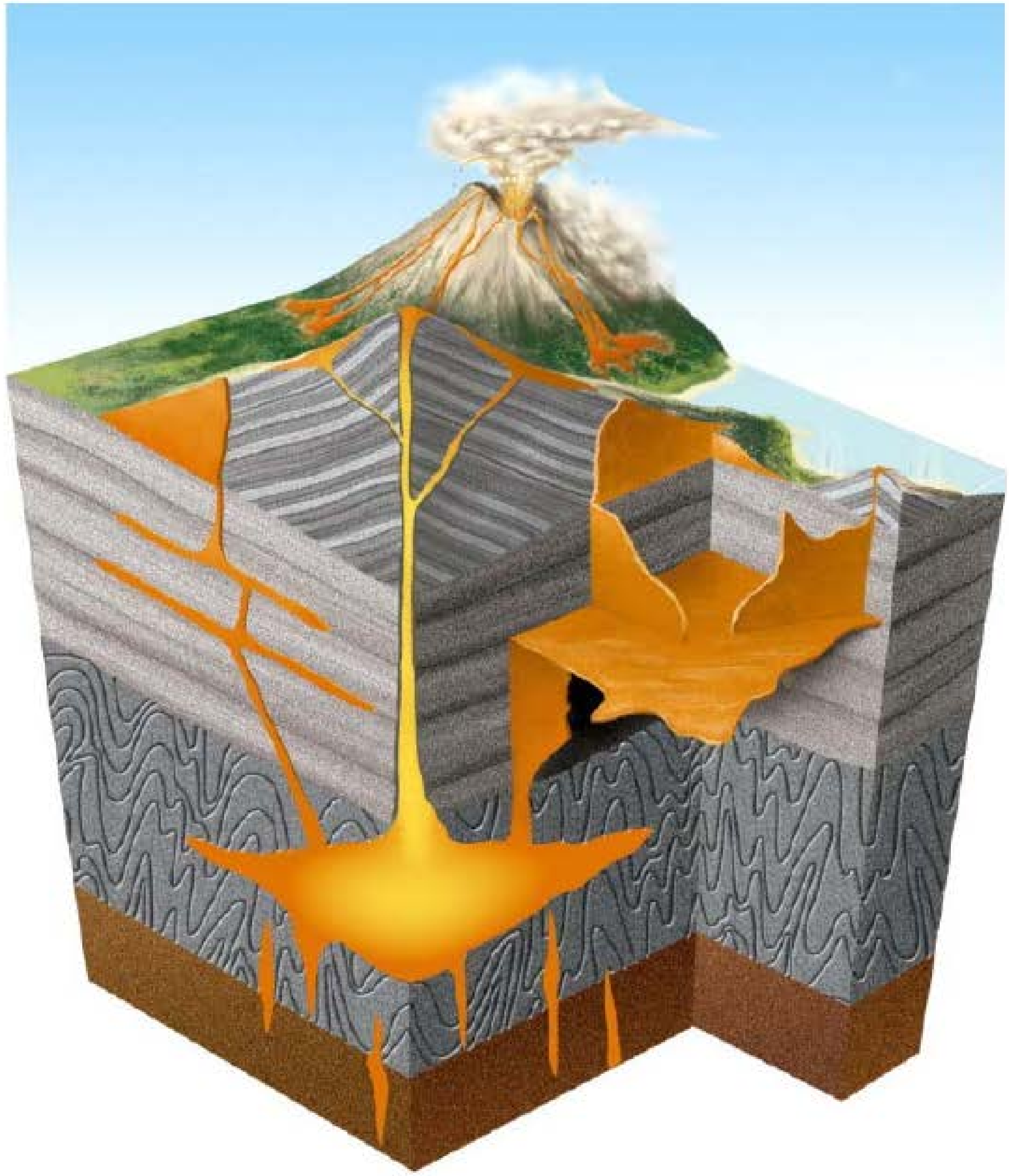
Metamorphic rocks

Formed by the alteration of pre-existing rocks in response to changing pressure and temperature



Magmatic (igneous) rocks

Igneous rocks result from the consolidation of magma at different conditions

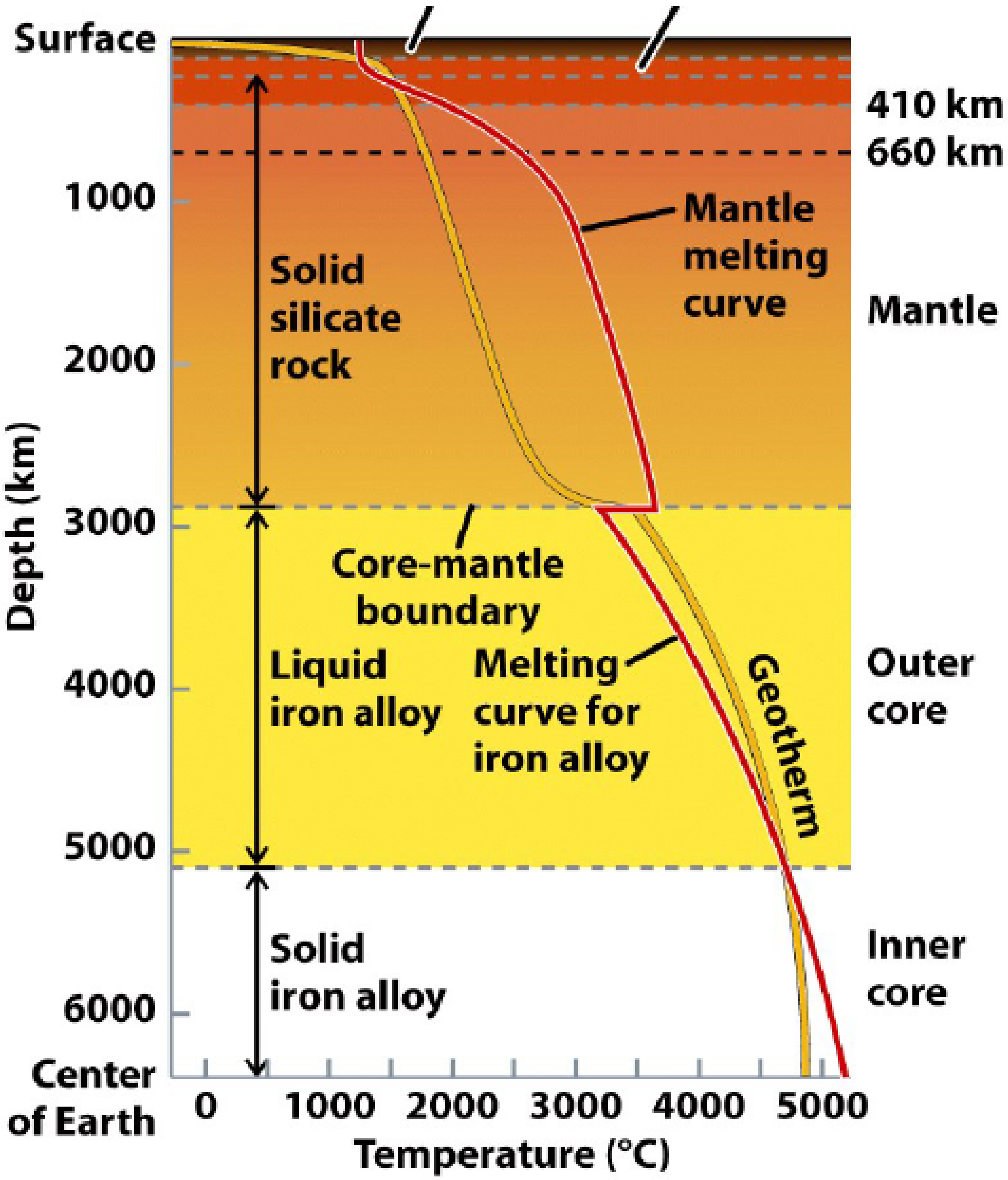


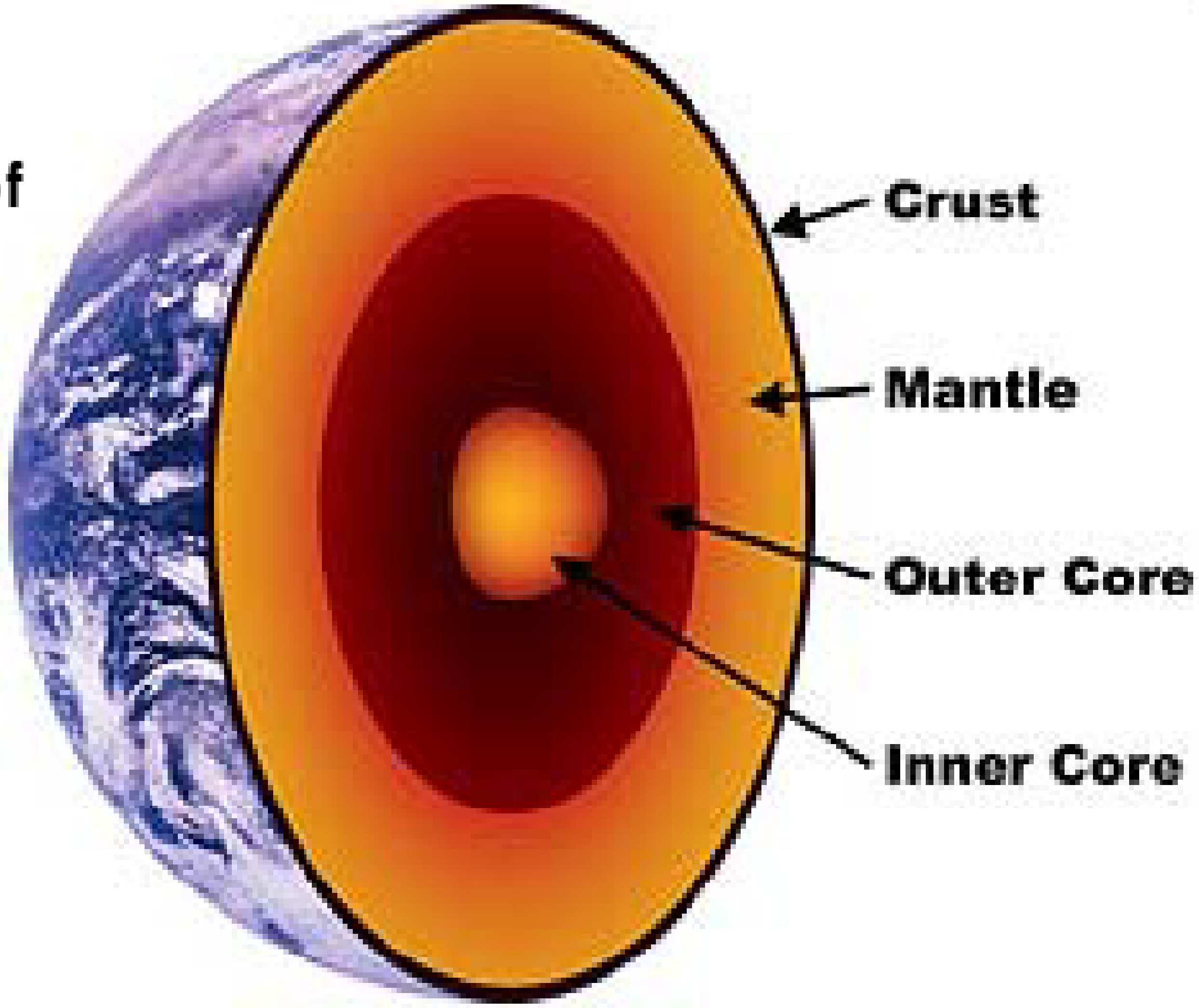
Three main stages
1) Magma generation
2) Magma transport (ascent)
3) Consolidation

Melt generation

The outer 3000km of the Earth are made of solid rocks

Where does magma come from?





Temperatures do increase with depth

But also the melting point also does

▼

With the partial exception of core, the Earth is solid.

▼

To produce magmatism, one needs to melt rocks.

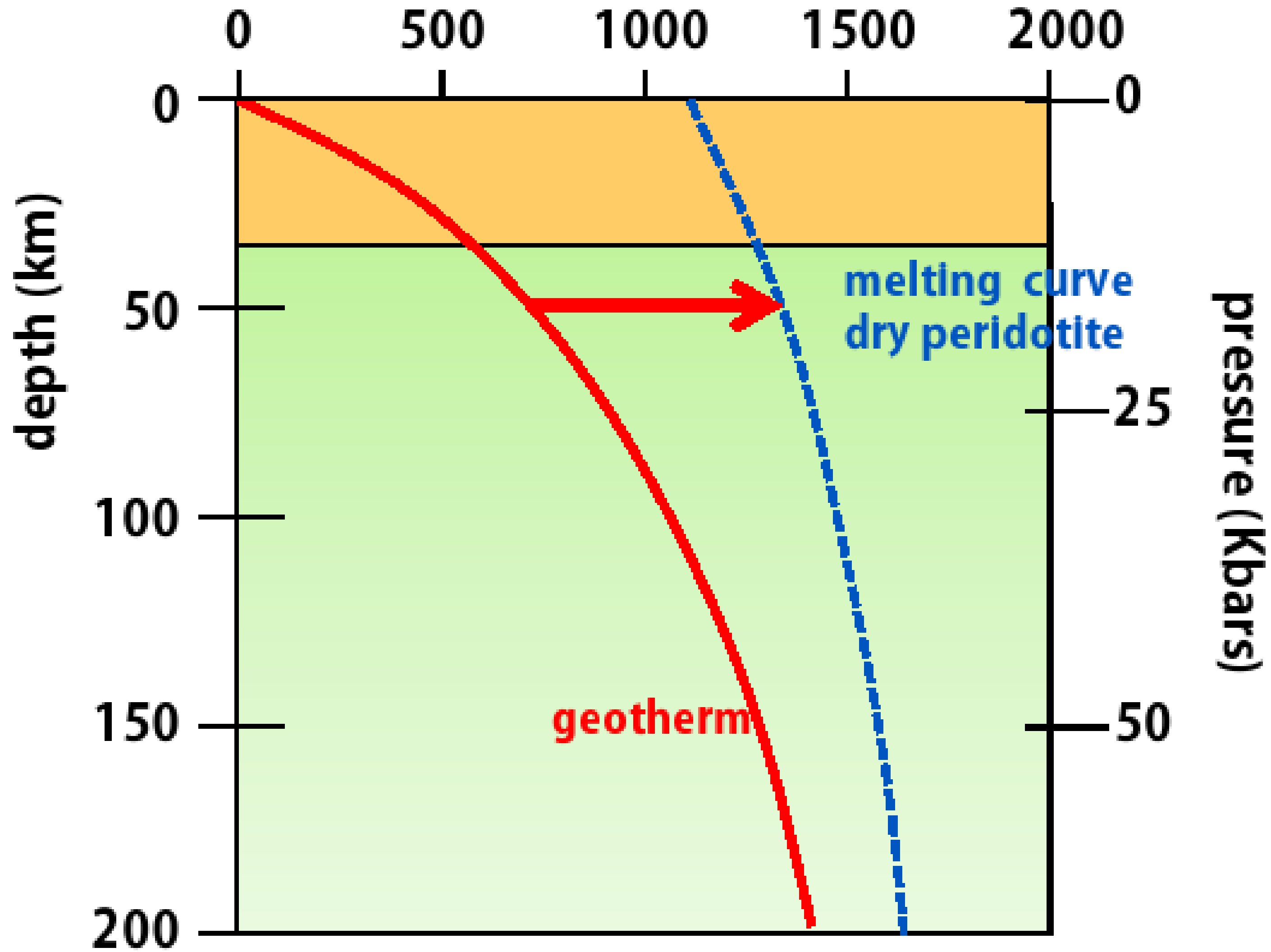
There are 3 different ways to do this

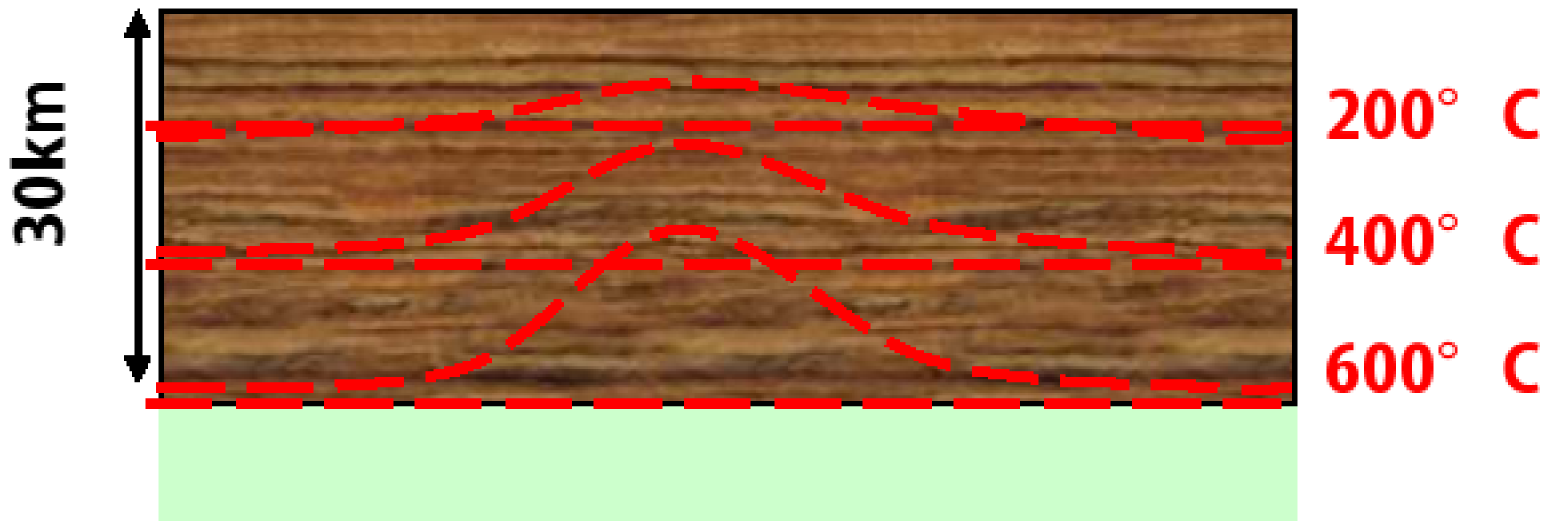
1. Increasing the temperature (=creating a thermal anomaly)
2. Decreasing the pressure
3. Adding fluids (water)

1. Creating a (large enough) thermal anomaly

Implies warming up rocks at a given depth until they start melting

100s of °C are needed!





Heating of this magnitude is not trivial

Materials can be heated up by conduction or advection.

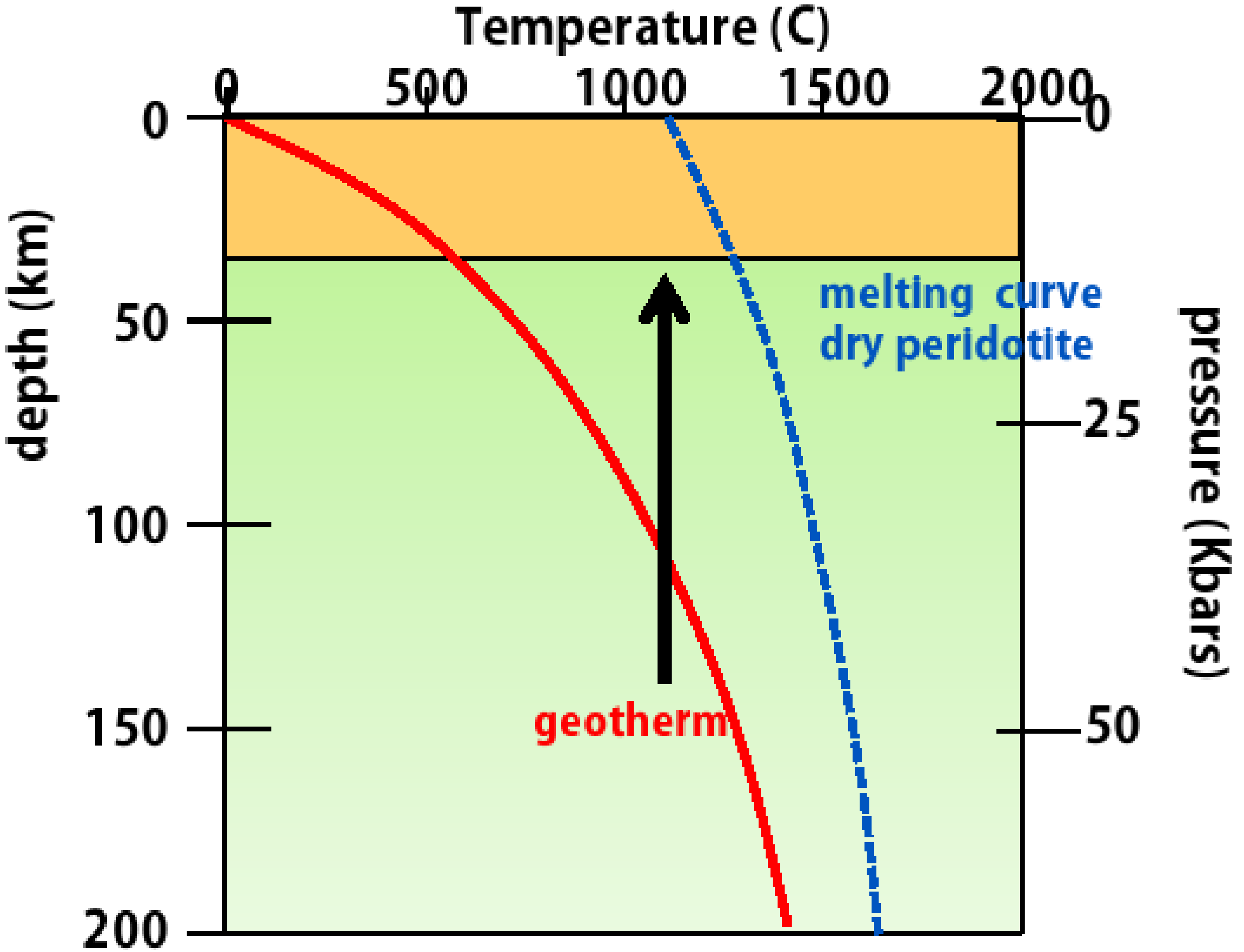
The 1st does not work, the 2nd needs magma

2. Melting by decompression

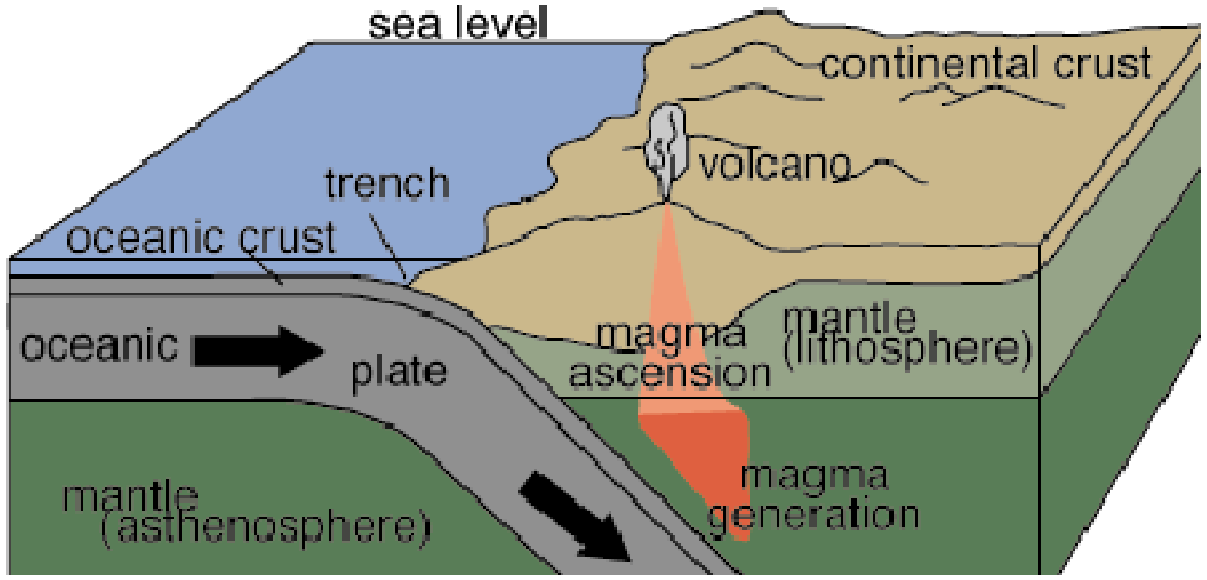
Melting temperatures are pressure-dependent

If pressures decrease enough, while temperatures do not, melting can take place

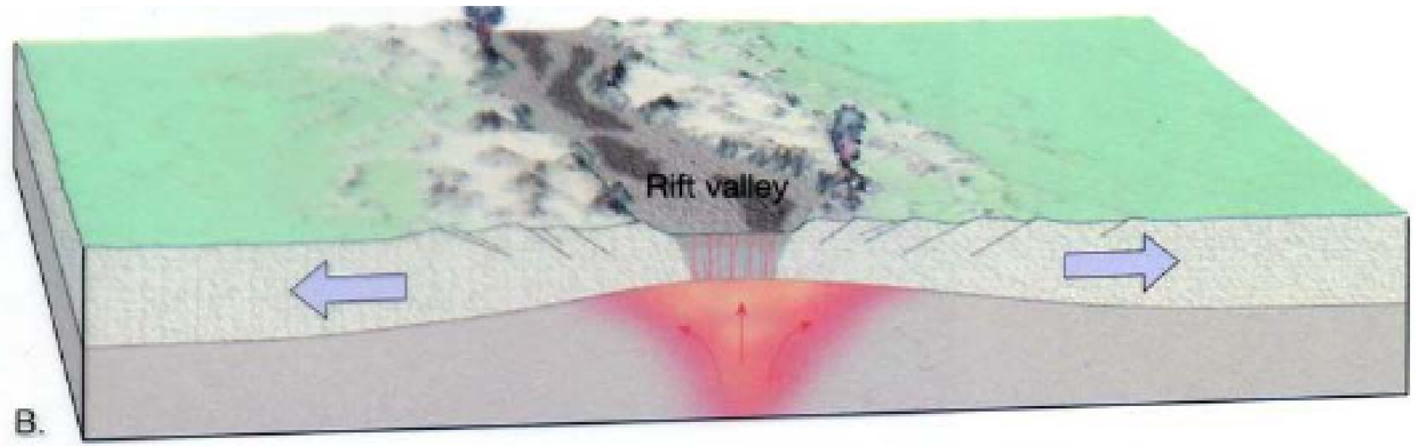
Two ways to do this:



