Einführung in die Geowissenschaften I

Minerals and Rocks

Thomas Ulrich

Week 1

- A few definitions
- The 3 main rock types
- The rock cycle

Why, What, How?

- Why do you think you need to take this course?
- What do you expect from the course (ask your neighbour)?
- What is your previous knowledge on minerals and rocks?
- What role do minerals and rocks play in (y)our life(s)?

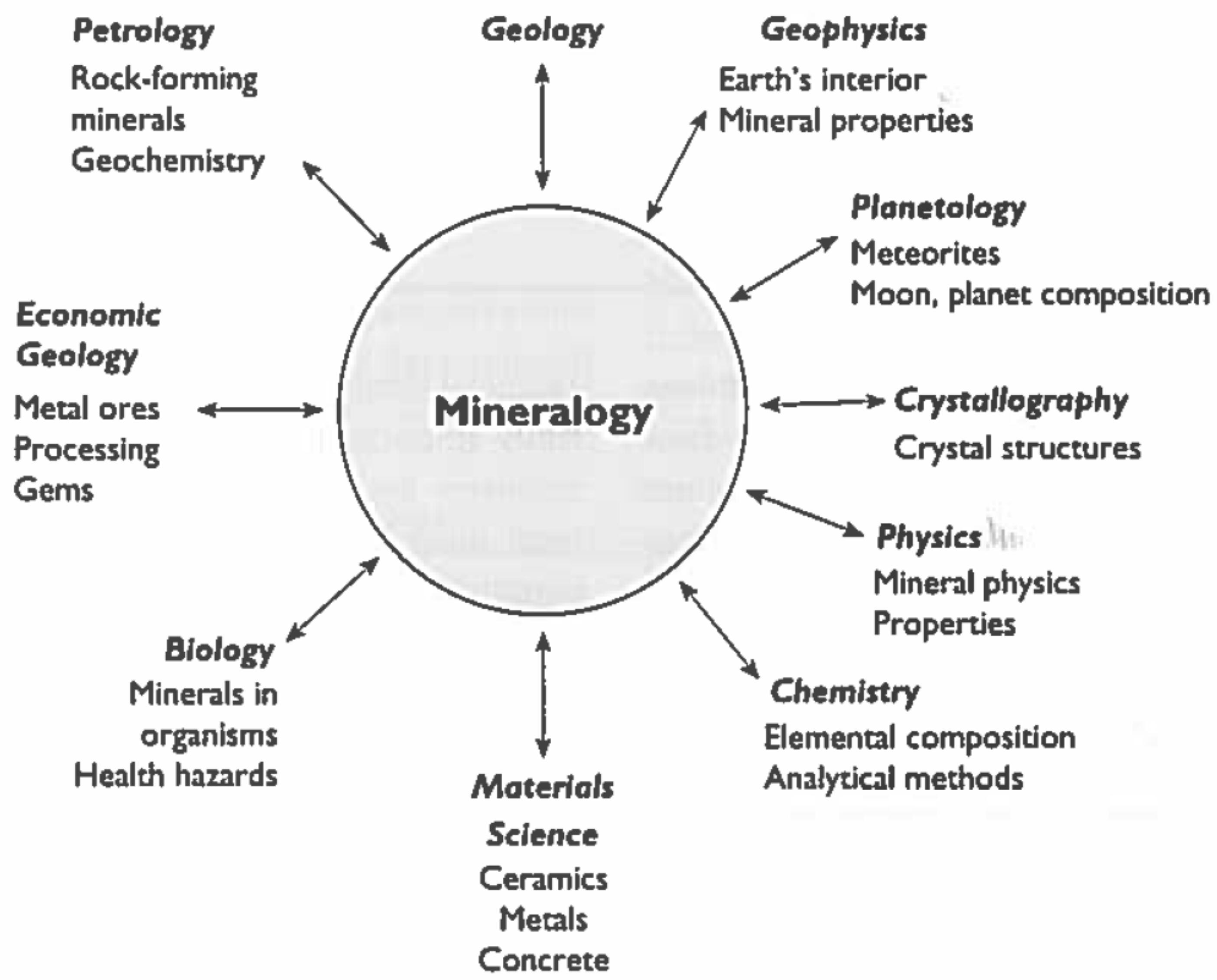
Course structure: Minerals and rocks part

- Introduction: Definition of minerals and rocks, rock types, rock cycle
- Minerals: Evolution, classification, properties, crystallography
- Minerals and society, applications
- Magmatic rocks: volcanic and plutonic rocks
- Metamorphic rocks: metamorphic facies, deformation, tectonic settings

Learning goals

- After the course you should be able to:

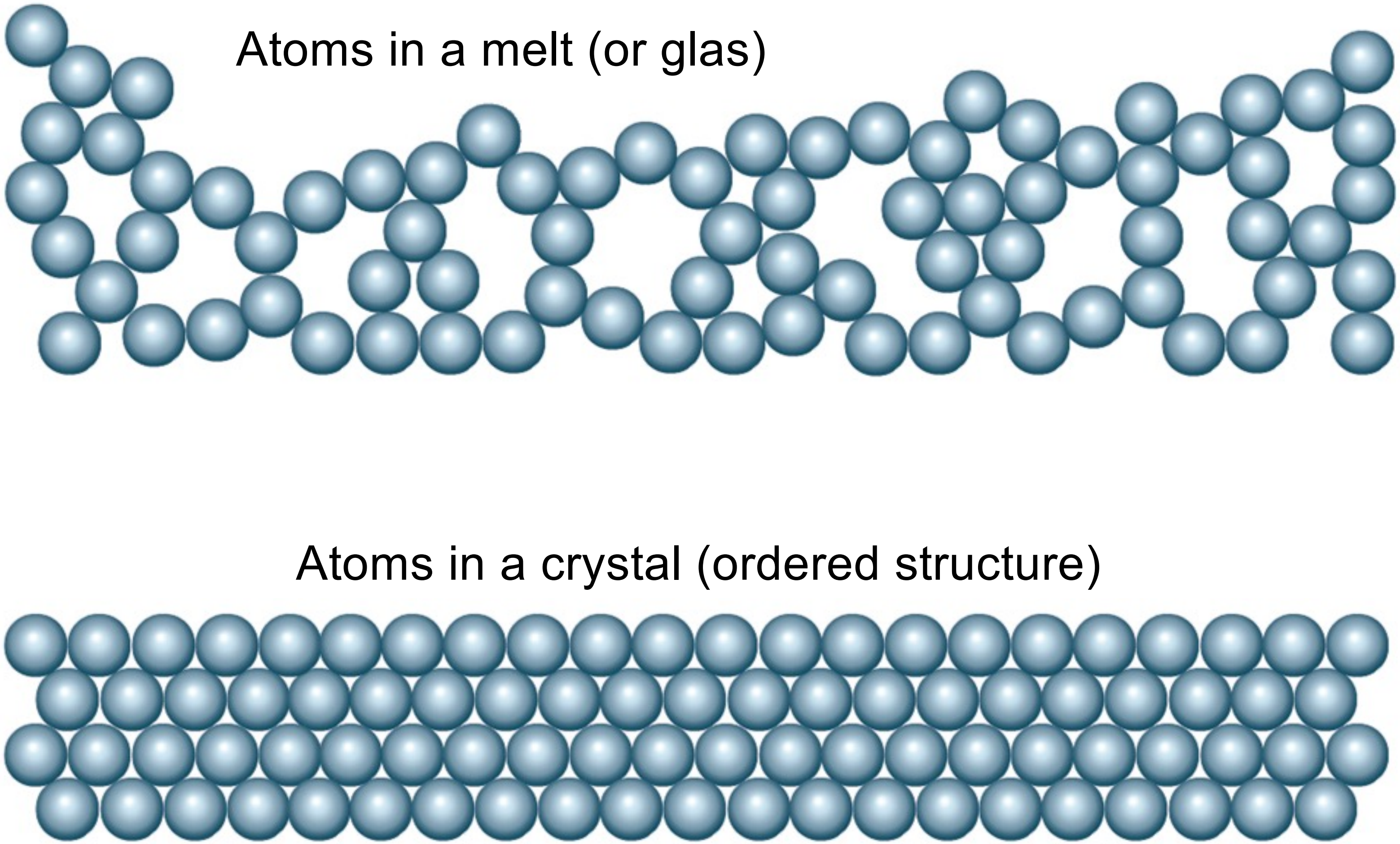
- identify the common minerals and rocks macroscopically
- know the general chemical composition of minerals
- explain how and where different minerals and rocks form
- explain the importance of minerals and rocks in the modern society


Mineralogy
Petrology
Rock-forming minerals
Geochemistry
Geology
Geophysics
Earth's interior
Mineral properties
Planetology
Meteorites
Moon, planet composition
Economic Geology
Metal ores
Processing
Gems
Crystallography
Crystal structures
Physics
Mineral physics
Properties
Biology
Minerals in organisms
Health hazards
Materials Science
Ceramics
Metals
Concrete
Chemistry
Elemental composition
Analytical methods

A few definitions

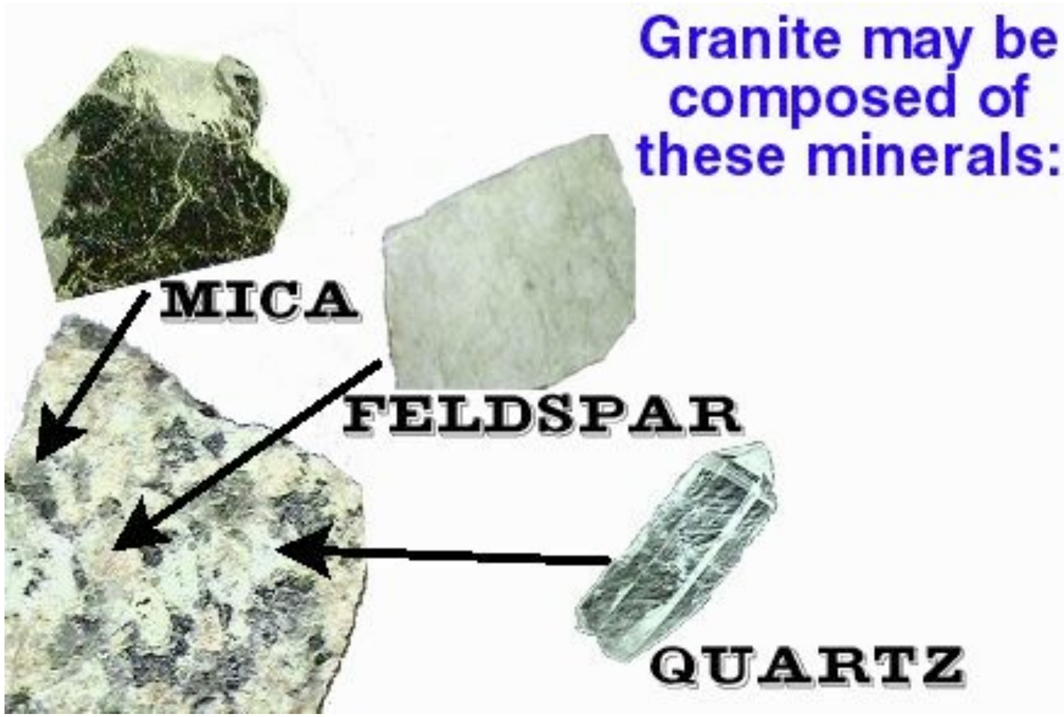
- **Element:** Na, Cl, O, S
- **Mineral:** halite (NaCl), quartz, feldspar, mica, amphibole, ….
  'Solid, naturally occurring, inorganic material with an ordered structure and a defined chemical composition'
- **Rock:** a composite of minerals (e.g., **granite:** quartz+feldspar+mica)
- **Crystal:** 'any solid material in which the component atoms are arranged in a definite pattern' (Britannica)


Geology Page
www.GeologyPage.com


Atoms in a melt (or glas)
Atoms in a crystal (ordered structure)

Rocks: Assemblage of minerals

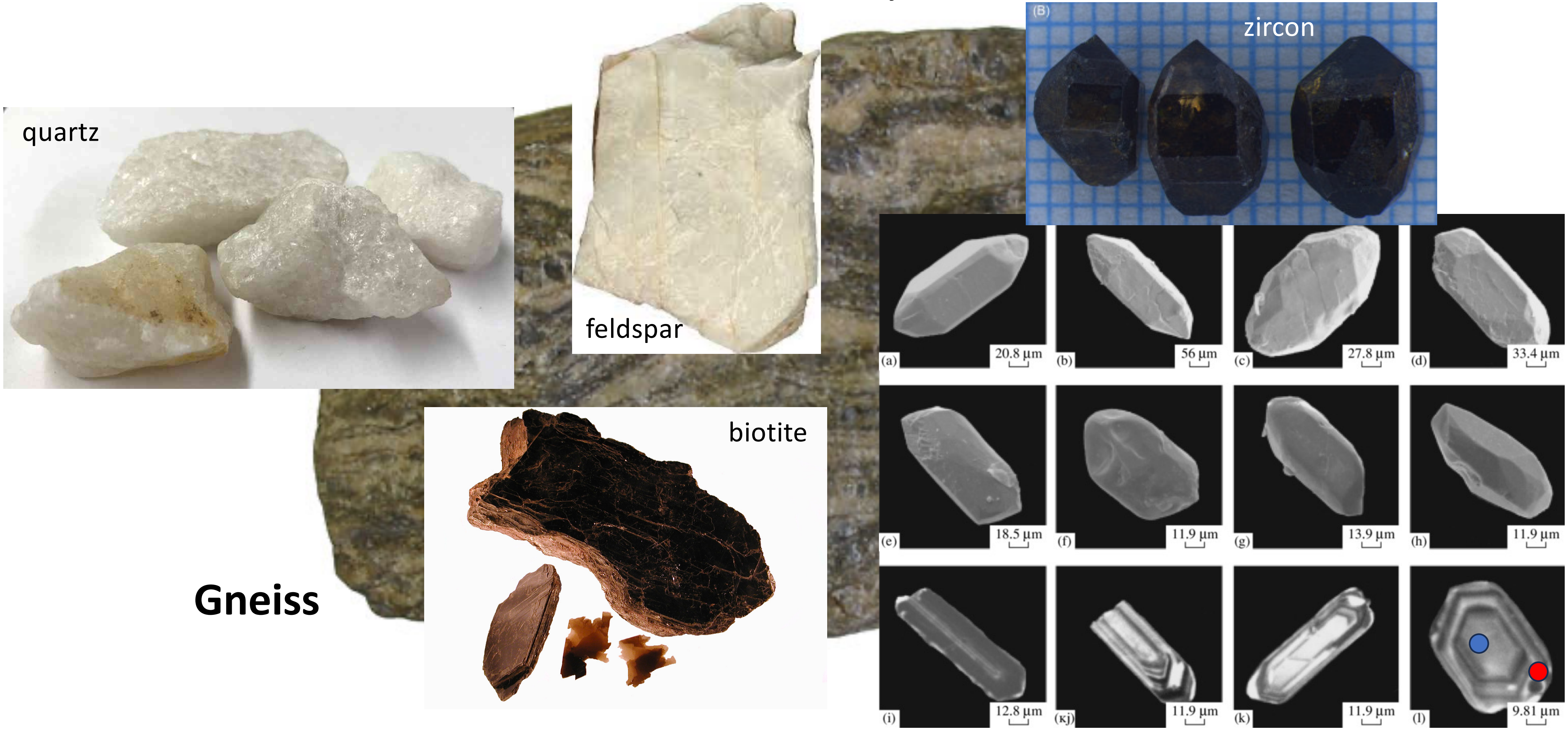
- Rocks consist typically of several different minerals. In some cases only of one type of mineral (limestone, quartzite)



What are rocks telling us?

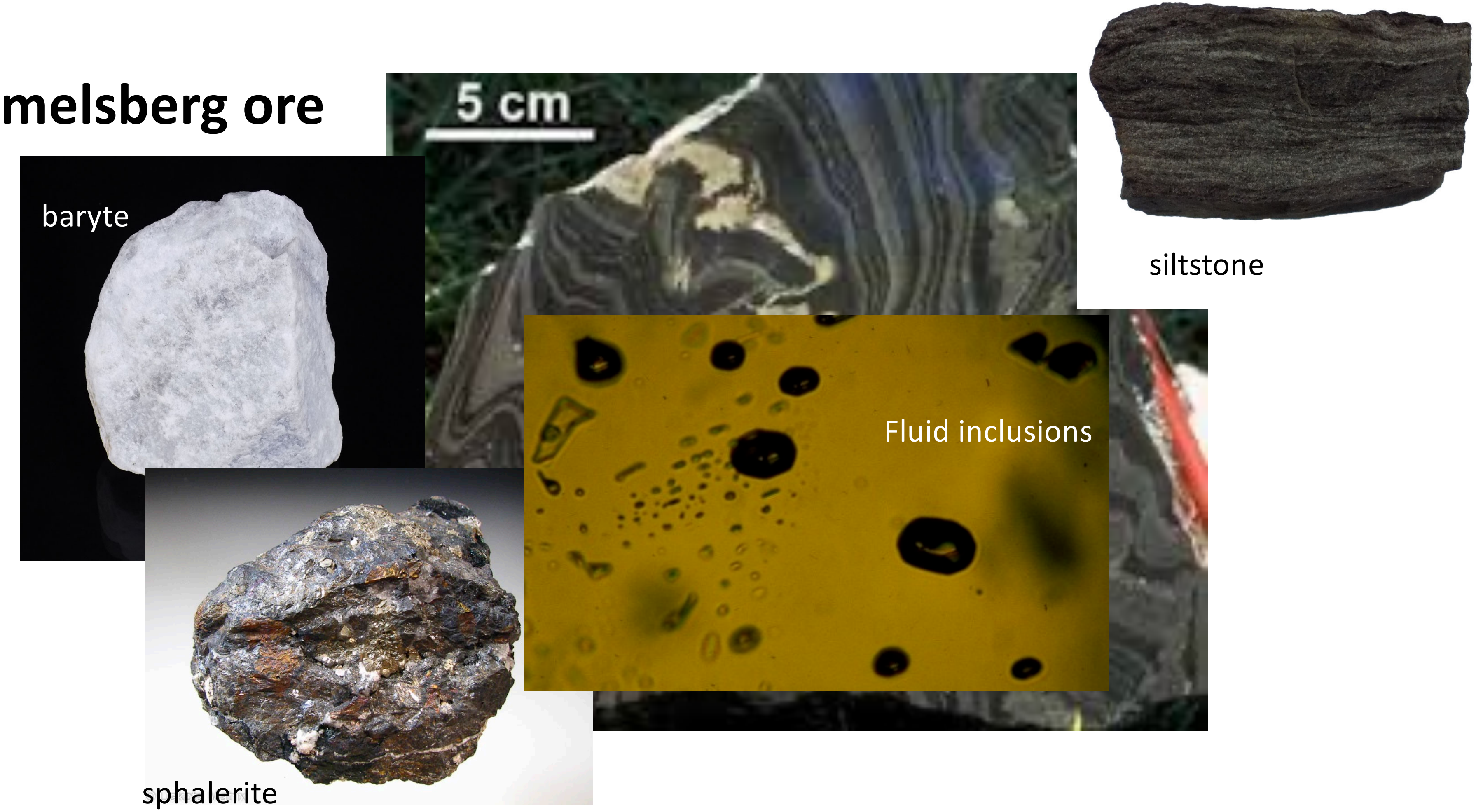
Discuss in pairs

Minerals and Rocks: A story or two



Minerals and Rocks: A story or two

Rammelsberg ore



Rocks: the 3 rock types

Rocks: the 3 general rock types

- Magmatic rocks

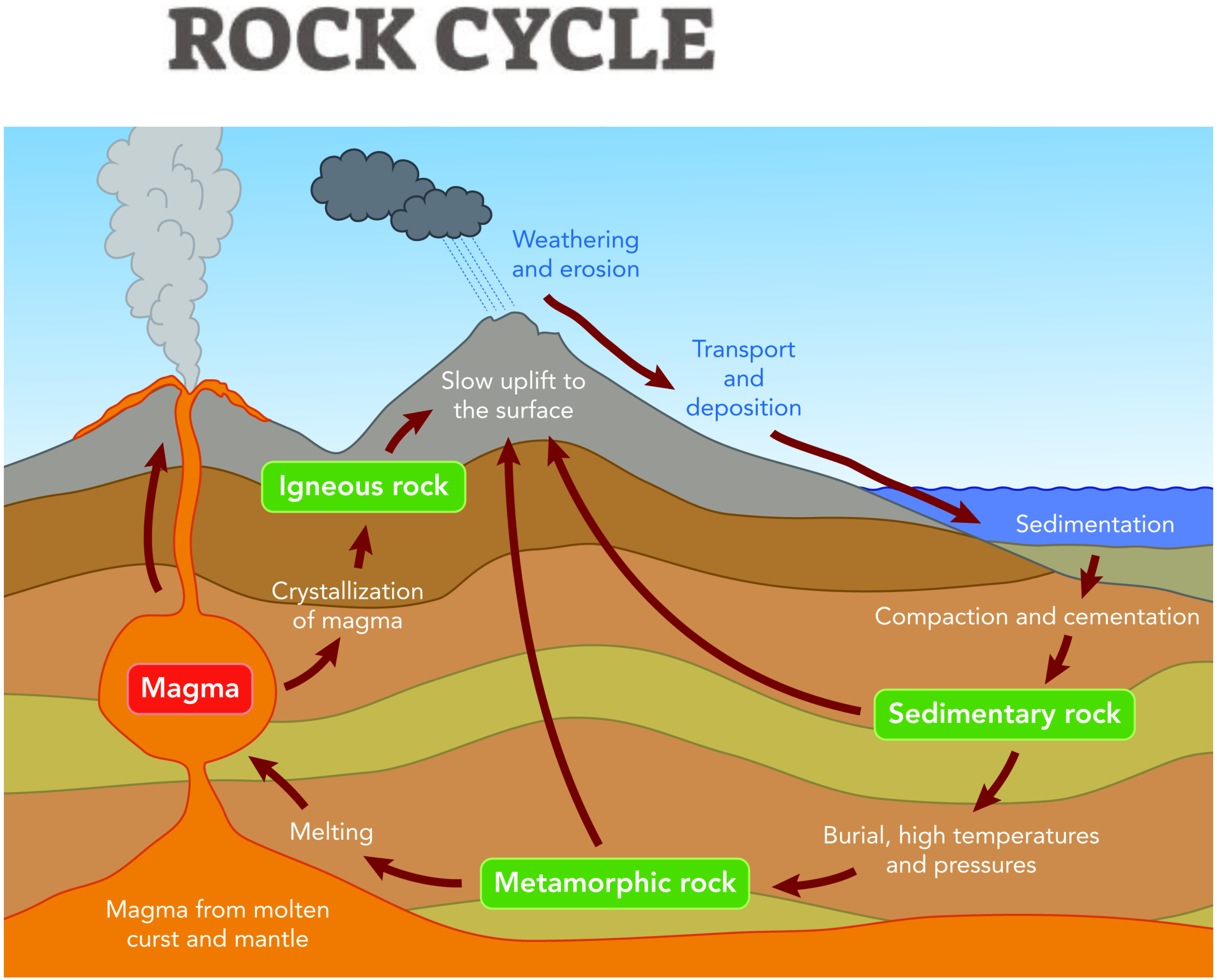
- Metamorphic rocks

- Sedimentary rocks

These general groups are based on the formation processes, and there are many different rocks in each group (see later).

Rocks:

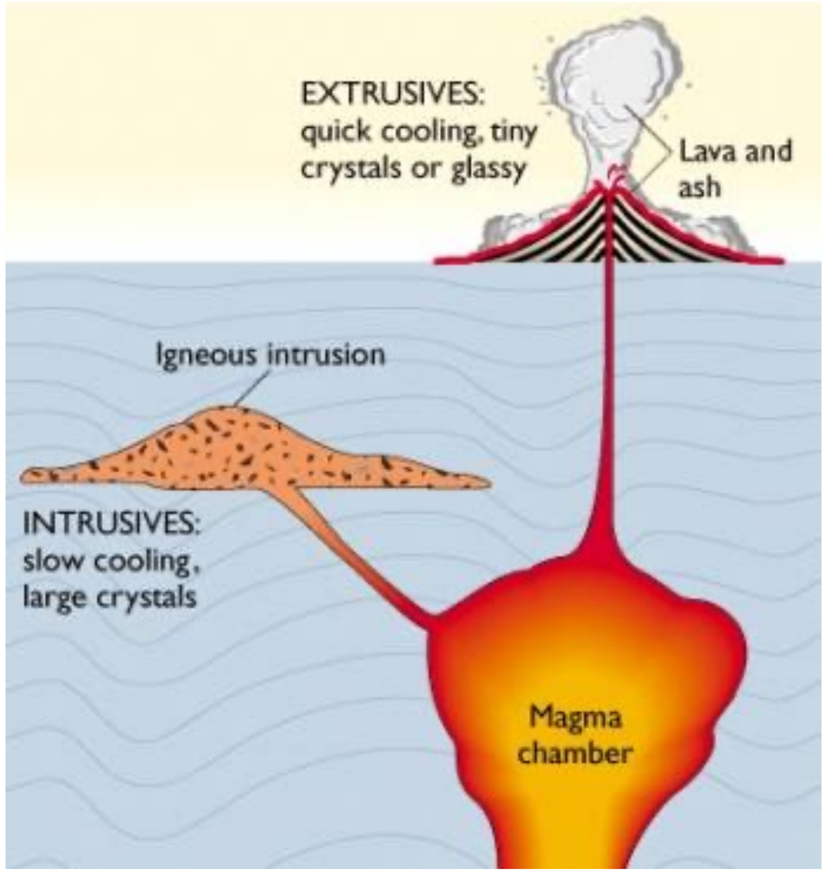
Pay attention to the processes that lead from one rock type to another one.



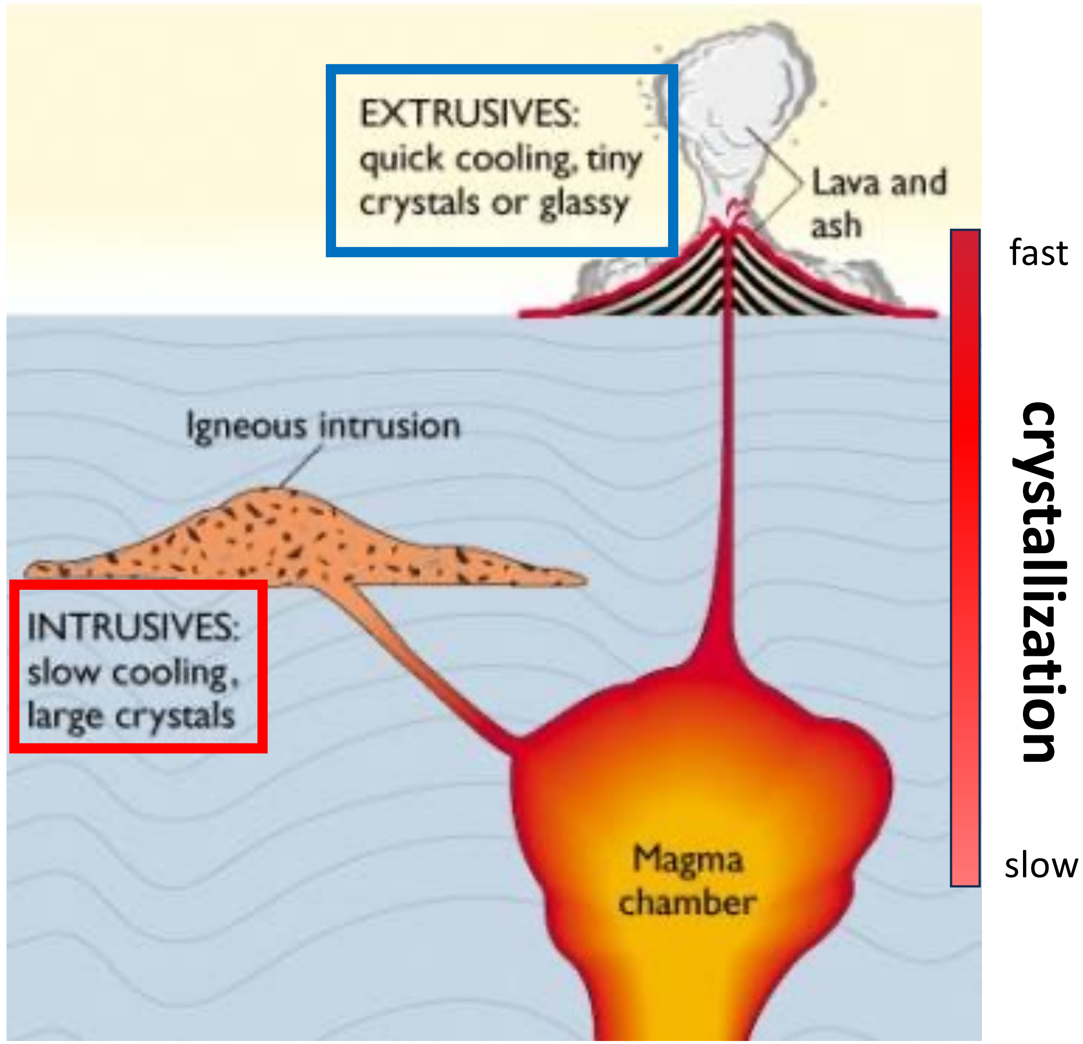
Rocks: Magmatic rocks

Start as molten rock at depth: **magma**

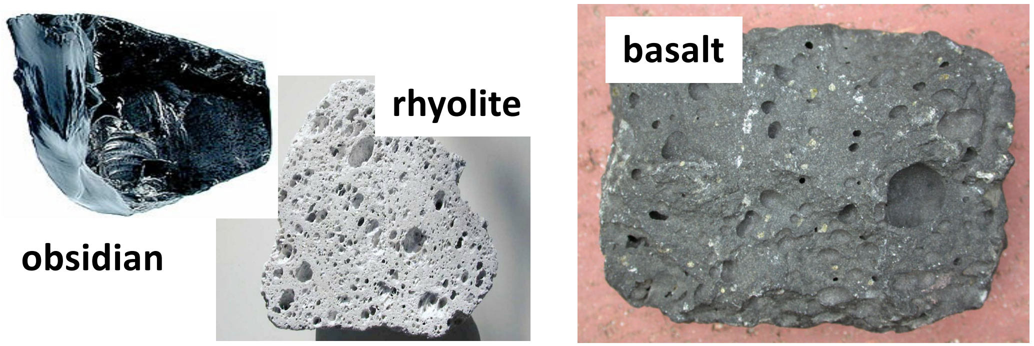
If erupted on land surface: **lava**



Rocks: Magmatic rocks



Rocks: Magmatic rocks, characteristics



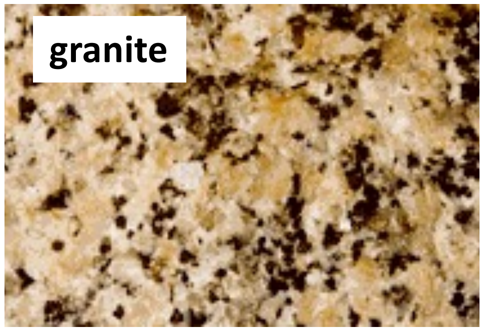
Volcanic (extrusive)

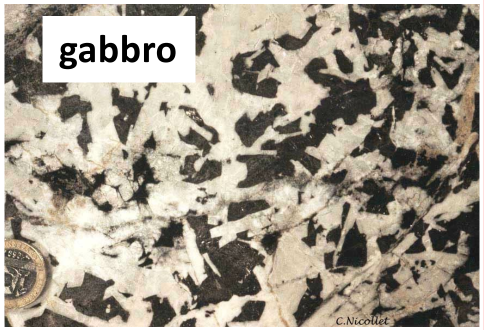
Fine-grained, glassy, no minerals visible, except for phenocrysts.

Feldspar phenocrysts

Some volcanic rocks are porous (vesicles). These pores are formed due to degassing during decompression of the melt.

Plutonic (intrusive)





Course-grained, minerals visible and irregularly intergrown

Rocks: Sedimentary rocks

All rocks exposed at the Earth surface will experience weathering and erosion.

These *physical and chemical* processes break down rocks into single minerals or new minerals

Sandstone

Rocks: Sedimentary rocks

Sedimentary rocks form due to accumulation (sedimentation) of weathered material.

Sandstone **(quartz grains)**

Shale **(clay minerals)**

Rocks: Sedimentary rocks

Some sedimentary rocks form due to precipitation from sea water or deposition of dead (micro)-organisms.

Limestone

Evaporites

(e.g., salt)

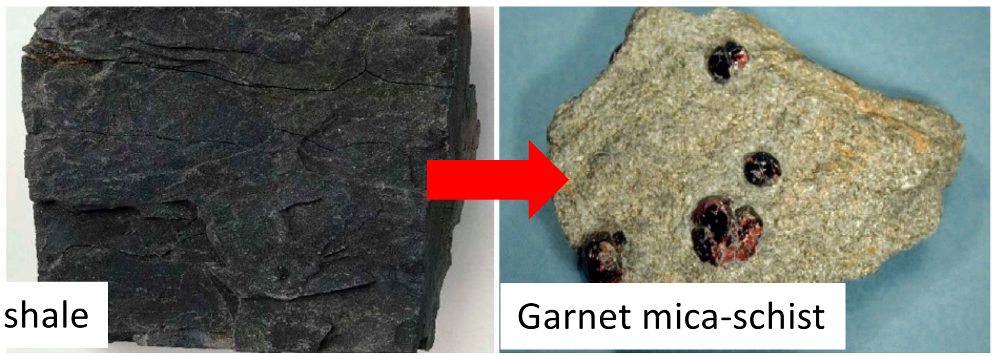
Rocks: Sedimentary rocks, characteristics

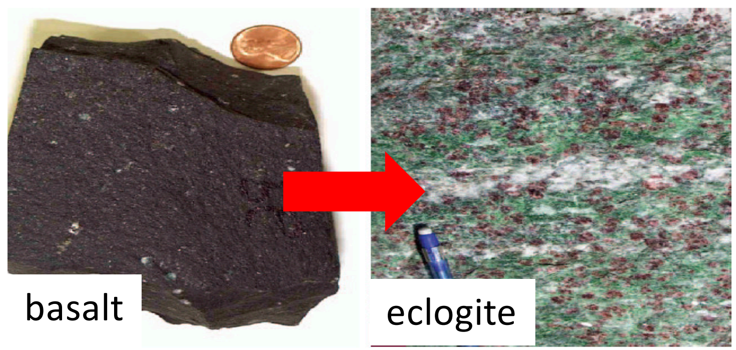
- Layering
- Cross bedding

Rocks: Metamorphic rocks

All rock types can be exposed to high temperature and/or pressure. **METAMORPHISM**

This will commonly change the mineralogy in the rock (formation of new minerals). New rock name.





Rocks: Metamorphic rocks, characteristics

Due to pressure and temperature changes the texture in the rock will also change (banding).

Granite

Gneiss

Not to confuse with sedimentary layering!

What I always will remember: week 1

- Minerals are the building blocks of rocks and ultimately of our planet.
- Minerals have a defined crystal structure and inorganic chemistry.
- The 3 rock types: magmatic, metamorphic, sedimentary
- The rock cycle and the processes associated
- Magmatic rocks are either volcanic (fine-grained, glassy) or plutonic (coarse-grained).
- Sedimentary rocks are the products of weathering and erosion of other rocks, or deposition/precipitation in water. They show often layering.
- Metamorphic rocks are the product of changing temperature and pressure conditions. They can show banding and deformation.

Possible flash cards

- Definition of mineral
- Crystal
- Rock
- Lava vs. magma
- Banding
- Layering
- Plutonic vs. volcanic
- Evaporite
- ….

‘last minute paper’

- Write down what was difficult to understand
- Write down what was easy to understand

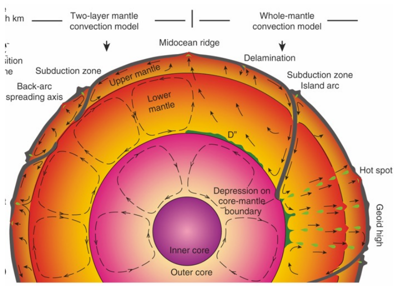

Minerals

Week 1

- The origin of minerals
- The mineral evolution
- The mineral classification

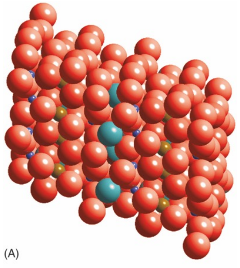
Mineral of the day

Minerals: The building blocks of Earth

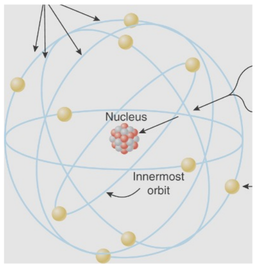


Earth

Rocks



Crystal structure

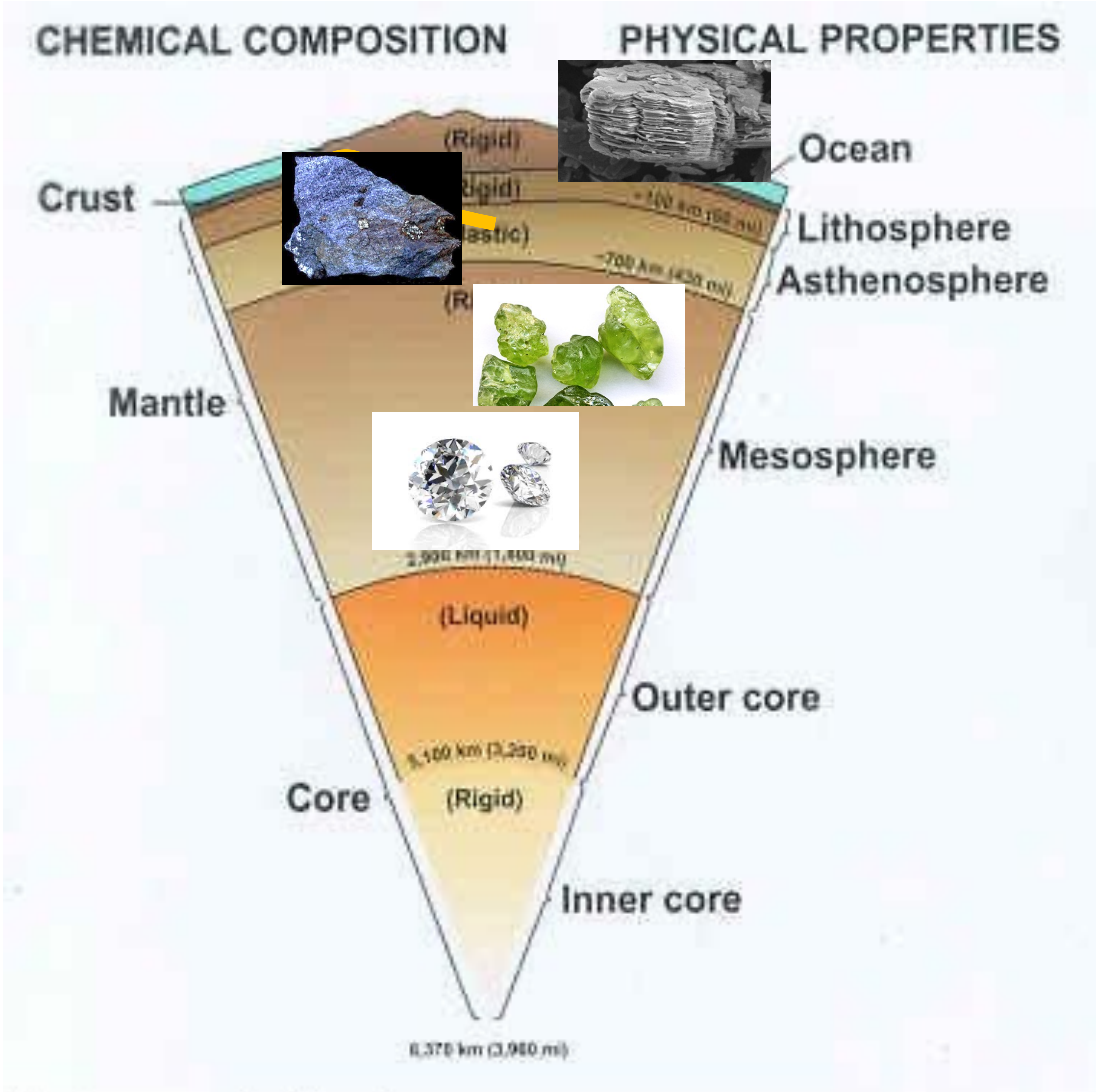


Atom structure

Minerals

MINERALOGY

There are over 5000 minerals known and several new ones are discovered every year. This large number is because minerals are only stable at certain physical (P-T) and chemical conditions.

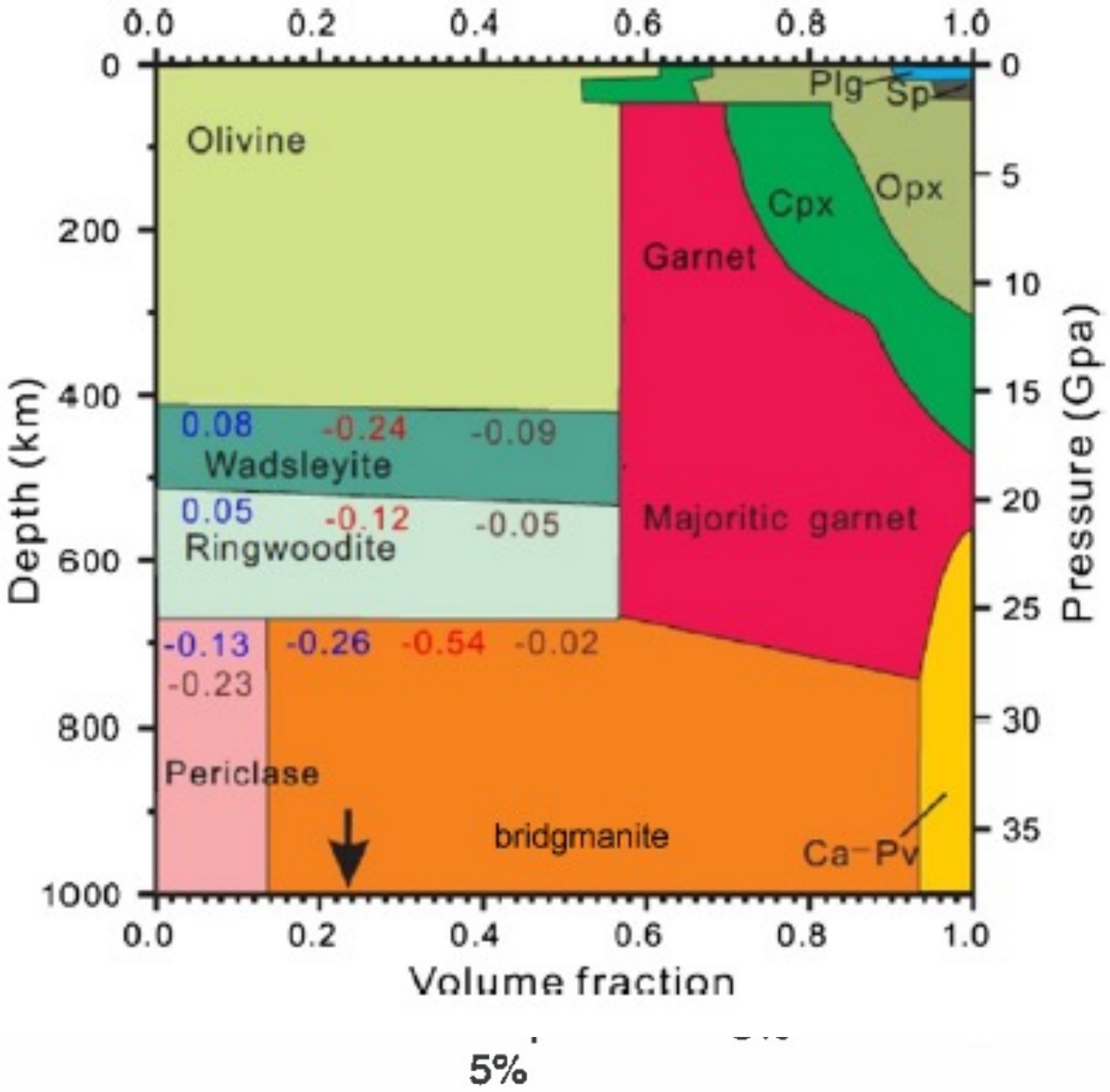


http://success.shoreline.edu

MINERALOGY

Our planet consists of different layers. There is a ‘handful’ of minerals that dominate in the different layers.

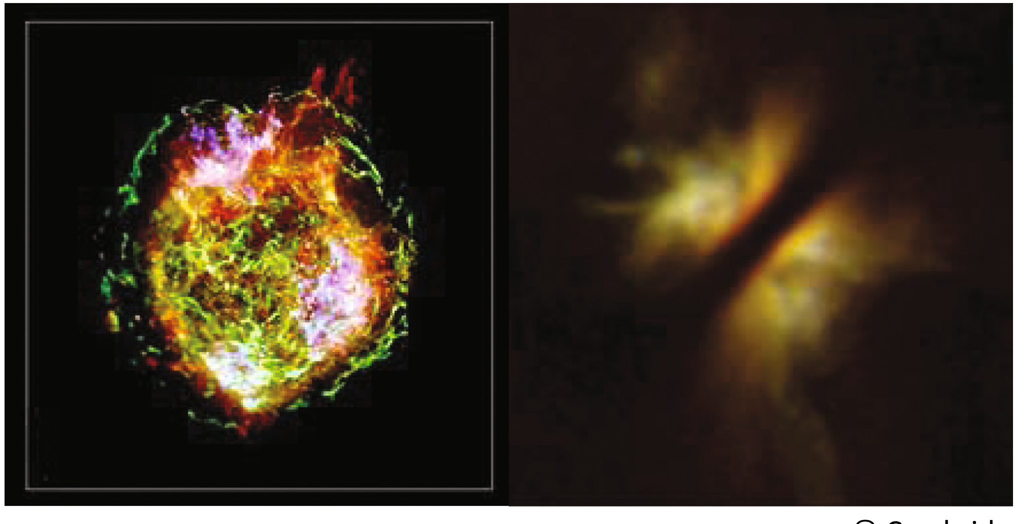
Crust: Feldspar, quartz, pyroxene
Upper mantle: Olivine
Lower mantle: Bridgmanite



But how did minerals originate?

Minerals: their origin, the very beginning…

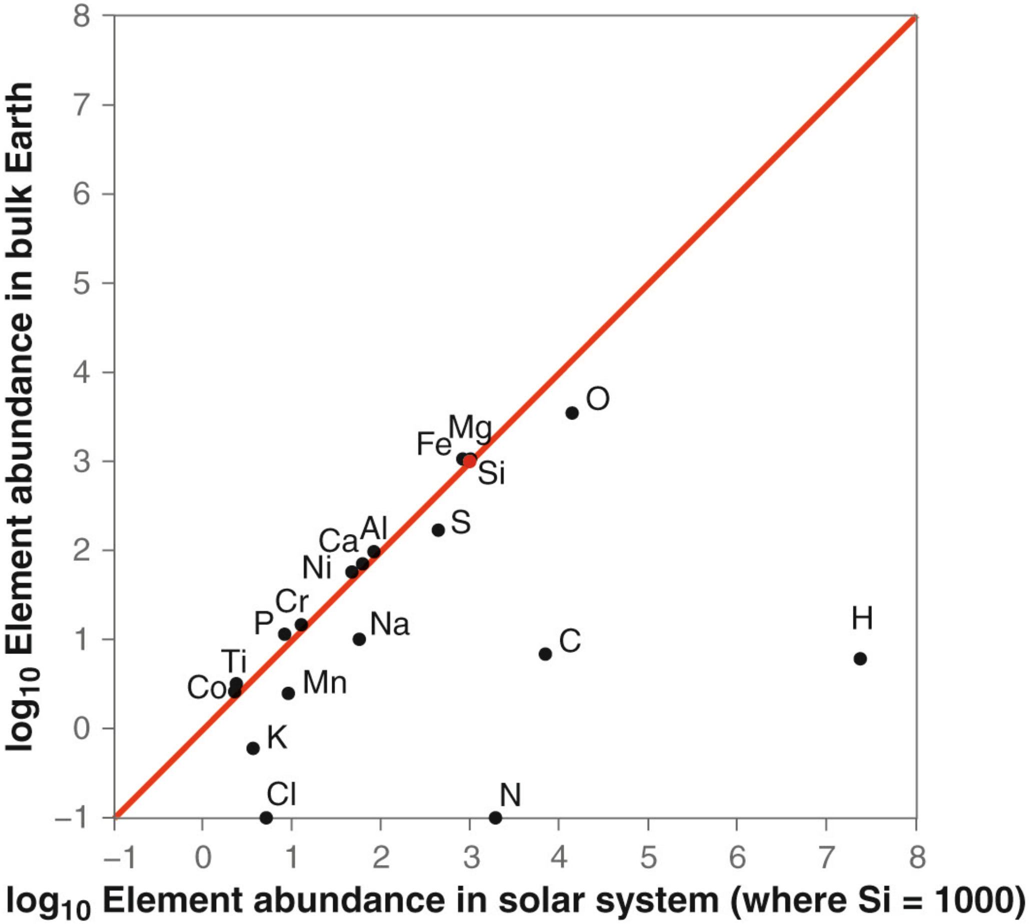
- Solar nebula and gravitational collapse and star formation (H, He, Si, Fe….). Information from meteorites.
- Supernovae (star explosions), formation of heavier elements.
- Mineral evolution



Minerals: Element abundances solar system vs. bulk earth

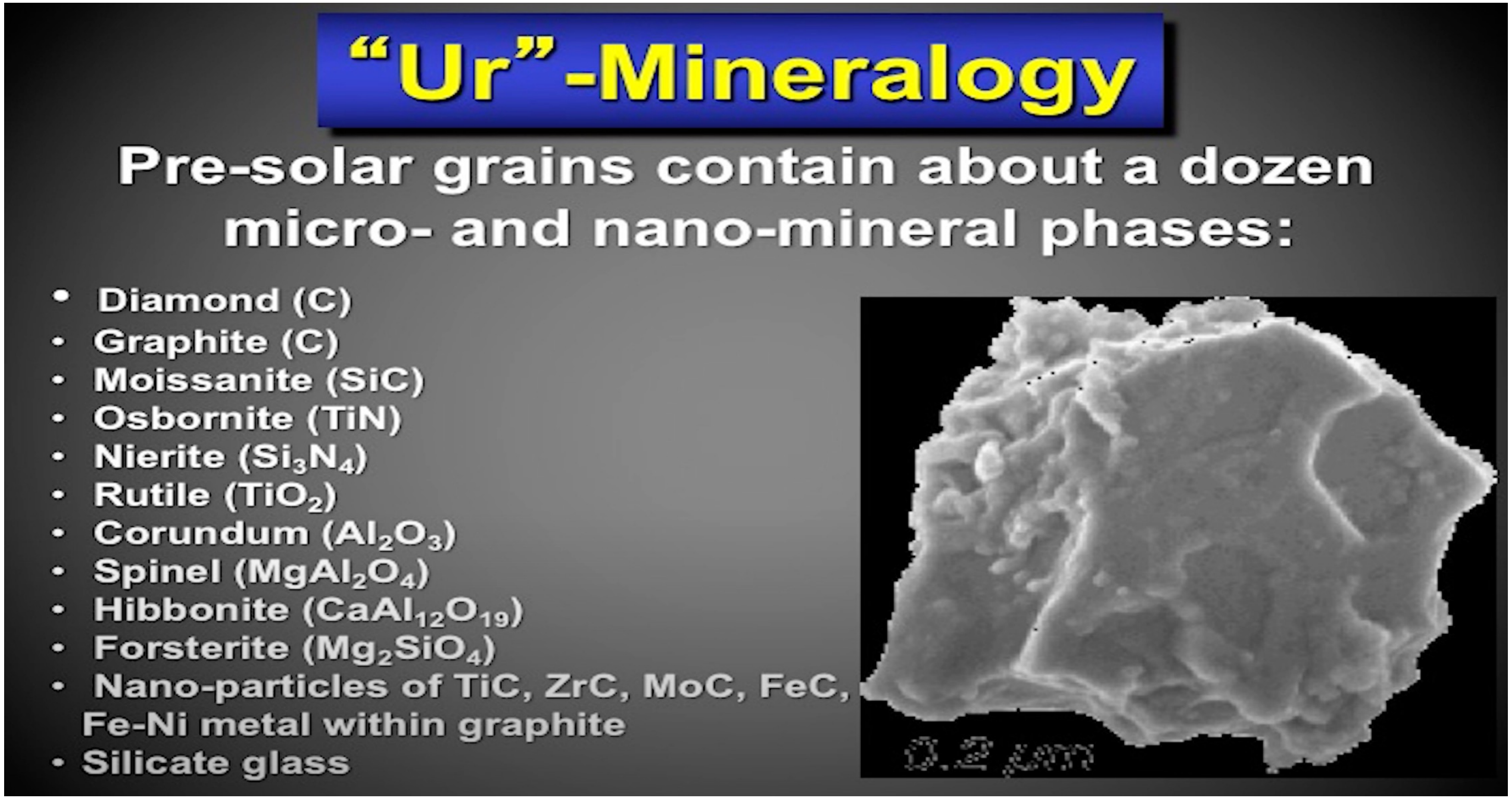
Element	Bulk solar system	Bulk Earth
H	2.431×10^7	6
He	2.343×10^6	-
O	14130	3494
C	7079	7
Ne	2148	-
N	1950	0.1
Mg	1020	1061
Si	1000	1000
Fe	838	1066
S	445	169
Ar	103	-
Al	84	97
Ca	63	71
Na	58	10
Ni	48	58
Cr	13	15
Mn	9.2	2.5
P	8.4	11.5
Cl	5.2	0.1
K	3.7	0.6
Ti	2.4	3.2
Co	2.3	2.6

(A)



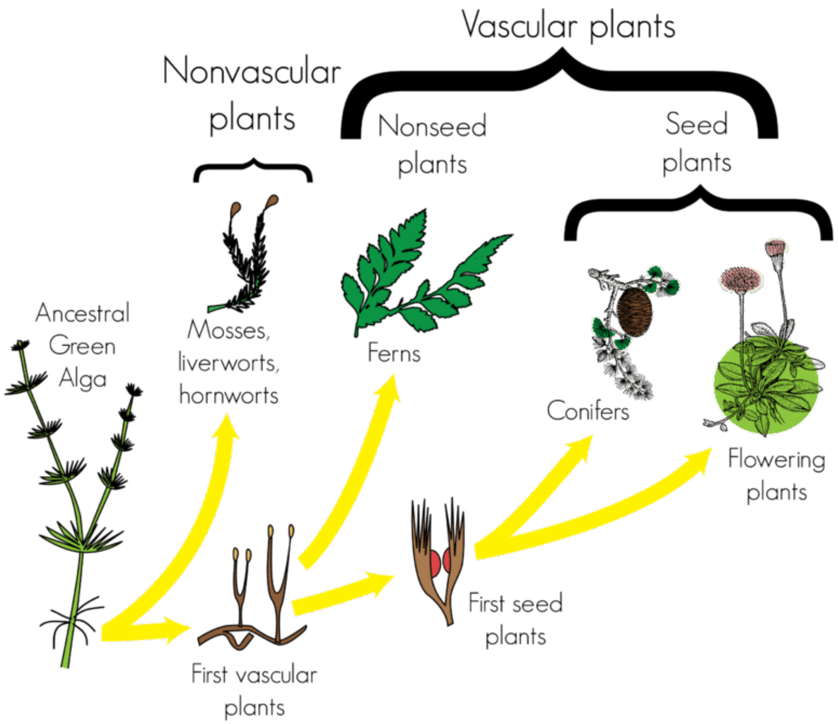
(B)

The very beginning…



Hazen 2019 (from you tube presentation)
https://www.youtube.com/watch?v=vvsRXWxOX-w

Minerals: Mineral classification and evolution



What about minerals?