Move rock upward very rapidly



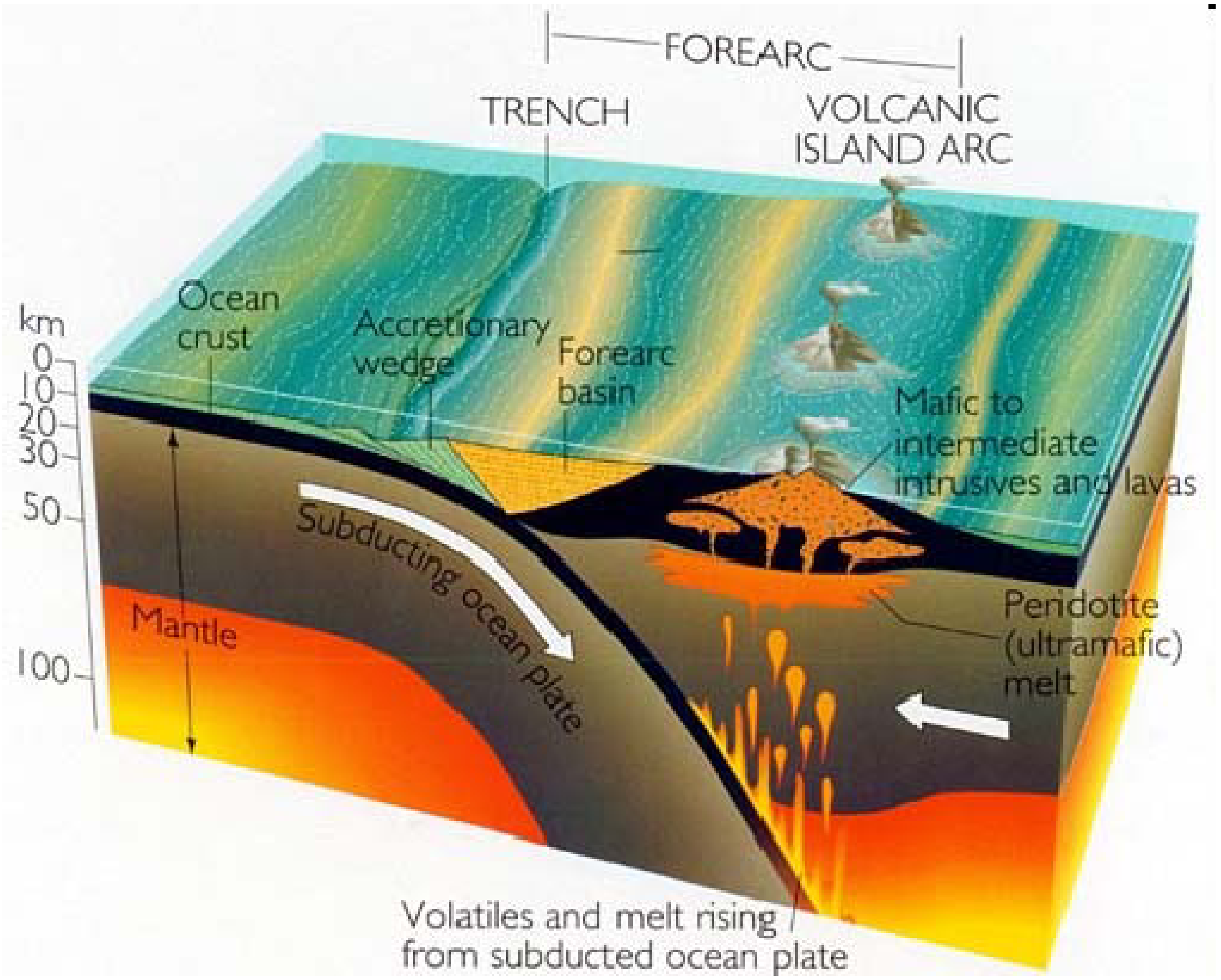
Decrease the overburden

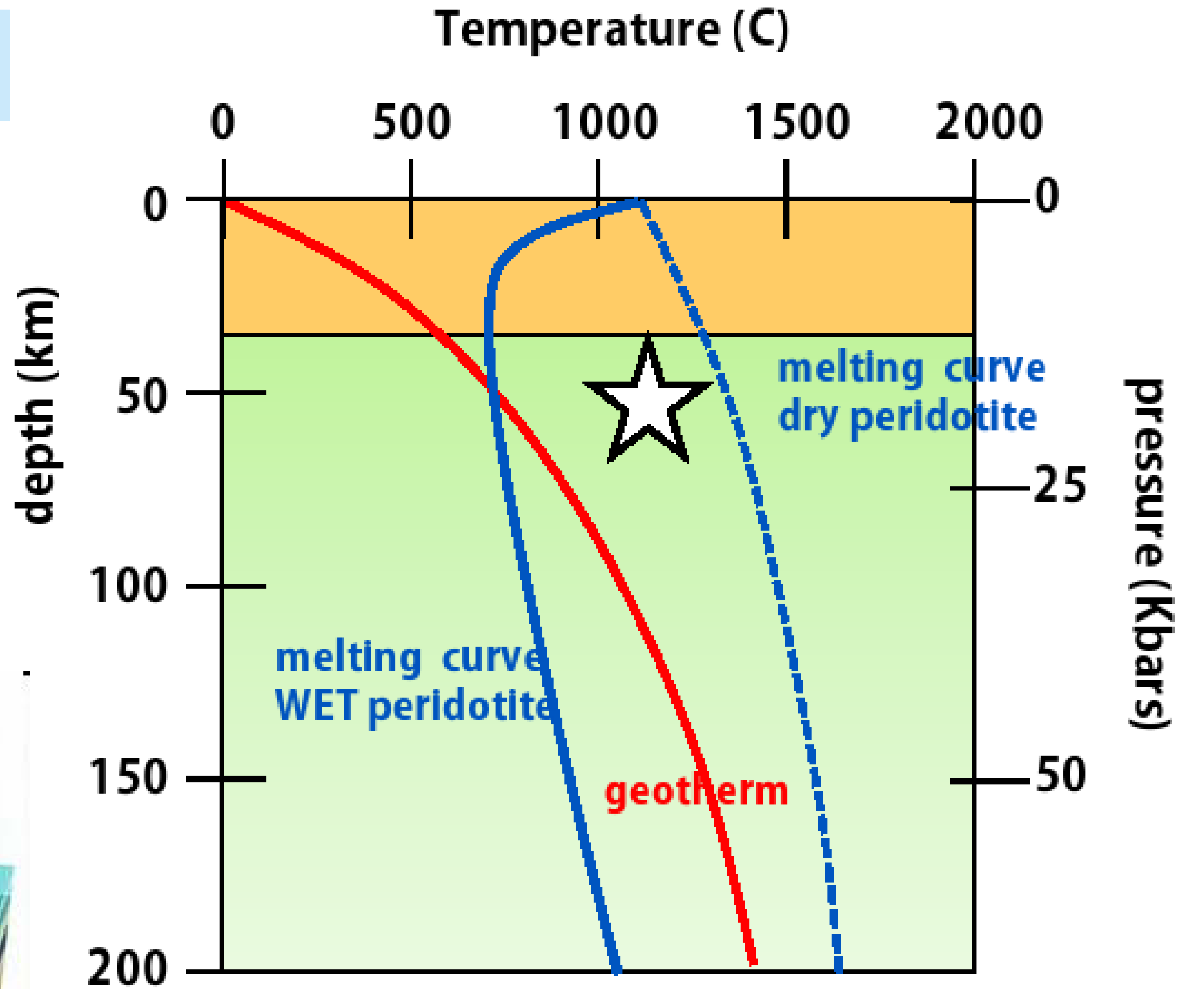


3. Melting by addition of fluids

Fluids provoke a substantial decrease in melting temperatures

Rocks start melting even if they do not move





This is what happens above subduction zones

(any idea where do the fluids come from?)

Melting starts! What kind of magma is produced?

for 1 mineral rock:

• melting takes place at one T

• the melt will have the same composition of the rock

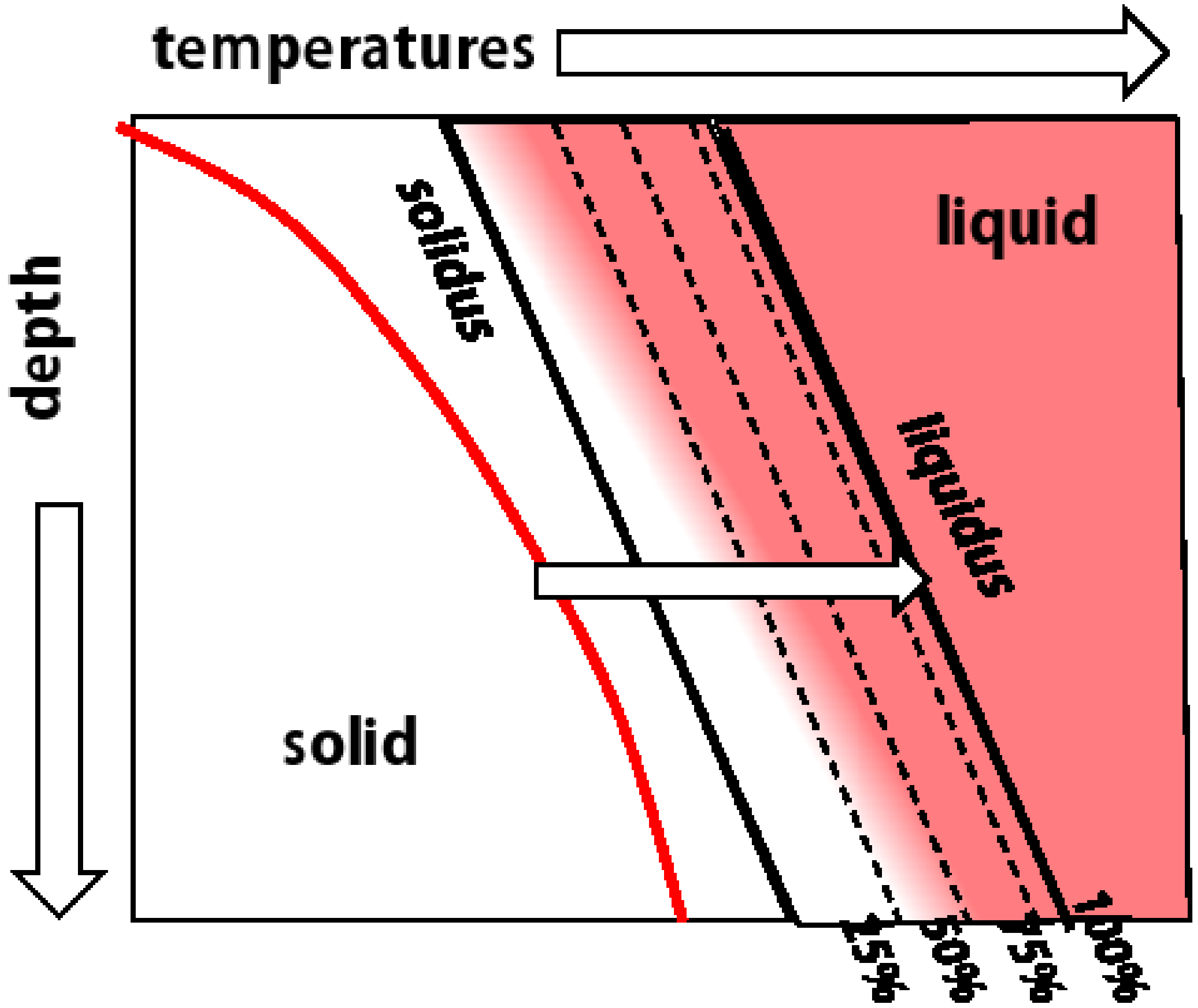
olivine	amphibole plagioclase	quartz
1000 °C	800 °C	600 °C

If rocks are composed of >1 mineral

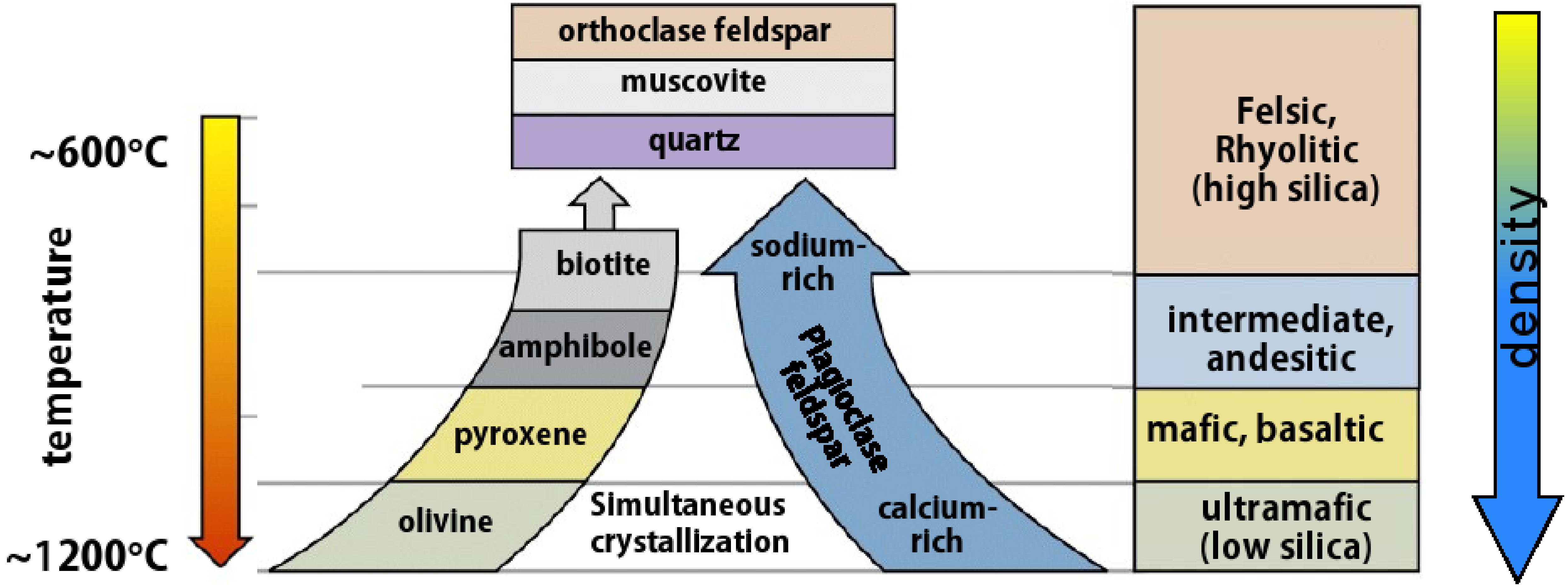
▪ each mineral will melt at different temperatures.

▪ temperature at the first drop of melt is the *solidus*, that at total melt is *liquidus*

▪ The composition of the melt will not coincide with that of the rock unless melting is complete. This is differentiation

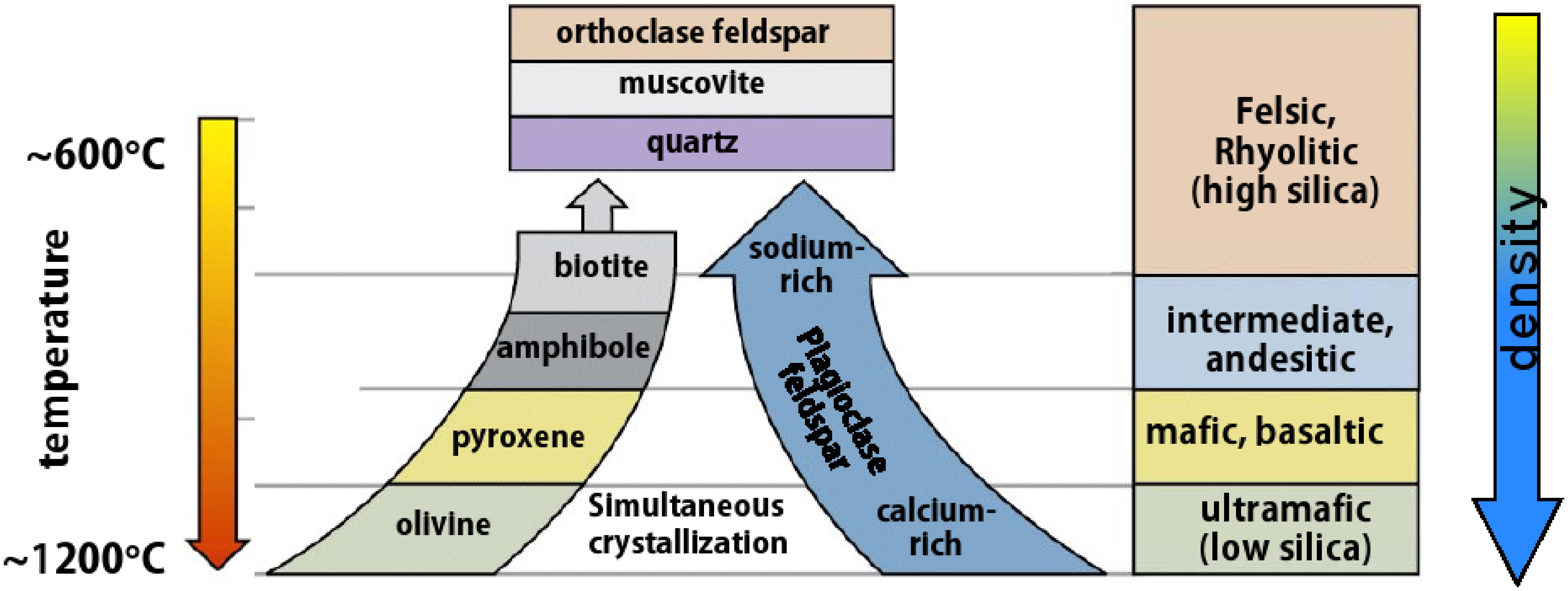


Predicting differentiation: Bowen's reaction series



The composition of the magma depends on a) the primary composition of the rock and b) the degree of melting

Silica rich magmas are lighter than silica-poor ones



Initial magmas are light magmas and tend to escape easily

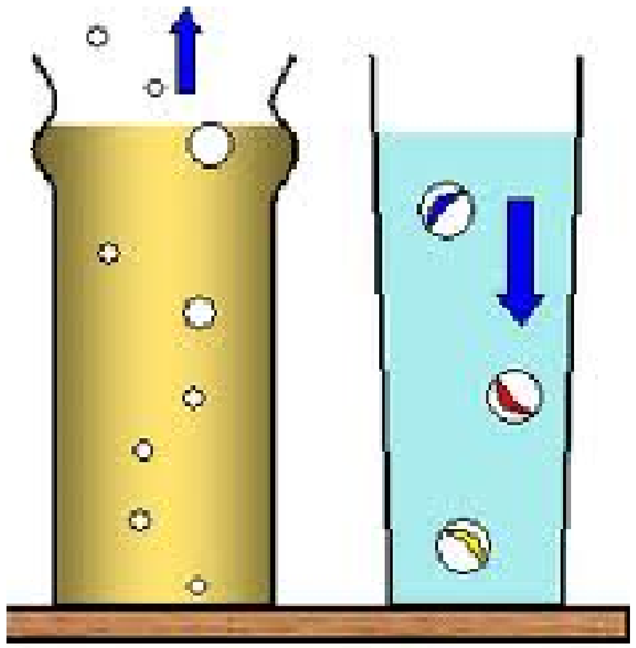
feldspar	quartz	biotite	pyroxene	olivine
2.56	2.62	3.09	3.2	3.32

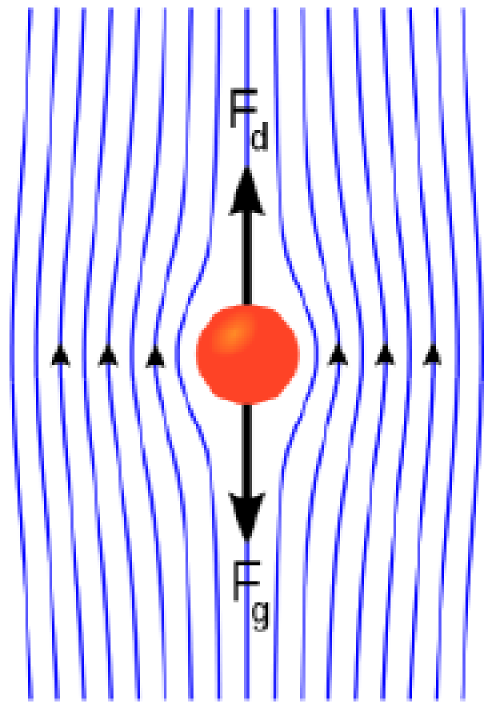
magma	basalt	andesite	rhyolite
	2.6-2.8	2.45-2.50	2.18-2.25

The upward movement of the magma

Magma starts moving upward driven by density difference (buoyancy).

A simple description is Stoke's law which describes density driven movements





$$v_s = \frac{\sigma_p - \sigma_f}{\mu} \frac{2}{9} g R^2$$

Vs = velocity
σp, σf = density of particle and fluid
R=particle diameter
M= fluid viscosity

Some values v_s = ?

See exercise

The good news is that rocks, undoubtedly poor fluids, can break creating pathways for the magma to move

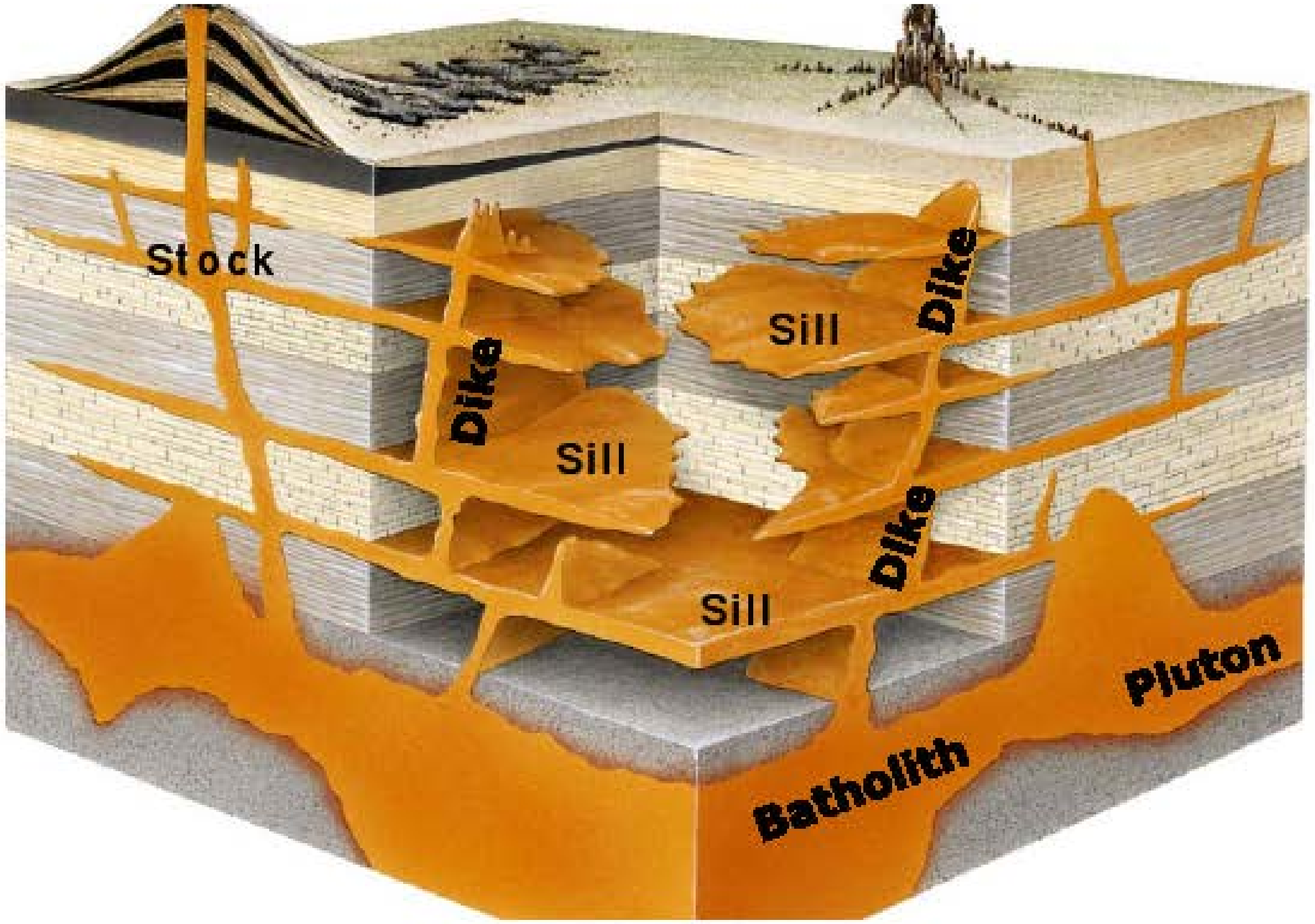
(obviously extra energy is needed)

Where does the magma does stop?