Mineral evolution

Hazen 2019 (from you tube presentation)
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Mineral evolution

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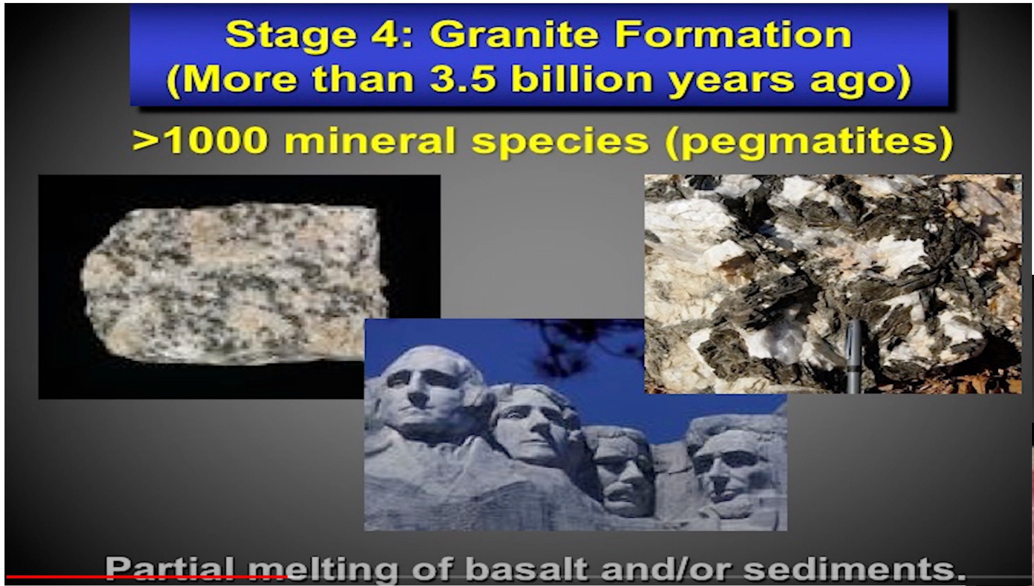
Mineral evolution



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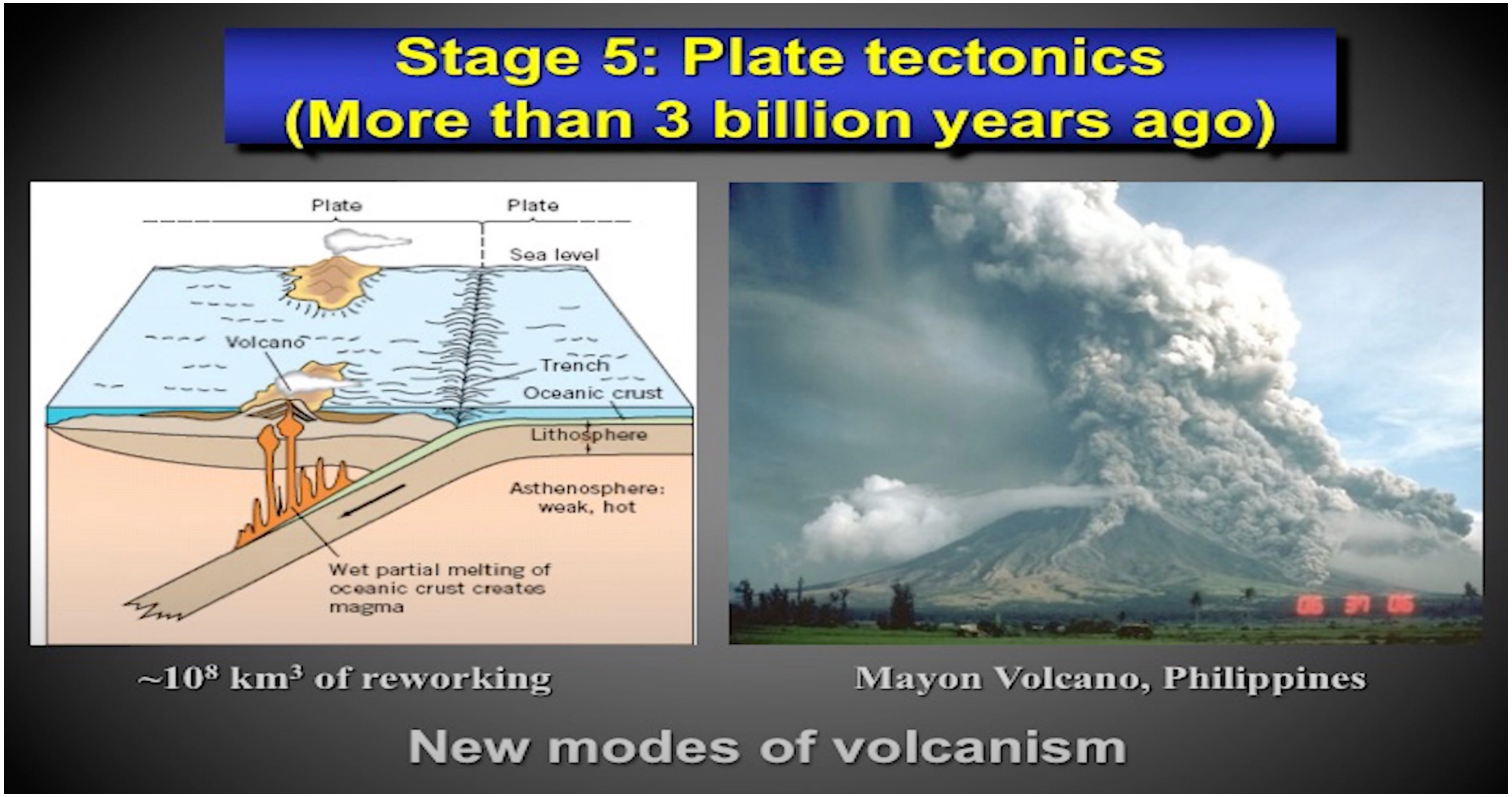
Mineral evolution



These processes get us up to 1500 minerals

Hazen 2019 (from you tube presentation)
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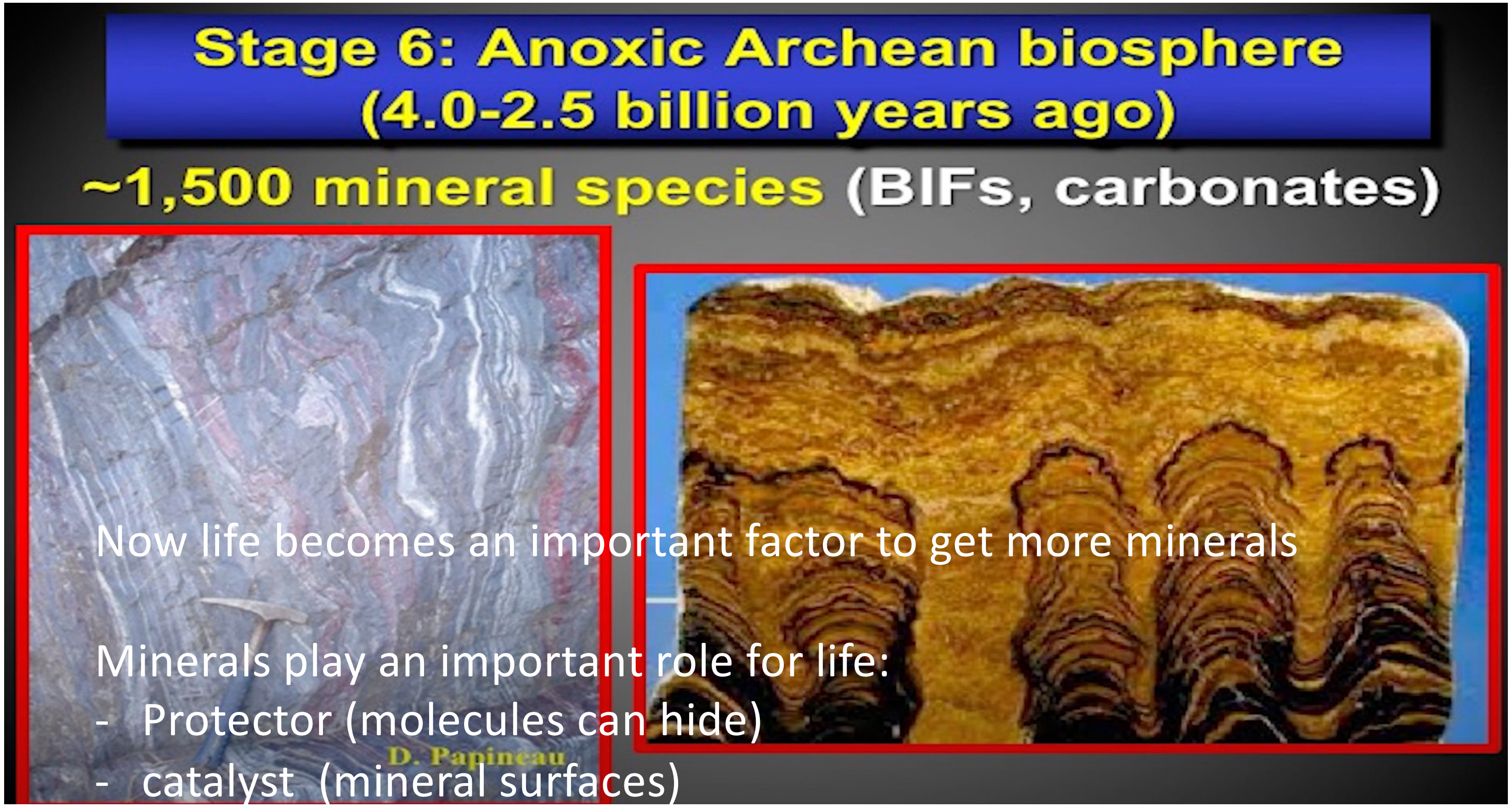
Mineral evolution



Now life becomes an important factor to get more minerals

Minerals play an important role for life:
- Protector (molecules can hide)
- catalyst (mineral surfaces)

Hazen 2019 (from you tube presentation)
https://www.youtube.com/watch?v=vvsRXWxOX-w

Mineral evolution

Photosynthesis/oxidation

Hazen 2019 (from you tube presentation)
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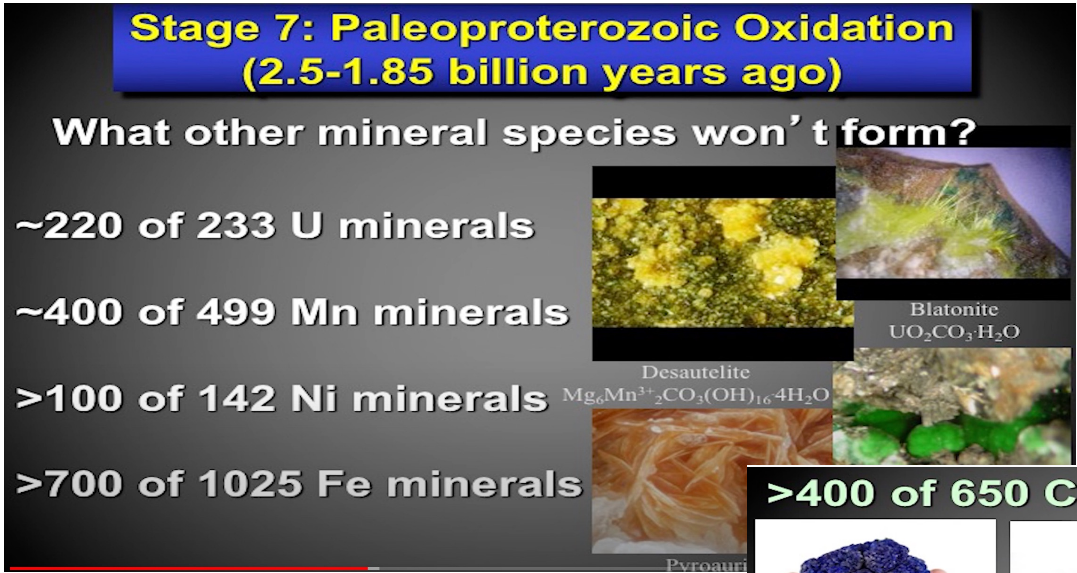
Mineral evolution



Only thanks to oxidation (life)

This is possibly the most important diversification moment (>4600 minerals)

Hazen 2019 (from you tube presentation)
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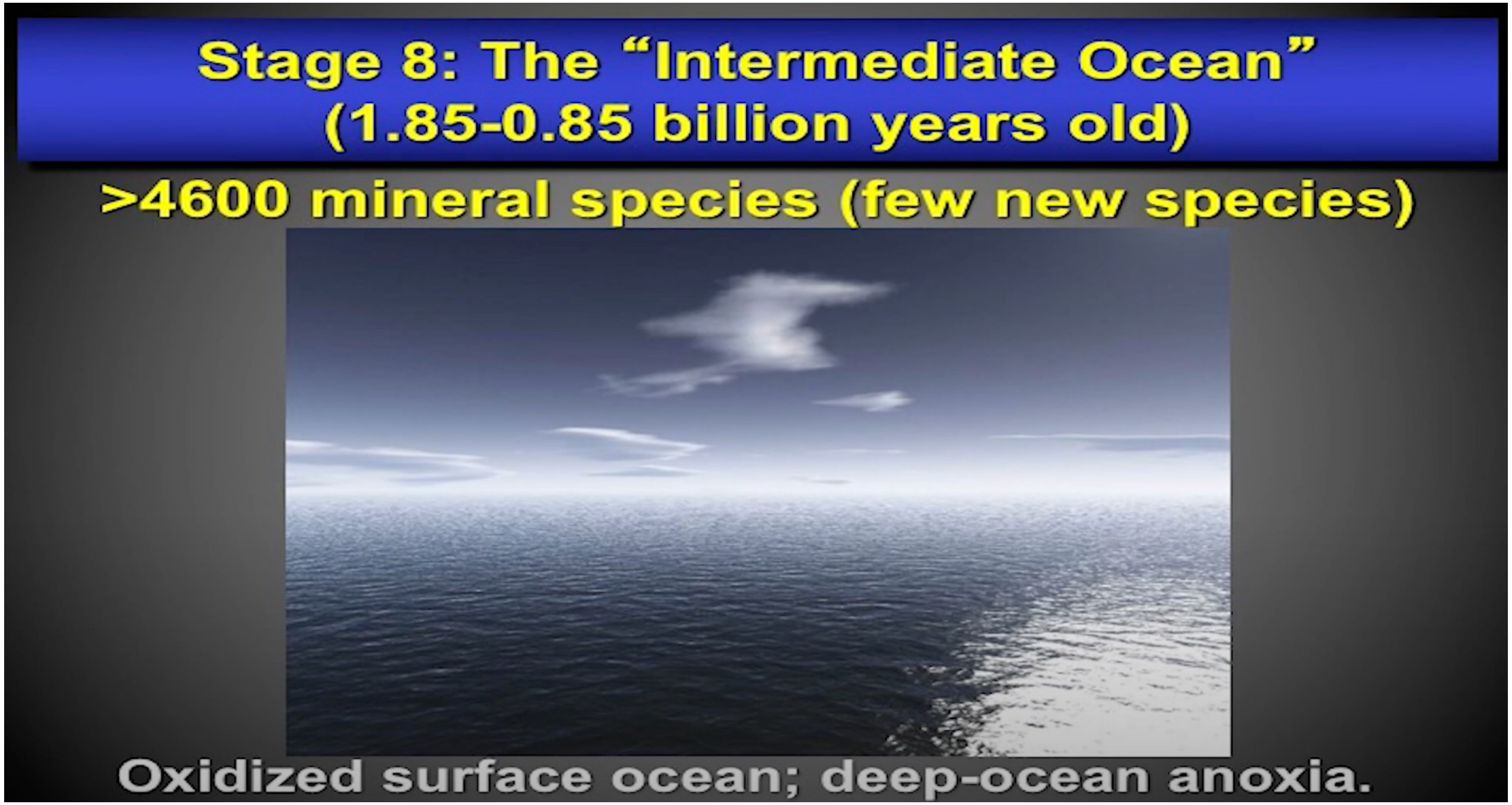
Mineral evolution



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Mineral evolution

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Mineral evolution

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Minerals: A new proposal for a classification; Mineral evolution

A concept developed by Robert Hazen and his group (check their publications/presentations https://hazen.carnegiescience.edu)

10 stages of mineral evolution

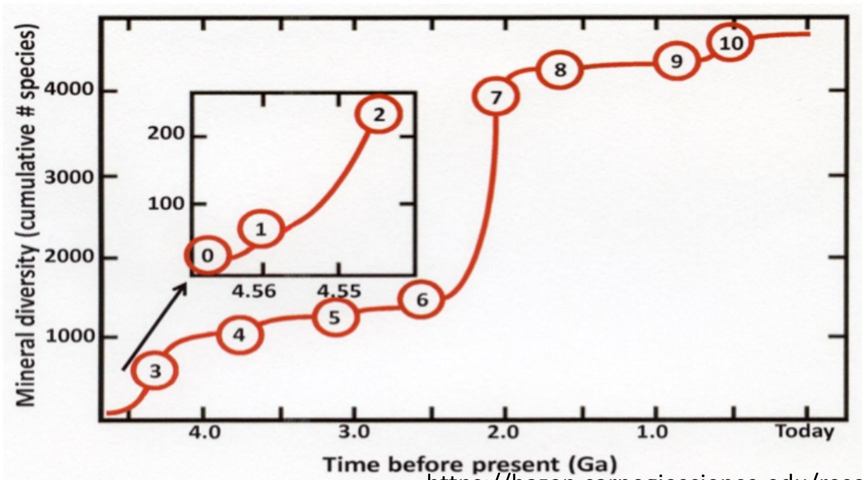
Table 1 THREE ERAS AND TEN STAGES OF EARTH'S MINERAL EVOLUTION

Era/Stage	Age (Ga)	Cumulative no. of species
Prenebular "Ur-Minerals"	>4.6	12
Era of Planetary Accretion (>4.55 Ga)		
1. Primary chondrite minerals	>4.56 Ga	60
2. Achondrite and planetesimal alteration	>4.56 to 4.55 Ga	250
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)		
3. Igneous rock evolution	4.55 to 4.0 Ga	350 to 500*
4. Granite and pegmatite formation	4.0 to 3.5 Ga	1000
5. Plate tectonics	>3.0 Ga	1500
Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)		
6. Anoxic biological world	3.9 to 2.5 Ga	1500
7. Great Oxidation Event	2.5 to 1.9 Ga	>4000
8. Intermediate ocean	1.9 to 1.0 Ga	>4000
9. Snowball Earth events	1.0 to 0.542 Ga	>4000
10. Phanerozoic era of biomineralization	0.542 Ga to present	4400+

* Depending on the volatile content of the planet or moon

Minerals: A new proposal for a classification; Mineral evolution

- A proposal to group minerals depending on their formation processes/environments (Hazen and Morrison, American Mineralogist, 2022)
- 10 stages of earth evolution, 57 environments and mineral formation processes



https://hazen.carnegiescience.edu/research/mineral-evolution

Minerals: Mineral classification

Strunz classification: based on chemistry and structure, including 10 classes. Introduced in 1941.

1. Native elements (minerals made of only one element)
2. **Sulfides**/sulfosalts
3. Halides
4. **Oxides**
5. **Carbonate**s/Nitrates
6. Borates
7. Sulfates
8. Phosphates
9. **Silicates**
10. (Organic compounds)

Why are the mineral groups in bold abundant on Earth?

What I always will remember: week 1

- Earth crust is dominated of feldspars, quartz and pyroxene
- Earth mantle is dominated by olivine (upper mantle) and bridgmanite (lower mantle), garnet
- The abundance of minerals depends on the element abundance
- Minerals are classified into 10 main classes based on their chemistry and structure

‘last minute paper’

- Write down what was difficult to understand
- Write down what was easy to understand

Week 2

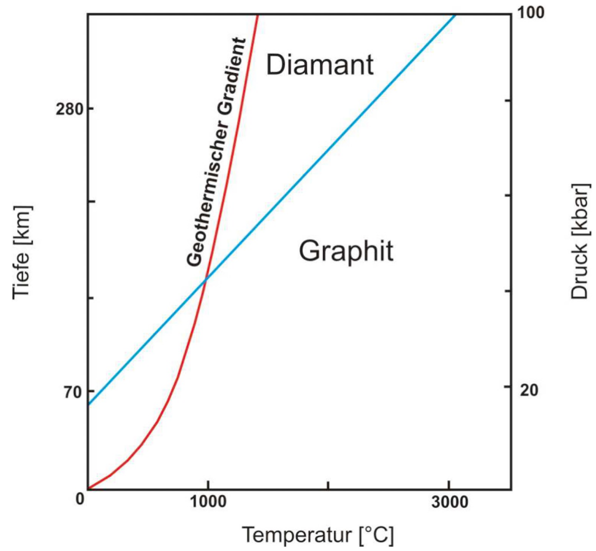
- Mineral properties

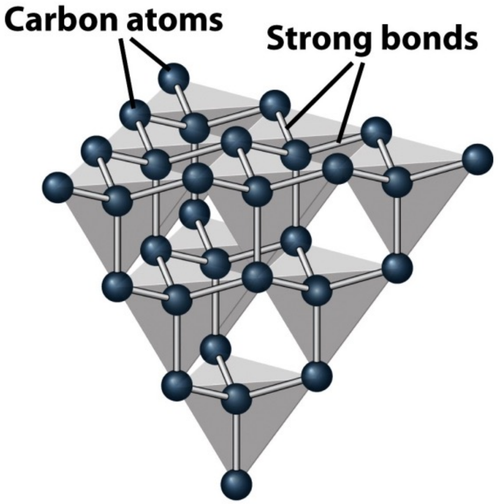
What was difficult to understand?

Mineral of the day

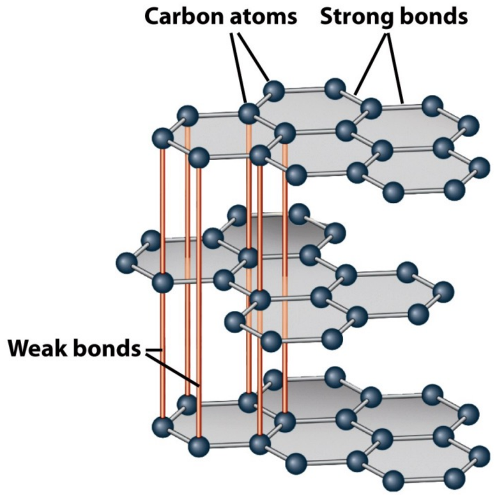
Mineral properties

- Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.





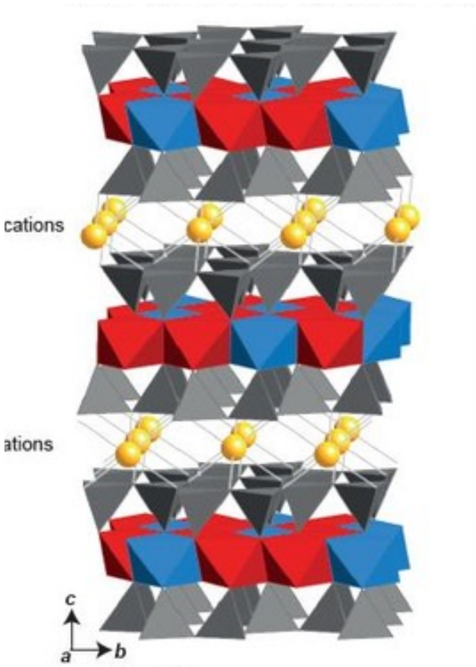
Diamond: hardest known mineral



Graphite: one of the softest minerals

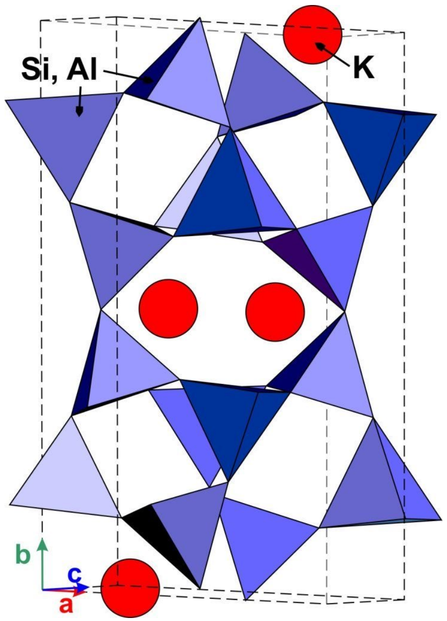
Mineral properties

- Many properties such as hardness, cleavage, conductivity, and density are directly related to the crystal structure.



biotite

One perfect cleavage
Flexible
Soft



feldspar

2 good cleavages
Brittle
Hard

Mineral properties

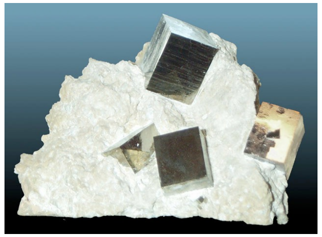
Properties of minerals to be used for their identification

- Hardness
- Cleavage/fractures
- Lustre
- Colour
- Streak
- Density
- Magnetism, reaction with HCl, birefringence

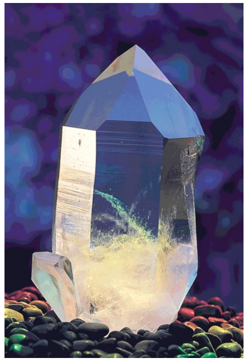
Mineral properties: Lustre

Lustre is the way the mineral reflects light

- **Metallic** (often ore minerals)



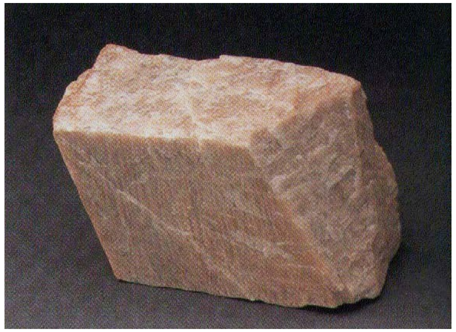
- **Non-metallic**



diamond **glassy** **pearl** **earthy**

Mineral properties: Colour

Colour is one of the most obvious feature, but not very characteristic for many minerals. Colour is not necessarily a good property for mineral identification. Low concentrations of trace elements in the crystal structure and crystal defects are responsible for different colors.



Alkali-feldspar

Quartz

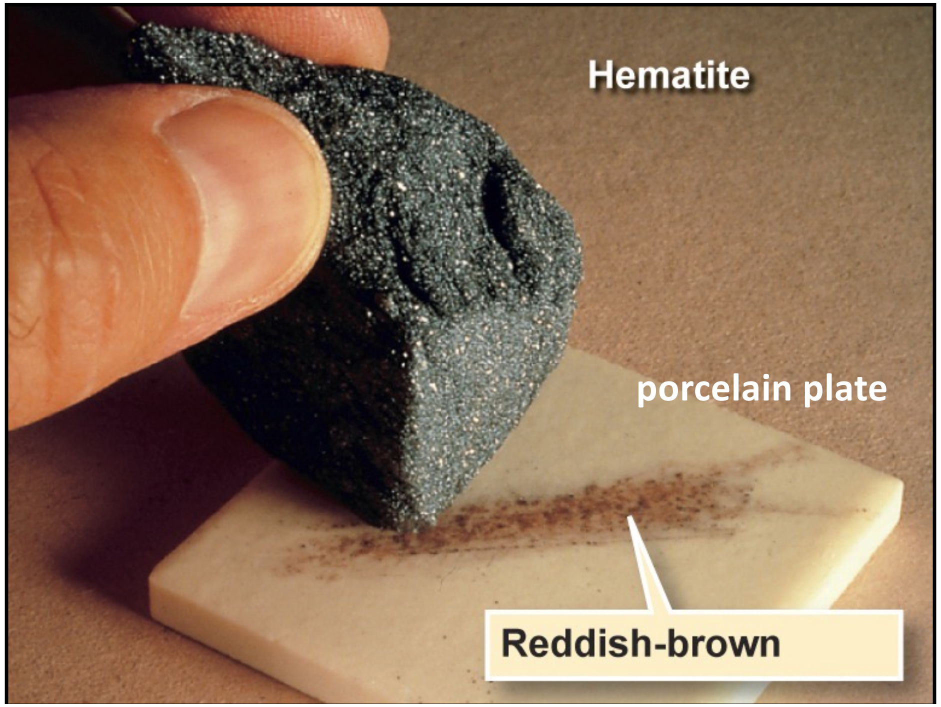
Corundum

Mineral properties: Streak

- The powder of a mineral has a characteristic colour. Therefore, the colour of the streak is a characteristic mineral property.

Gold vs. pyrite

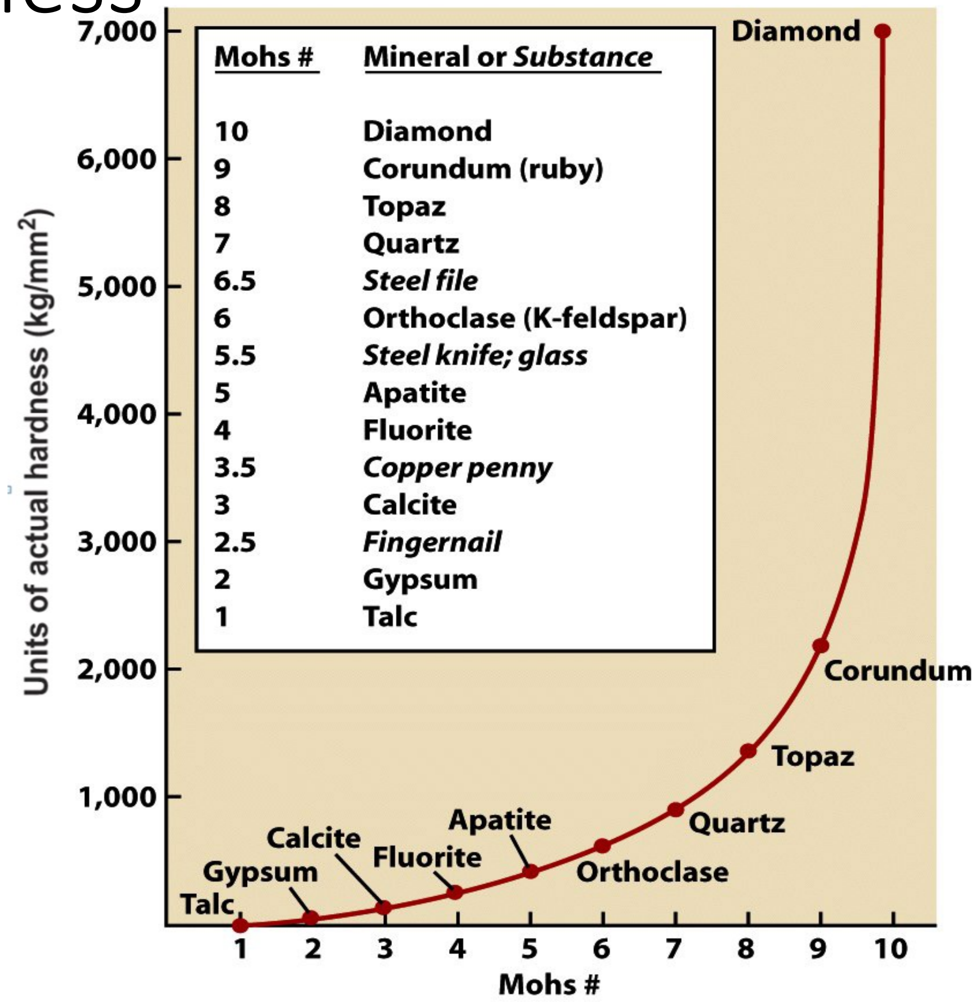
	Gold	Pyrite
colour	yellow	yellow
streak	yellow	black
density	19.3g/cm3	5g/cm3
hardness	3	6



Mineral properties: Hardness

- A simple test with a set of specific minerals (Moh's hardness scale).

- Finger nail, H: 2.5
- Copper coin, H: 3.5
- Glass plate, H: 5.5
- Pocket knife, H: 5.5



Mineral properties: Density

A rough distinction can be made between rock-forming minerals and ore minerals. Depends on crystal structure and chemical composition.

Example: Galena (PbS): feels distinctly heavy (7.6g/cm^3)

- Rock-forming minerals: 2.2-4.5 g/cm^3
- Ore minerals: >5 g/cm^3

Mineral properties: Cleavage/fracture

This is the way a mineral breaks. Commonly along one or several planar planes.

Biotite: one perfect cleavage

Feldspar: good cleavage

Calcite: 3 good cleavages

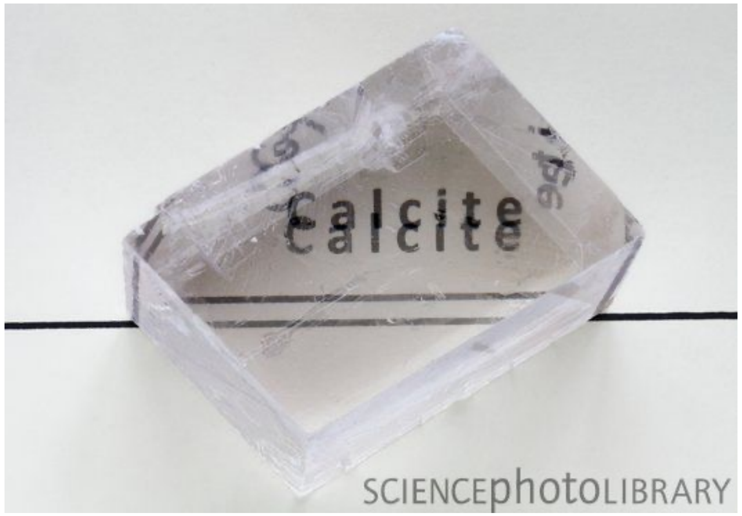
If there is no cleavage then it is called fracture.

Quartz has no cleavage, but conical fractures

Mineral properties: specific properties

- **Magnetite:** magnetic, Pyrrhotite: moderately magnetic

- **Calcite:** reaction with HCl ($CaCO_3$ +2HCl = $CaCl_2$ + CO_2 + H_2O), high birefringence



What I always will remember: week 1

- Mineral properties depend on the crystal structure and chemistry
- The main properties to be used for mineral identification (macroscopically)

Possible flash cards

- Birefringence

Week 1b

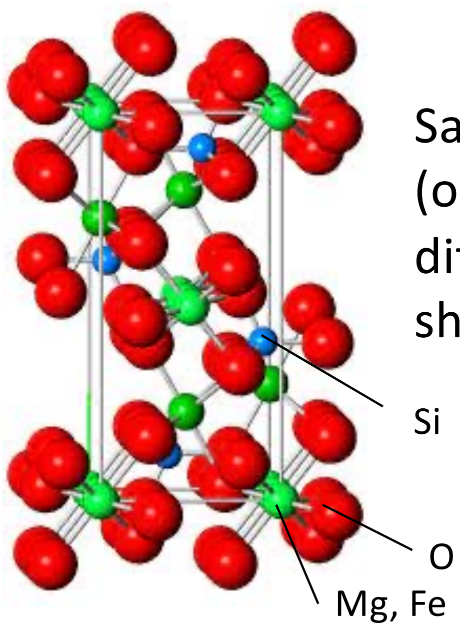
- Crystal structures

Mineral of the day

Crystal structures: the arrangement of atoms in a crystal

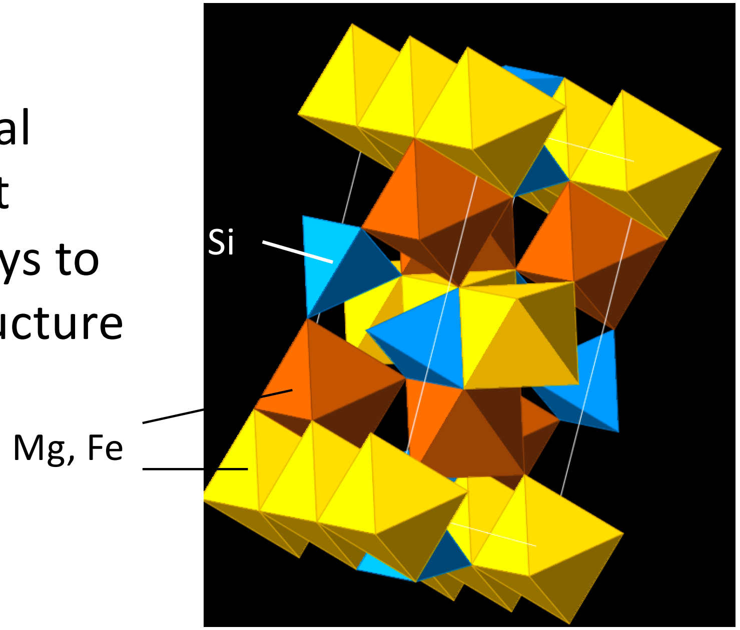
- Crystal structures can be shown in different ways. Basically, it shows how the atoms are arranged in the crystal.

Example: Olivine



Ball+stick model

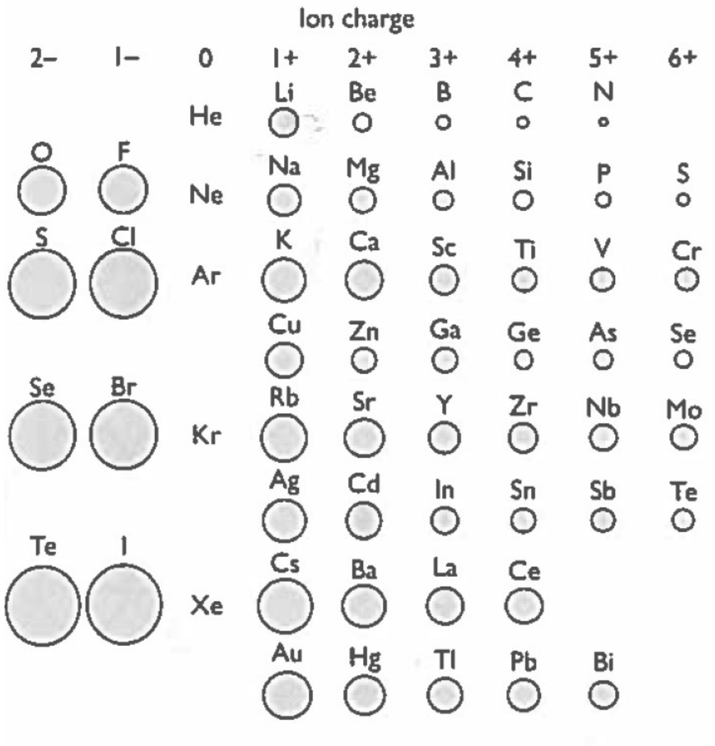
Same mineral (olivine), but different ways to show its structure

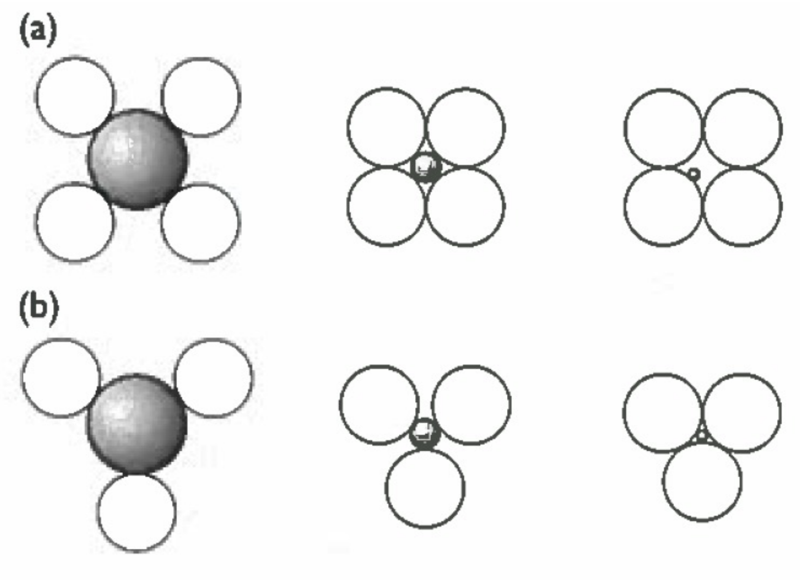


Polyhedra

Crystal structures: the arrangement of atoms in a crystal

- Not all possible combination of ions are possible due to size and charge differences.





Crystal structures: Most common polyhedra

There are certain combination possible that result in a specific coordination number (CN). It indicates how many direct neighbours a central ion will have.

The coordination numbers relate to a range of radius ratios.

Radius ratio = Cation radius/Anion radius

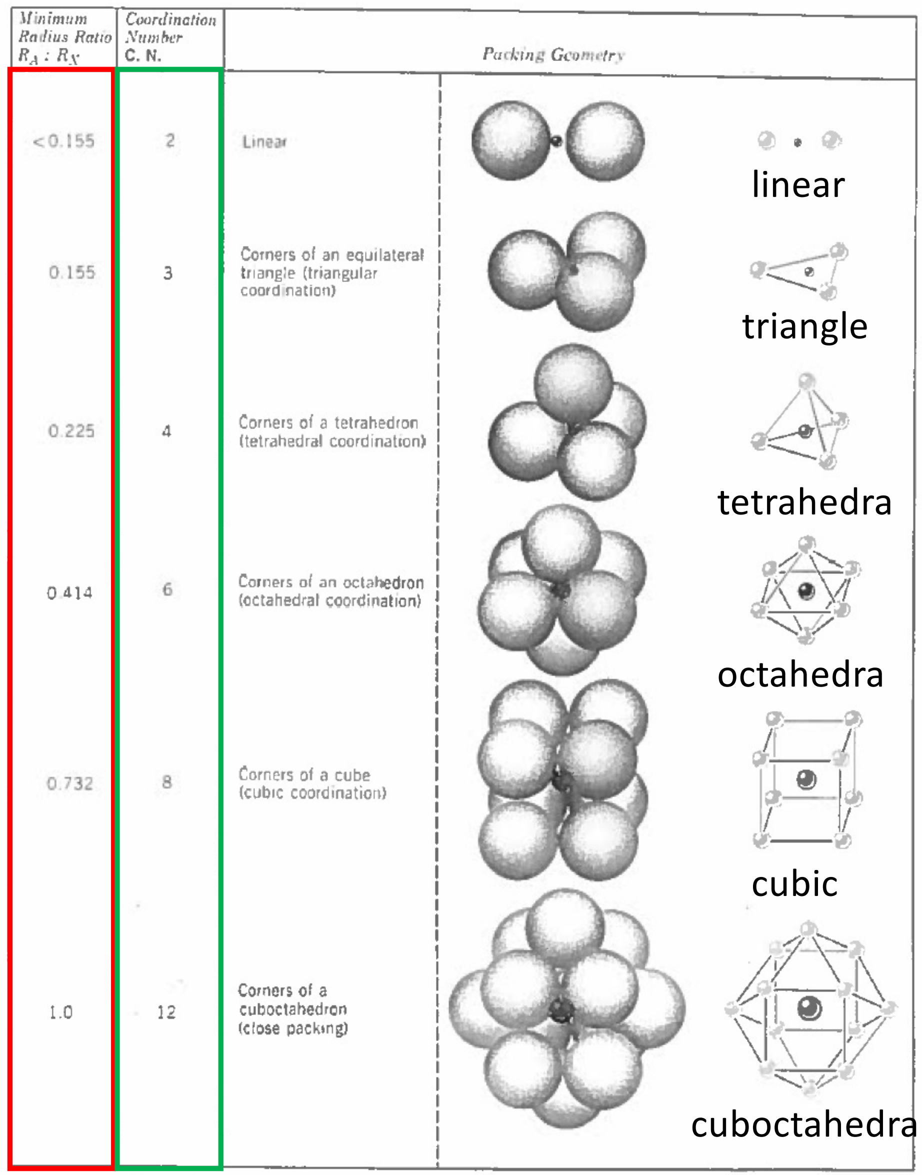
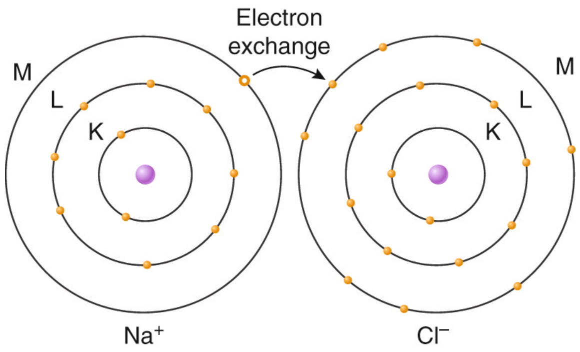
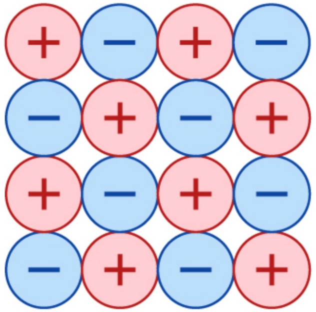


FIG. 3.36 Atomic packing schemes.

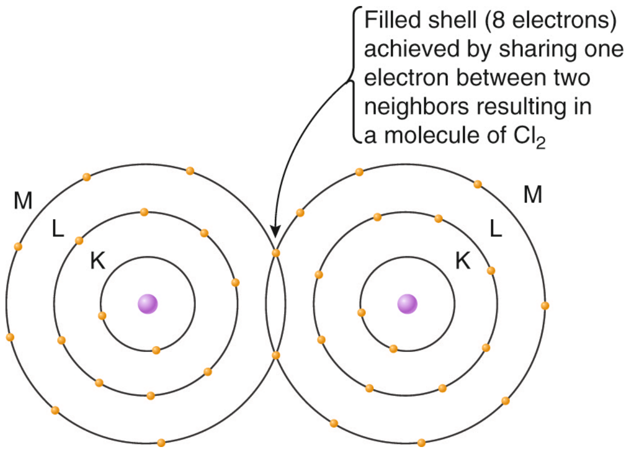
Crystal structures: bonding

Ionic

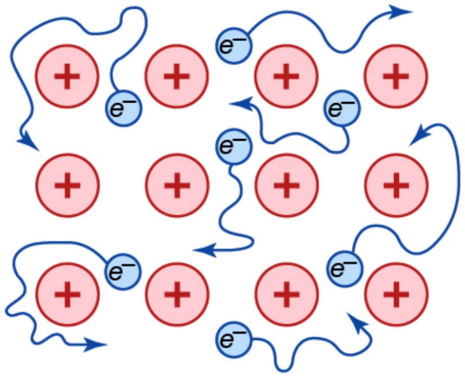


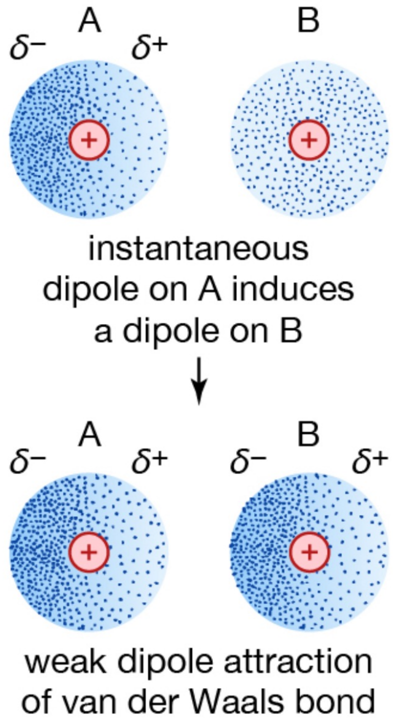


Covalent



Metallic





Van der Waals

Crystal structures: activity

Bonding and physical properties of minerals

- Why are metals good conductors (electric, thermal)?

What I always will remember: week 2

- Depending on size and charge of the ions the crystal structure consists of certain ion combinations (polyhedral) such as triangle, tetrahedra, octahedra, cubic, cuboctahedra
- The radius ratio between cation and anion determines the ideal polyhedral for specific ions.
- Ions will bond different in crystal structures (ionic, covalent, metallic, van der Waals)

Week 2

- Crystallography: Symmetry and crystal structure systems

Crystallography: Symmetry

- The crystal structure is the repetition of the geometrical arrangement of the atoms in the crystal structure, which is reflected in the form of the crystal.
- There 3 symmetry elements that are used to determine the crystal structure system

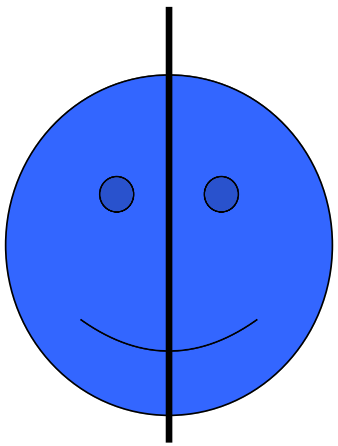
- Planes

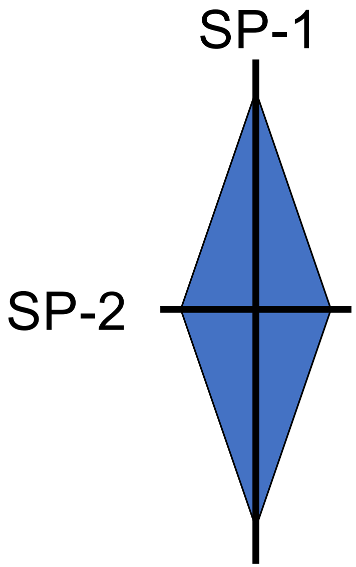
- Rotation axes

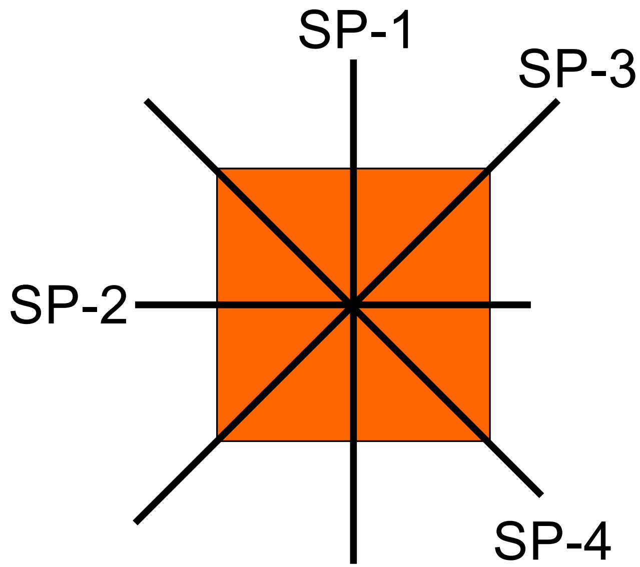
- Symmetry centre

Crystallography: Symmetry planes

One symmetry plane (SP)

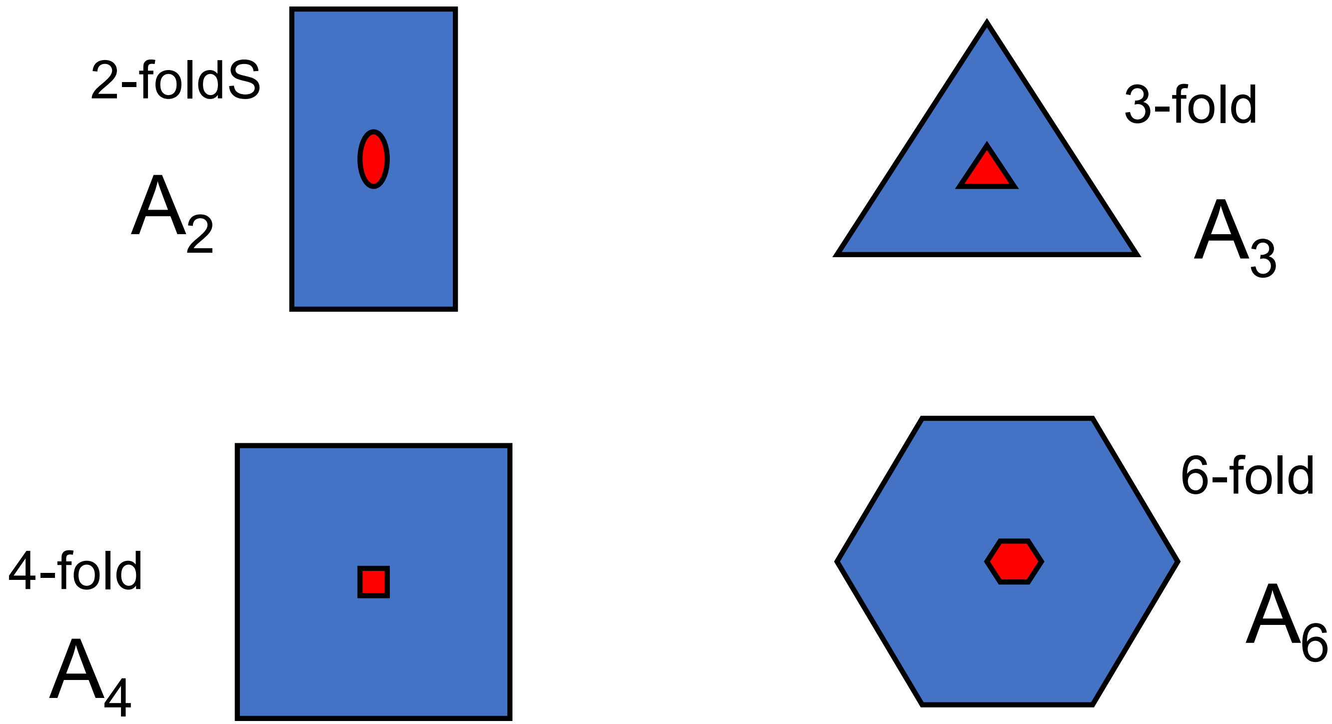






Crystallography: Rotation axes

The most common rotation axes are 2, 3, 4, and 6-fold



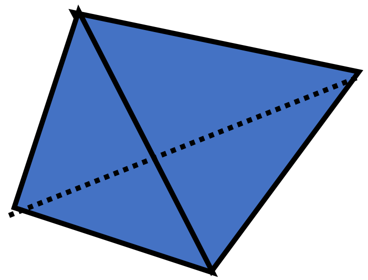
Crystallography: Symmetry centre (C)

Crystal planes or edges occur in pairs at opposite sides of a central point in the crystal

Symmetry centre

C

A tetraheder has no symmetry centre



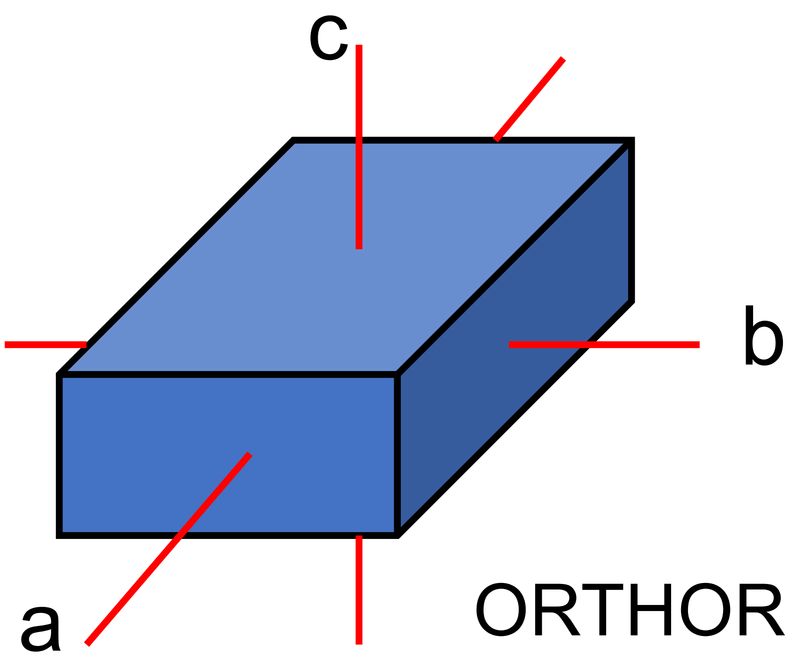
Crystallography: the 7 crystal systems

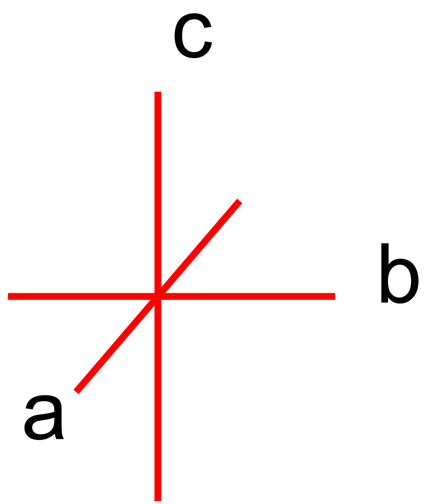
CRYSTAL SYSTEM	**MINIMUM SYMMETRY**
CUBIC	4 A_3
TETRAGONAL	1 A_4
HEXAGONAL	1 A_6
TRIGONAL	1 A_3
ORTHORHOMBIC	3 A_2
MONOCLINIC	1 A_2
TRICLINIC	no symmetry

Coordinatesystem with ”0” point in the c entre of the crystal

Axes are called a, b and c

ORTHORHOMBIC ($3A_2$)

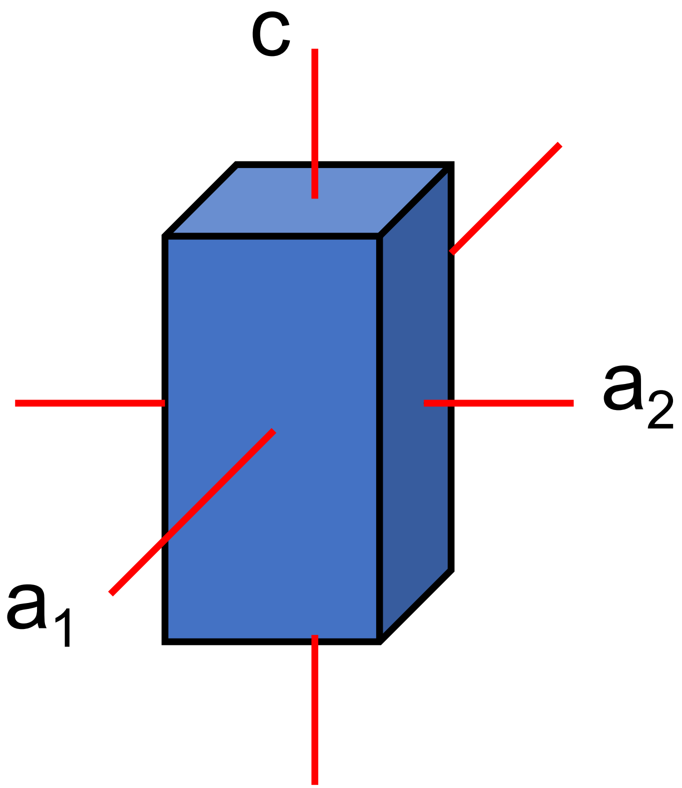


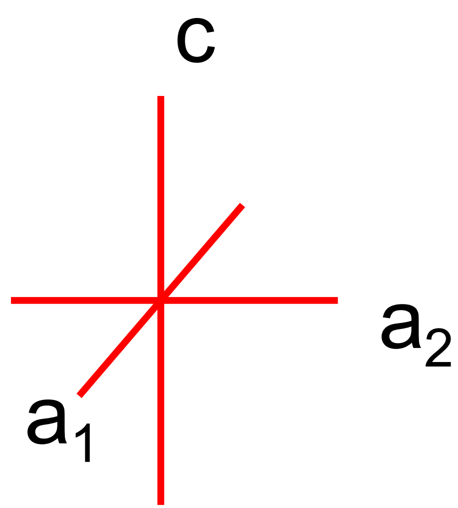


ALL ANGLES = 90°

ORTHORHOMBIC a = ~~b~~ = ~~c~~

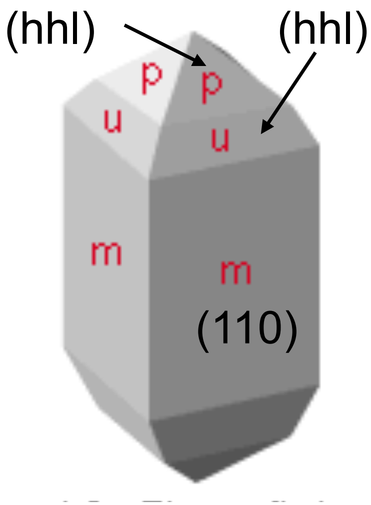
TETRAGONAL (1 A_4)





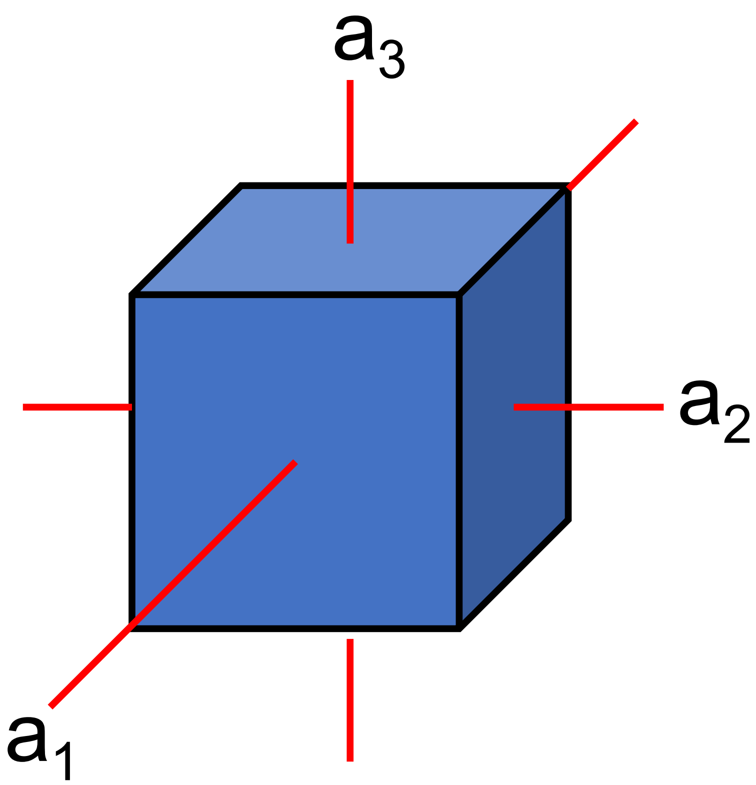
All angles = 90°

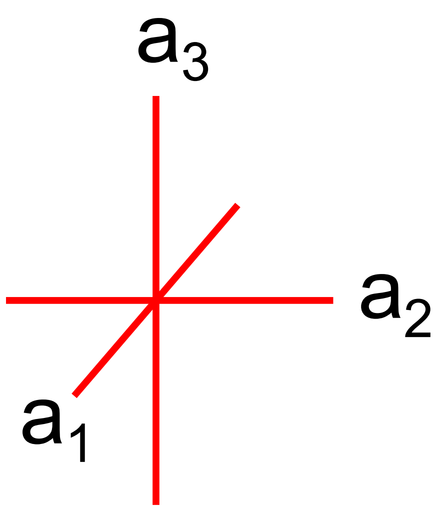
TETRAGONAL $a_1 = a_2 \neq c$



Zircon

CUBIC ($4A_3$)