While moving upward, magma will cool and the $\Delta\rho$ will also decrease.

If the (δ_p- δ_f) remains large (negative) the magma can reach the surface (volcano, lava).

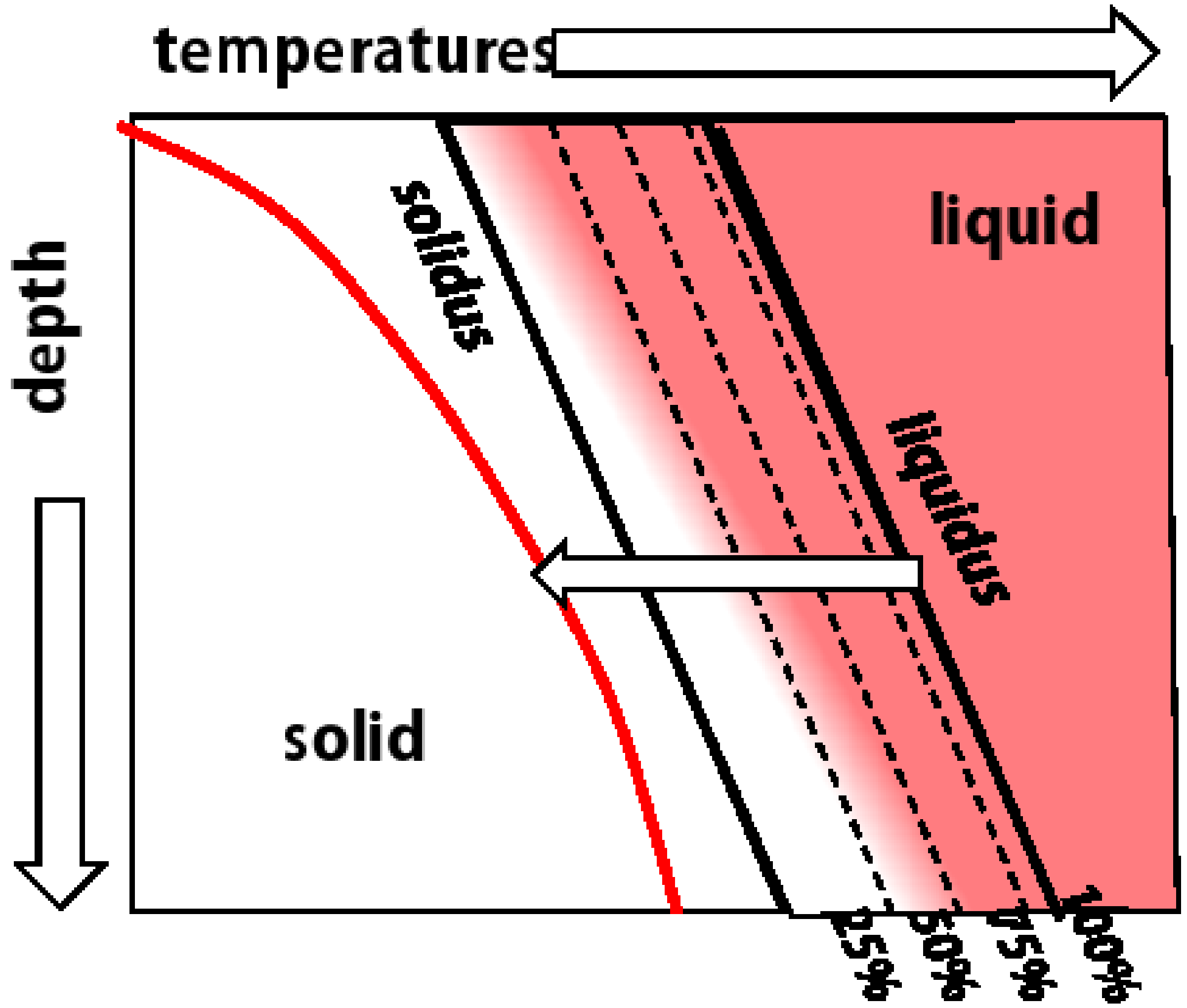
If it becomes too small, magma will stop somewhere on its way up, completely cool and solidify. An intrusive rock is born

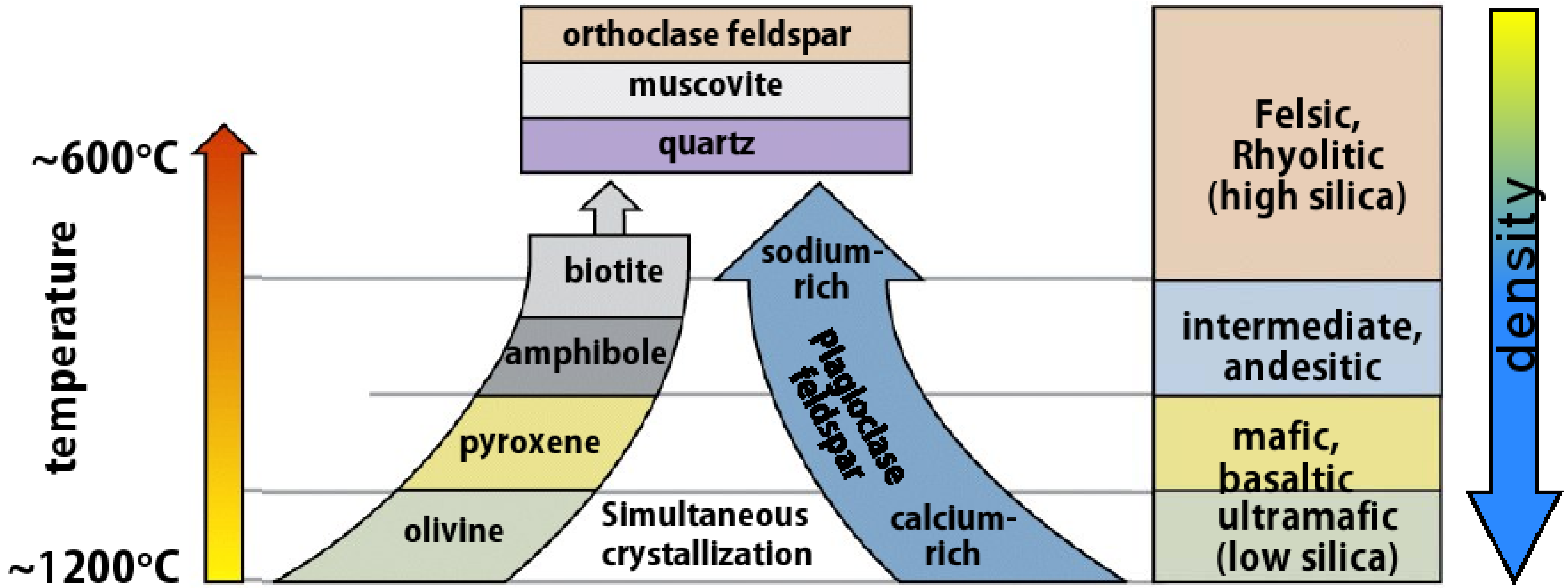


Consolidation can happen in a variety of settings

Different names are adopted

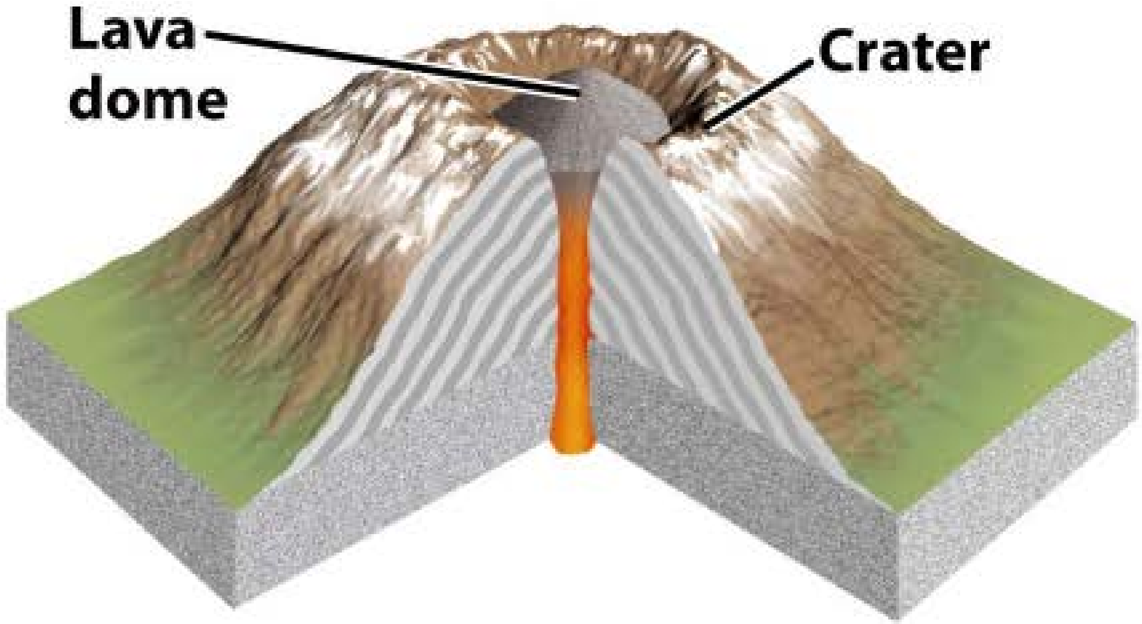
- Magma starts cooling and solidifies
- Progressive cooling will cause precipitation of high-T (heavy) phases first and lower-T (lighter) later.
- Differentiation (segregation) takes place





Acid magmas

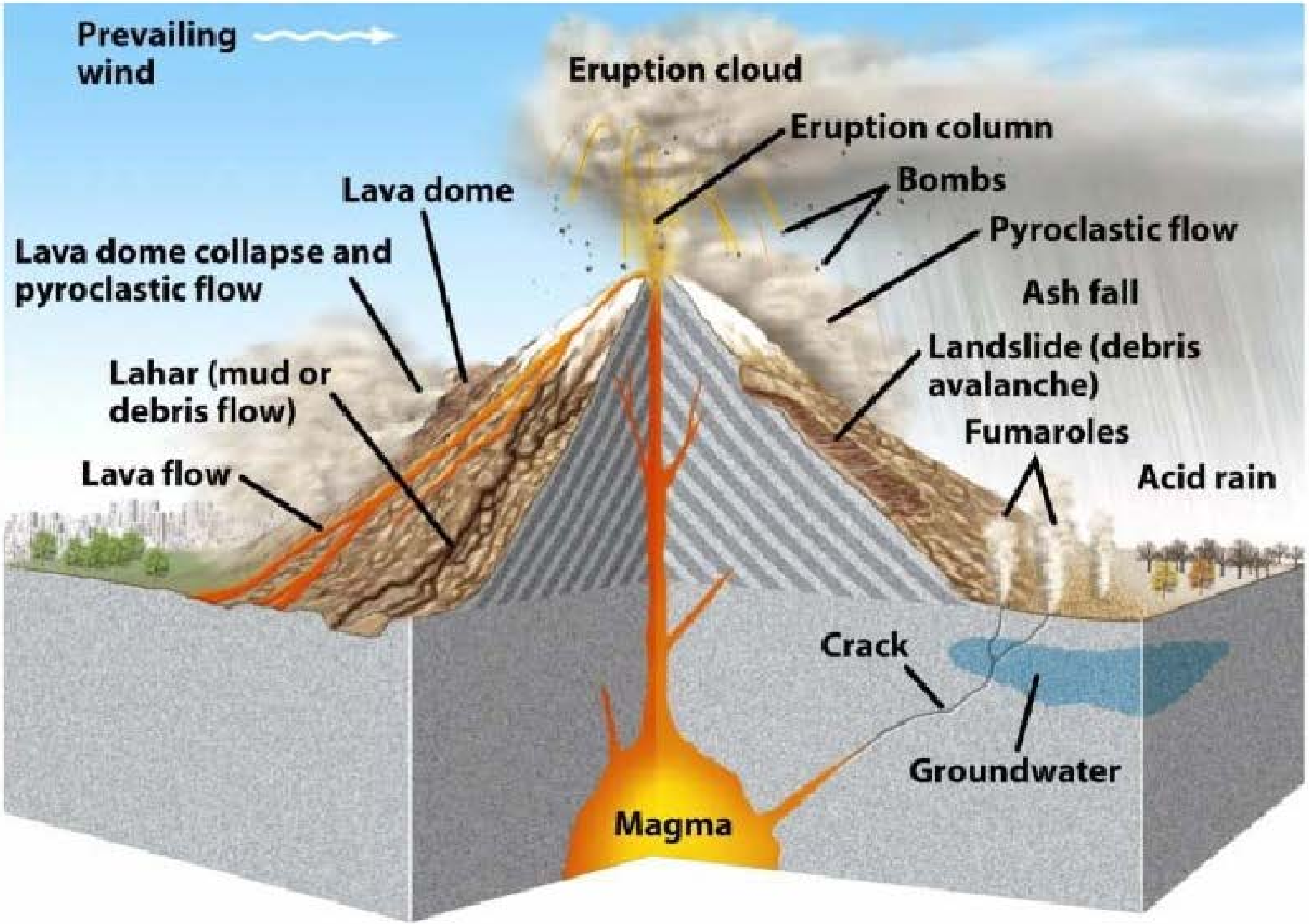
More acid magmas (>70% SiO_2) have lower temperatures (600-800°), are more viscous



Volcanoes are steep and aerially restricted

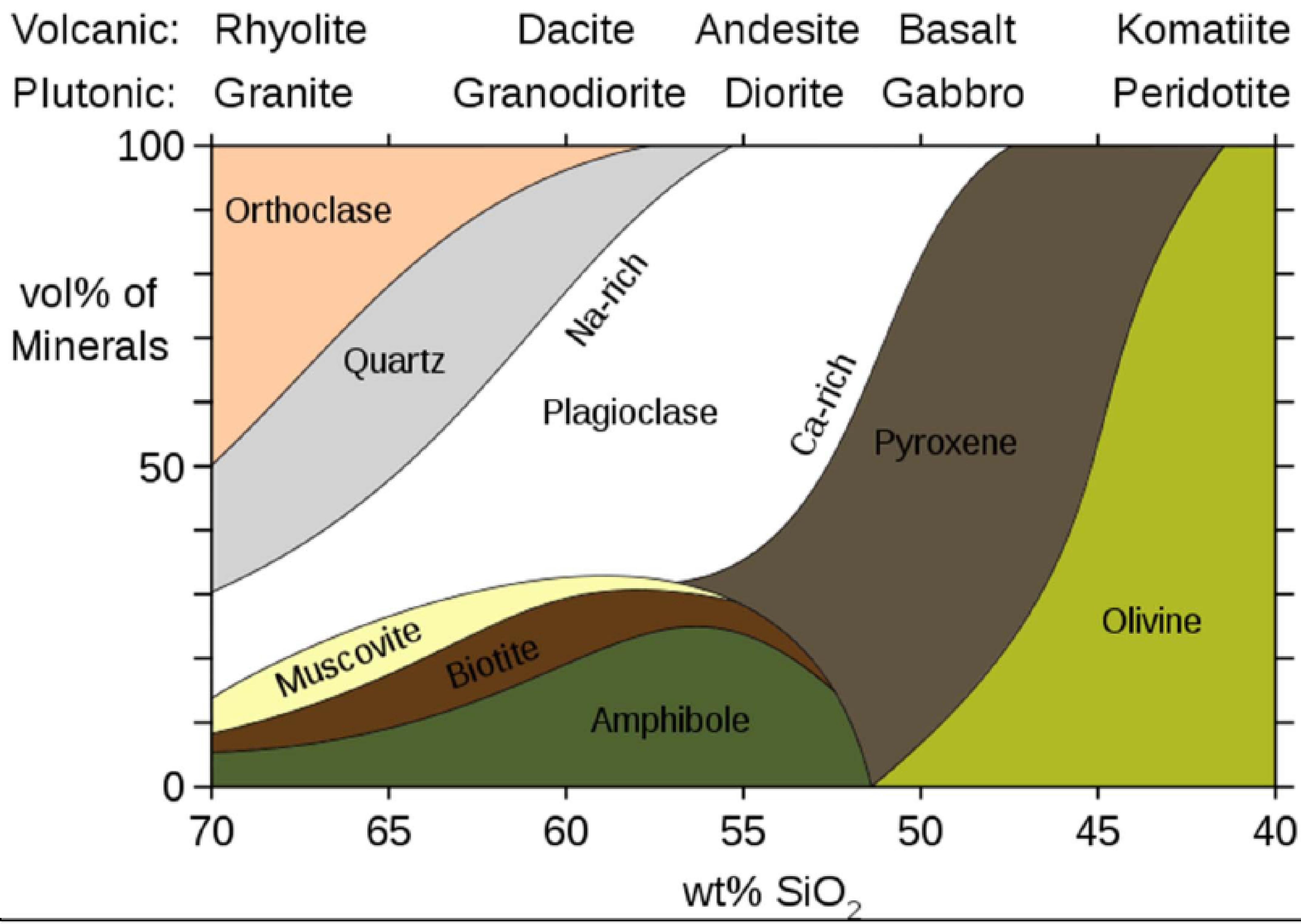
Eruptions are very explosive (thereby much more dangerous than basic volcanoes)

Volcanoes ejectsnot only lava but a lot of pyroclastic stuff (bombs, ashes...)



Magmatic rocks: classification

- **Names of magmatic rocks depend on their mineralogy**
- **Different names are given to intrusive (plutonic) and extrusive (volcanic rocks)**



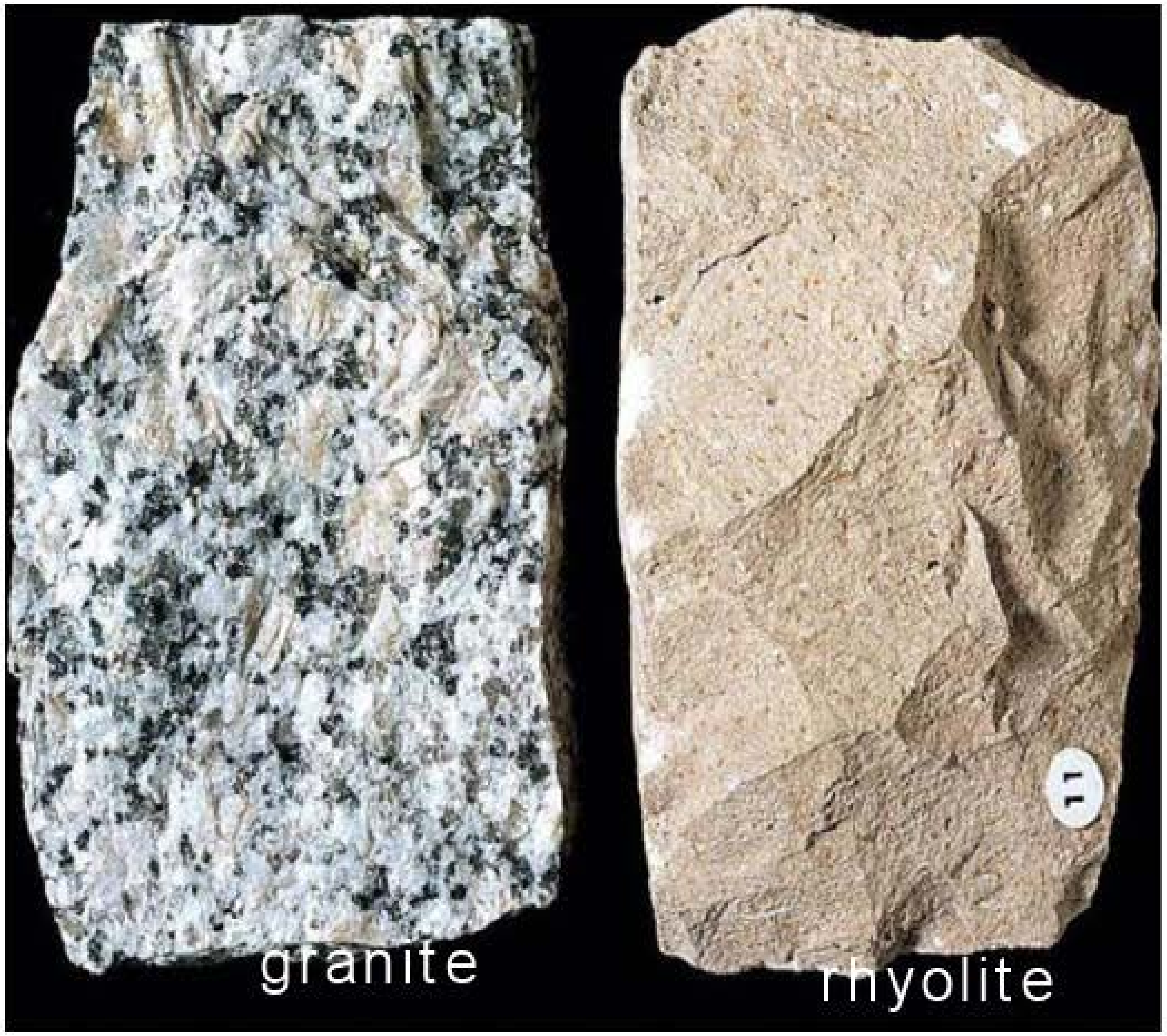
Two rocks with the same composition but different names

Intrusive rocks

Typically coarse-crystalline (slow-cooling).

Extrusive rocks

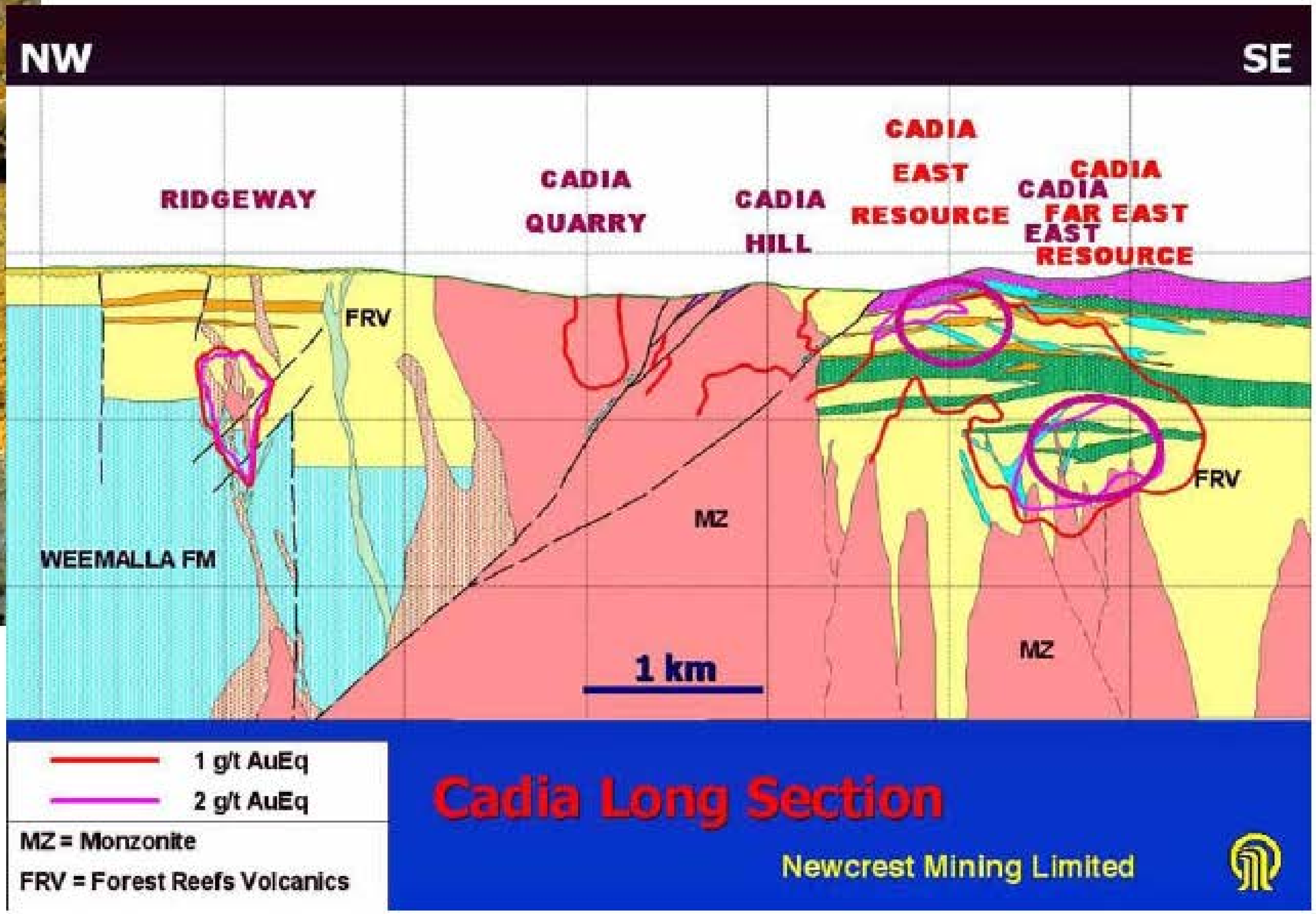
Typically microcrystalline. Magma solidifies on the surface cooling rapidly, with insufficient time for crystals to grow

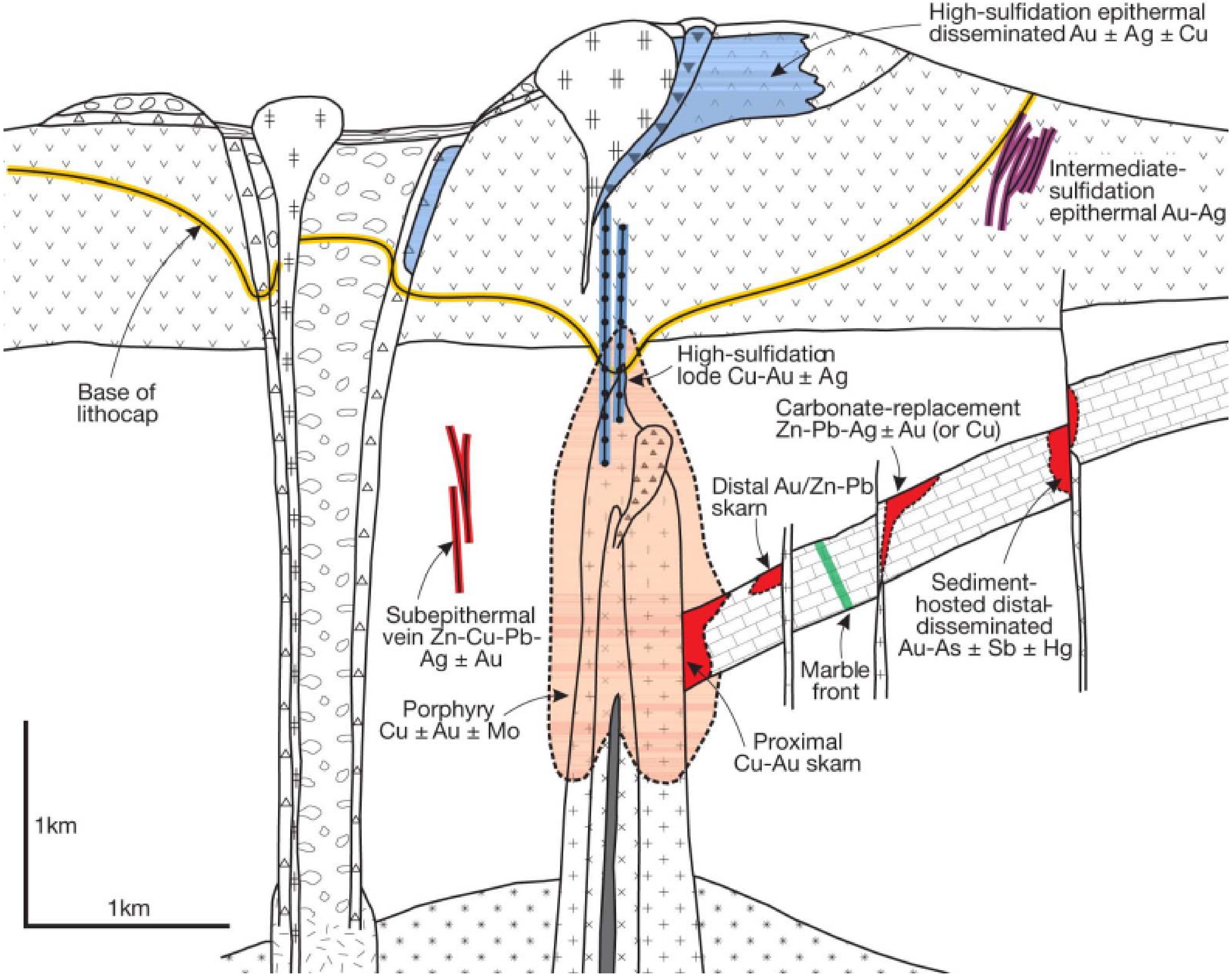


Some magmatism-related issues

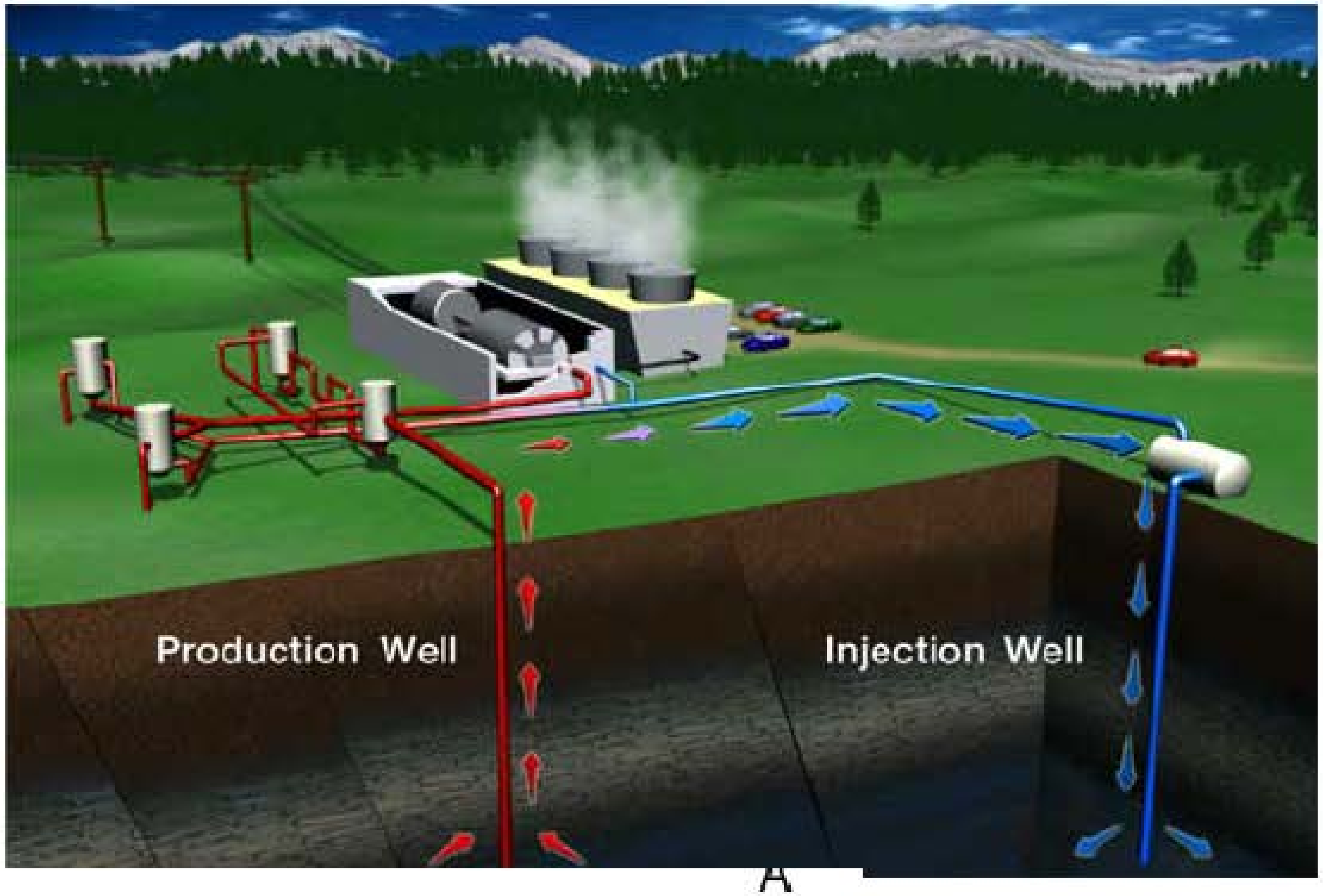
Magmatism is the major source of heat at shallow crustal levels and of hot, chemically-loaded fluids. Great economic importance

Porphyry coppers

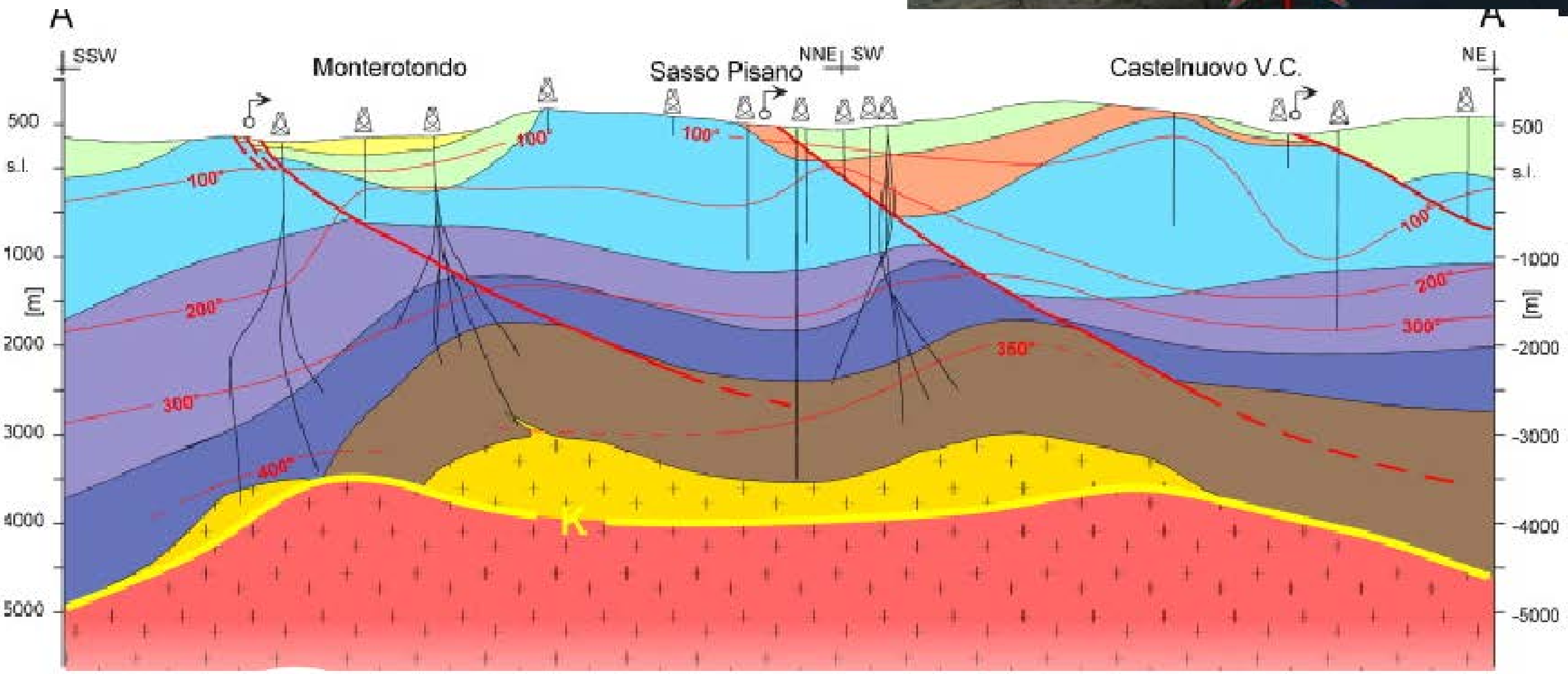



High-sulfidation epithermal disseminated Au ± Ag ± Cu
Intermediate-sulfidation epithermal Au-Ag
Base of lithocap
High-sulfidation lode Cu-Au ± Ag
Carbonate-replacement Zn-Pb-Ag ± Au (or Cu)
Distal Au/Zn-Pb skarn
Subepithermal vein Zn-Cu-Pb-Ag ± Au
Sediment-hosted distal-disseminated Au-As ± Sb ± Hg
Marble front
Porphyry Cu ± Au ± Mo
Proximal Cu-Au skarn
1km
1km

geothermal energy



The Larderello geothermal field

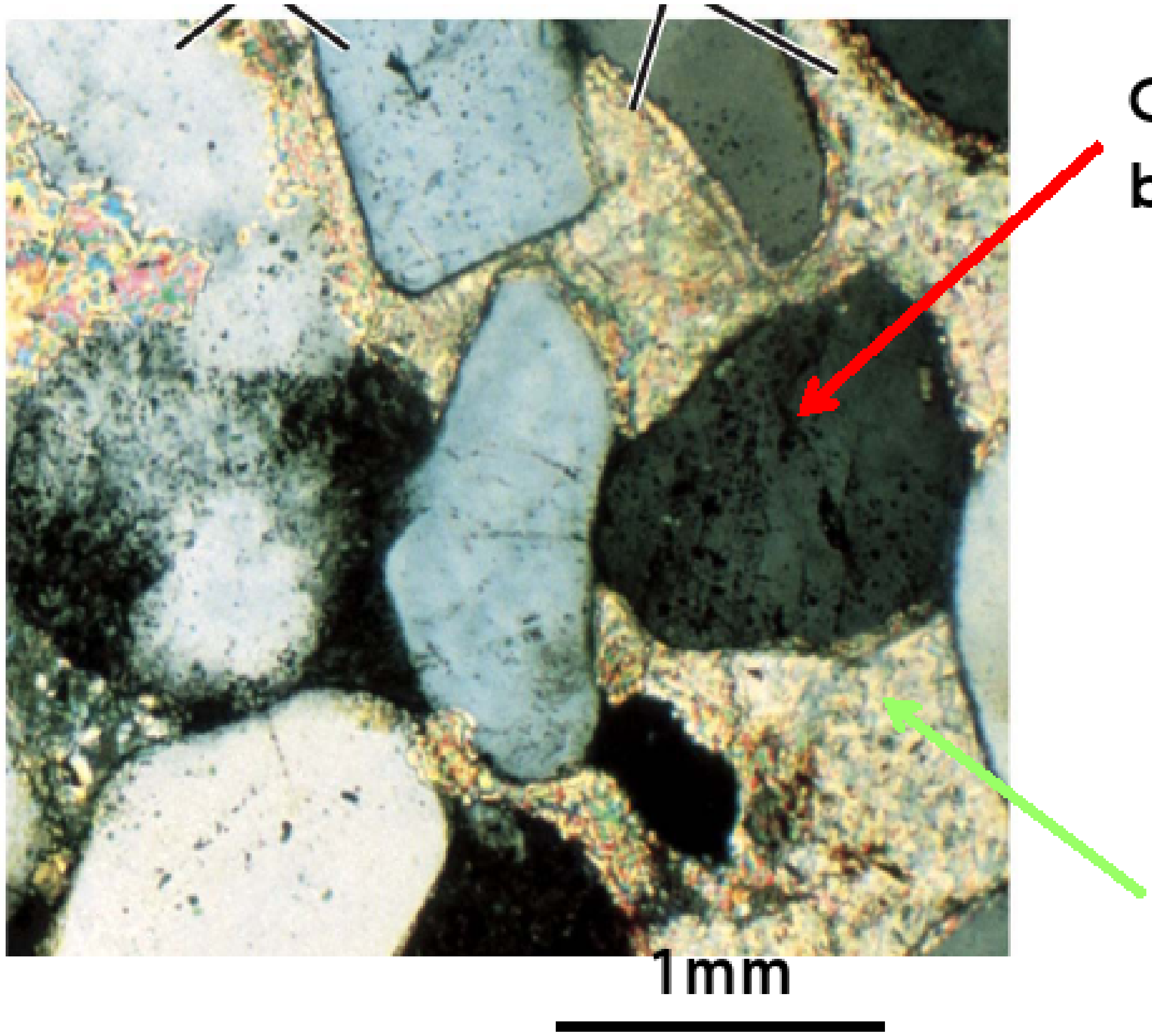


Rocks which form at the surface of the Earth (inclusive of water masses) through a) erosion of pre-existing rocks, b) life-related processes and c) purely chemical processes

Terrigenous rocks

Formed from the erosion and mobilization of older rocks

Composed of grains (=clasts) and (filled) space between them

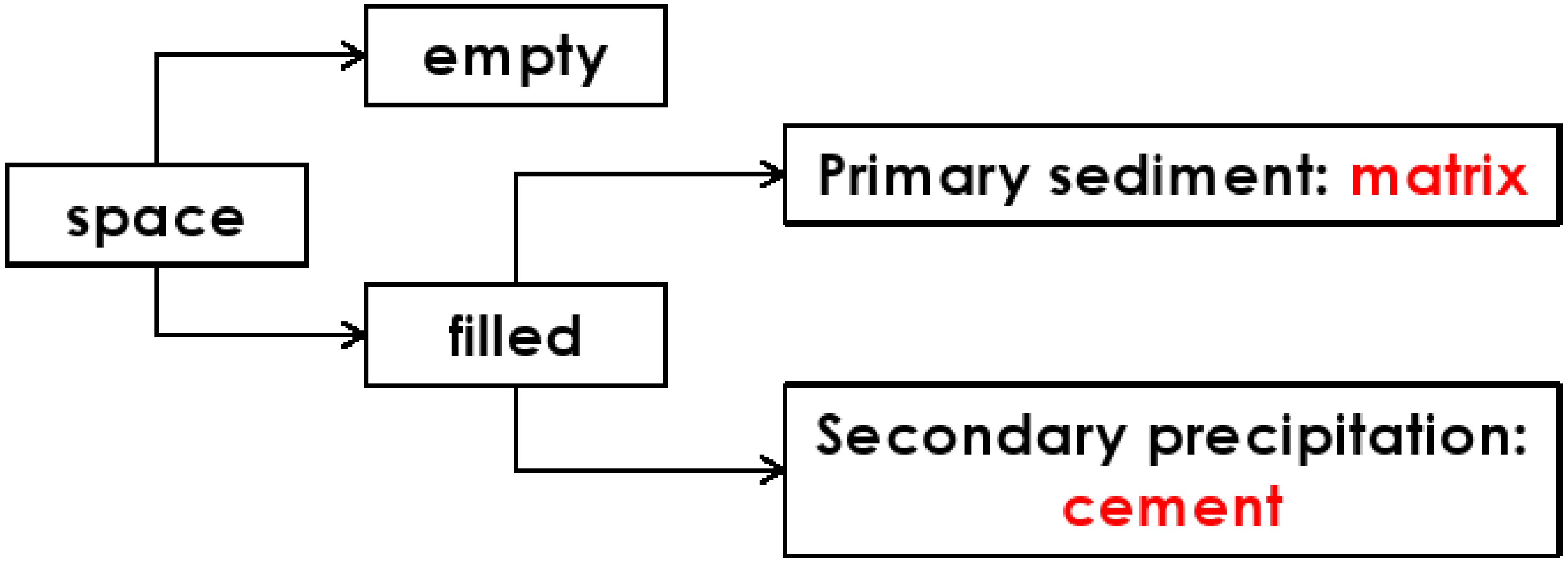


Clasts: typically pieces of rocks but can be also organic material etc

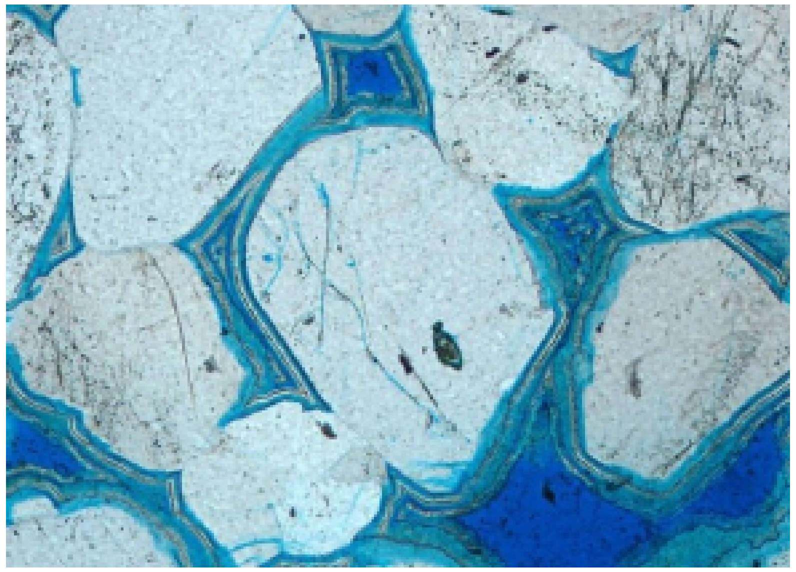
Interclast space

NB: clasts and matrix are not related to any absolute dimension!!

Space between clasts:



with matrix (= finer-grained portion of the primary sediment)



with cement (= newly precipitated minerals)

Defining and understanding matrix, cement etc is crucial for determining porosity and permeability

Classifying sedimentary rocks in terms of clast size

Particle Size	Sediment	Rock	
COARSE	GRAVEL		
Larger than 256 mm	Boulder	Conglomerate	
256–64 mm	Cobble	Conglomerate	
64–2 mm	Pebble	Conglomerate	
MEDIUM			
2–0.062 mm	SAND	Sandstone	(=arenite)
FINE	MUD		
0.062–0.0039 mm	Silt	Siltstone	
Finer than 0.0039 mm	Clay	Mudstone (blocky fracture) Shale (breaks along bedding) Claystone	

- Rock names are on the basis of the size of the clasts not of the matrix, which will be finer-grained (no absolute size implied)
- The composition of the clasts is irrelevant

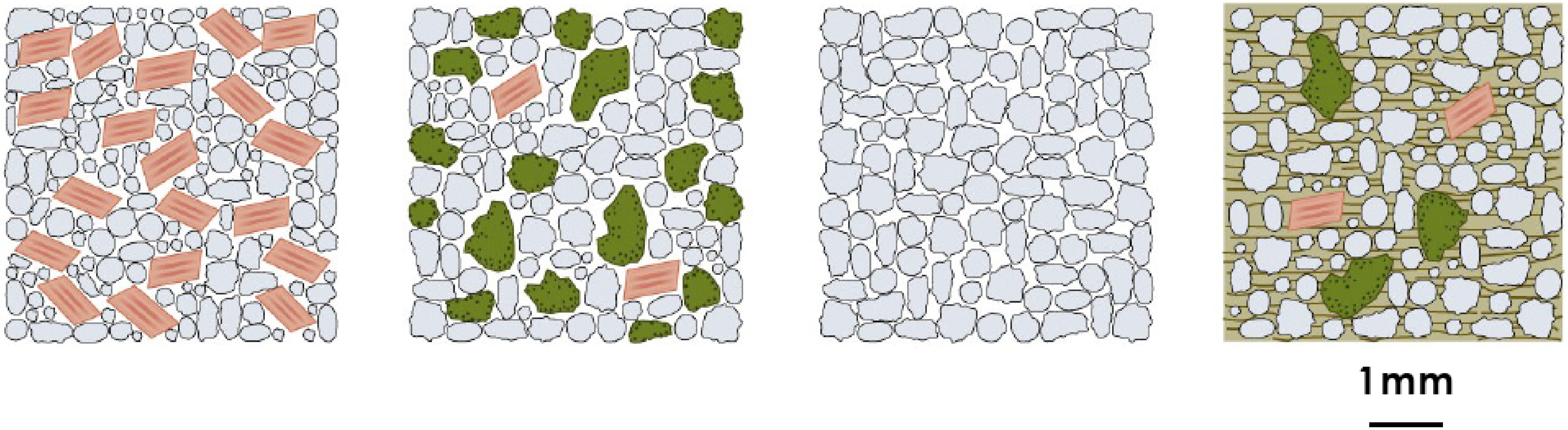
The composition of grains can also be added

quartzitic sand (quartzarenite)

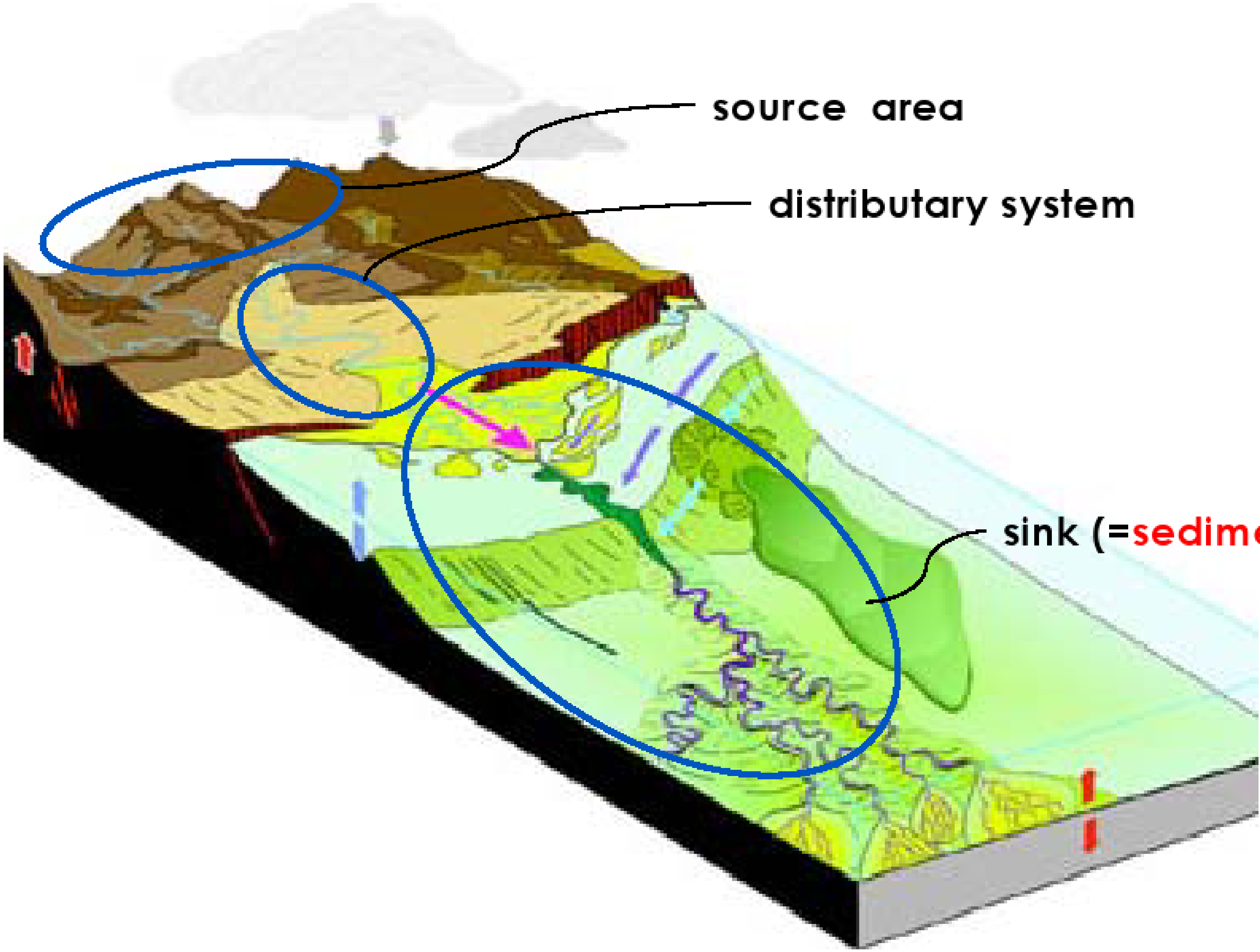
- feldspar rich sand
- ……
- ……..