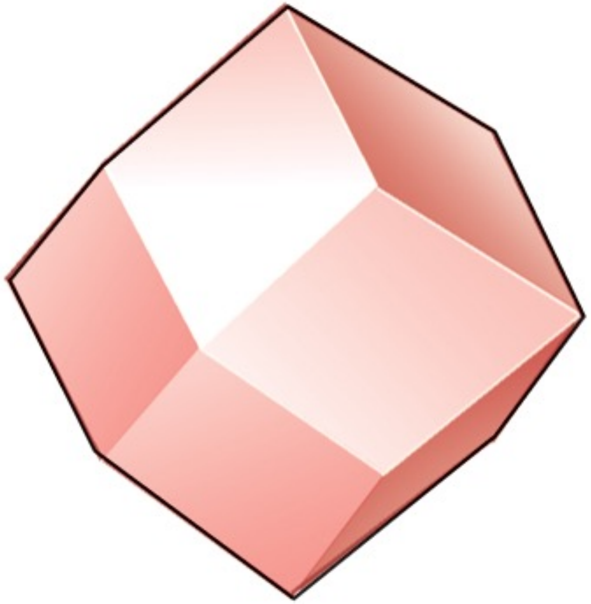


ALLE VINKLER = 90°

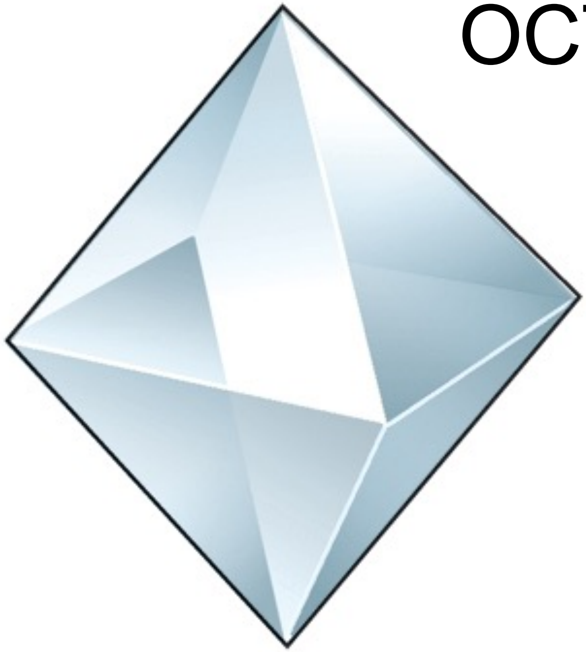
CUBIC $a_1 = a_2 = a_3$

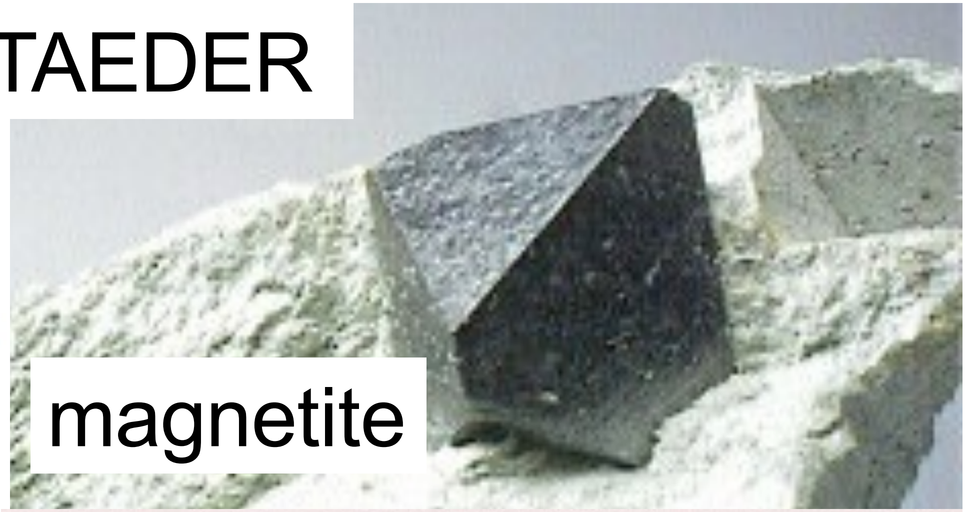
Halite and pyrite are two examples with cubic crystal systems

Rhombedodecaeder $\{110\}_{12}$
is also the cubic crystal system
GARNET

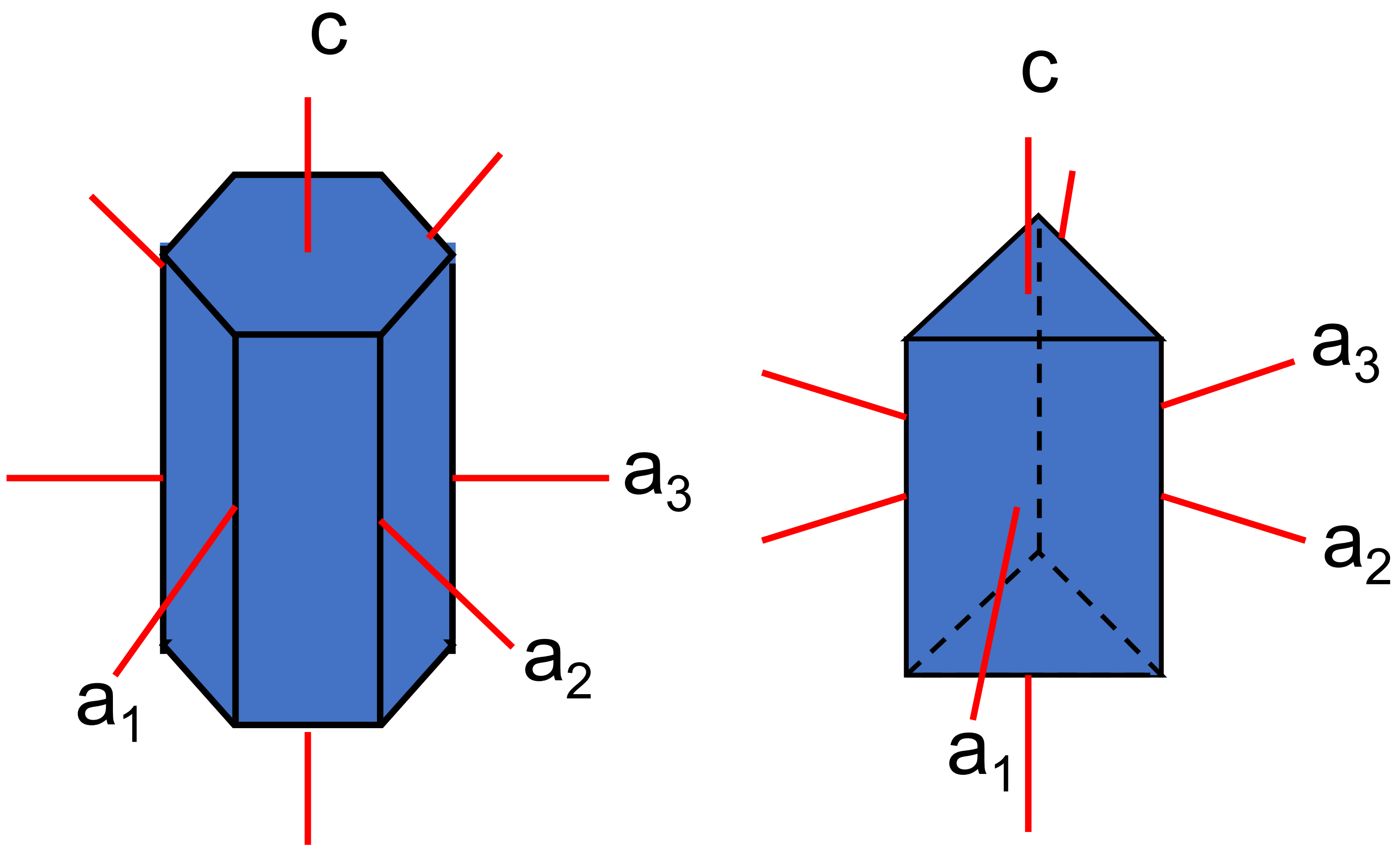


OCTAEDER

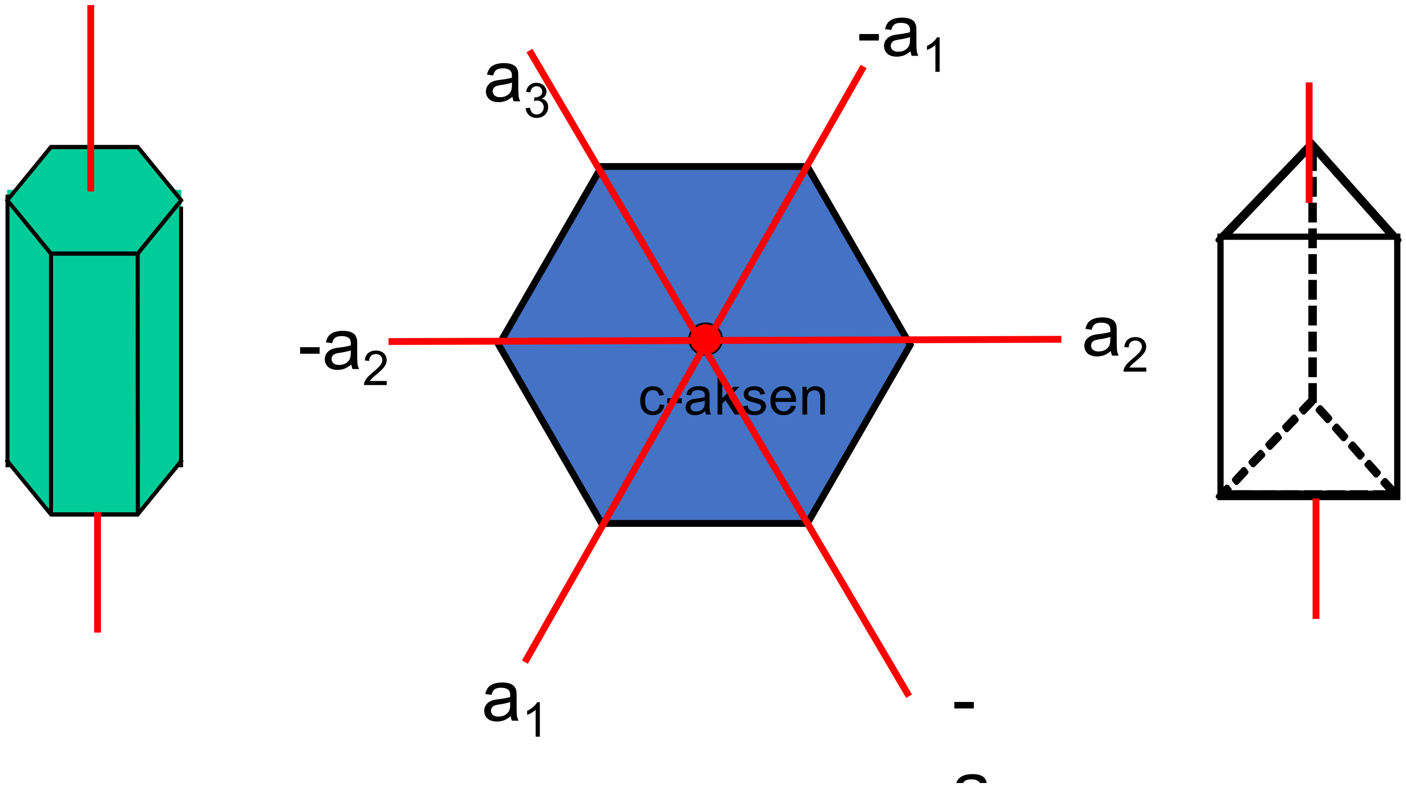




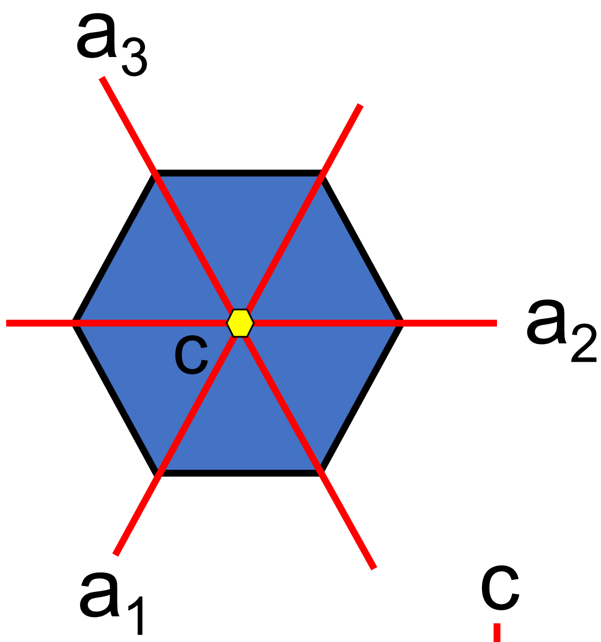
HEXAGONAL ($1A_6$) and TRIGONAL ($1A_3$)



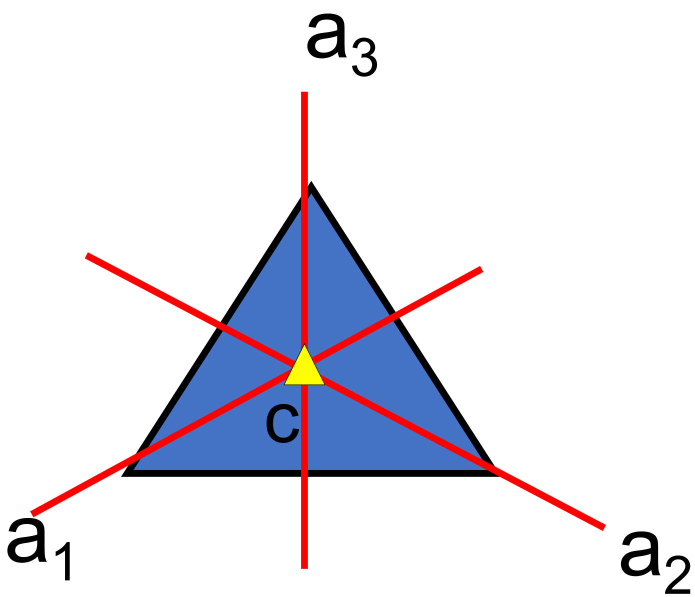
In the **HEXAGONALE** and the **TRIGONAL** system 4 axes are used

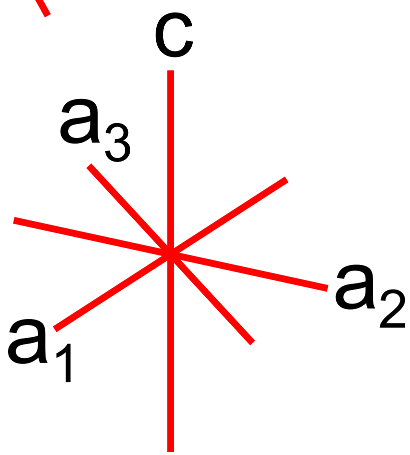


HEXAGONAL



TRIGONAL

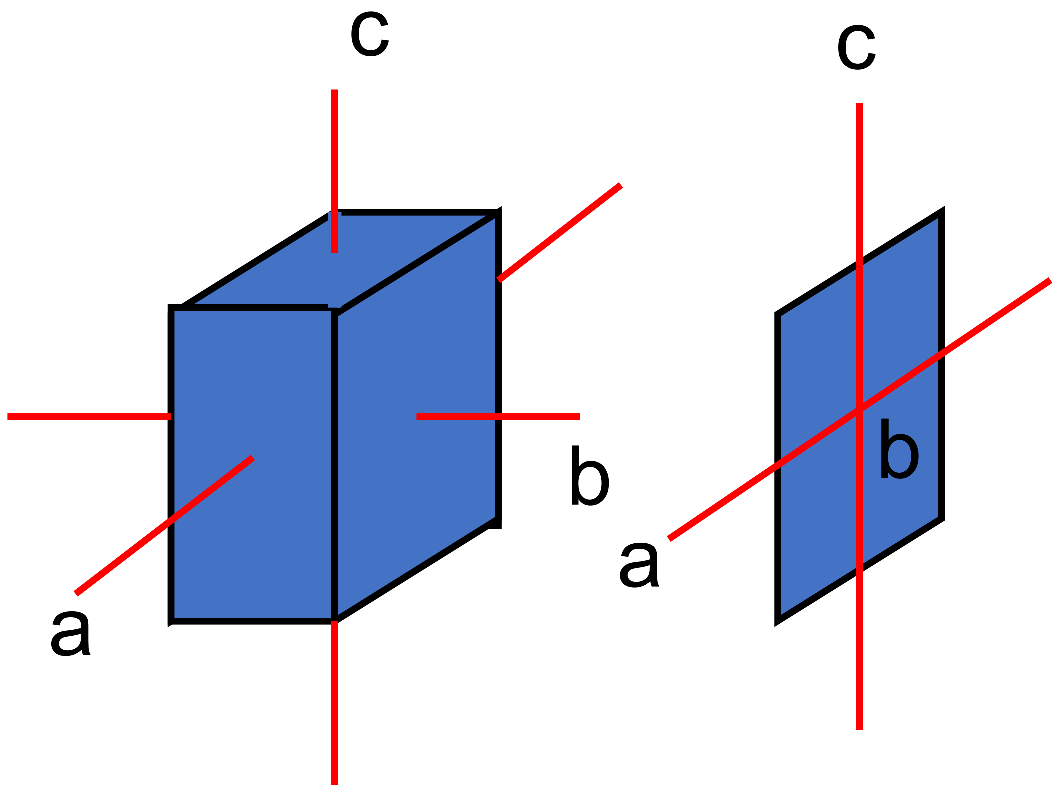




$$a_1 = a_2 = a_3 \neq c$$

$$a_1 \wedge a_2 \wedge a_3 = 120^\circ$$

MONOCLINIC ($1A_2$)

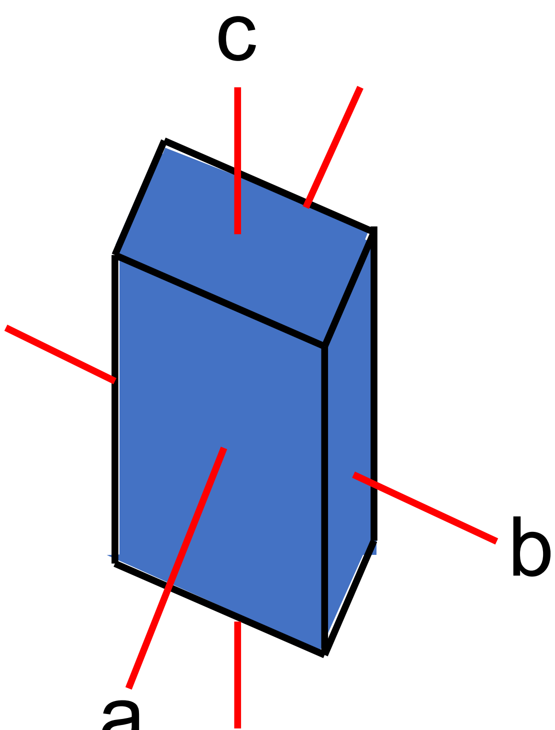


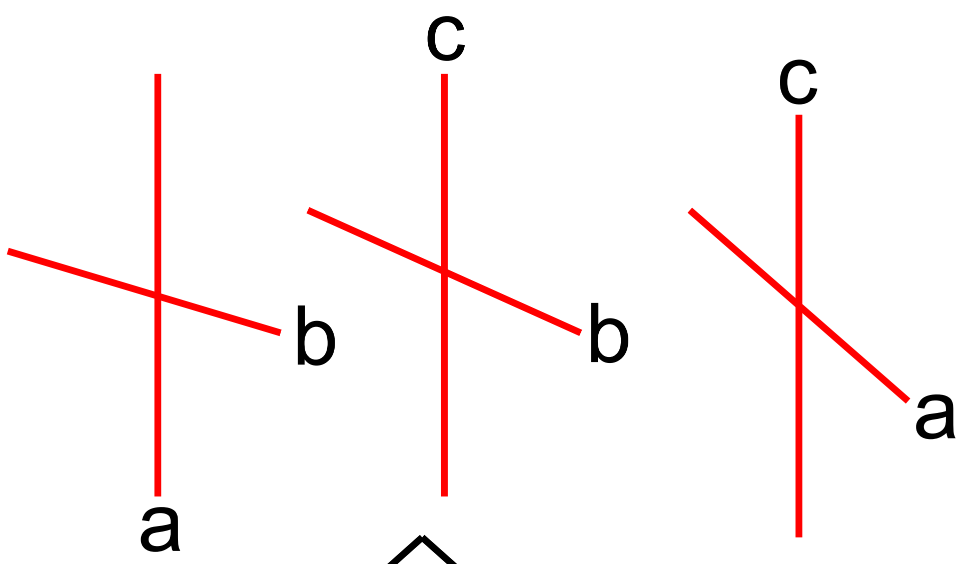
$\widehat{a \quad b} = 90^\circ$

$\widehat{b \quad c} = 90^\circ$

$\widehat{a \quad c} \neq 90^\circ$

TRICLINIC (no symmetry)



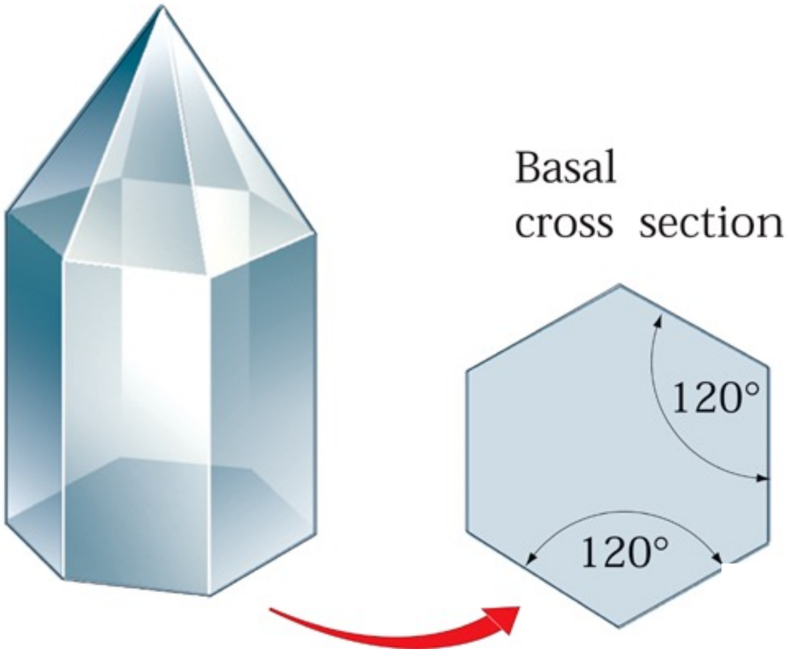


$a \wedge b \neq 90^\circ$

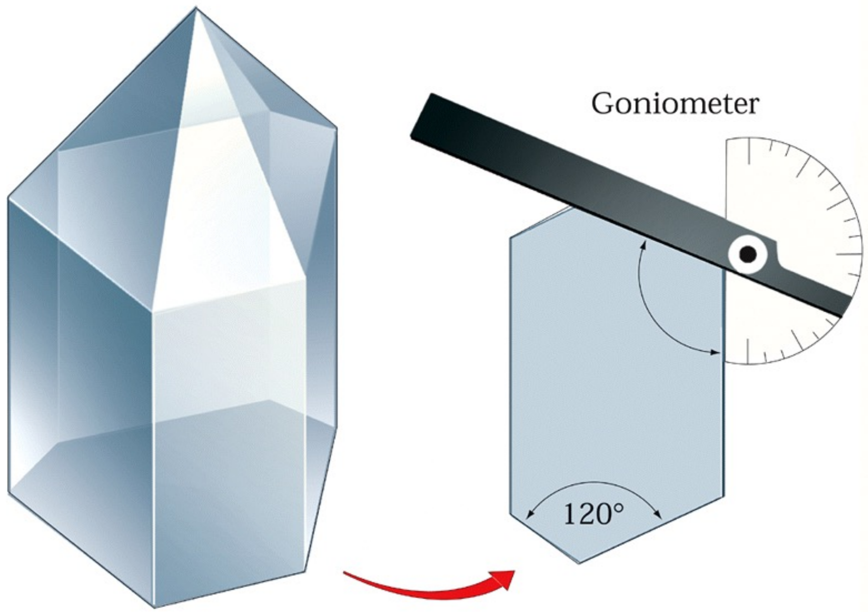
$b \wedge c \neq 90^\circ$

$a \wedge c \neq 90^\circ$

Important rule



Angles between crystal planes are diagnostic

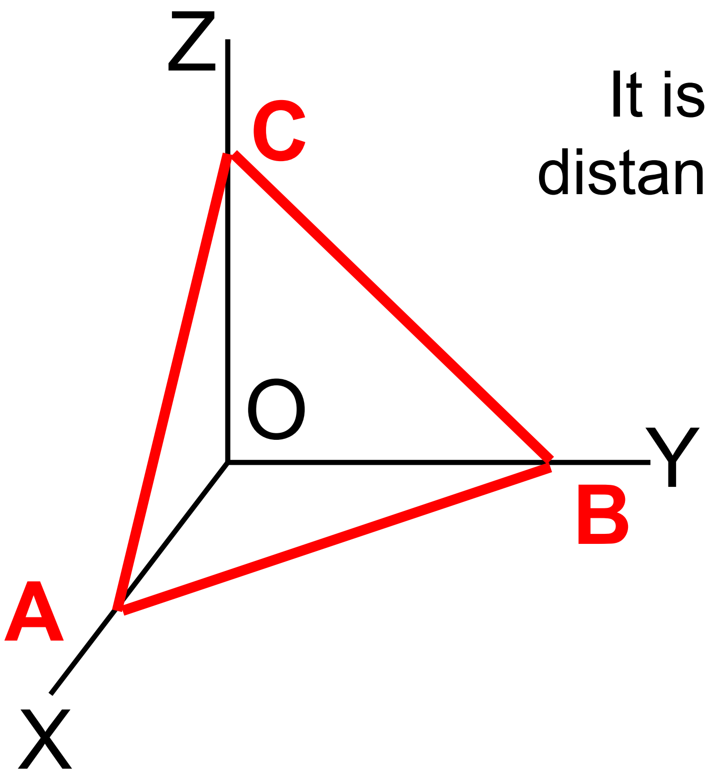


Natural crystals have often irrgular sized planes, but the angles are the same as in ideal crystal shapes (Nicolas Steno, 1669)

Crystallography: Activity

Determine all the symmetry elements in the given figures

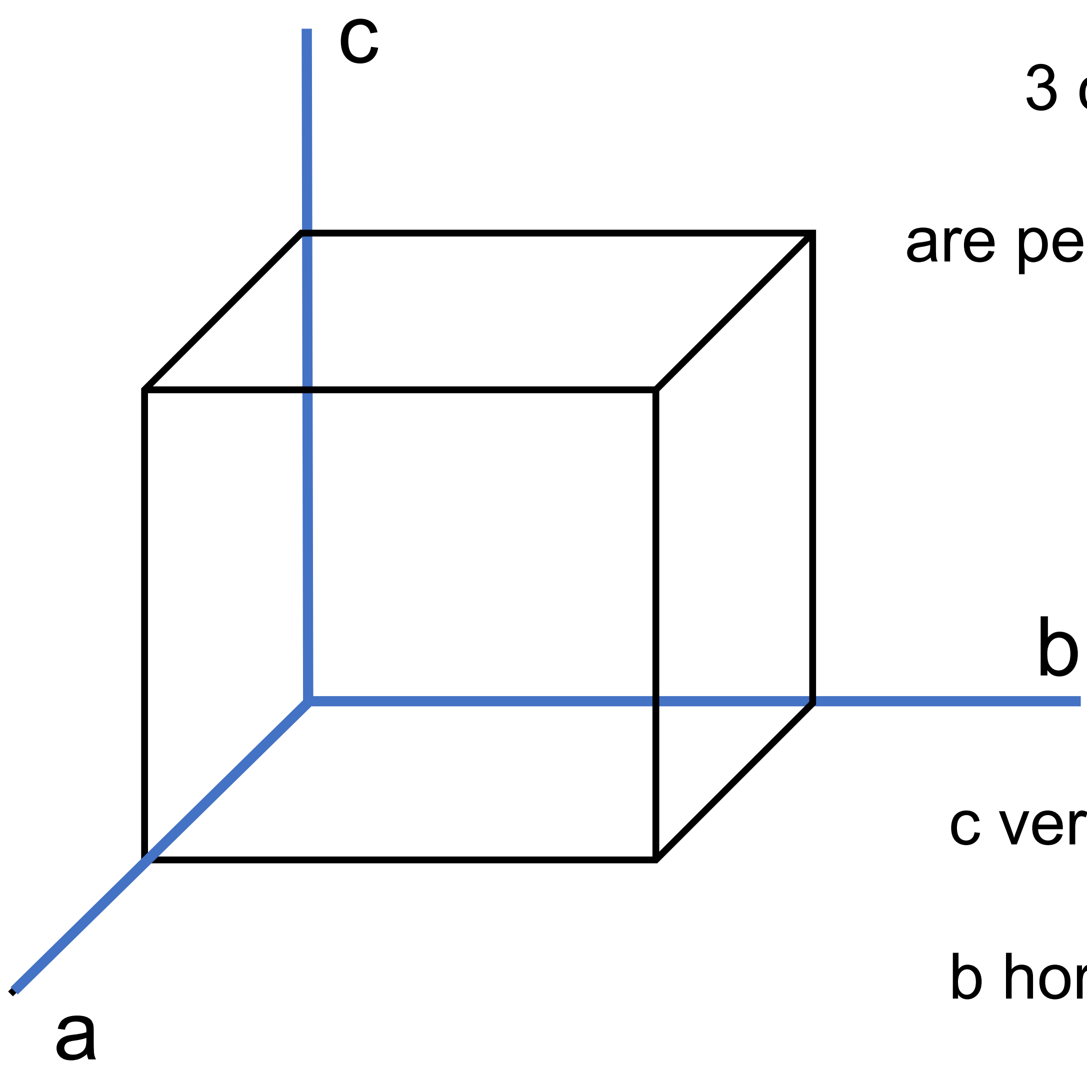
Crystallography: Naming of crystal planes



A system to name (to index) crystal planes, proposed by W.F. Miller in 1836

Miller Index

It is based on the reciprocal value of the distance from the coordination system centre