and some traditional names

Arkose: feldspar-rich | **Lithic sandstone:** rock fragment–rich | **Quartz arenite:** pure quartz | **Graywacke:** matrix-rich



The source-to-sink approach

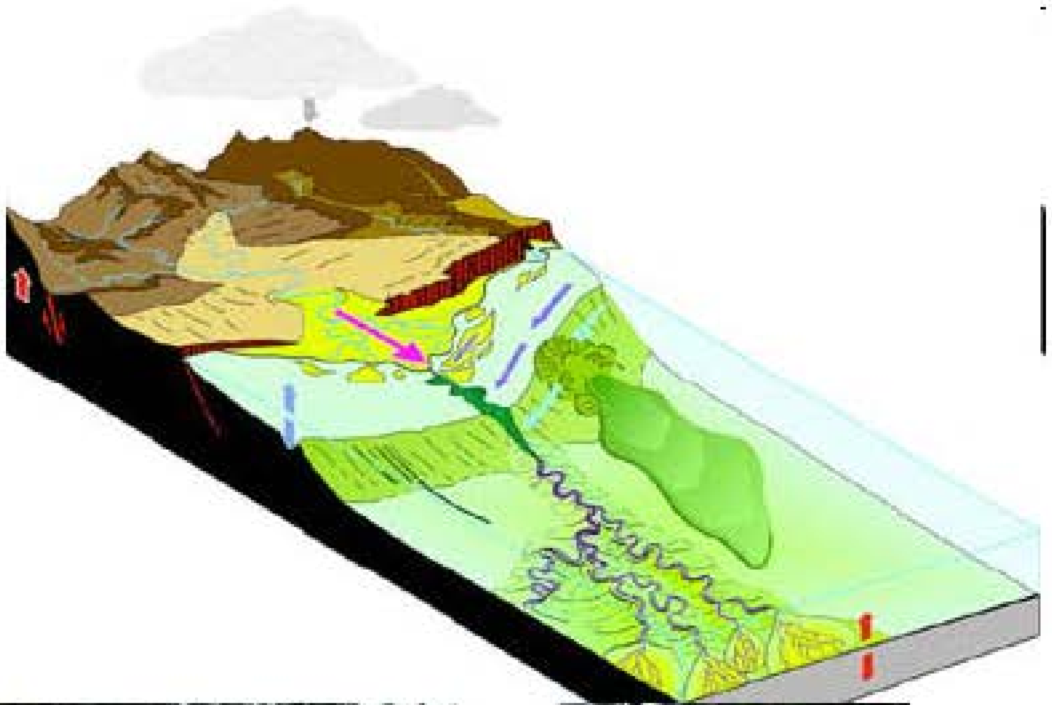


The source area

Here it is decided how much and what type of sediments is produced, depending on

- kind of rocks exposed
- Amount of uplift/exhumation
- climate

Note: all these change through time



The distributary system

Gravity, water, wind etc will remove the sediments from the production area and transport them until they find a place to rest (the sink)

Rivers are a major part of the distributary system

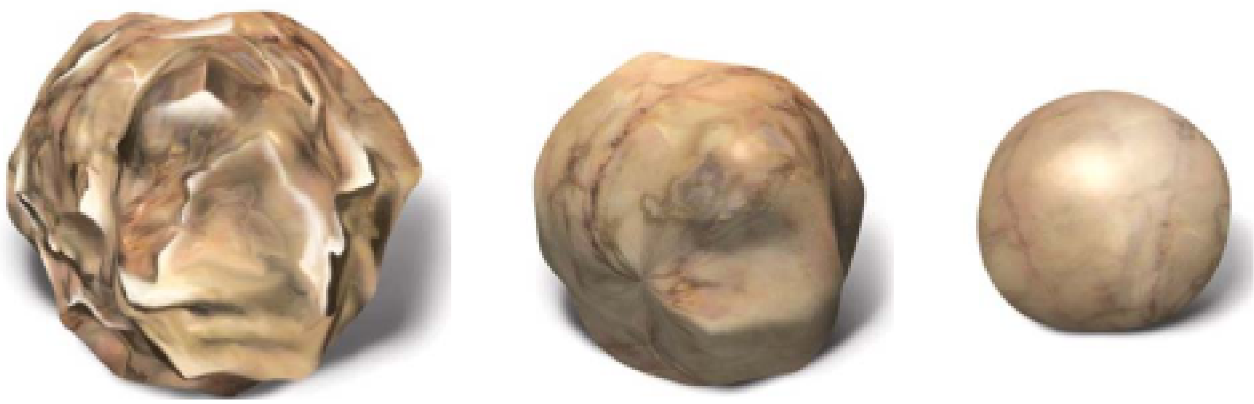
Transport and movement can modify the sediment delivered to the sink
(=sediment characteristics in the sink depend also on transport)

Mechanical modifications

Movement (collisions) rounds clasts

Movement (collision) breaks particles making them smaller

Currents select grains on the basis of their weight (volume and density)

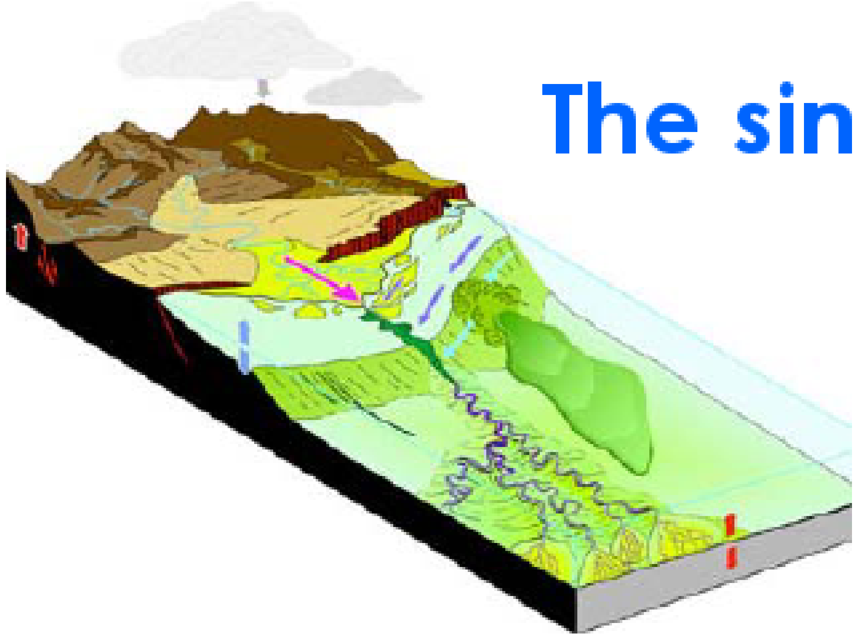


Chemical changes

affect clasts during transport (dissolution etc)

In an immature rock, clasts are not rounded, poorly sorted and of different types

In a mature rock, clasts are rounded, well sorted and of one dominant type



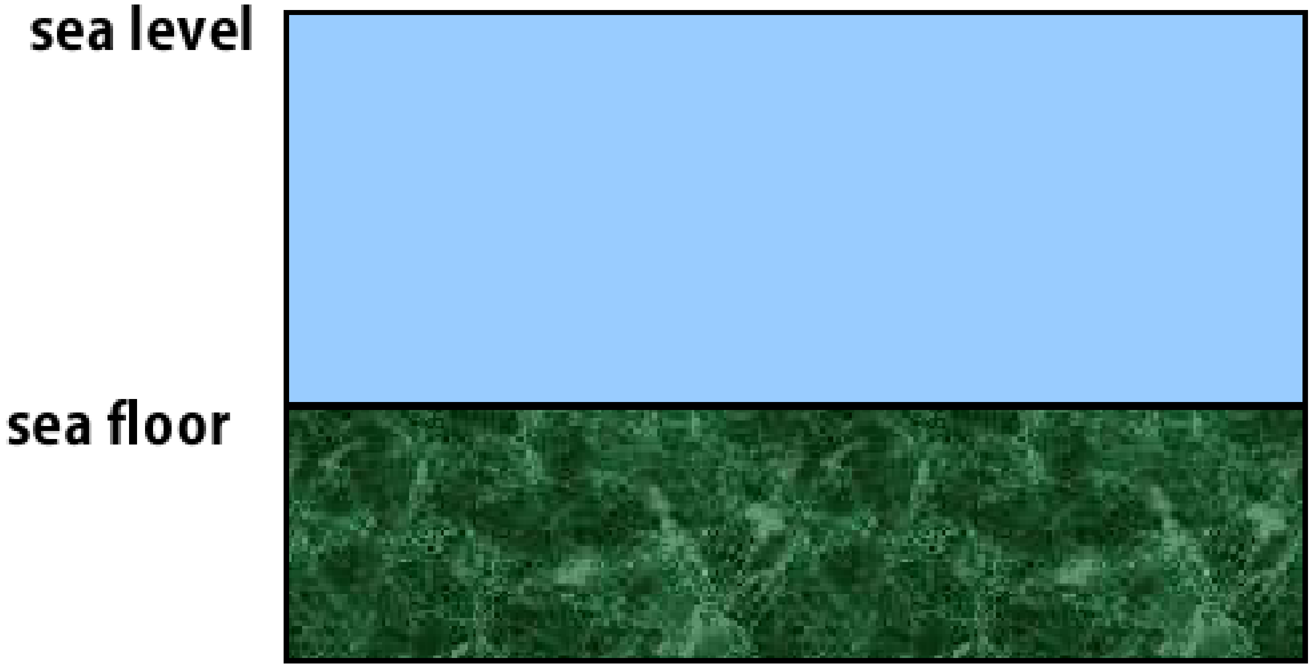
The sink:

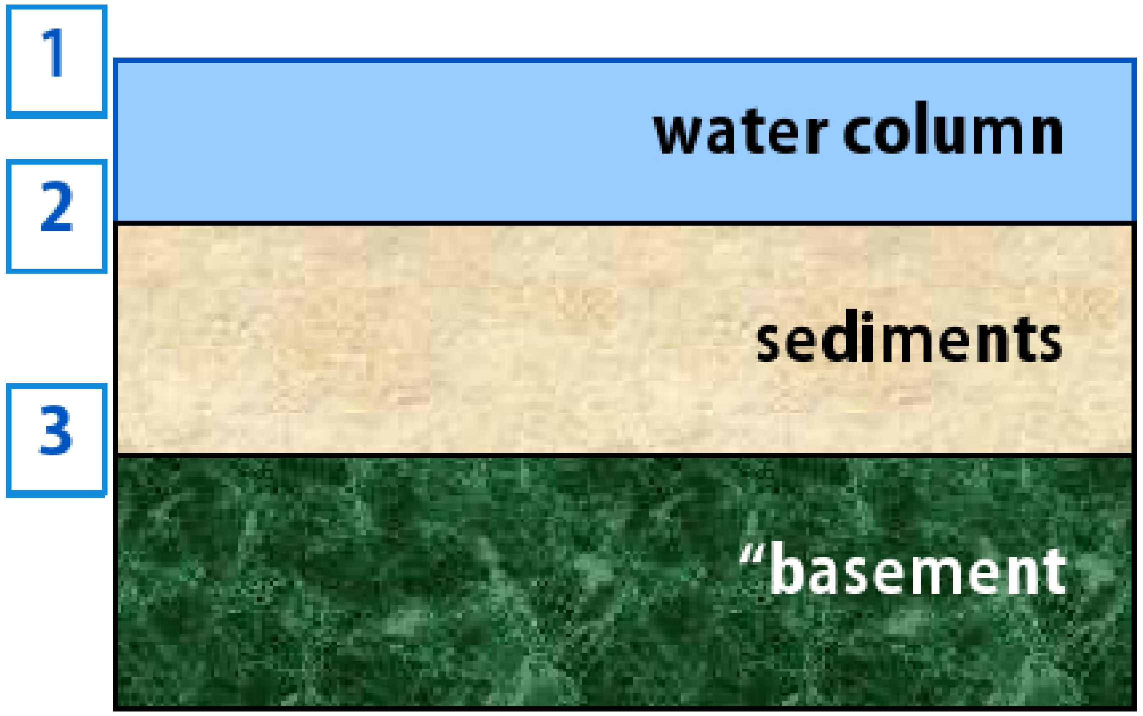
A place where the transport agents can dump their sediments

=

a place where accommodation space is available

The best accommodation space is between the top and bottom of a water column (sea better than lake)
(sediments dumped above sea level are very unstable)

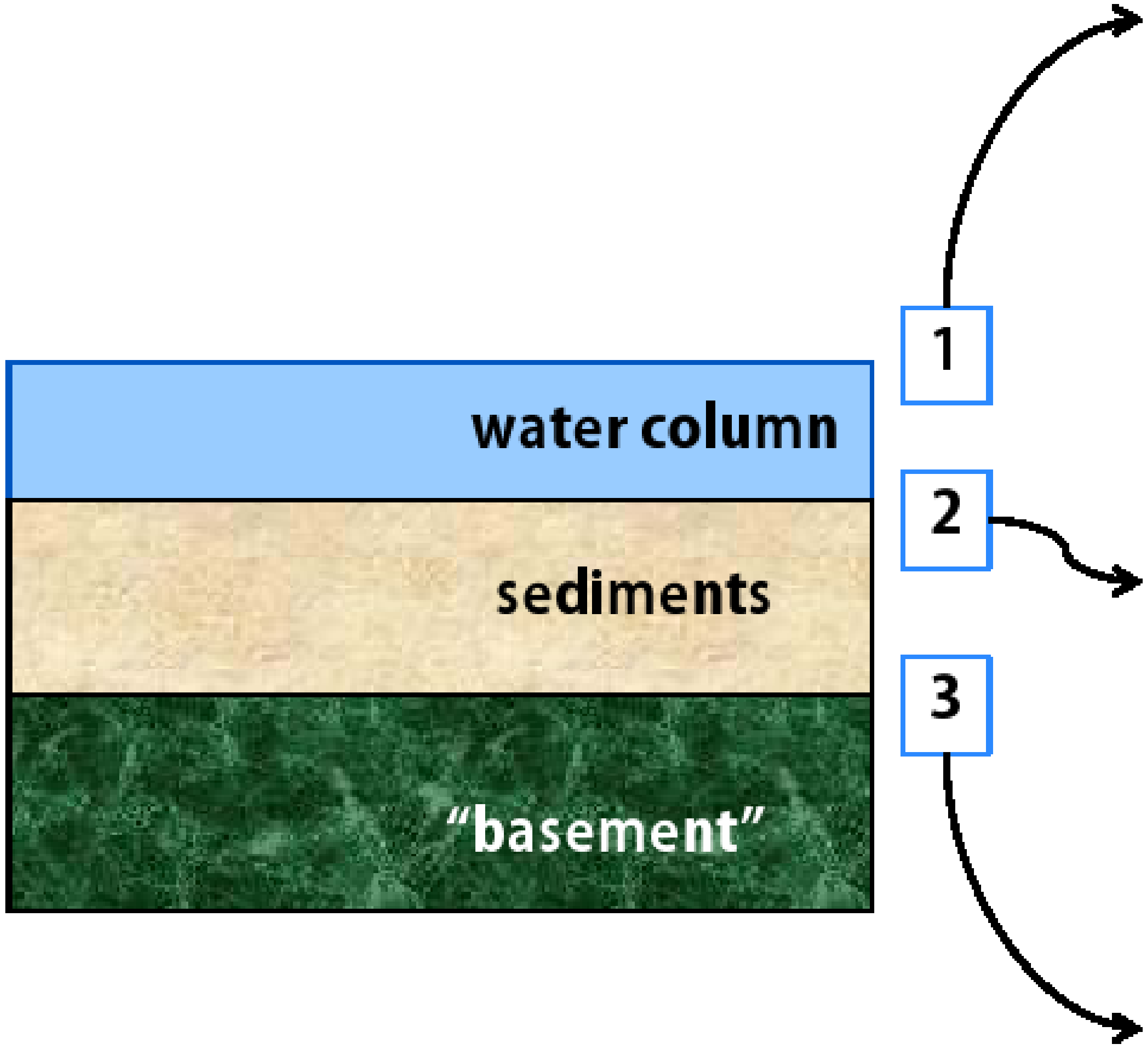




A first layer of sediment is deposited

Three relevant surfaces

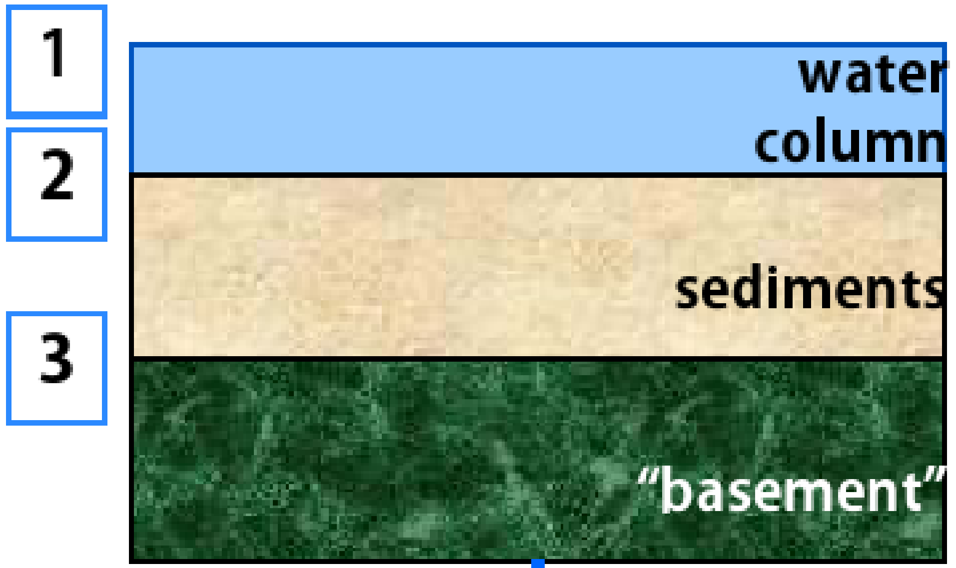
1) sea level
2) sea floor
3) bottom of the sedimentary succession



Controlled by global sea level changes

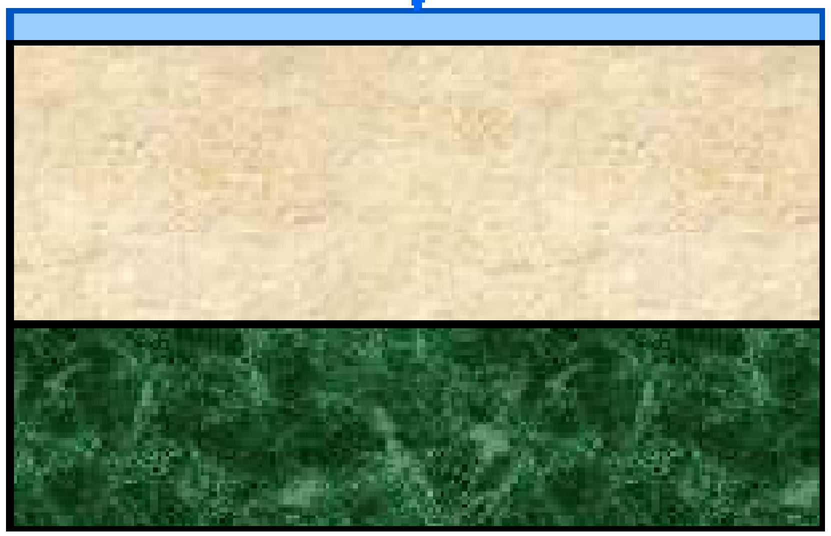
Controlled by the amount of sediments. Controls the depositional environment, also called facies (shallow vs deep water)

Controlled by tectonics
Controls the thickness of the deposited sediments



If 3 does not move, the water column will be progressively filled

If 3 moves downward (subsidence) a lot of sediments can be accumulated

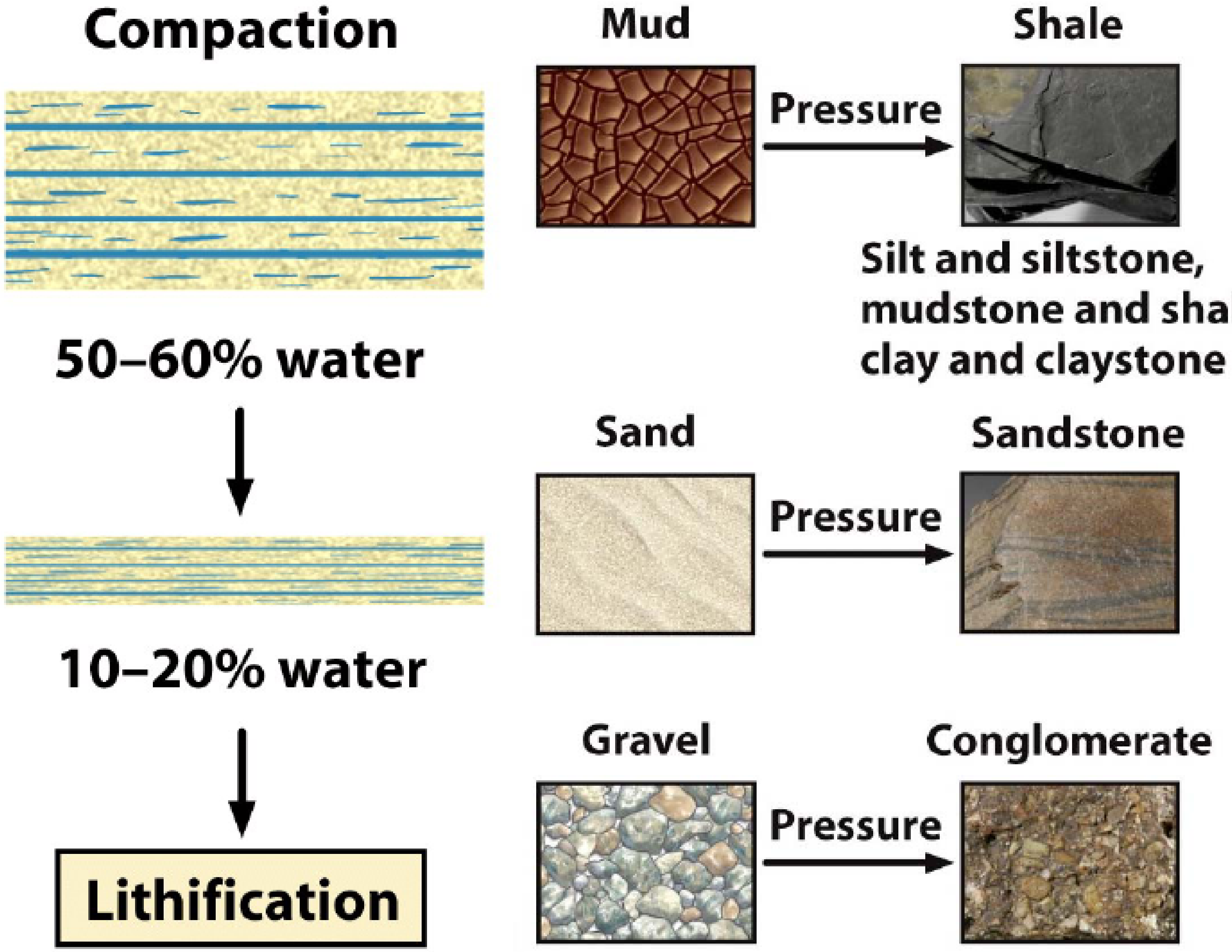


- the water column=maximum thickness of sediments
- the facies of the sediment will change through time

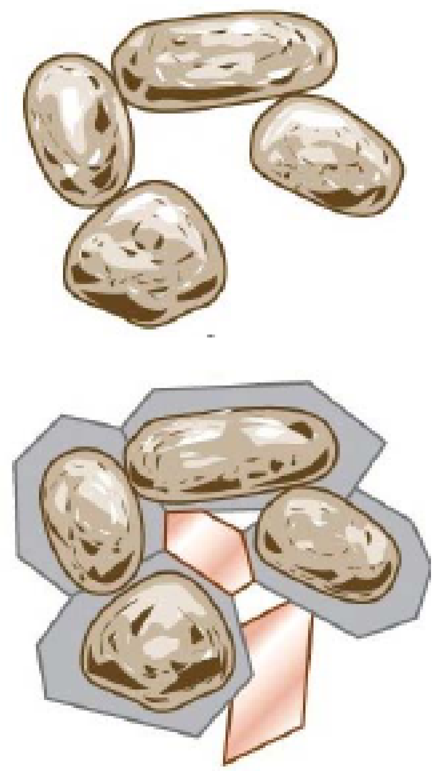
- Thicknesses can be very large (kms)
- Facies do not change necessarily

Transforming loose sediments in rocks

During subsidence , sediments will be gradually covered by other, newly arrived sediments and, slowly but surely, will become rocks (lithification).



cementation can provide an important contribution to lithification

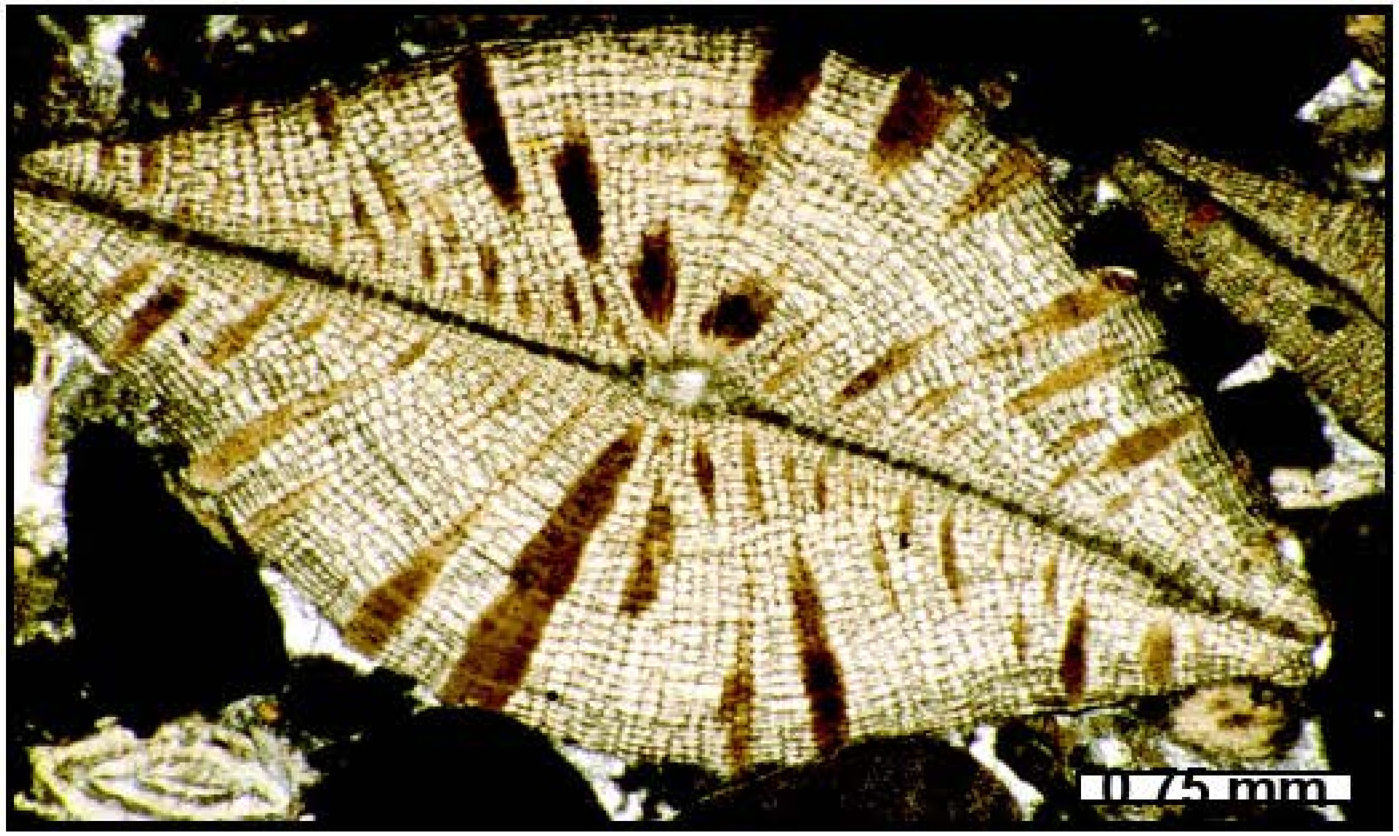


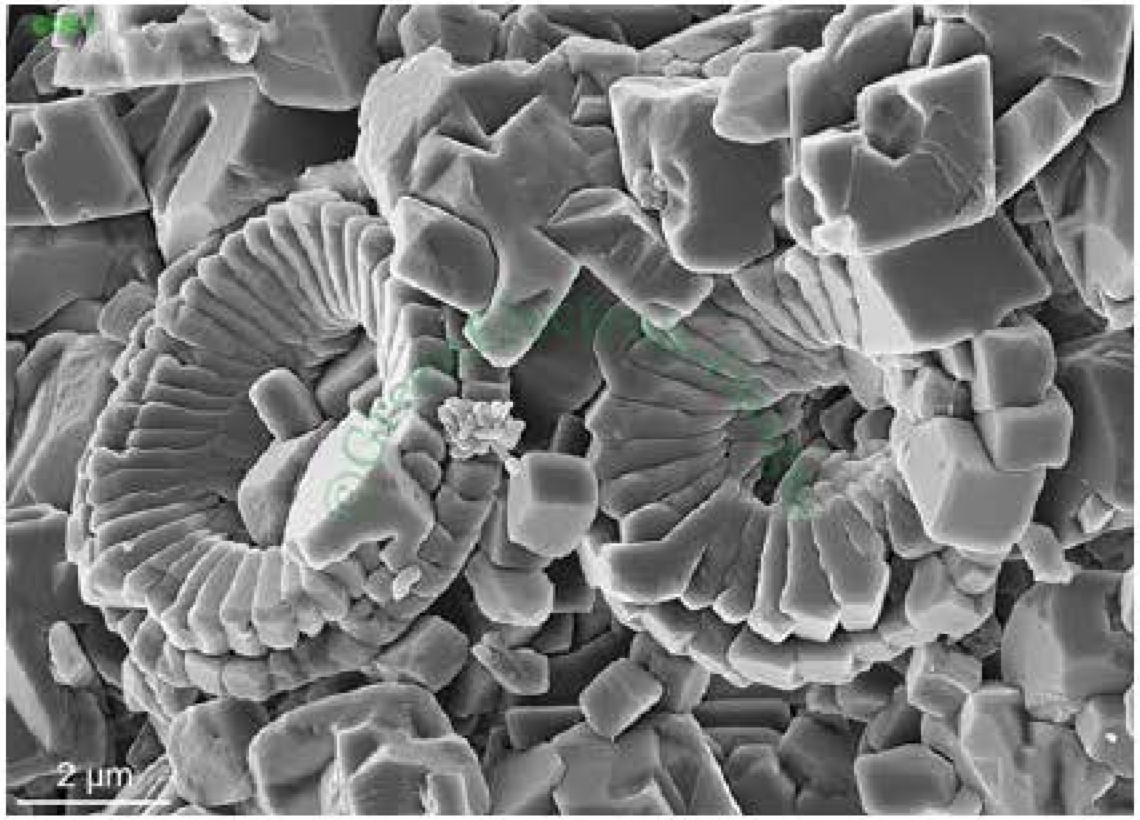
Biological sedimentary rocks
(fossilized remnants of plants and/or animals, chemical precipitates)

Carbonates (limestones and dolomites) are by far the most important

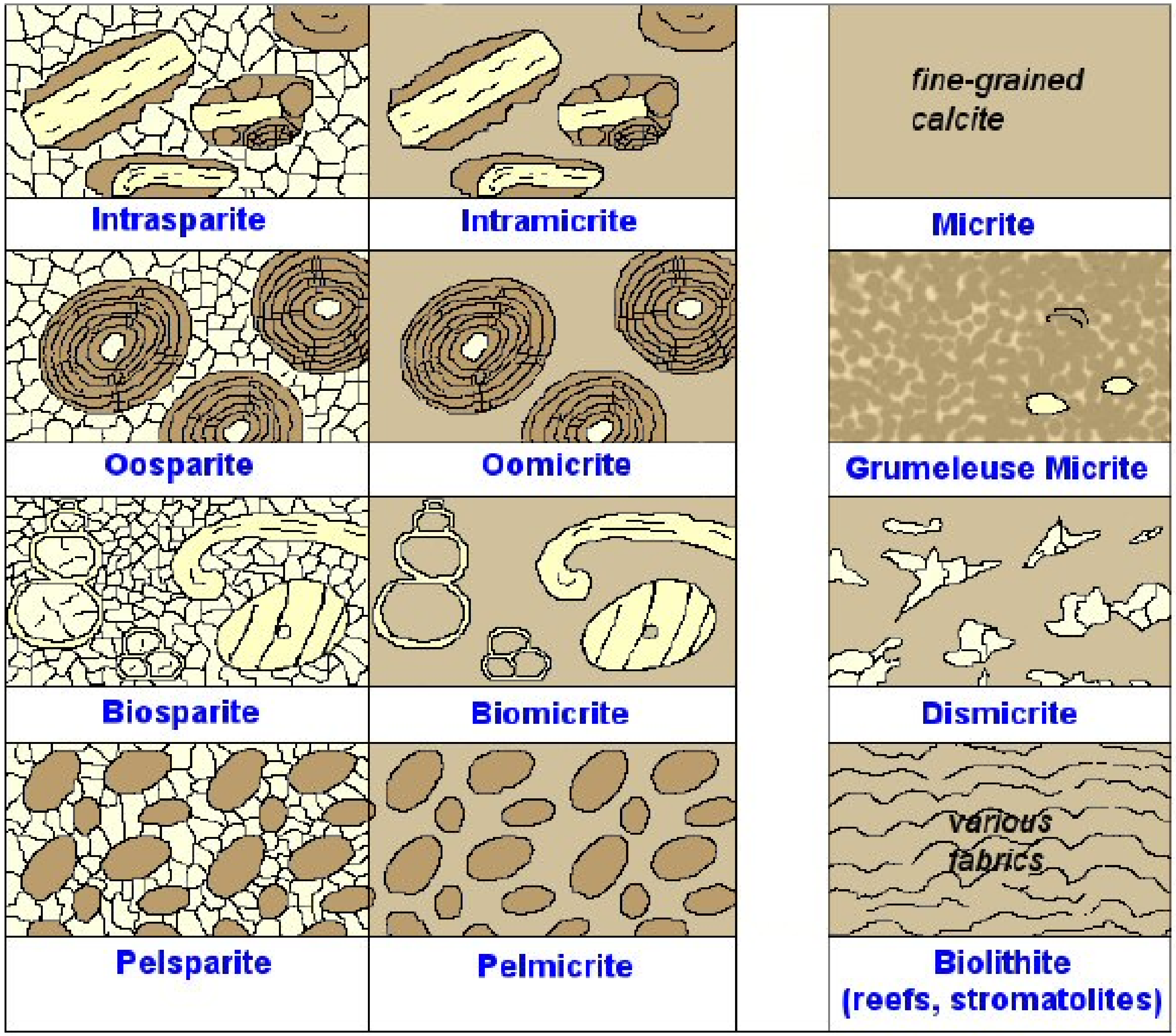
Sediment	Rock	Chemical Composition	Minerals
BIOLOGICAL			
Sand and mud (primarily bioclastic)	Limestone	Calcium carbonate ($CaCO_3$)	Calcite (aragonite)
Siliceous sediment	Chert	Silica (SiO_2)	Opal, chalcedony, quartz
Peat, organic matter	Organics	Carbon compounds; Carbon compounded with oxygen and hydrogen	(coal), (oil), (gas)

Carbonates are generated by life!





Carbonates have their special classification schemes



Folk's Classification of Limestones - a modified version based on Folk (1962). Coarser varieties can be classified with "rudite" endings. E.g. - biosparrudite, biomicrudite. Grumeleuse micrite is clotted micrite, common in lagoonal facies. Like pelmicrites and pelsparites it may have ostracod valves. *Ian West & Tonya West (c) 2005.*

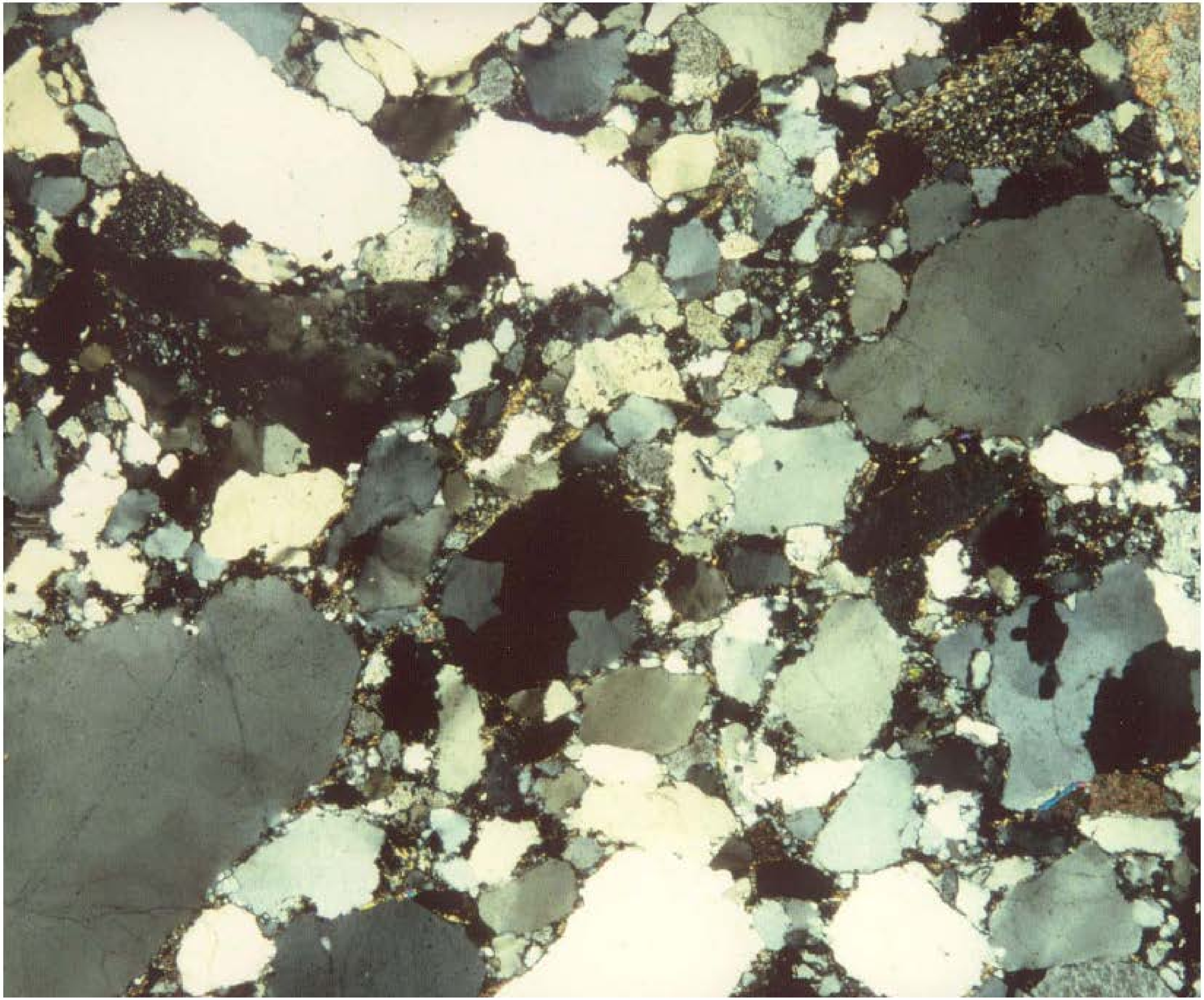
more will follow

Chemical sedimentary rocks

Typical examples are evaporites, sediments formed by progressive evaporation of sea water.

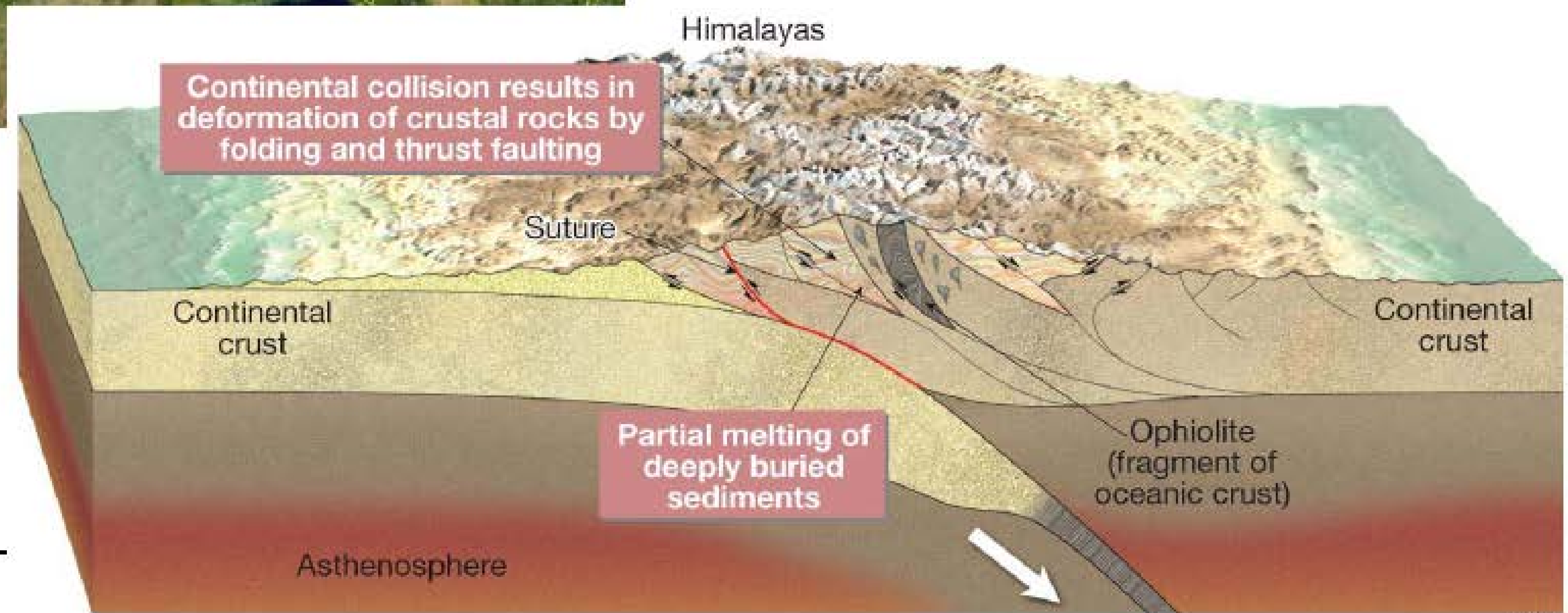
Sediment	Rock	Chemical Composition	Minerals
CHEMICAL			
No primary sediment (formed by diagenesis)	Dolostone	Calcium-magnesium carbonate ($CaMg[CO_3]_2$)	Dolomite
Iron oxide sediment	Iron formation	Iron silicate; oxide (Fe_2O_3); limonite, carbonate	Hematite, siderite
Evaporite sediment	Evaporite	Sodium chloride (NaCl); calcium sulfate ($CaSO_4$)	Gypsum, anhydrite halite, other salts

The formation of many "chemical" rocks is stimulated by organic activity!

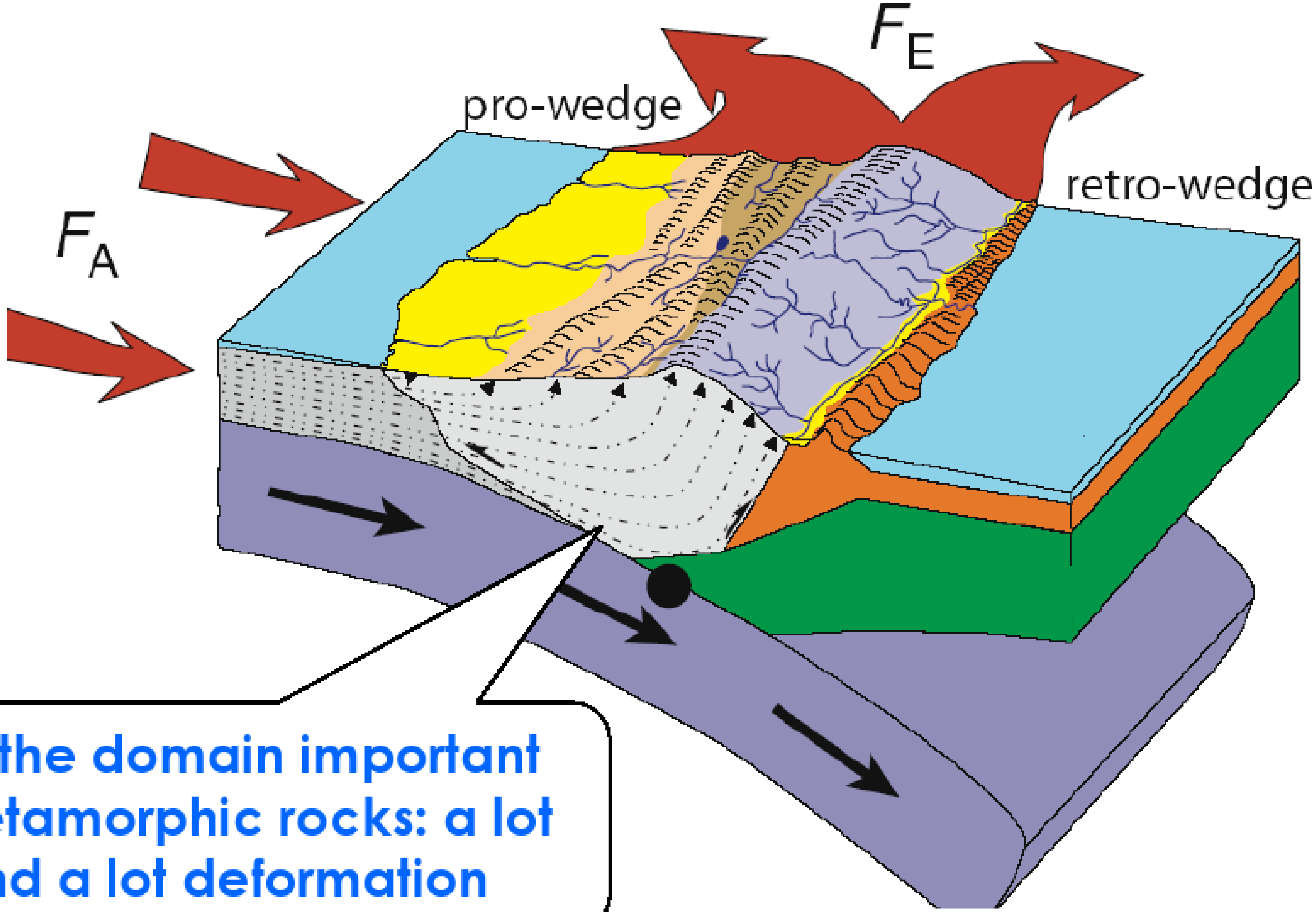


Metamorphic rocks

develop when parent (sedimentary, magmatic, metamorphic) rocks have been subjected to higher-than-normal pressure and/or temperatures



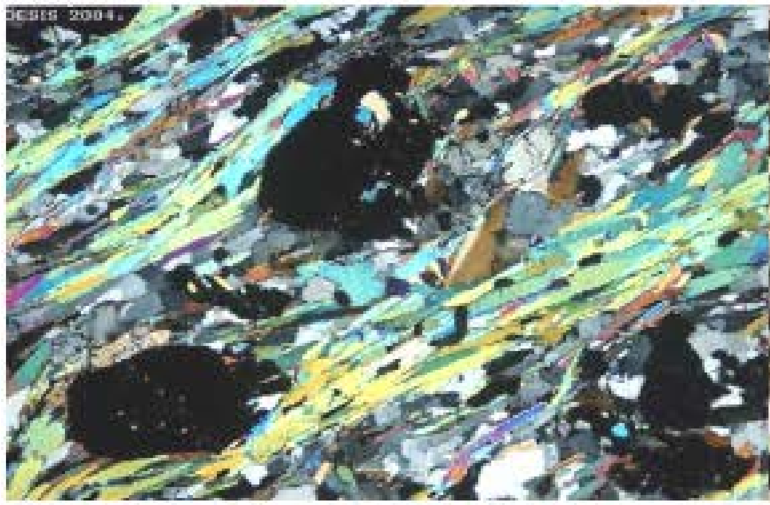
The way orogens work



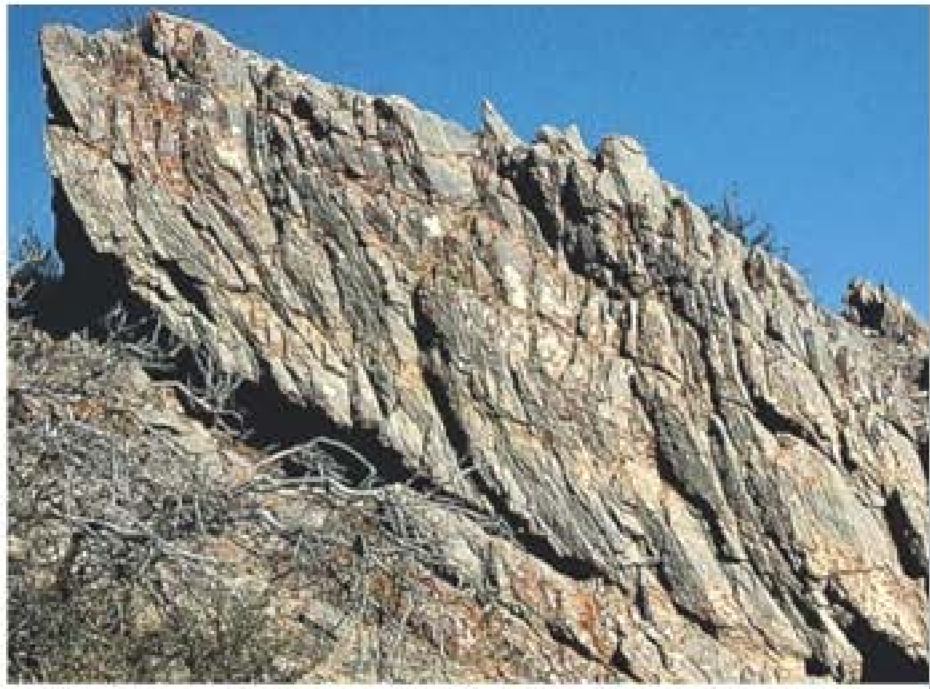
This is the domain important for metamorphic rocks: a lot of T and a lot deformation