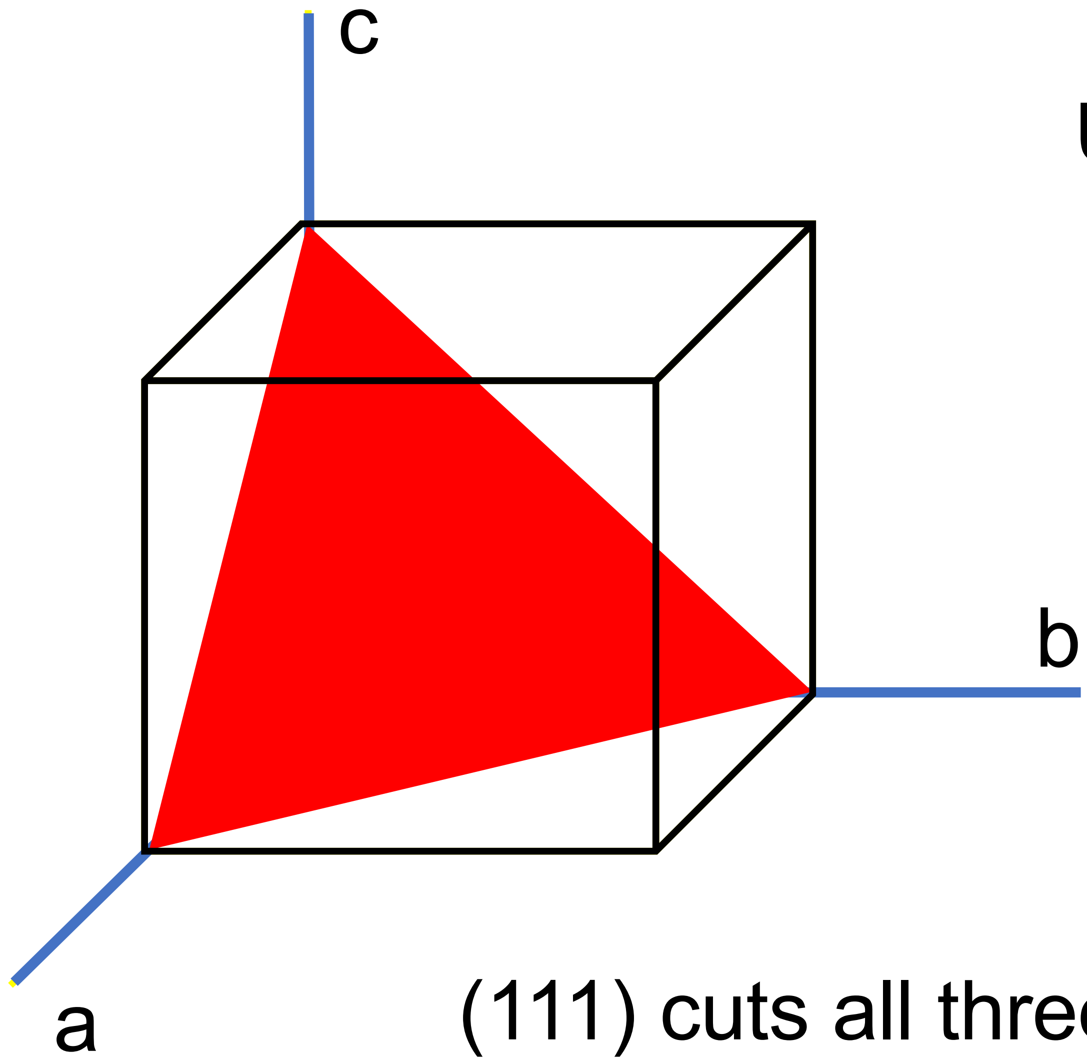


3 crystallographic axes
a, b, c
are perpendicular to each other

c vertical

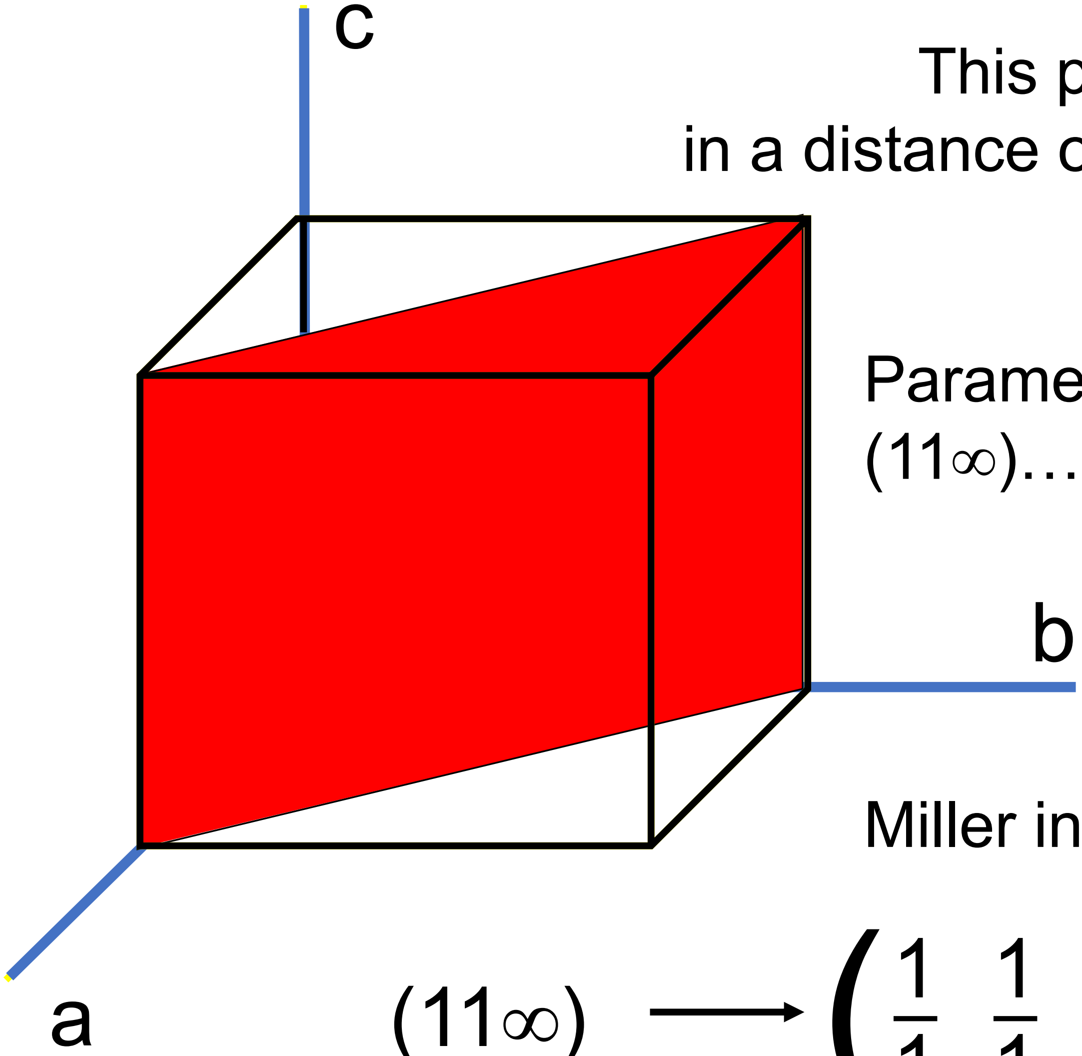
b horizontal

a perpendicular to the plane



Unit plane
(111)

(111) cuts all three axes

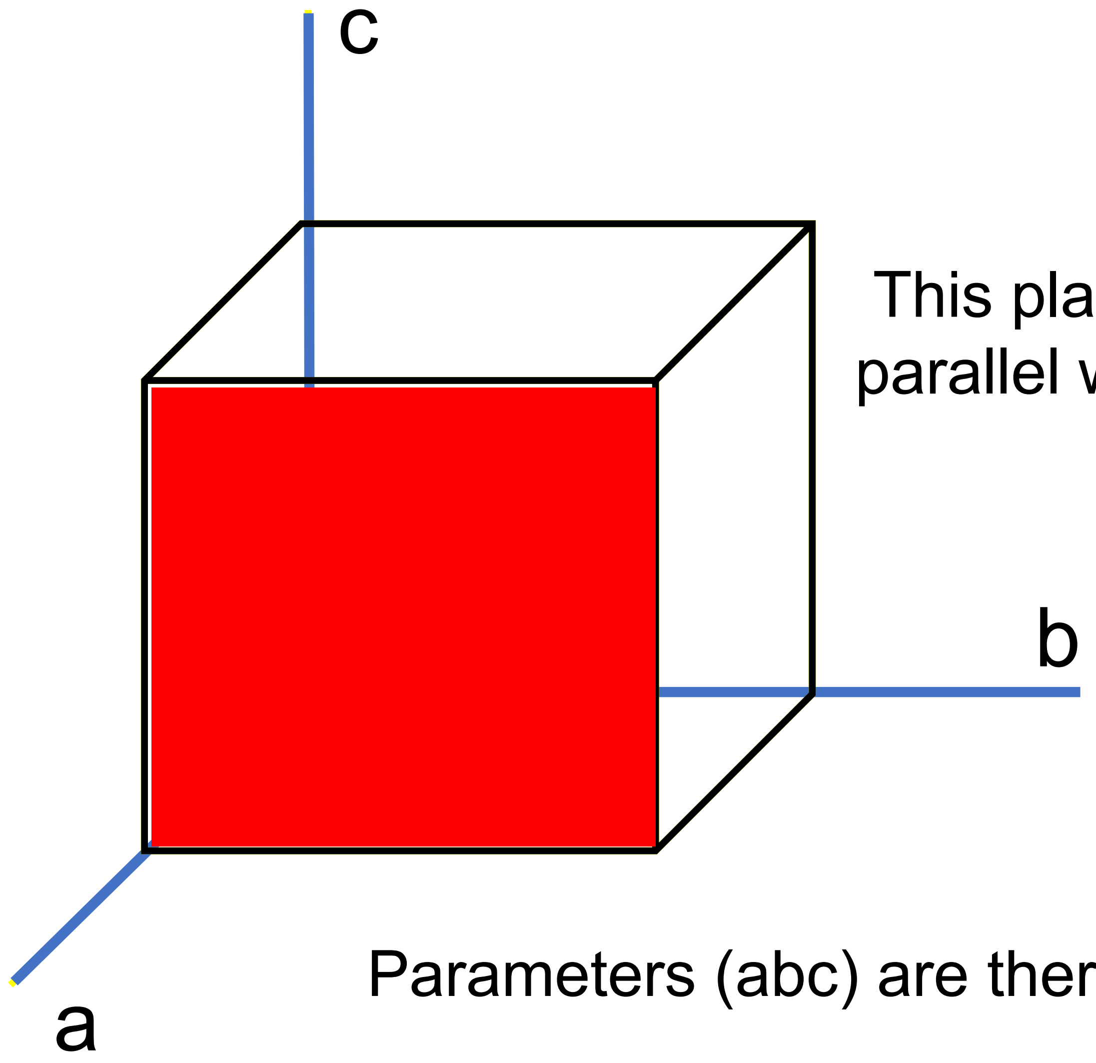


This plane cuts a and b
in a distance of 1, but is parallel to c-axis

Parameters (abc) are therefore
(11∞)…hence…

Miller indices use reciprocal:

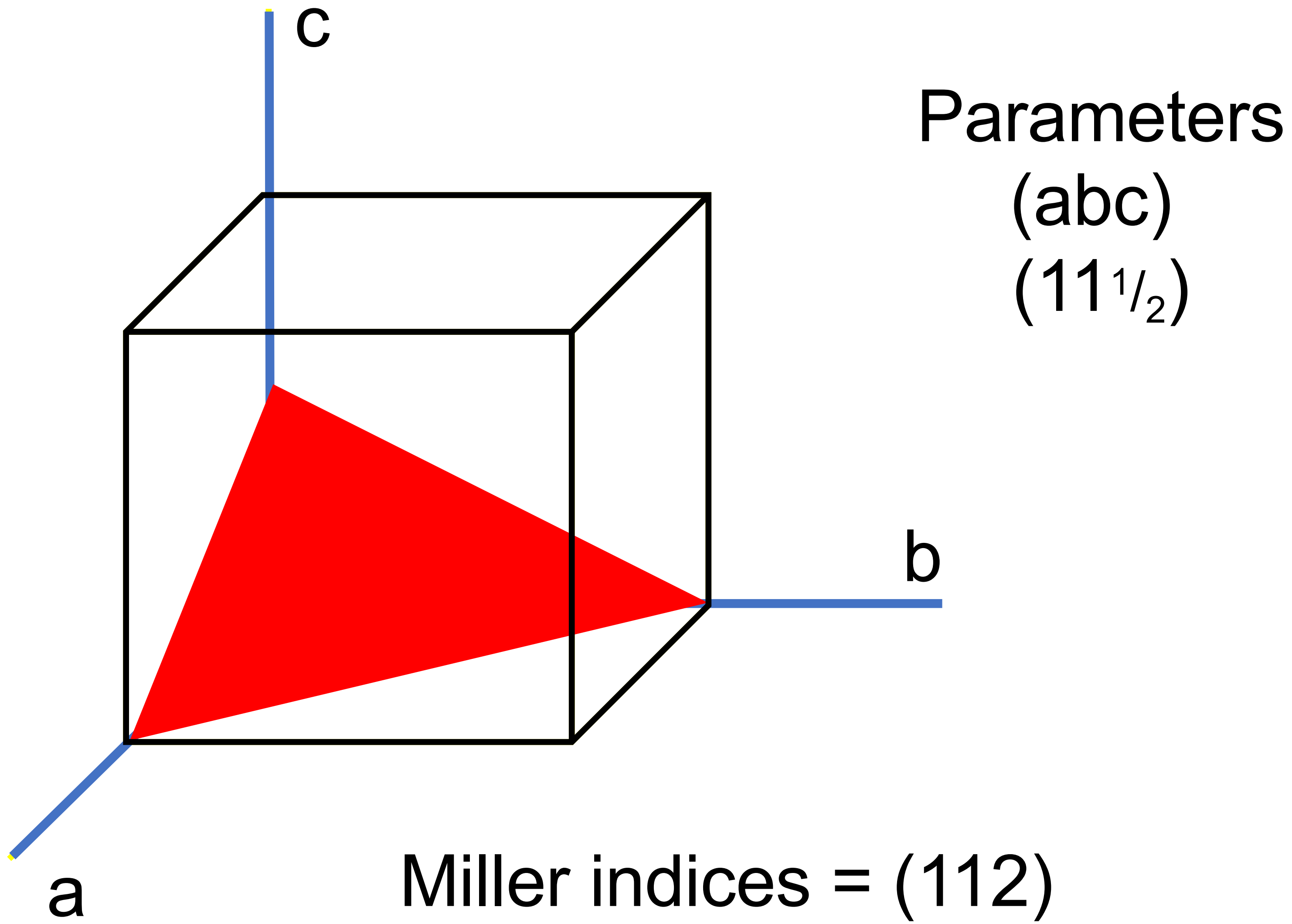
$$(11\infty) \longrightarrow \left(\frac{1}{1}\ \frac{1}{1}\ \frac{1}{\infty}\right) \longrightarrow (110)$$

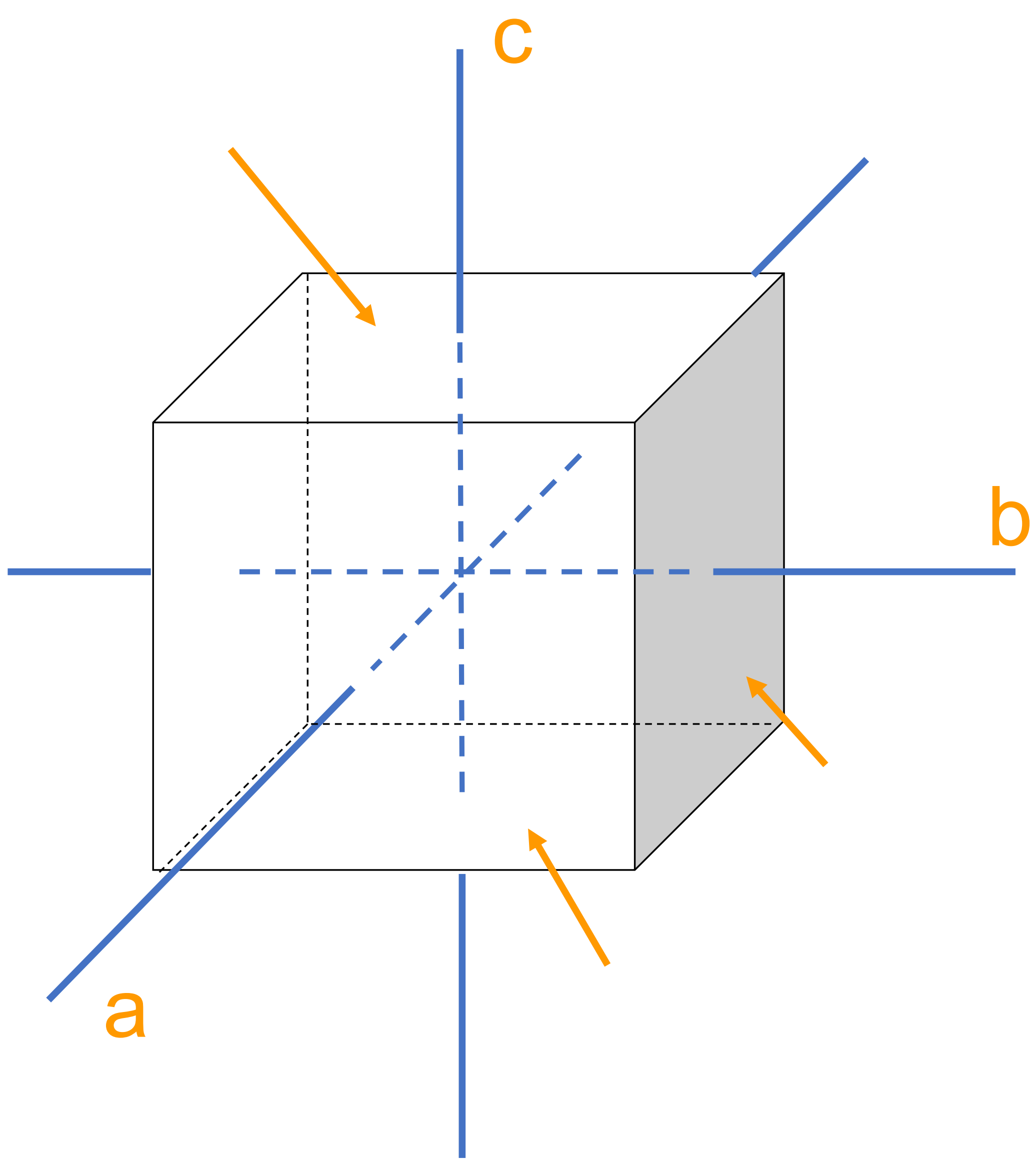


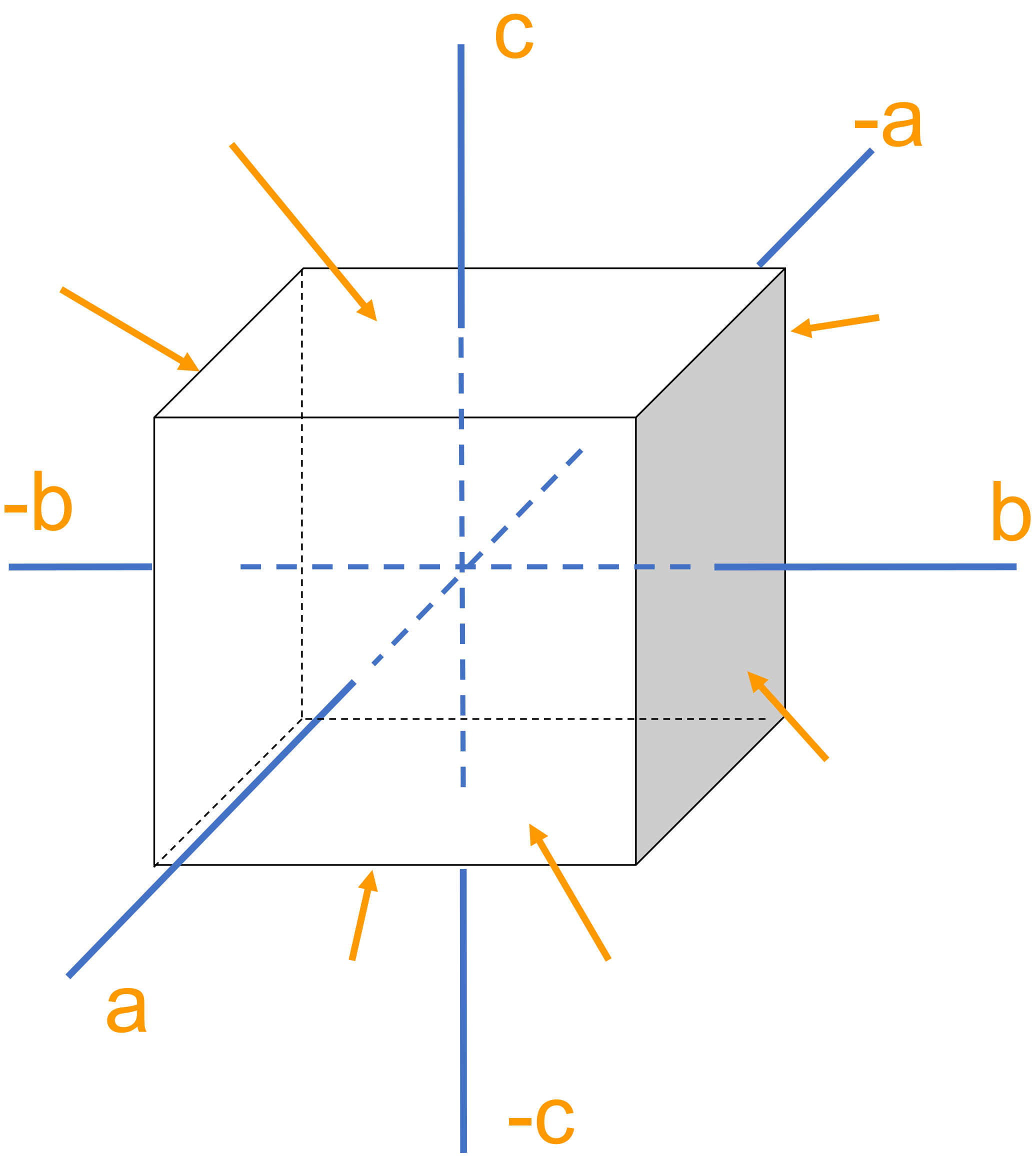
This plane cuts a and is parallel with both b and c

Parameters (abc) are therefore (1∞∞)

Miller indices are (100)


c
b
a
Parameters
(abc)
(11 1/2)
Miller indices = (112)


c
b
a


c
-a
-b
b
a
-c

A cube has 6 identical planes with Miller indices:

$(100)\ (\bar{1}00)\ (010)\ (0\bar{1}0)\ (001)\ (00\bar{1})$

CUBE-FORMEN consists of these 6 planes

As a common description we use this type { } of parentheses

$$\{100\}_6$$

Crystallography: Activity

Determine the crystal planes on the different shapes

What I always will remember: week 2

- The 7 crystal systems and their minimum symmetry elements
- The angles between crystal planes is diagnostic and characteristic for the crystal systems
- Miller indices

‘last minute paper’

- Write down what was difficult to understand
- Write down what was easy to understand

Week 2b

- Native minerals
- Silicate minerals (Nesosilicates)

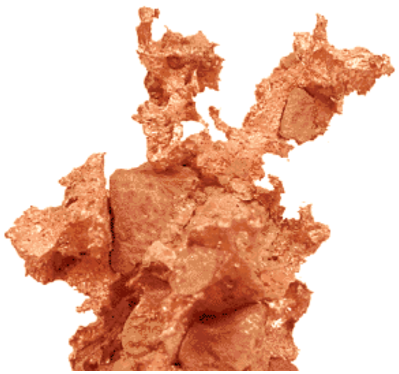
Native minerals

- This group of minerals consists of single chemical elements:

For example Au, Cu, Ag, S, C

Gold (Au)

Silver (Ag)

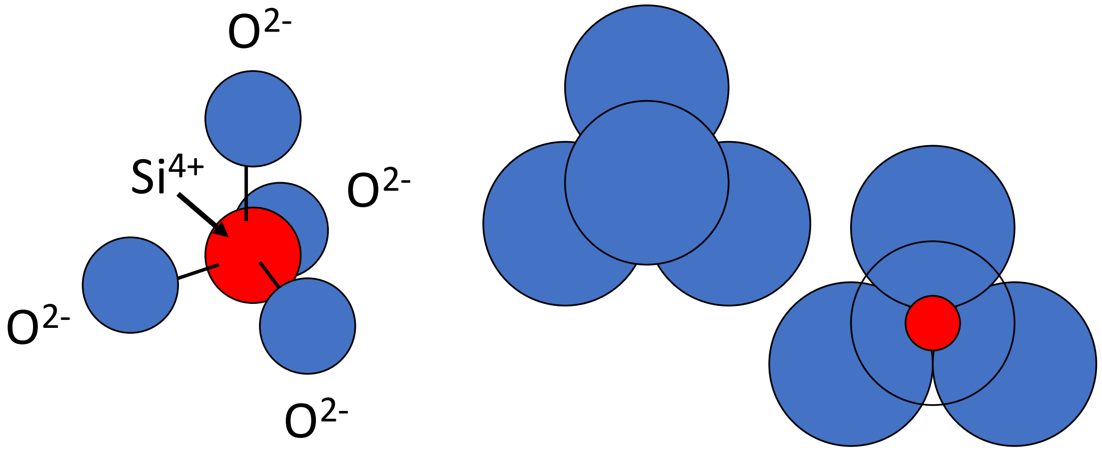


Copper (Cu)

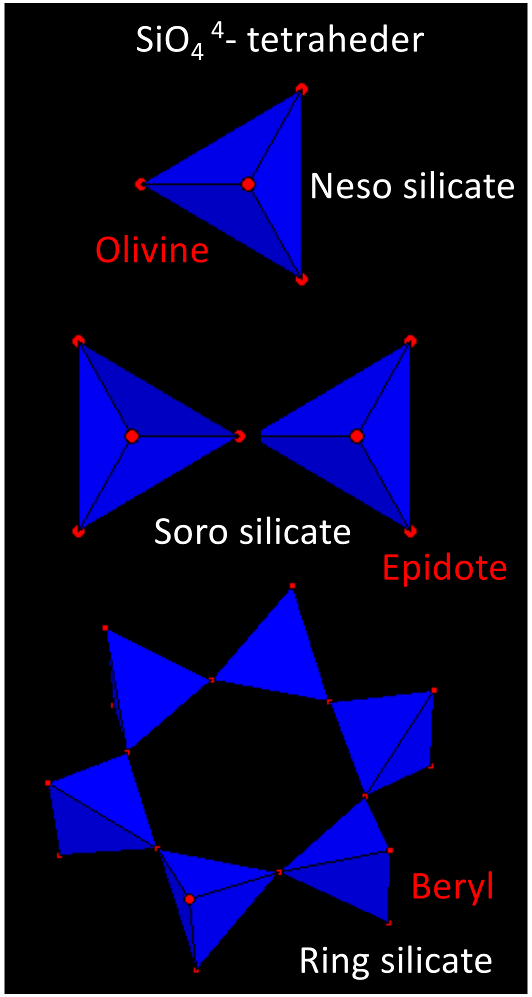
Sulfur (S)

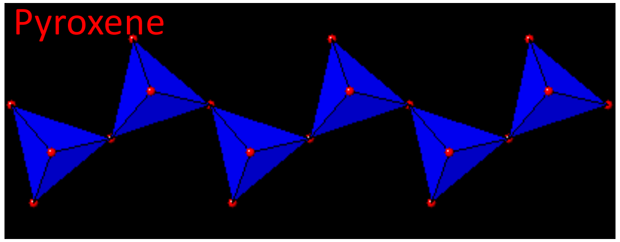
Silicate minerals: structure

- The most important building block of silicates is the $(SiO_4)^{4-}$ tetraheder (remember the radius ratio).
- Silicates are the most abundant minerals and many of them are rock-forming.
- Other important cations in some of the silicate minerals are: Al^{3+} , Fe^{2+} , Fe^{3+}, Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}

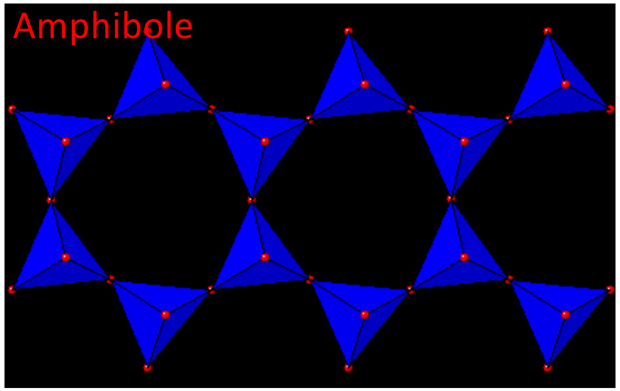


Silicate minerals: structure

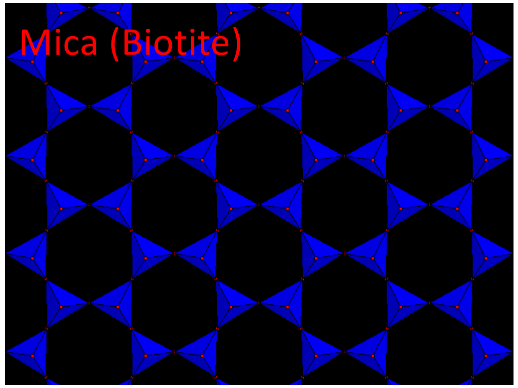




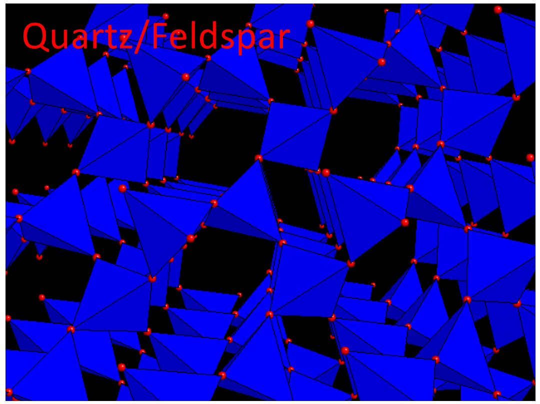
Ino silicate (single chain)



Ino silicate (double chain)



Sheet silicate



Framework silicate

Nesosilicates

- Olivine
- Zircon
- Garnet
- Sillimanite, andalusite, kyanite (disthene)
- Staurolite
- Titanite (Sphene)
- Topaz