When physical conditions (pressure and/or temperature) change:

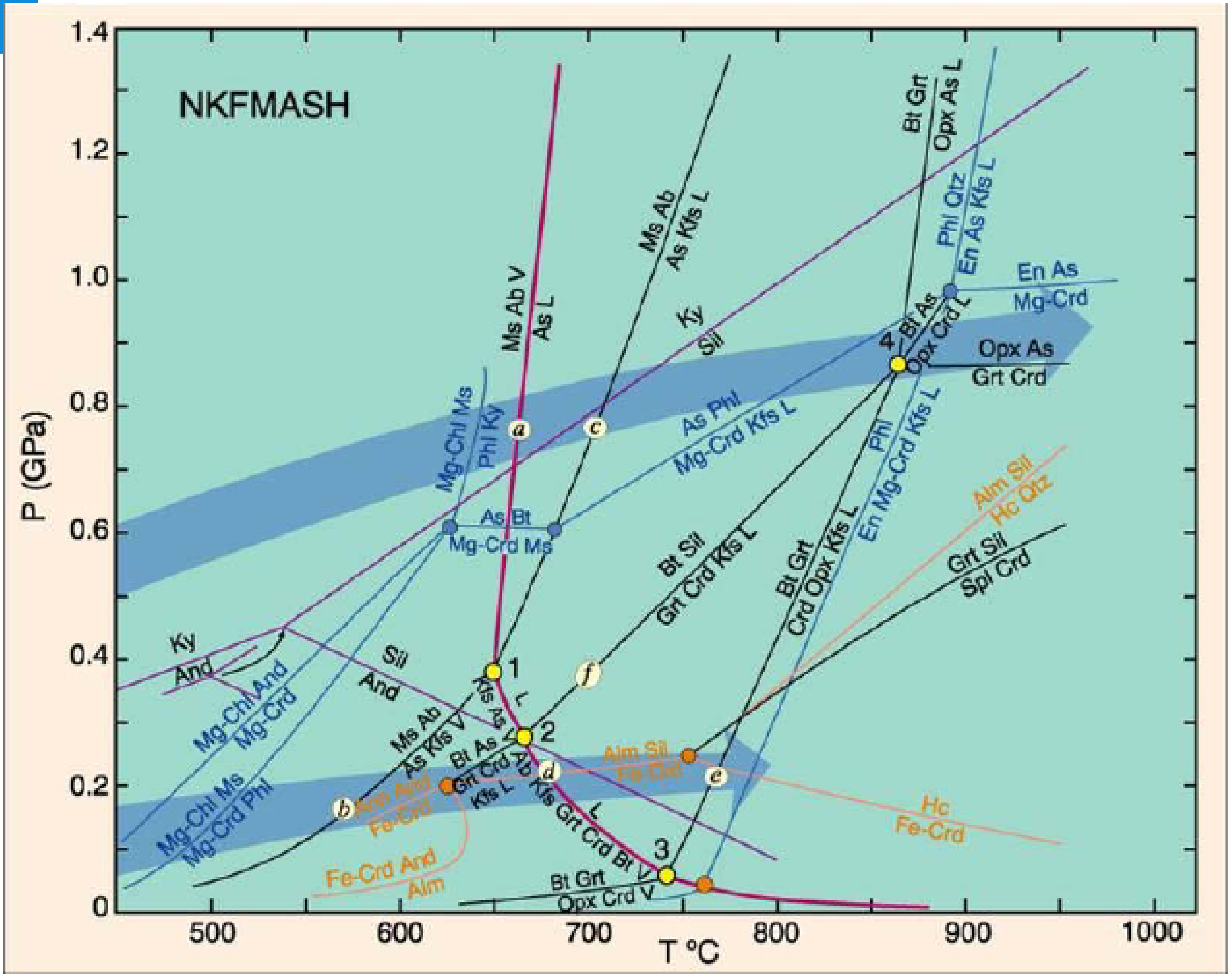
Minerals become unstable, and react with each other creating new minerals



The rock will be deformed producing foliations and lineations (texture) and resulting in a completely different rock

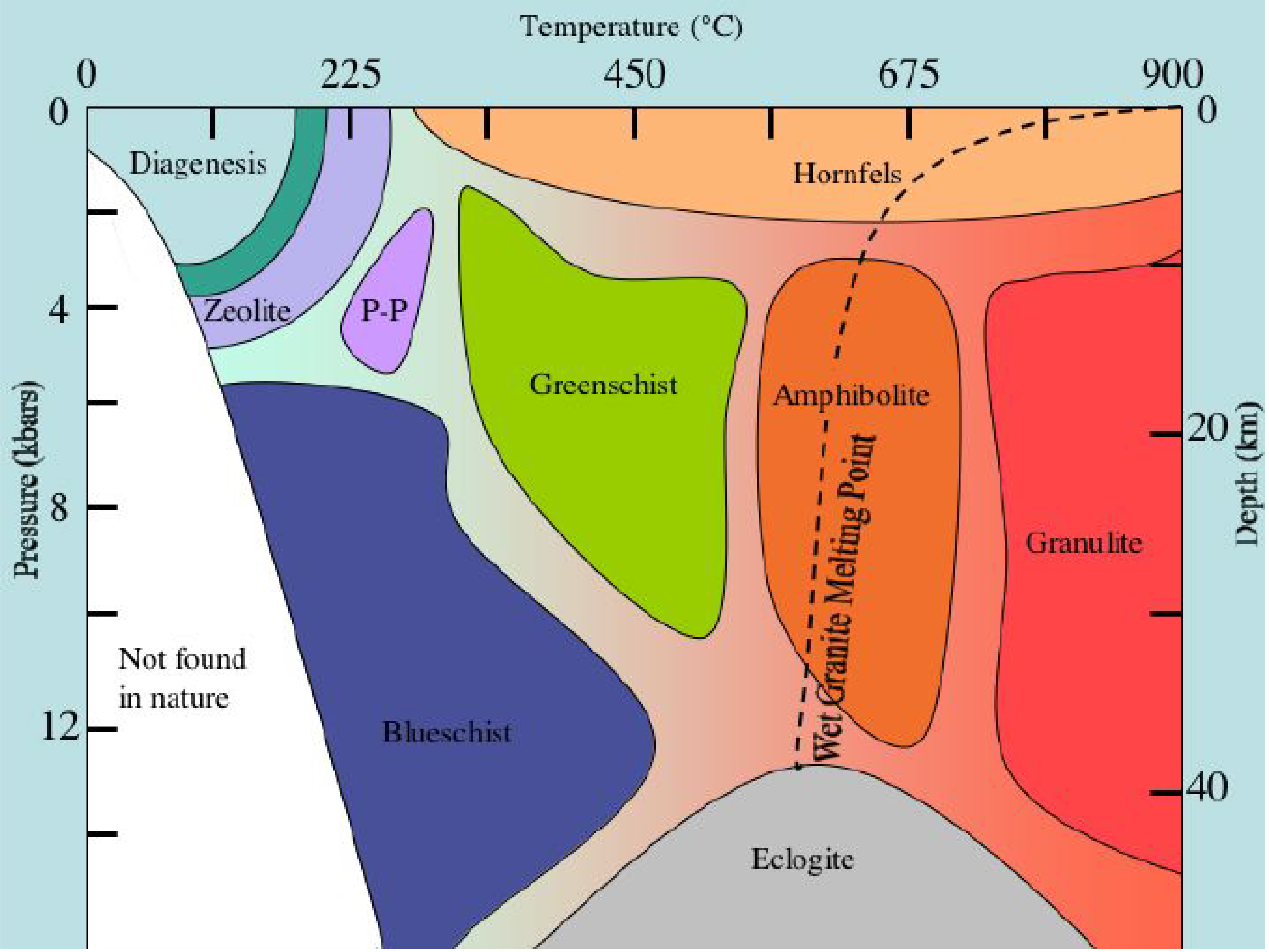


Mineralogical changes take place when rocks pass from one stability field to the other. Experimental petrology provides information on the pressure, temperature conditions at which the mineral changes take place



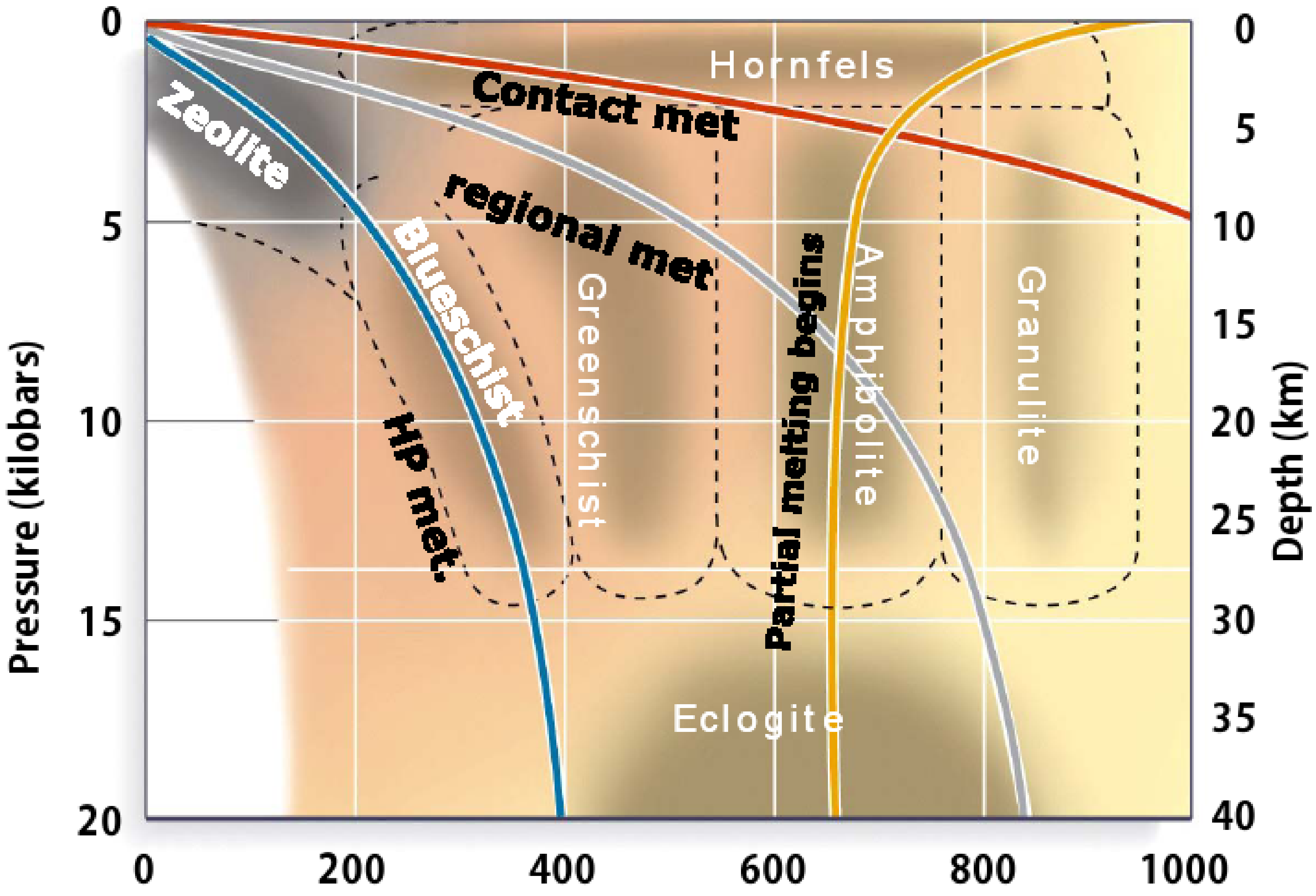
In this way one can link the mineralogical composition of a rock to the p and T conditions of formation

On the basis of the mineral assemblages, metamorphic facies are defined



Three typical gradients:

- HT/LP when temperatures are higher than what predicted by the regional gradient

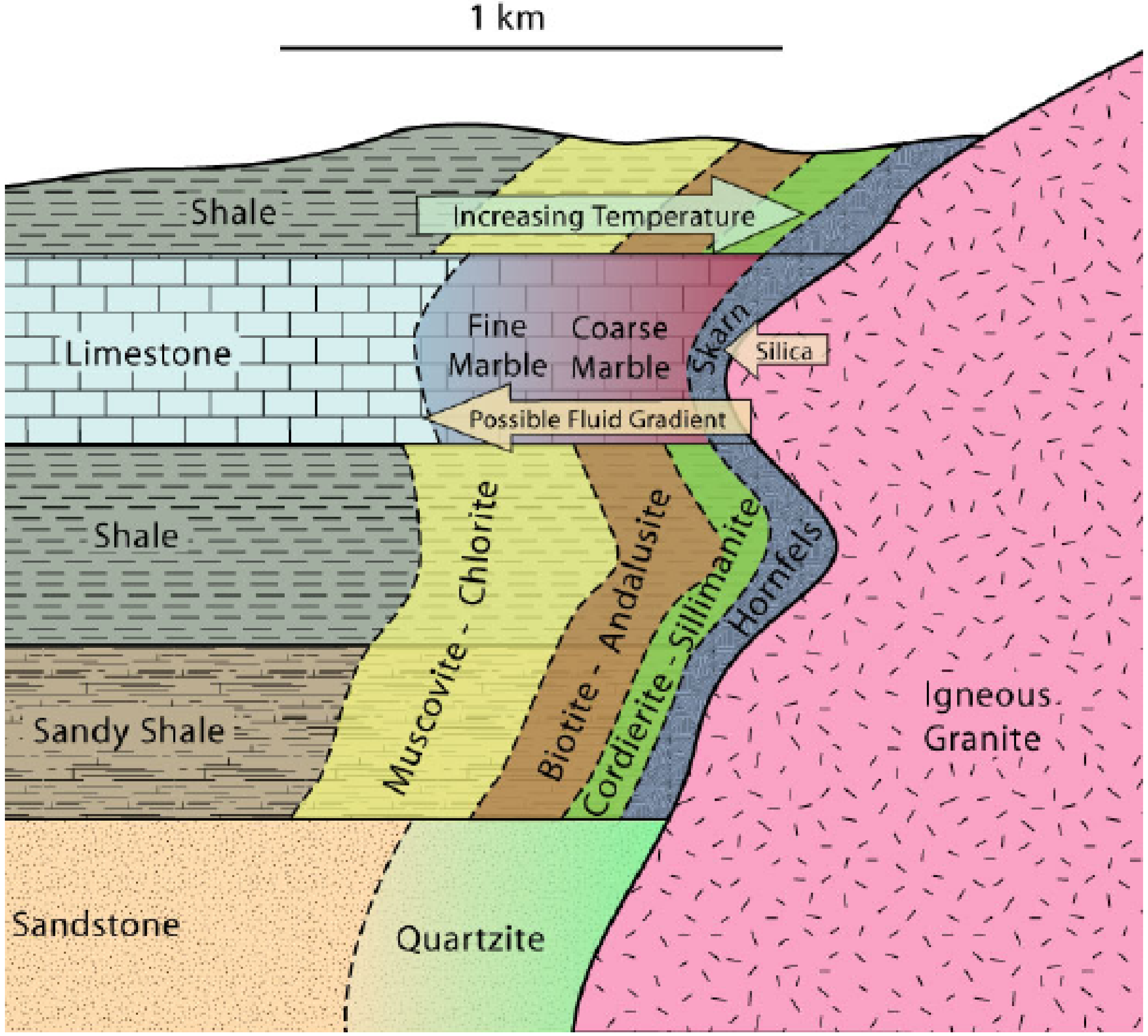


- The regional gradient (Barrovian metamorphism)
- HP/LT when temperatures are lower than what predicted by the regional gradient (high pressure metamorphism)

Rocks following these paths differ from each other
Resulting rocks depend, obviously, also on the primary rock (protolith)

Contact metamorphism (HT/LP)

Basically associated with a magmatic intrusion

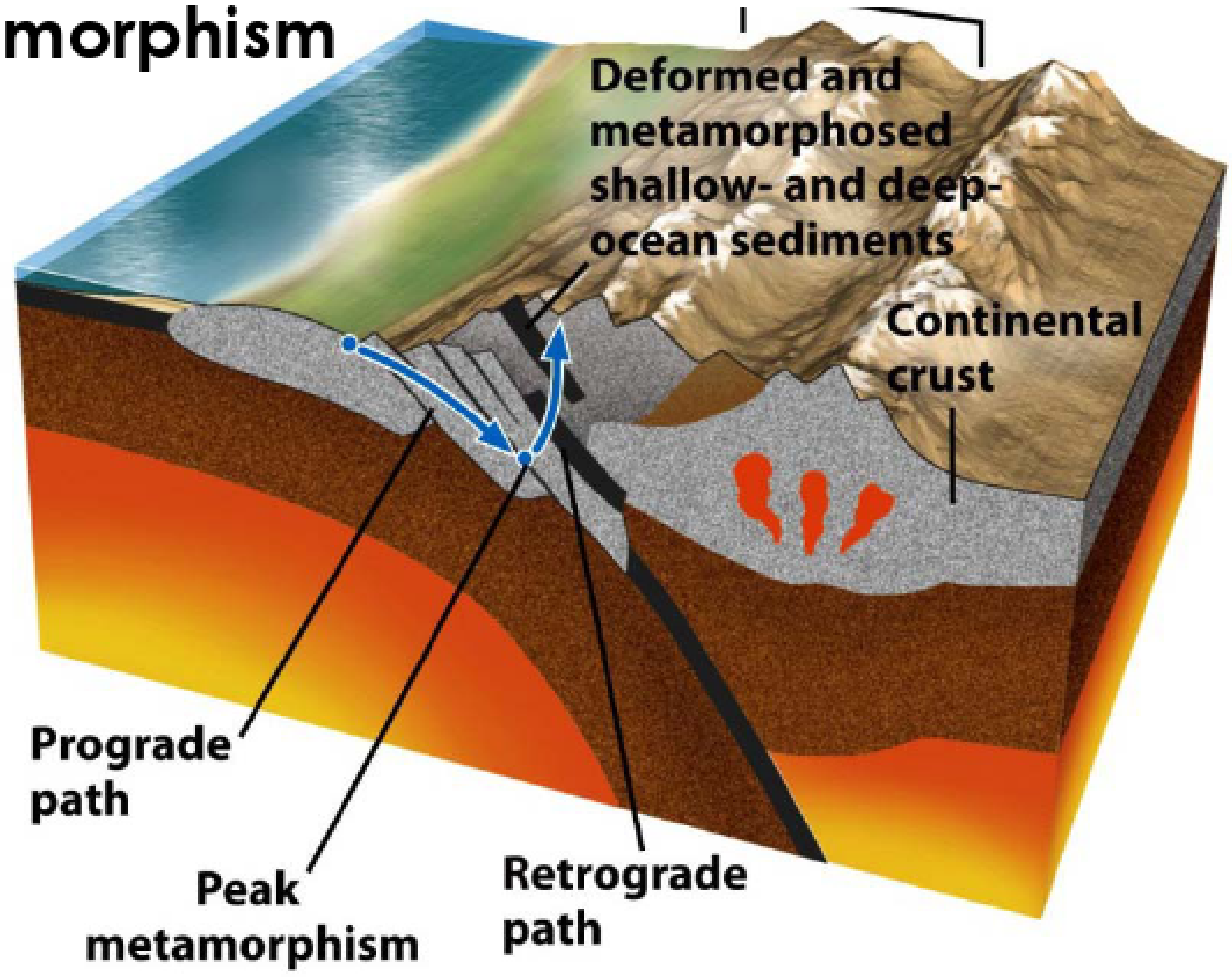


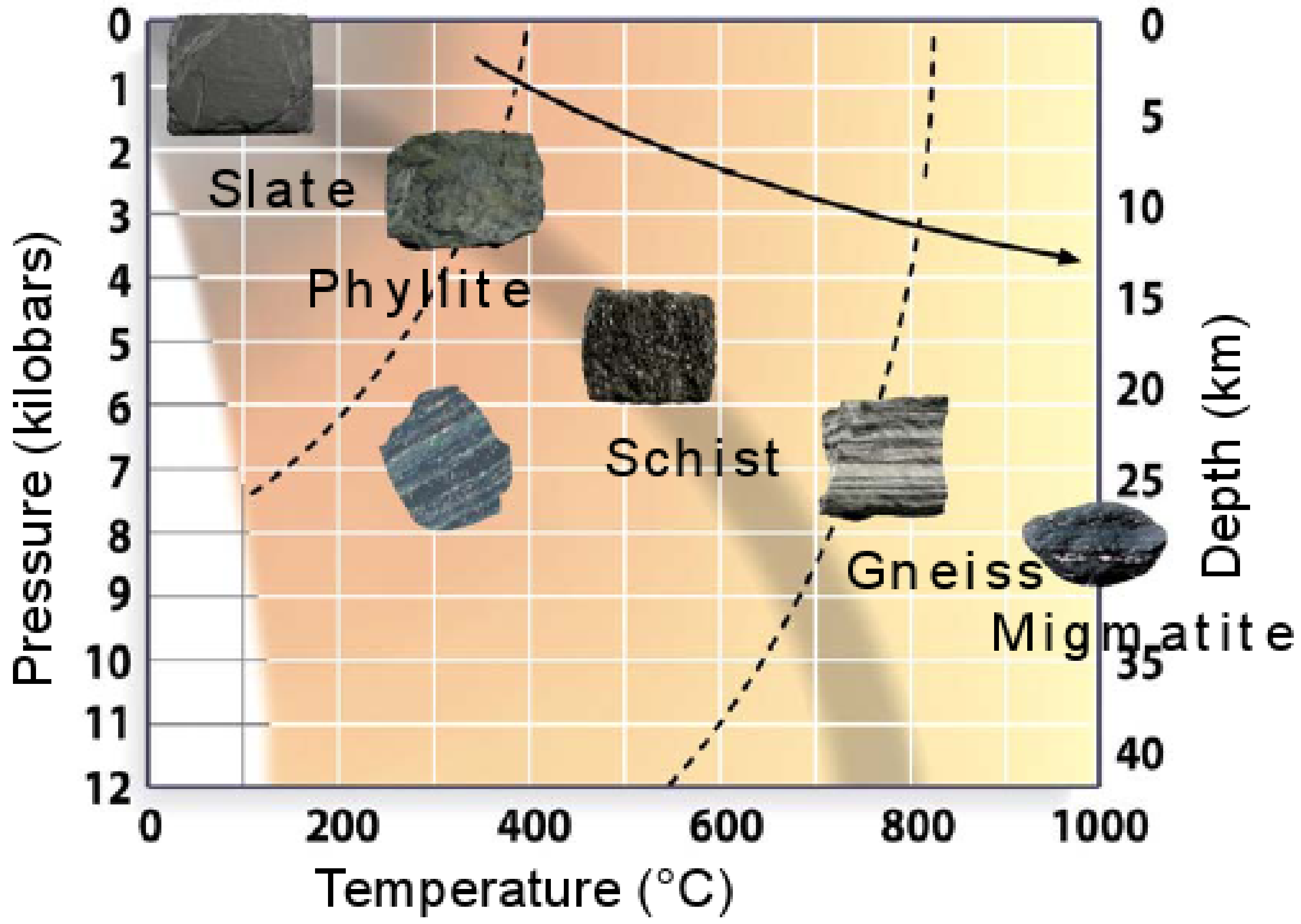
- Contact metamorphic rocks tend to preserve their primary aspect (massive or layered)
- The size of crystals increases with increasing temperatures (=towards the intrusion)
- Fluid circulation is strong and profoundly impacts the rock mineralogy (ore deposits)

The grain-size of a marble is much larger than that of the parent rock

Regional (Barrovian type) metamorphism

Follows regional "normal" gradient.
Occurs in continental convergence (collision) zones and is coupled with strong deformation





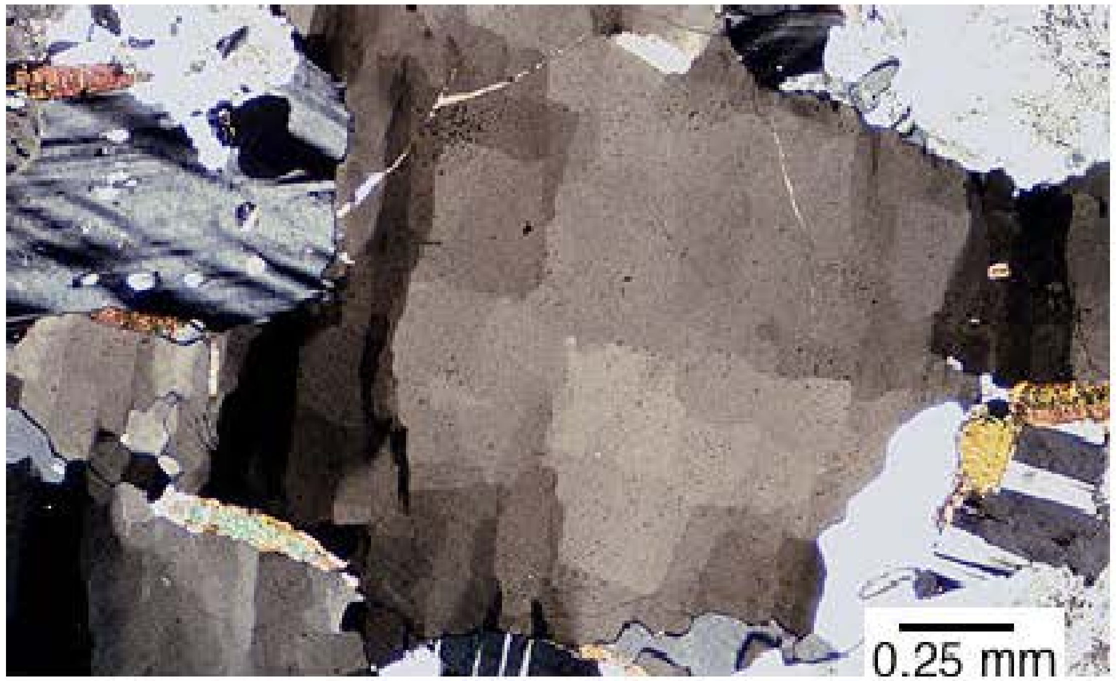
The normal transition for fine-grained rocks