Silicate minerals: Nesosilicate: **Olivine**

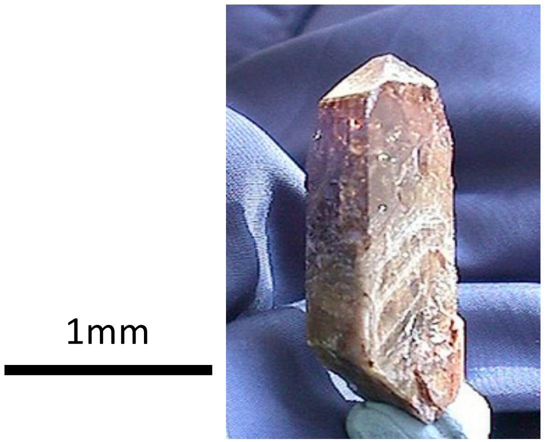
- The most abundant mineral in the upper mantle, occurs together with pyroxene +/- garnet (rock called: peridotite)
- Occurs commonly in (mafic and ultra-mafic) magmatic rocks
- Consists of Mg and Fe-rich varieties (forsterite and fayalite)
- Colour typically green
- Easy weathered and

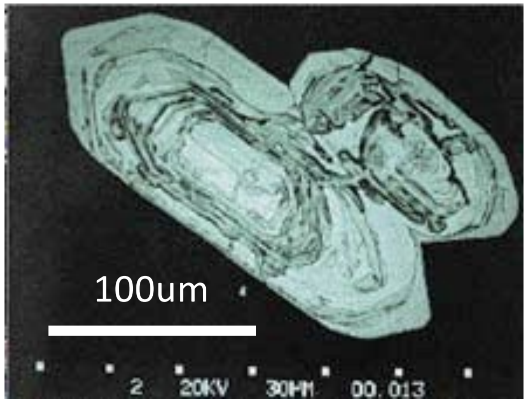
altered to serpentine


Mantle nodule (xenolith)

Silicate minerals: Nesosilicate: **Zircon**

- Not a rock-forming mineral, only accessory phase (in many different rocks). Commonly brown, yellow
- Can contain U, Th and therefore used to date rocks
  - $^{238}U \longrightarrow {}^{206}Pb$ half life time 4,47 billion years
  - $^{235}U \longrightarrow {}^{207}Pb$ half life time 0,704 billion years





Silicate minerals: Nesosilicate: **Garnet group**

- Garnet occurs typically in **metamorphic rocks**

Cubic
General formula: $R^{2+}_3R^{3+}_2[SiO_4]_3$
Several varieties

Garnet groups $R^{2+}{}_3R^{3+}{}_2[SiO_4]_3$

***Pyralspitserien*: $R^{2+}{}_3Al_2[SiO_4]_3$**

Pyrope	$Mg_3Al_2[SiO_4]_3$
Almandine	$Fe_3Al_2[SiO_4]_3$
Spessartine	$Mn_3Al_2[SiO_4]_3$

***Ugranditserien*: $Ca_3R^{3+}{}_2[SiO_4]_3$**

Uvarovite	$Ca_3Cr_2[SiO_4]_3$
Grossular	$Ca_3Al_2[SiO_4]_3$
Andradite	$Ca_3Fe_2[SiO_4]_3$

Silicate minerals: Garnet group, occurrence

Pyrope
$Mg_3Al_2[SiO_4]_3$

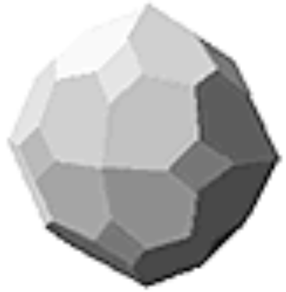
Red, occurs in rock called ECLOGITE together with a green pyroxene (omphacite)

Eclogite forms under high pressure metamorphism of basalt

Silicate minerals: Garnet group, occurrence

Almandine
$Fe_3Al_2[SiO_4]_3$

3.8 Garnet. Trapezohedron and Dodecahedron



Garnet. Dodecahedron and Trapezohedron

Silicate minerals: Garnet group, occurrence

Almandine $Fe_3Al_2[SiO_4]_3$

The most common garnet, dark red-brown.
Occurs in metapelitic rocks (gneisses, schists)

METAPELITE is the name for a metamorphosed, originally **clay**-rich sedimentary rock.
Metapelites contain aluminium-rich minerals e.g., biotite, muskovite, Al_2SiO_5 minerals, almandine, staurolite,

Silicate minerals: Garnet group, occurrence

Grossular

$Ca_3Al_2[SiO_4]_3$

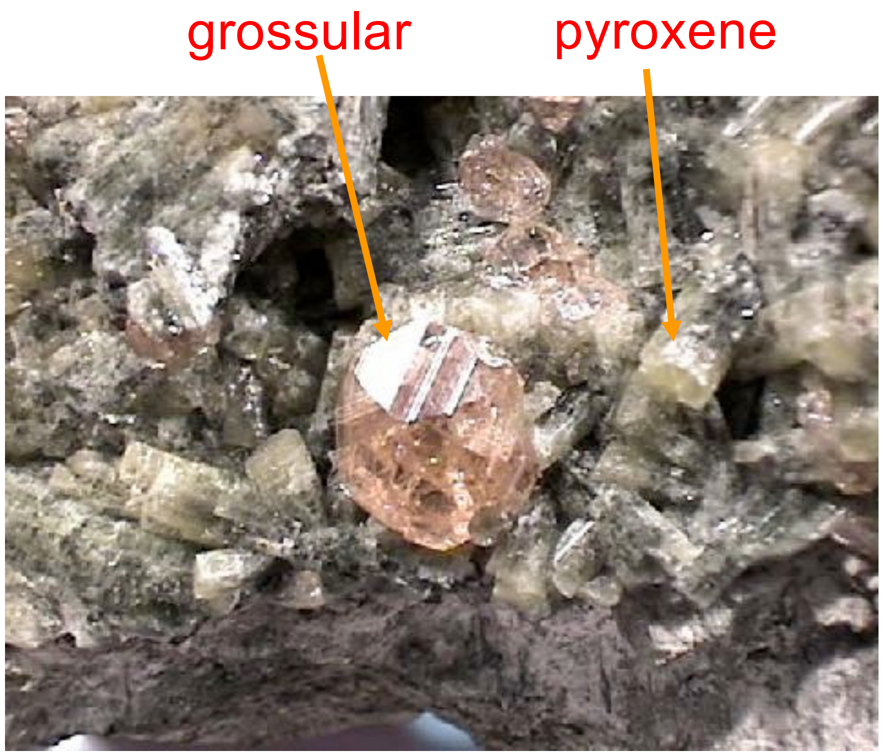
Colour varies, depending on Al^{3+} - Fe^{3+} substitution

Colourless, greenish, redish, yellow, red-brown

Silicate minerals: Garnet group, occurrence

Grossular $Ca_3Al_2[SiO_4]_3$

Metamorphosed marl
(limestone + clay).
Ca from limestone
Al from clay
SiO_2 fra quartz



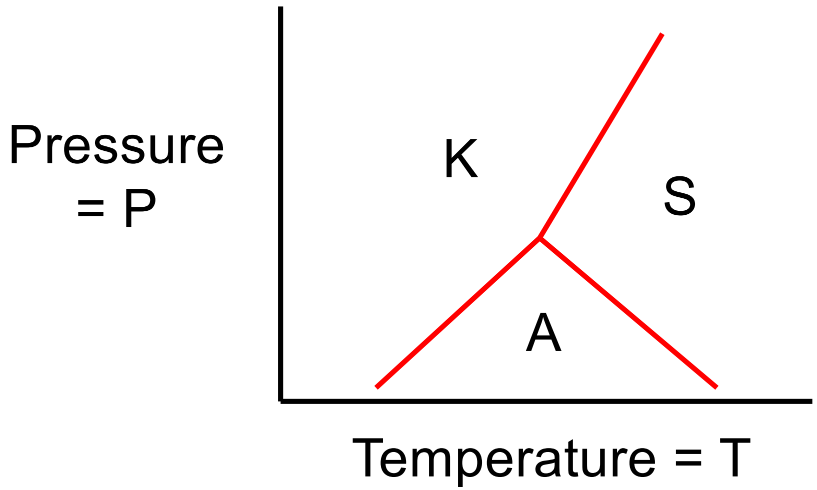
Silicate minerals: Nesosilicates: **Alumosilicates**

3 Minerals with the same composition (Al_2SiO_5) = **Polymorphs**

ANDALUSITE - orthorhombic

SILLIMANITE - orthorhombic

KYANITE (DISTHENE) - triclinic

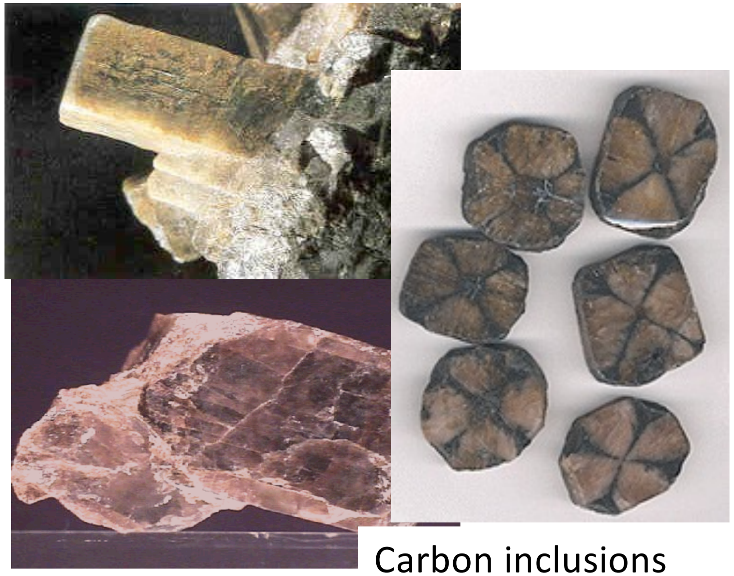


Triple point at
4kbar og 500° C

Silicate minerals: Alumosilicates, occurrences

They are **index minerals** in metamorphic rocks (in Metapelites)

Andalusite, red-brown, white, light red



Carbon inclusions
form Chiastolite (cross)

Sillimanite, white, light brown,
fibrous

Kyanite, light blue, tabular

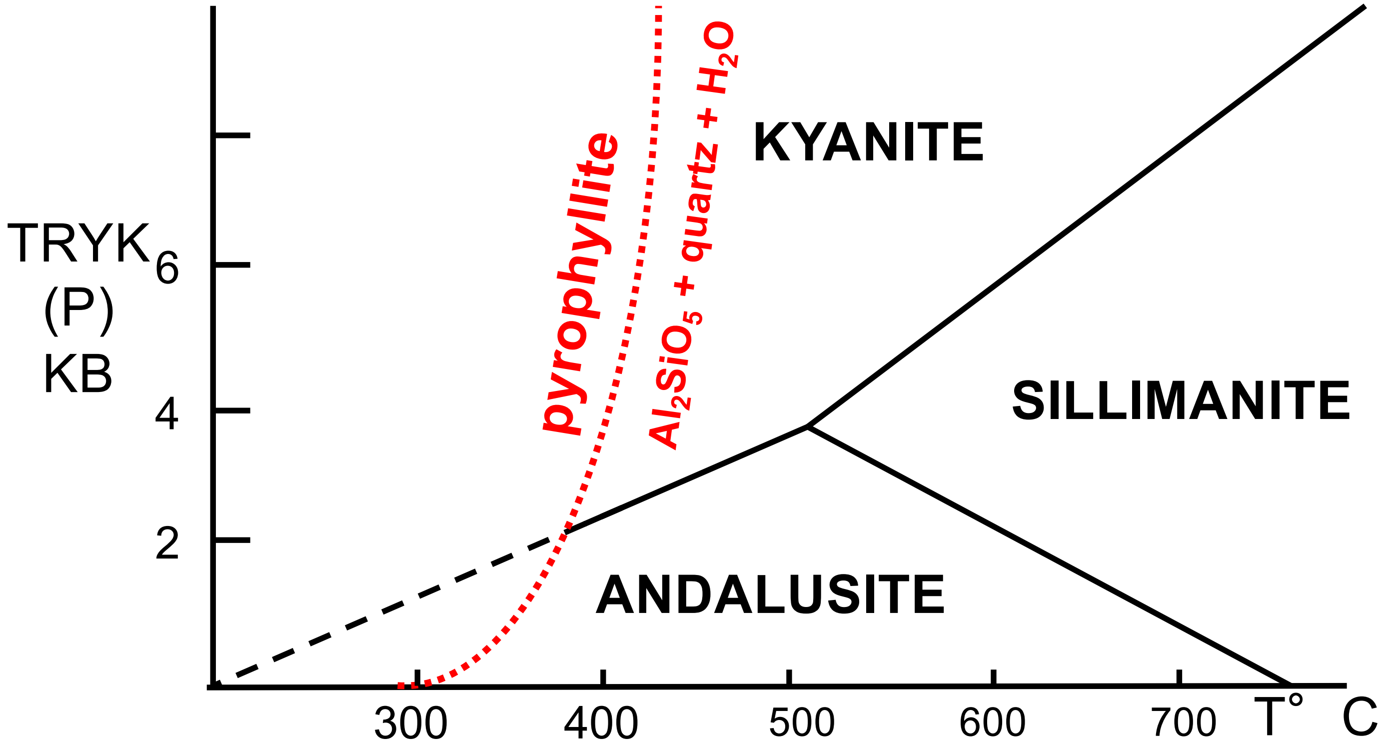
Metamorphism of clay-rich rocks

$$Al_2[Si_2O_5](OH)_4 + 2SiO2 = Al_2[Si_2O_5]_2(OH)_2 + H_2O$$

kaolinite + quartz = pyrophyllite + water

$$Al_2[Si_2O_5]_2(OH)_2 = Al_2SiO_5 + 3SiO2 + H_2O$$

pyrophyllite = kyanite or andalusite + quartz + water

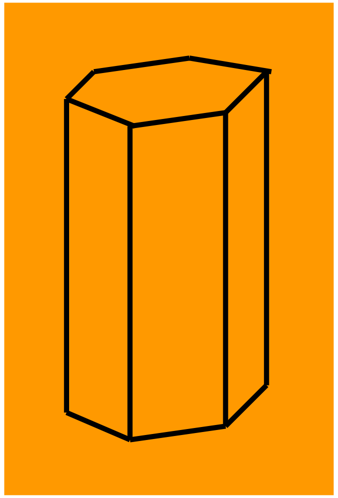


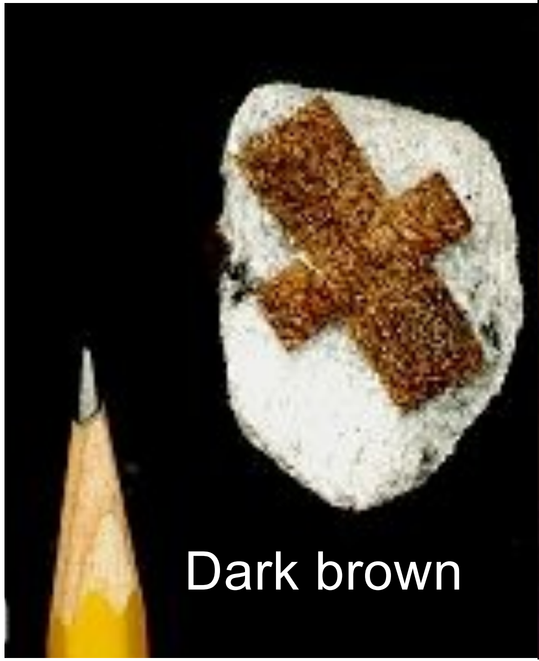
Silicate minerals: Nesosilicates: **Staurolite**

$(Fe,Mg)_2Al_9O_6[SiO_4]_4(O,OH)_2$

$Fe^{2+} \longleftrightarrow Mg^{2+}$ Al-rig $[SiO_4]$-groups gtoups

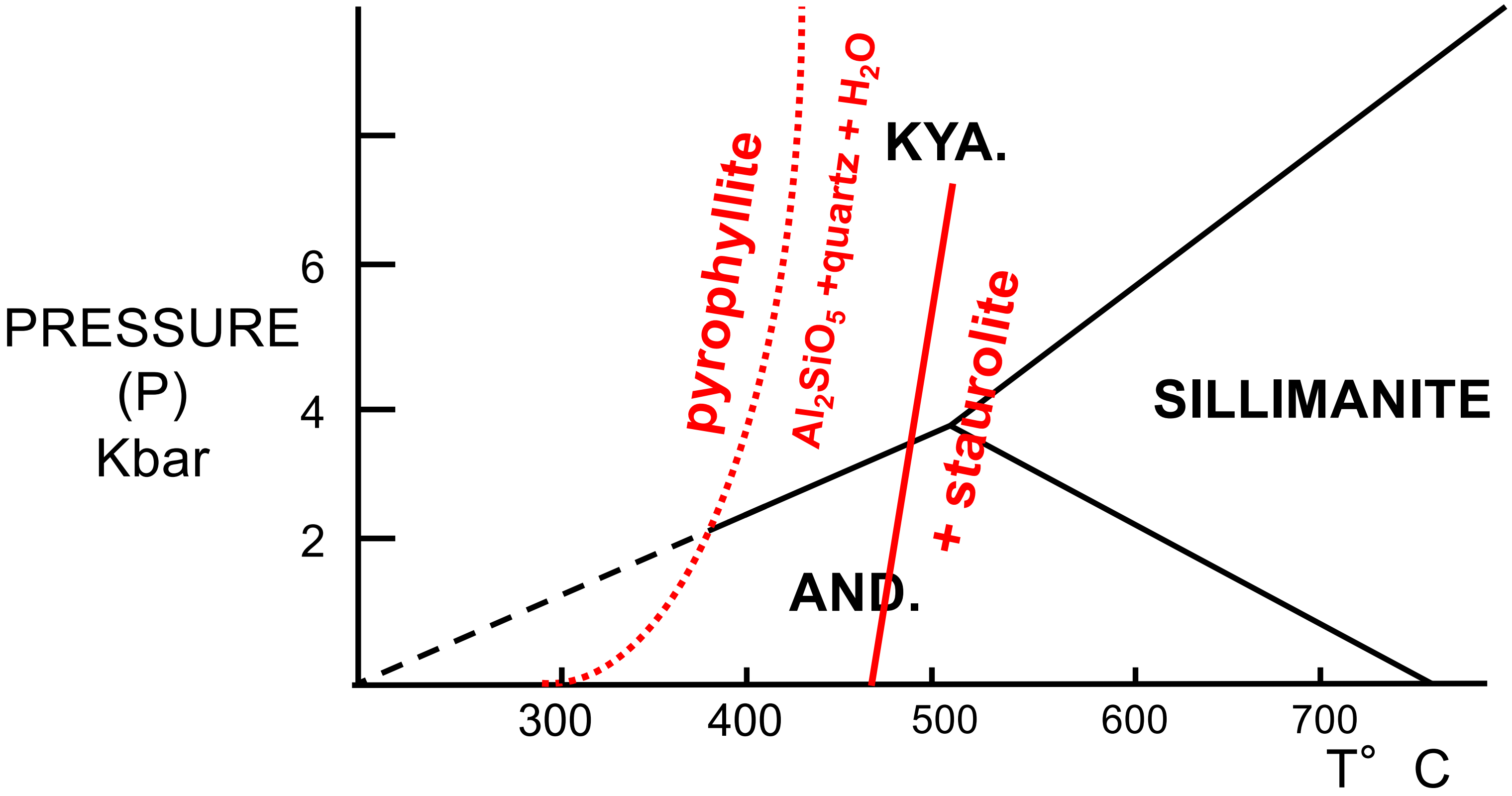
Monoklinic
(pseudo-orthorhombic)





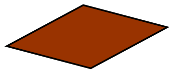
Silicate minerals: Staurolite, occurrences

Forms at **>500° C** in metapelitic rocks



Silicate minerals: Nesosilicates: **Titanite** (Sphene)

$CaTi[SiO_4](O,OH,F)$

Monoklinic 

Brown, green yellowish
Occurs as an accessory phase in magmatic and metamorphic rocks, similar to zircon

Silicate minerals: Nesosilicates: **Topaz**

$Al_2[SiO_4](OH,F)_2$

Orthorhombic

Colorless, yellow green, gray

Occurs typically in SiO2-rich magmatic rocks (granite, pegmatites, veins)

Silicate minerals: Sorosilicates: **Epidote**

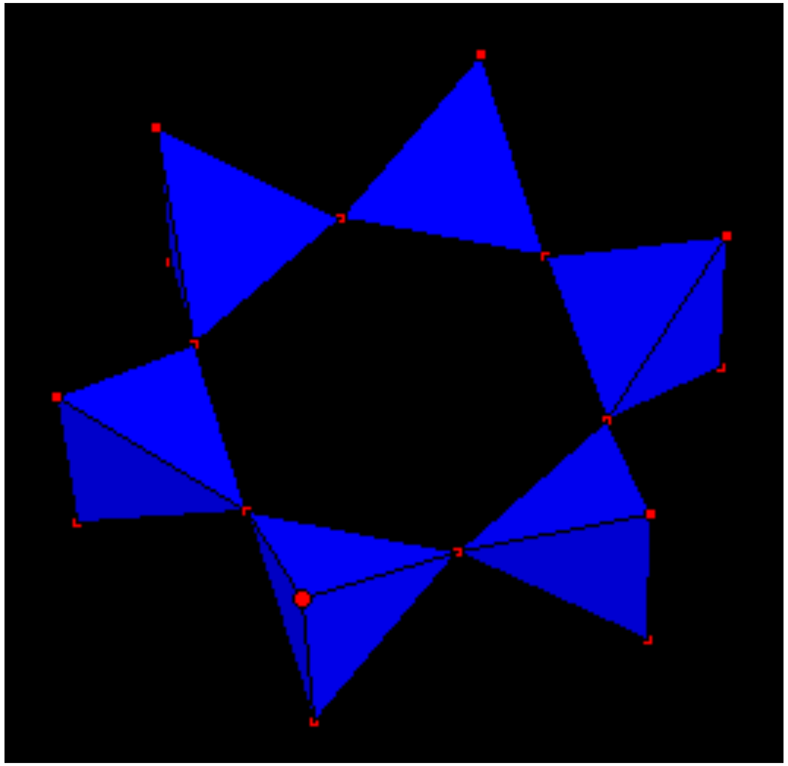
- Epidote (group)

Silicate minerals: Epidote, occurrence

Green
Occurs in greenschists (metamorphic rock)
Greenschists form at around 300C with the addition of water to mafic rocks (basalt, oceanic crust).
Seafloor hydrothermal metamorphism.

Silicate minerals: Ringsilicates

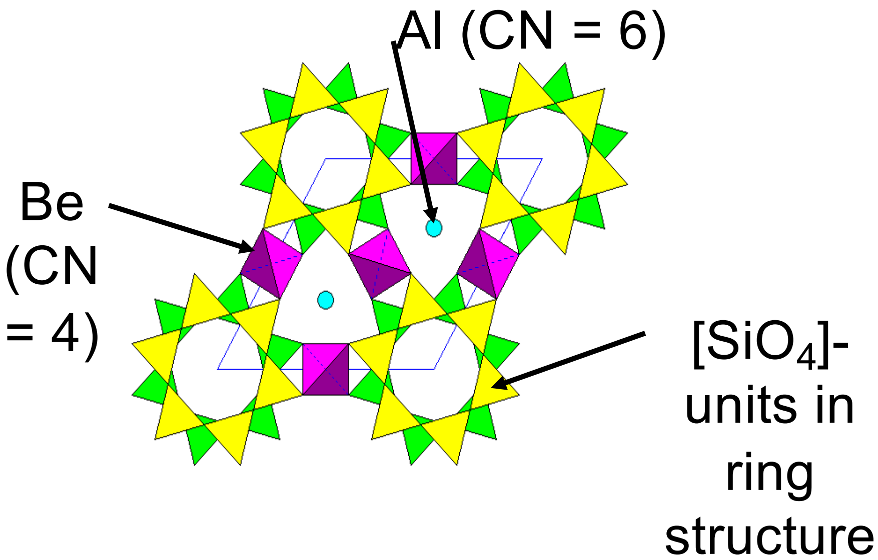
- Beryl
- Tourmaline



Silicate minerals: Ringsilicates: **Beryl**

$Be_3Al_2[Si_6O_{18}]$

Hexagonal



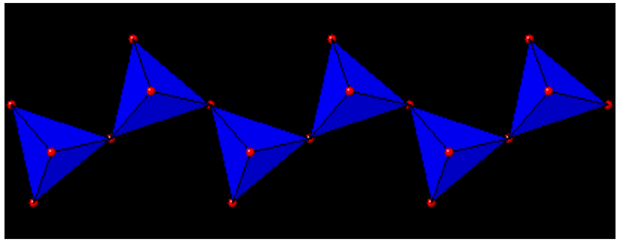
aquamarin

Silicate minerals: Ringsilicates: **Tourmaline**

$NaX_3Al_6(\mathbf{B}O_3)_3[Si_6O_{18}](O,OH,F)_4$

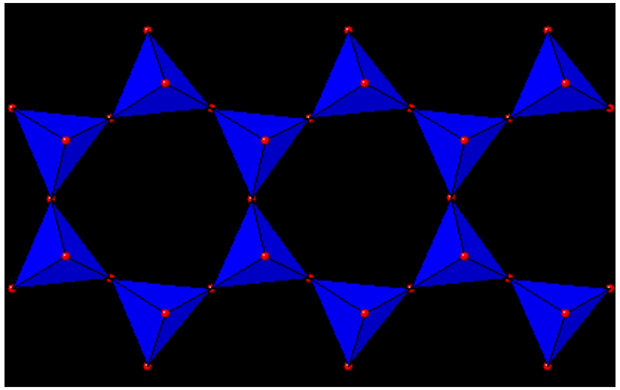
Occurs in pegmatites, which are fractionated SiO_2 and H_2O-rich melt.
Together with beryl, topaz, mica.
B^+ and Be^+ are small cations concentrated in late, fractionated melt.

Silicate minerals: Inosilicates



Single chains of SiO_4^{4-} -tetrahedra $(Si_2O_6)^{4-}$

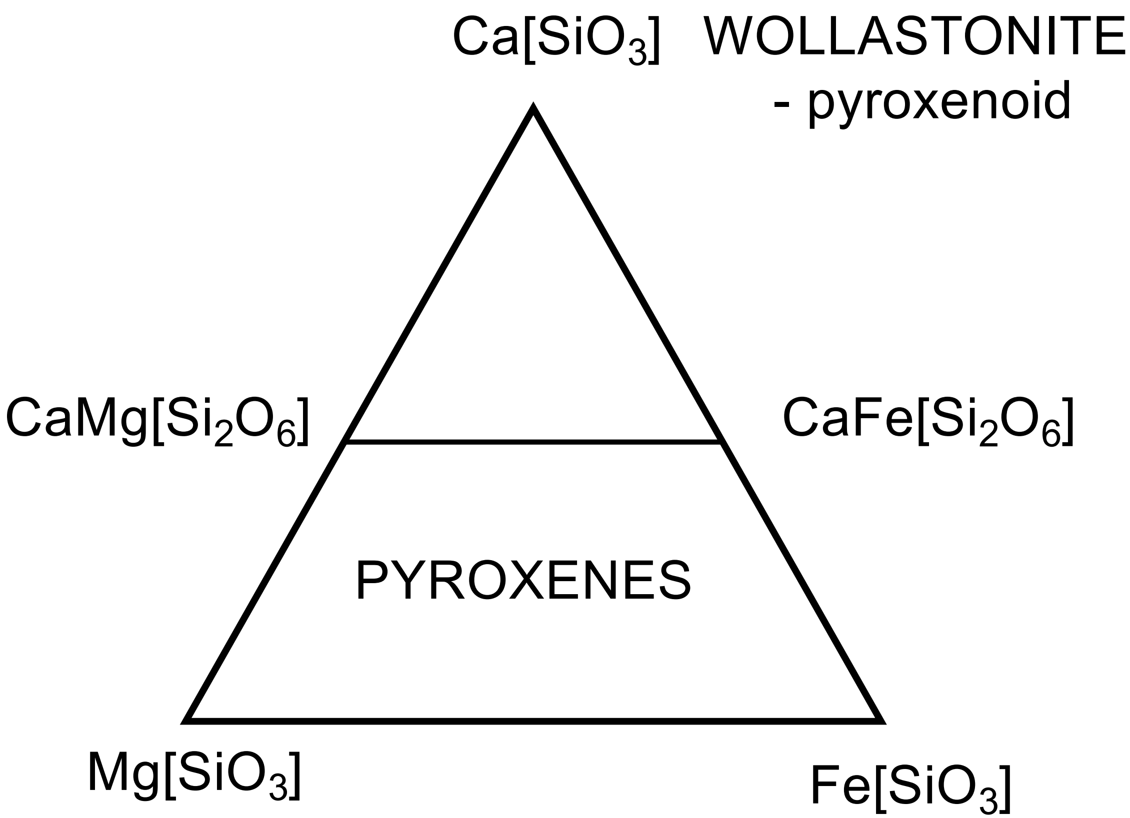
Pyroxenes: Orthopyroxene (orthorhombic, Mg-Fe), Clinopyroxene (monoclinic, Ca-Mg-Fe)

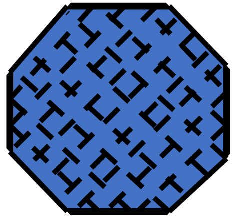


Double chains of SiO_4^{4-} -tetrahedra $(Si_4O_{11})^{6-}$

Amphiboles

Silicate minerals: Inosilicates: **Pyroxenes**



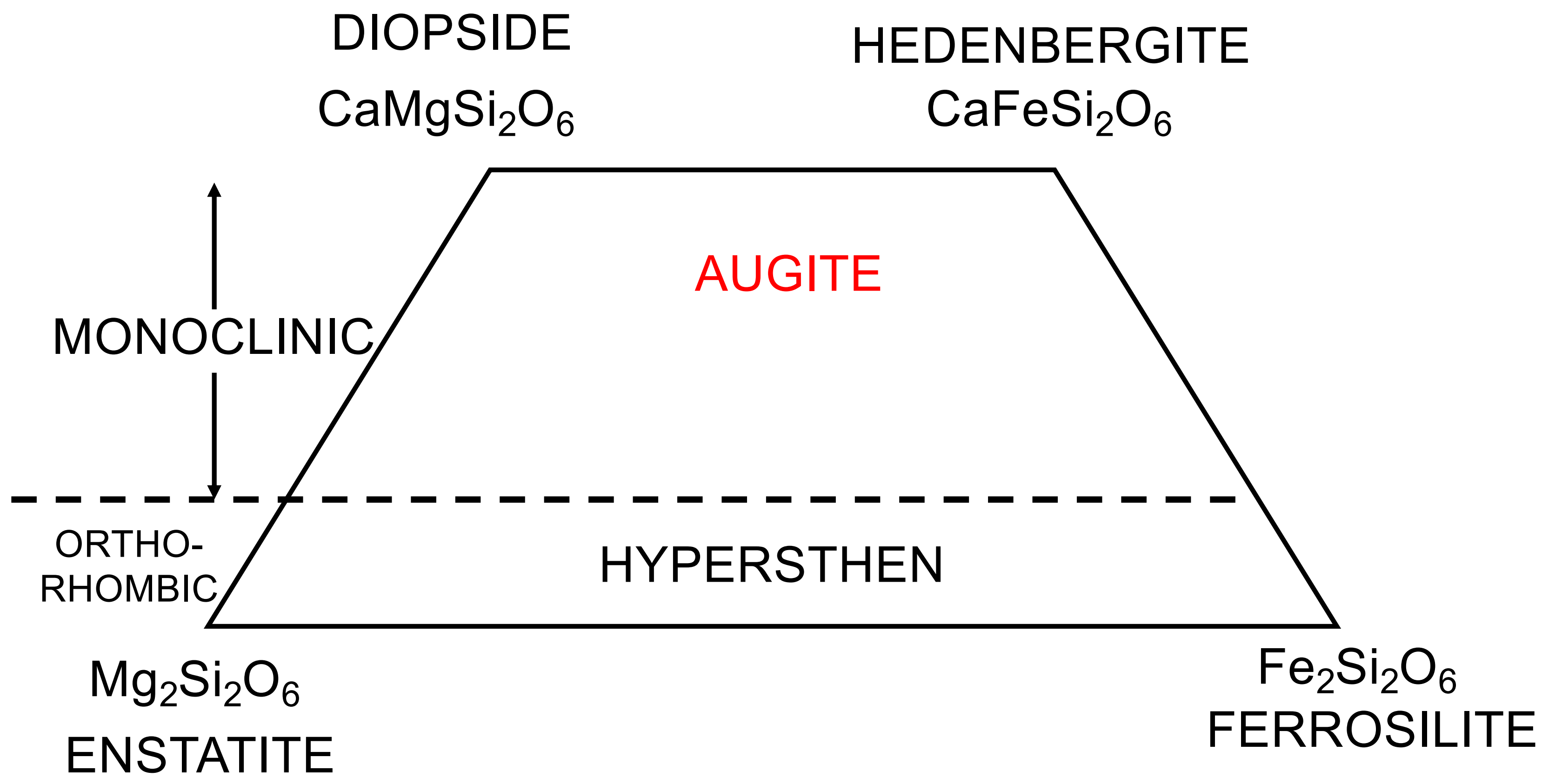


CLINOPYROXENE
Diopside-Hedenbergite

ORTHOPYROXENE
Enstatite-Ferrosilite

Silicate minerals: Inosilicates: Pyroxene

Ca - Mg - Fe pyroksener

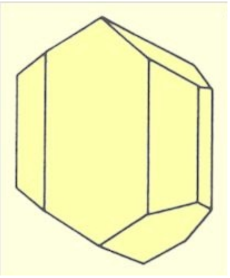


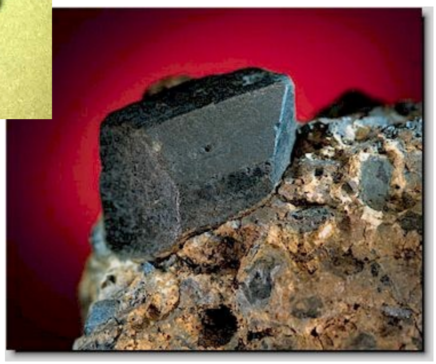
Silicate minerals: Pyroxene, occurrences

Occurs in mafic and ultramafic rocks. Both volcanic (basalt) and plutonic (gabbro).