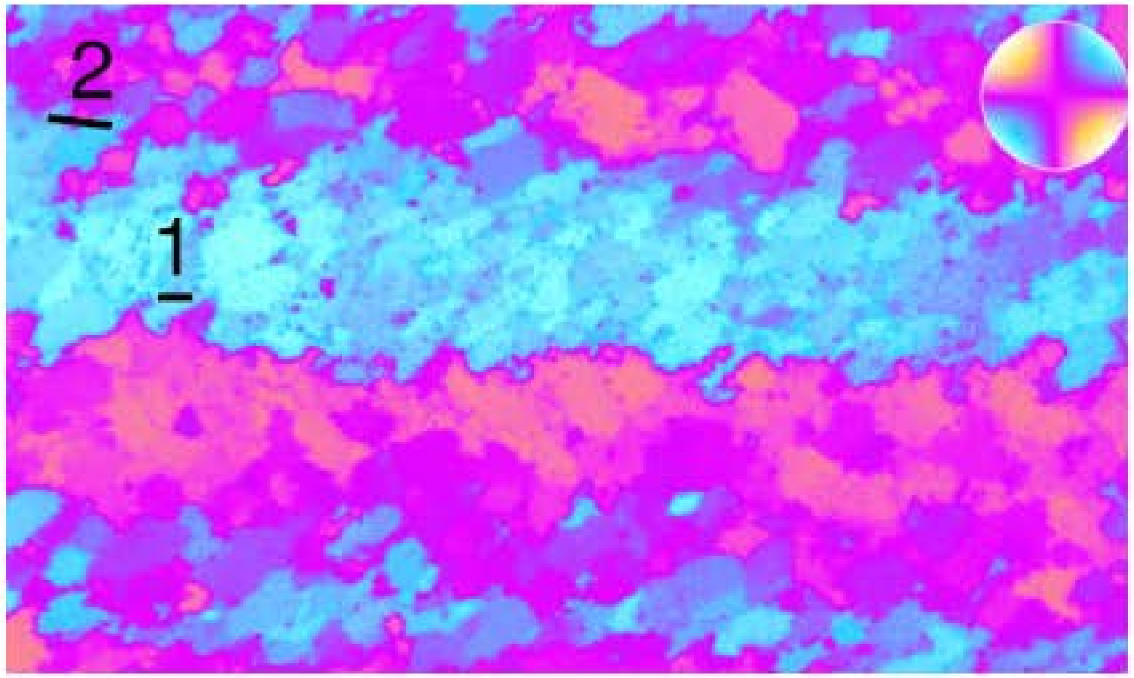
Rocks formed during regional metamorphism are characterized by

- strongly developed foliation
- intensive folding

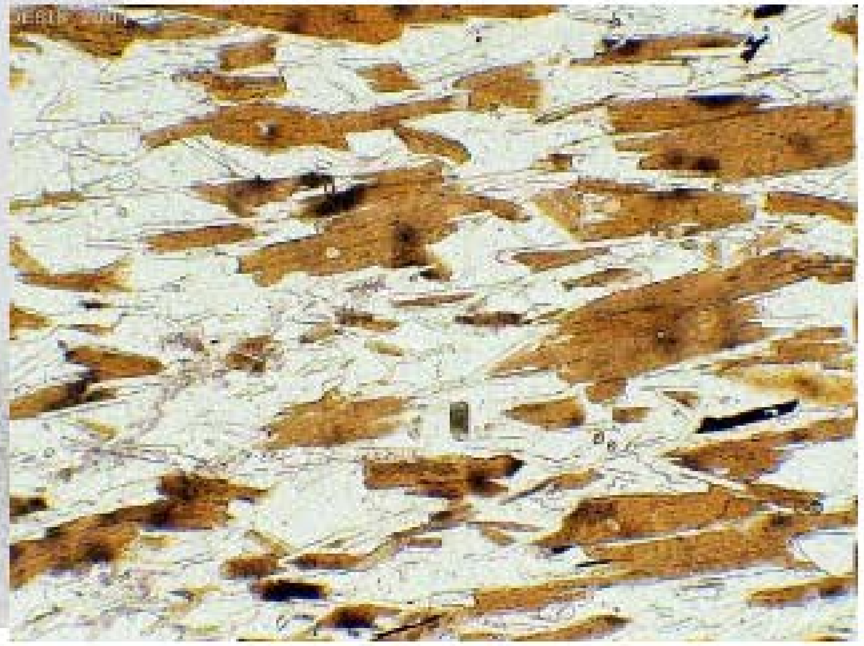
Looking inside the rock, recrystallization is pervasive:

Recrystallization: solid-state changes in grain size



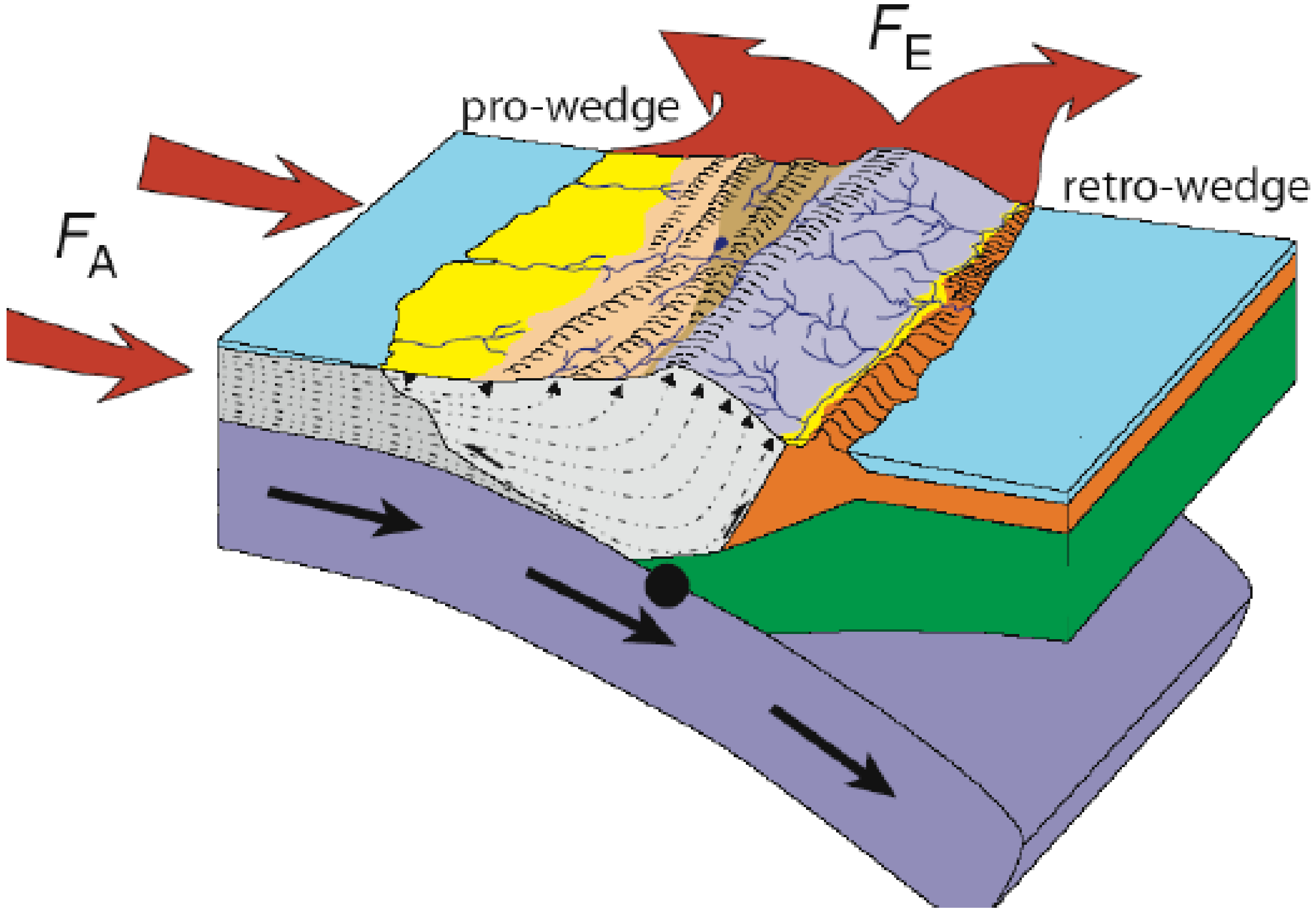


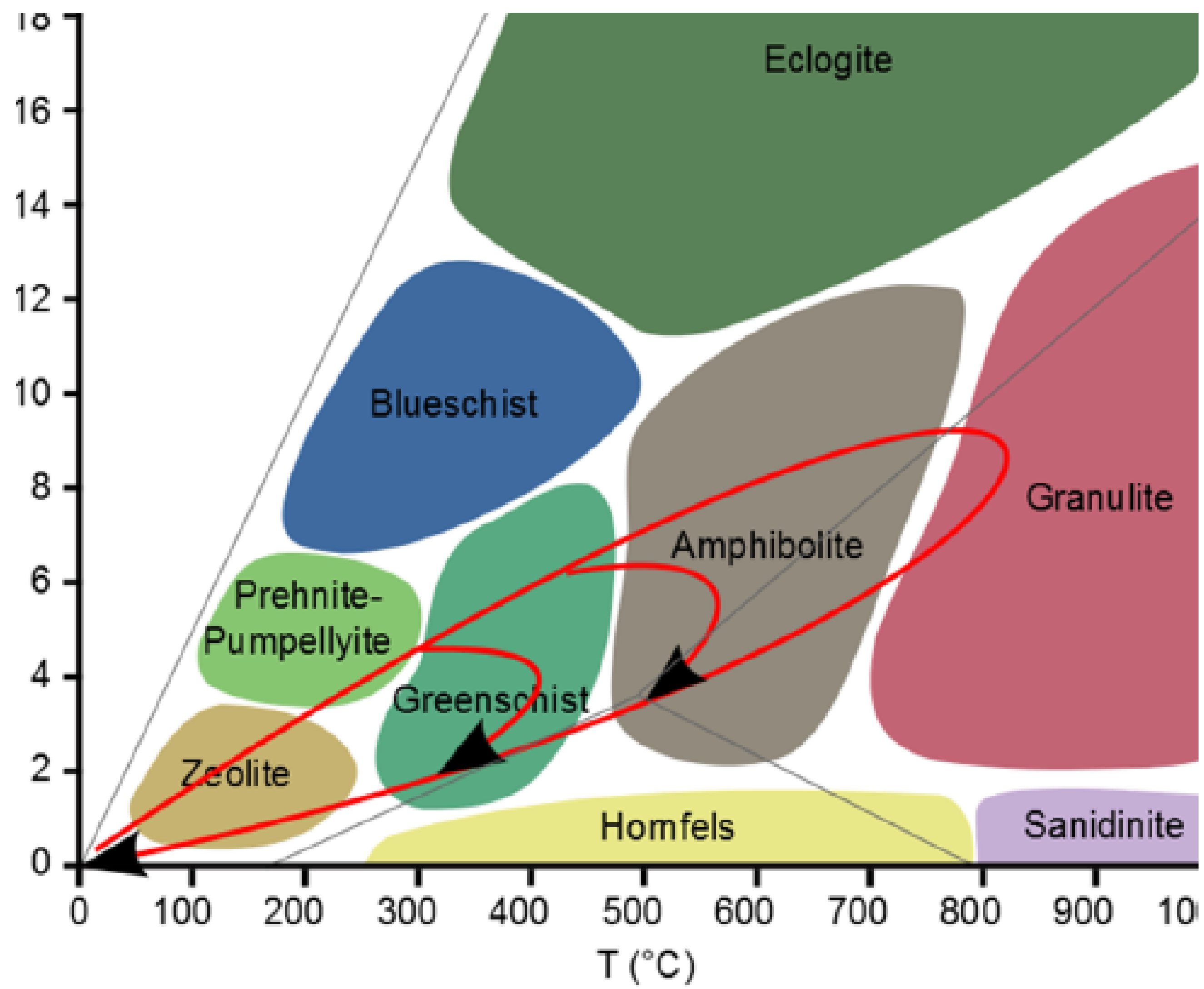
Recrystallization: solid-state changes mineral structure and composition



When things get very bad.. part of the rock begins to melt and a migmatite is formed

Some of the rocks deformed deep in the orogen will come back to the surface for you to collect (exhumation). This has to happen rapidly enough to prevent re-equilibration (also helped by the lack of water)

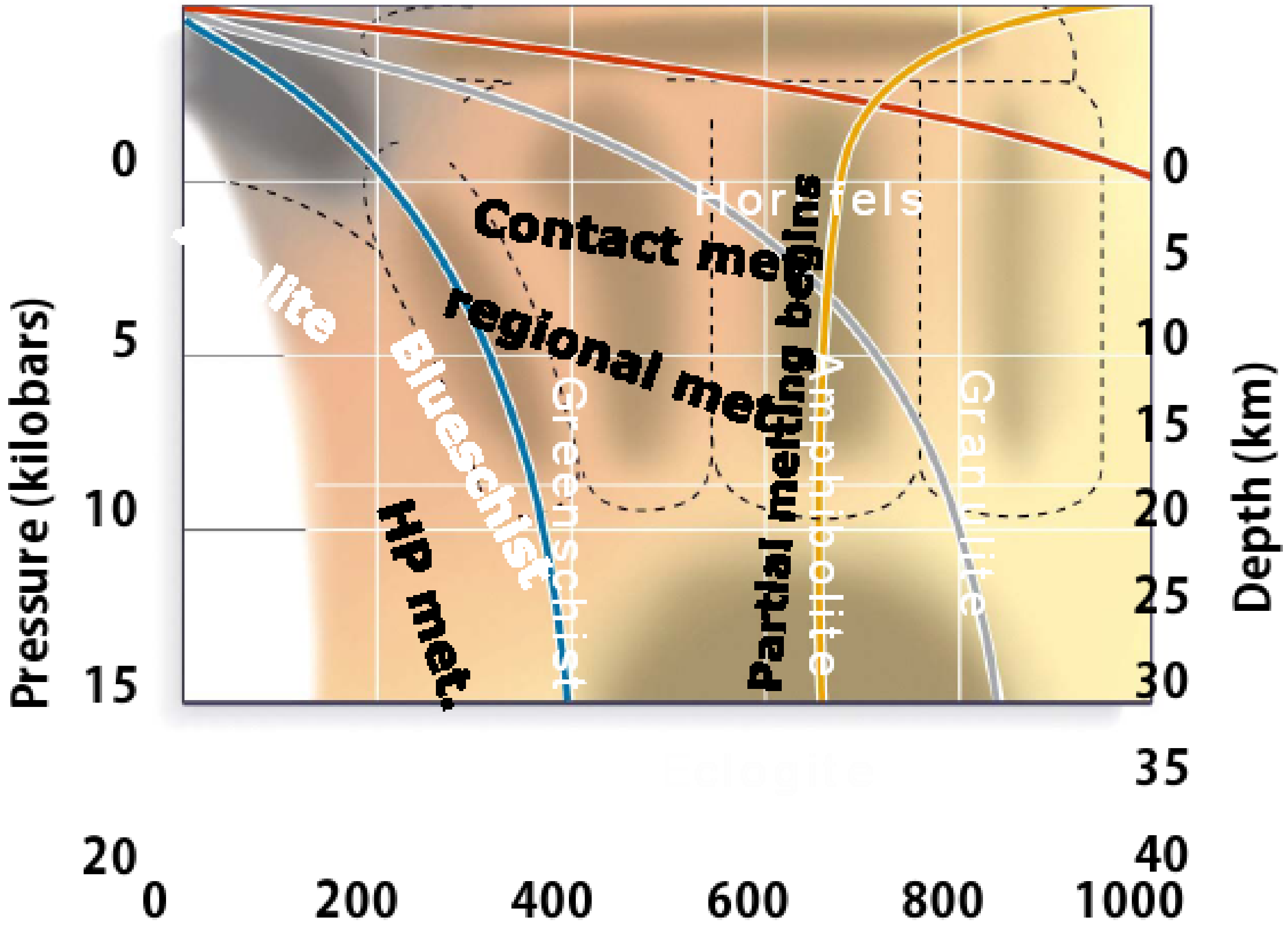


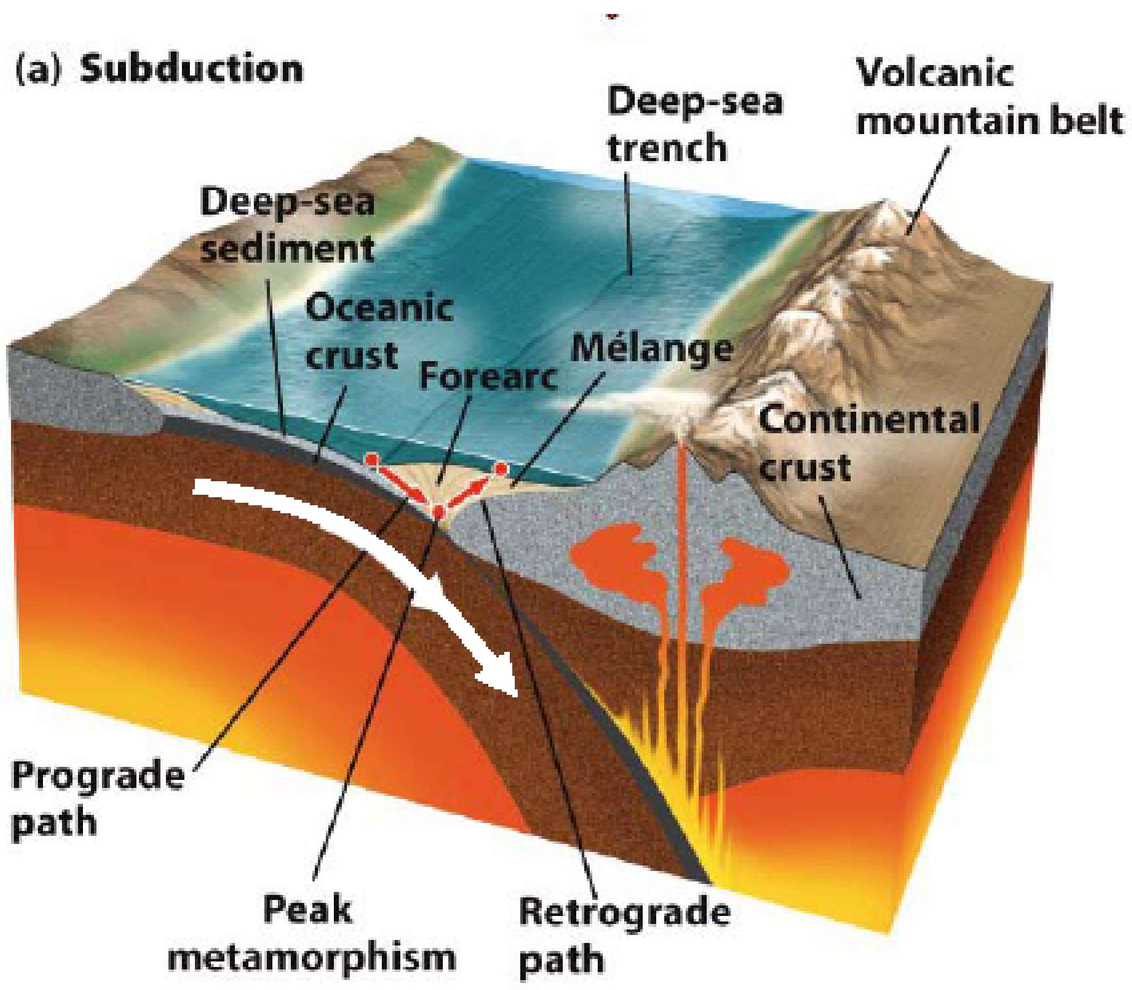


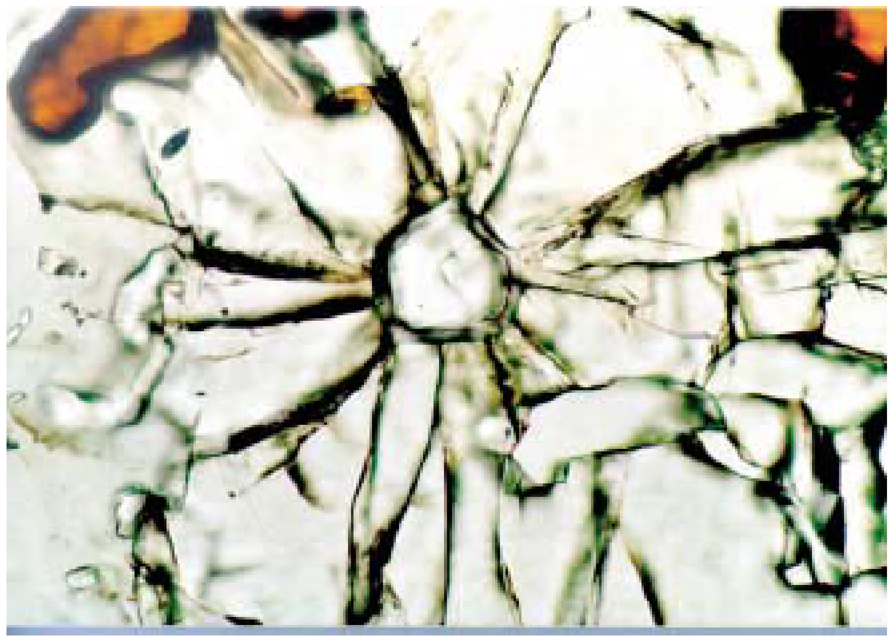
Blueschists

Form at pressures much higher than what predicted by the regional gradient

Typically form along subduction zones: the main mechanism to bring rocks at very large depths (>100km)

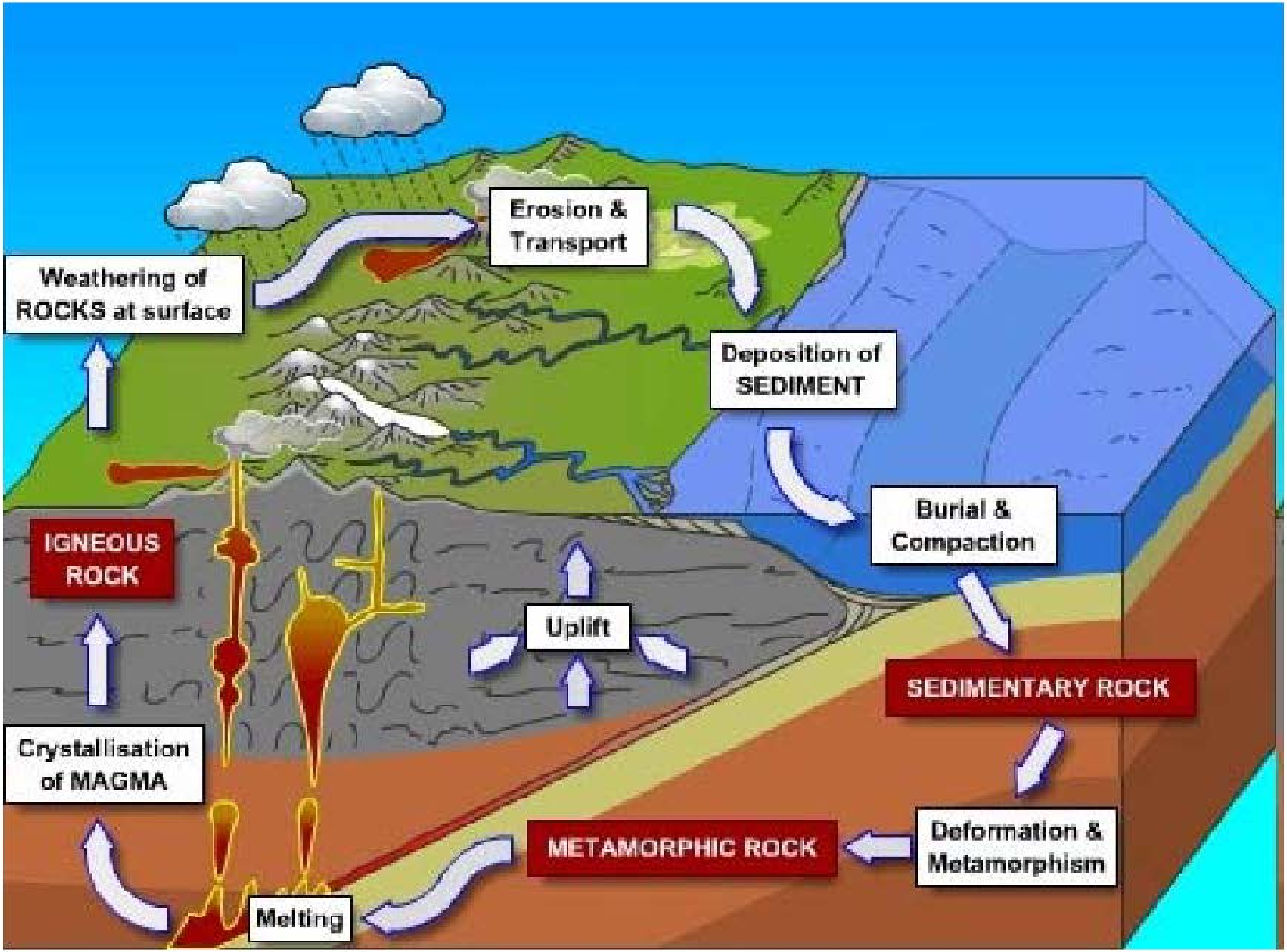






This was a diamond (formed at 100km depth) and brought back to the surface

The rock cycle



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