Mg-rich members in primitive rocks Fe-rich in more evolved rocks.

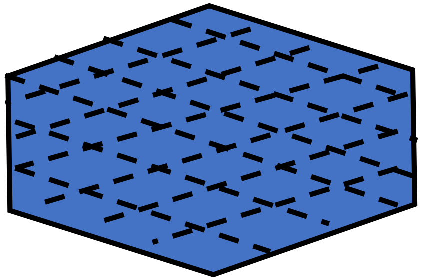
In high temperature metamorphic rocks.





Silicate minerals: Inosilicates: **Amphiboles**

Double chains



General formula

$$A_{0-1}B_2C_5[T_8O_{22}](OH)_2$$

A = Na, K B = Ca, Na, Mg, Fe C = Mg, Fe, Al

T = Si, Al

Space for large cations (K^+) Al^{3+} substitutes for Si^{4+}

(OH)-groups

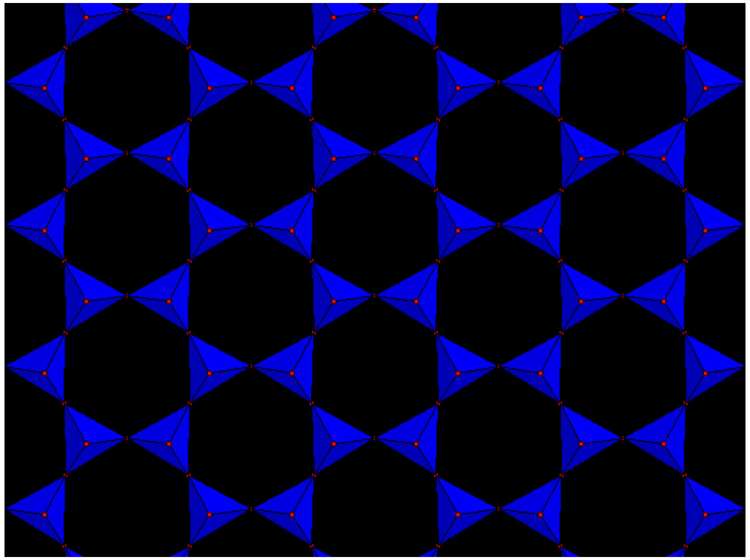
Silicate minerals: Amphiboles, occurrences

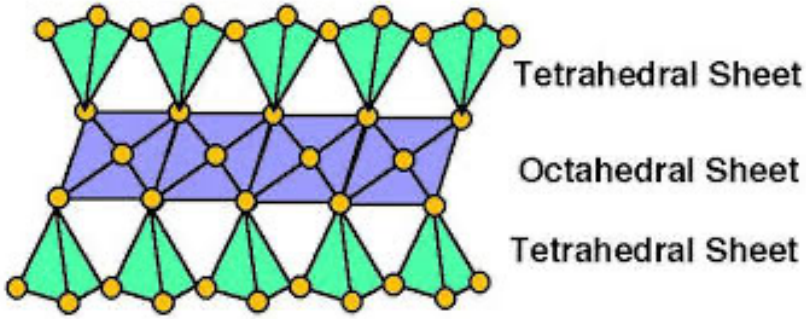
ACTINOLITE - TREMOLITE
Green-white/gray
greenschist, metam. dolomite
Ca-Mg-Fe

HORNBLENDE
black
granite, amphibolite
Na-Ca-Fe-Mg

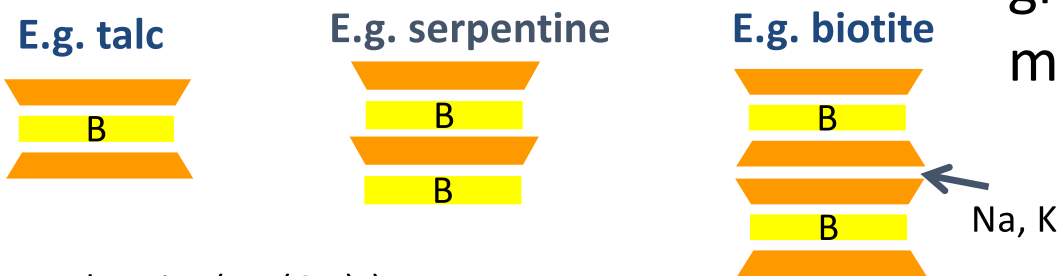
GLAUKOPHANE
blue
blueschist
Na-Mg

Silicate minerals: Phyllosilicates (sheet silicates)





Different stacking combinations lead to different kinds of phyllosilicates (mica group, clay minerals, serpentine minerals…)



B: brucite ($Mg(OH)_2$)

All phyllosilicate contain OH-groups

Silicate minerals: Phyllosilicates: Serpentine

$Mg_3[Si_2O_5](OH)_4$

Forms during metamorphism of OLIVINE - $(Mg,Fe)_2[SiO_4]$

Requires the presence of H_2O

Serpentine contains no Fe, and therefore, magnetite (Fe_3O_4) is forming simultaneously

A rock that almost only consists of serpentine is called a SERPENTINITE

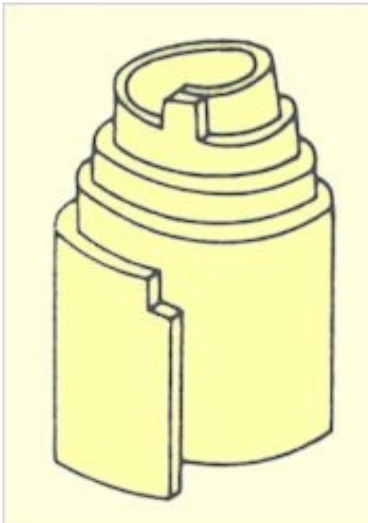
Silicate minerals: Phyllosilicates: **Serpentine**

H = 3-5

Commonly green

Chrysotile and antigorite are varieties of serpentine

Sheet structure
- But fibrous habitus



Veins o fserpentins -
Fibres are perpendicular

Silicate minerals: Phyllosilicates: **Talc**

$Mg_3[Si_4O_{10}](OH)_2$

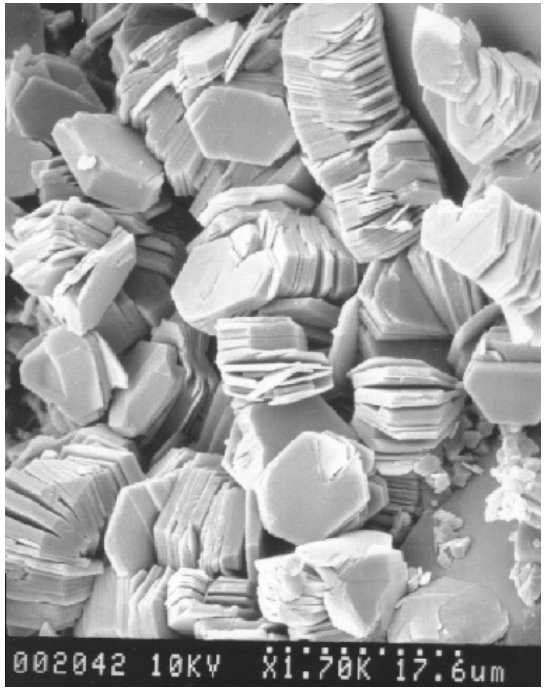
Defines hardness 1 on the Mohs scale

Occurs together with serpentine

H = 1

A rock that almost consists only of talc is called a soapstone

Silicate minerals: Phyllosilicates: **Kaolinite**



Kaolinite $Al_2[Si_2O_5](OH)_4$ is a clay mineral

Clay minerals are a large group of minerals and make up the smallest size fraction (<4um) in sediments

H = ca. 2

Clay minerals form during the weathering or alteration of feldspar

Kaolinite occurs in soil and in sedimentary
Other clay minerals: Montmorillonite illite

Silicate minerals: Phyllosilicates: **Micas**

Micas are an important group of phyllosilicates and are characterized by perfect basal cleavage

$$XY_{2-3}[Z_4O_{10}](OH)_2$$

X = K^+ Y = Al^{3+}, Mg^{2+}, Fe^{2+} Z = Si^{4+}, Al^{3+}

Micas have an open structure and space for larger cations such as K^+

Silicate minerals: Phyllosilicates: **Micas**

Muskovite

$KAl_2[AlSi_3O_{10}](OH)_2$, white, silvery

Occurs in mica schists (metamorphic rock) and some magmatic granitic rocks

Biotite

$K(Mg,Fe)_2[AlSi_3O_{10}](OH)_2$, brown, black

Occurs in granitic rocks and some metamorphic ones (mica schist)

Silicate minerals: Phyllosilicates: **Micas**

Chlorite

$(Mg,Fe,Al)_6[(Si,Al)_4O_{10}](OH)_{8,}$ green

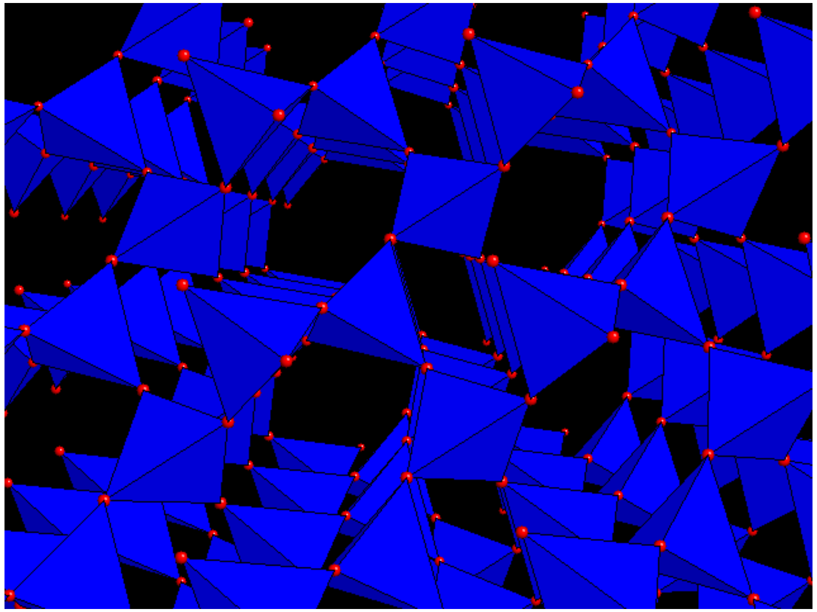
Occurs in greenschists (metamorphic rock) 100-500C

Lepidolite

$K(Li, Al)_{2\text{-}3}\ [(Si,Al)_4O_{10}](OH, F)_{2,}$ lilla

Occurs in pegmatites, source of Li

Silicate minerals: Tectosilicates

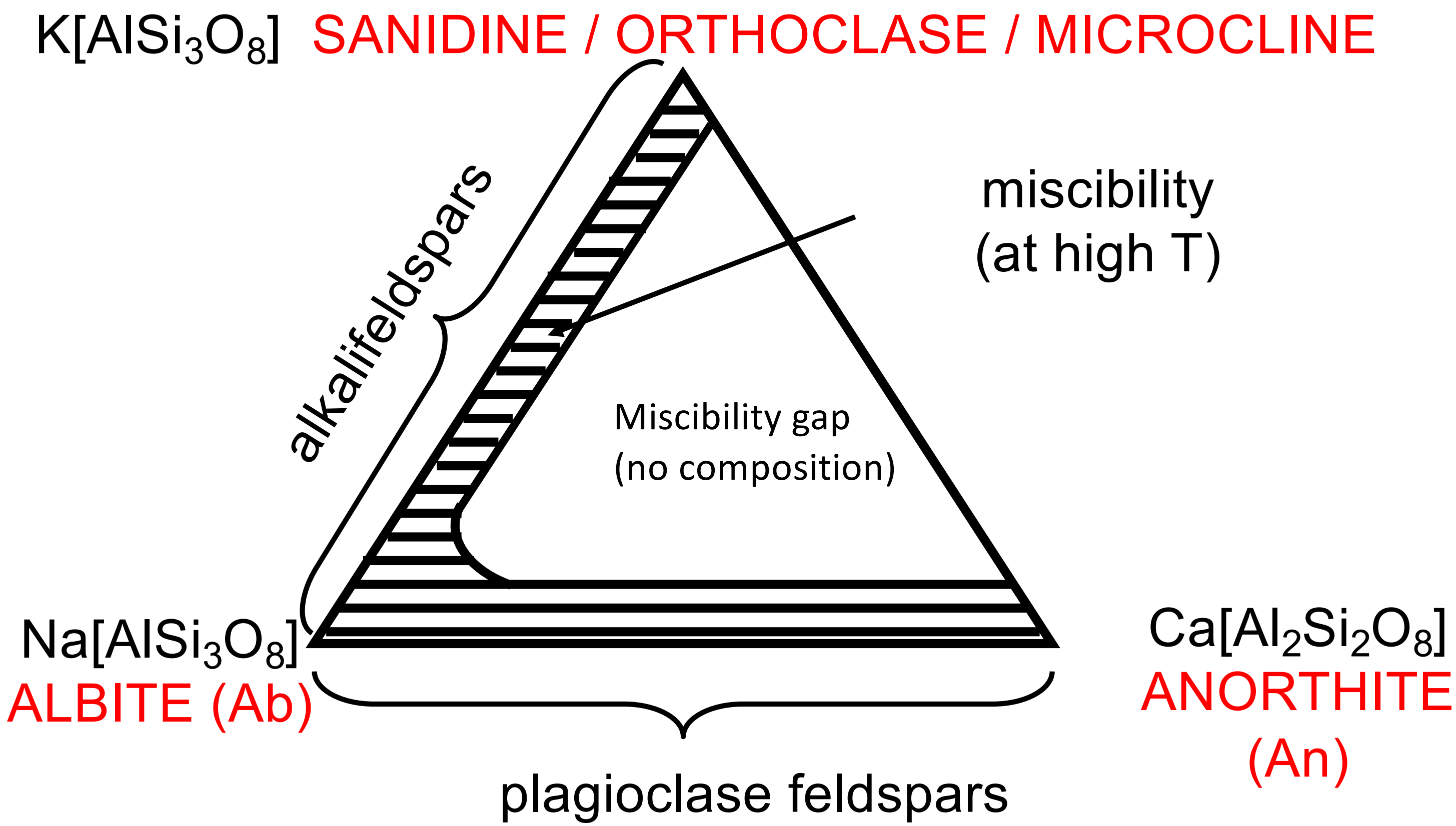


3D gitter structure of SiO_4^{4-} units

- **Quartz**
- **Feldspars: alkali-feldspar, plagioclase**
- **Feldspatoids: leucite, nepheline, sodalite**
- **Zeolites**

Feldspars, together with quartz, are among the most abundant and common minerals in the Earth’s crust.

Silicate minerals: Feldspars



Silicate minerals: Tectosilicates: **Alkalifeldspars**

Compositions between $K[AlSi_3O_8]$ og $Na[AlSi_3O_8]$

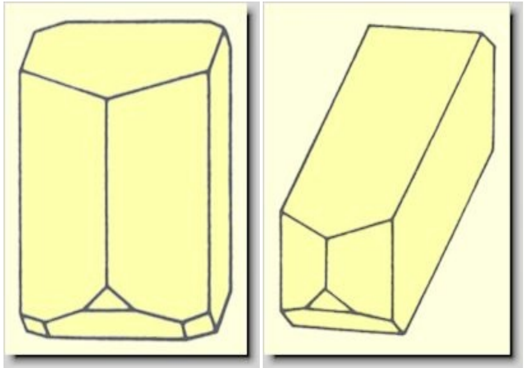
K-rich alkalifeldspar occurs in 3 polymorphs:

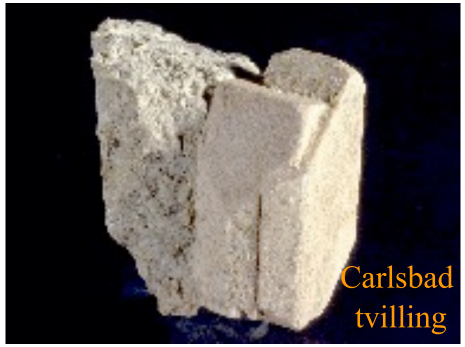
ORTHOCLASE	monoclinic, slightly pink/white	low temperature
MICROCLINE	triclinic, /grey	low temperature
SANIDINE	monoclinic, white/grey	**high** temperature

The structural change includes an ordering of Al-Si distribution. At high T disordered, at low T ordered.

Silicate minerals: Tectosilicates: **Alkalifeldspars**

Sanidine: occurs only in high temperature rocks such as volcanic rocks and high-grade metamorphic rocks (granulite)



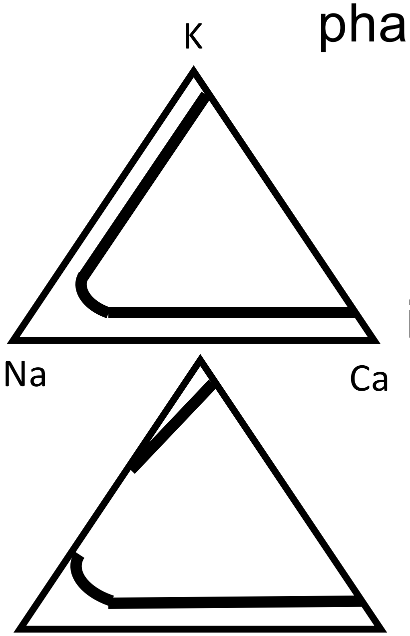


Ortholcase: occurs in ‘low’ temperature magmatic rocks such such as granite, pegmatite, and metamorphic rocks (gneiss)

Silicate minerals: Tectosilicates: **Alkalifeldspars**

When alkalifeldspar first crystallizes in a magma chamber it is SANIDINE.
There is 100% miscibility between Na- og K- feldspat.
At fast cooling the sanidine-structure is preserved.

During slow cooling the structure is divided into two phases - a K-rich and a Na-rich one.

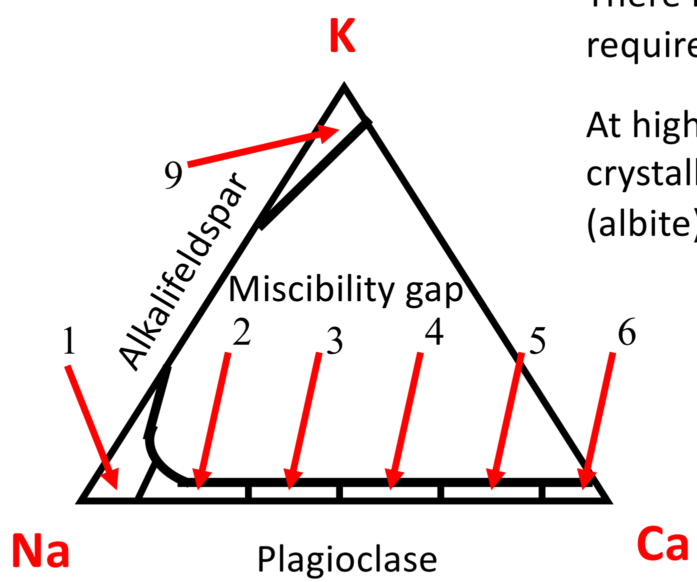


There occurs EXSOLUTION

The K-rich phase (ORTHOKLAS) is commonly dominating and includes, the Na-rich phase (ALBIT) as small spots or veinlets

This exsolution texture ist called a PERTHITE

Silicate minerals: Tectosilicates: **Plagioclase**



There is complete miscibility between Na and Ca. But it requires a coupled-substitution: $Na^{+} + Si^{4+} \Longleftrightarrow Ca^{2+} + Al^{3+}$

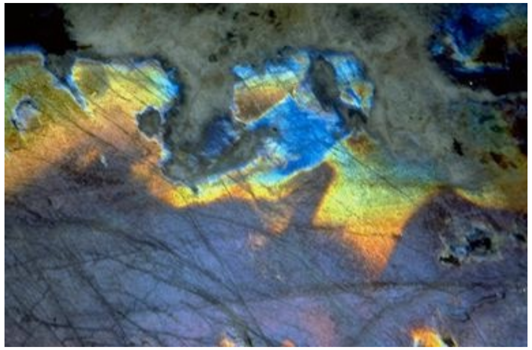
At high temperature, the anorthite (Ca-rich) endmember crystallizes and the composition changes to more Na-rich (albite) with decreasing temperature.

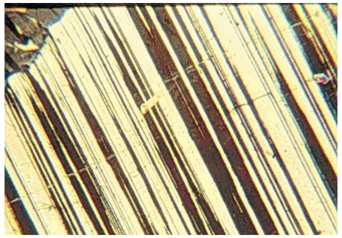
1 = ALBITE 2 = OLIGOCLASE 3 = ANDESINE 4 = LABRADORITE
5 = BYTOWNITE 6 = ANORTHITE 7 = ANORTHOCLASE
8 = SANIDINE 9 = ORTHOCLASE eller MICROCLINE

Silicate minerals: Tectosilicates: **Plagioclase**

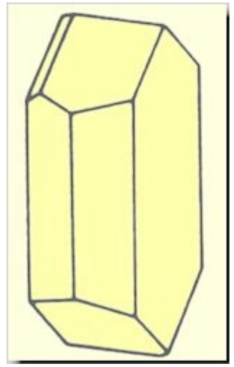
Plagioclase crystals are tabular, lath-shaped. They are white/gray, H= 6

Some plagioclase shows labradorescence (reflection of light along twin lamellas)





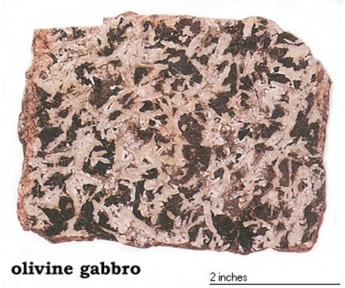
Under the microscope



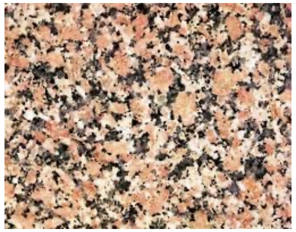
Silicate minerals: Tectosilicates: **Plagioclase**

Plagioclase is common in many magmatic rocks both felsic (rhyolite/granite) and mafic (basalt/gabbro)

Basalt

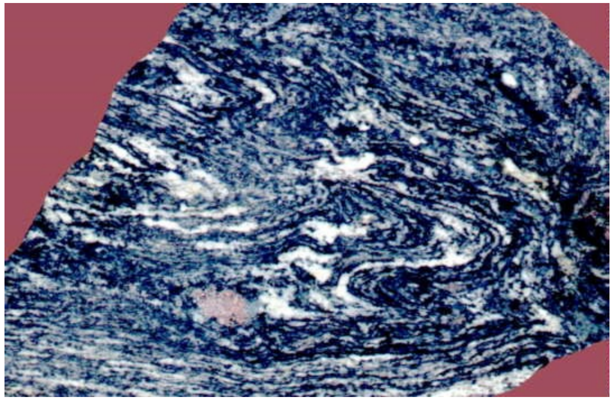


Gabbro



Granite

Plagioclase is also common in several metamorphic rocks (greenschists, amphibolite, gneiss)



Amphibolite with plagioclase (white) and amphibole (black). The red mineral is garnet.

Silicate minerals: Tectosilicates: **Feldspatoids**

This group of minerals is related to feldspar, buthas lower SiO_2 content

Nepheline $Na[AlSiO_4]$

$$Na[AlSi_3O_8] - 2SiO_2 = Na[AlSiO_4]$$

albite nepheline

Leucite $K[AlSi_2O_6]$

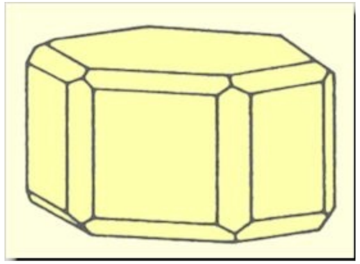
$$K[AlSi_3O_8] - SiO_2 = K[AlSi_2O_6]$$

K-feldspar leucite

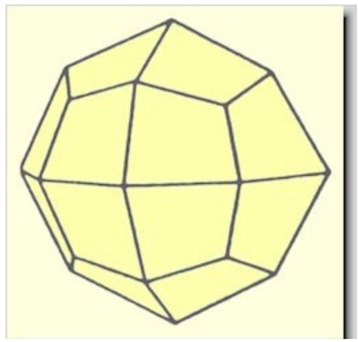
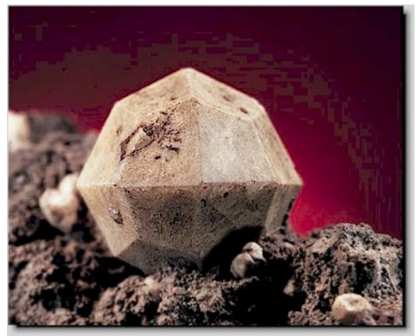
Feldspatoids never occur together with quartz

Silicate minerals: Tectosilicates: **Feldspatoids**

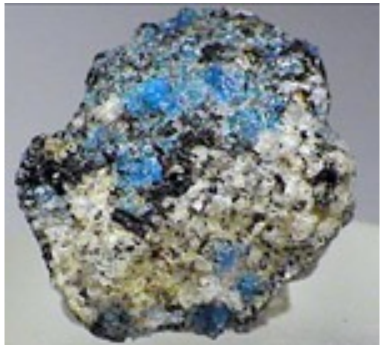
Nepheline: hexagonal, white/grey, H=5.5.-6 and occurs in SiO_2 undersaturated <u>plutonic</u> rocks



Leucite: cubic, white/grey, H=5.5.-6 and occurs in SiO_2 undersaturated <u>volcanic</u> rocks (e.g. Vesuvius)

Silicate minerals: Tectosilicates: **Feldspatoids**



Sodalite: cubic, colourless to dark blue, H= 5-6 occurs in SiO_2 undersaturated, alkaline magmatic rocks. Related to nepheline. $Na_8(Al_6Si_6O_{24})Cl_2$

Nosean: cubic, colourless to variable colours, H= 5-6 occurs in SiO_2 undersaturated, alkaline magmatic rocks. Related to nepheline. $Na_8(Al_6Si_6O_{24})(SO_4)$. H_2O.

Silicate minerals: Tectosilicates: **Zeolites**

Zeolites are a large group (>45) of minerals with special properties due to their crystal structure that contain open channels.

Analcime Na [AlSi2O6] · H2O
Natrolite Na2 [Al2Si3O10] · 2H2O
Chabasite Ca [Al2Si4O12] · 6H2O

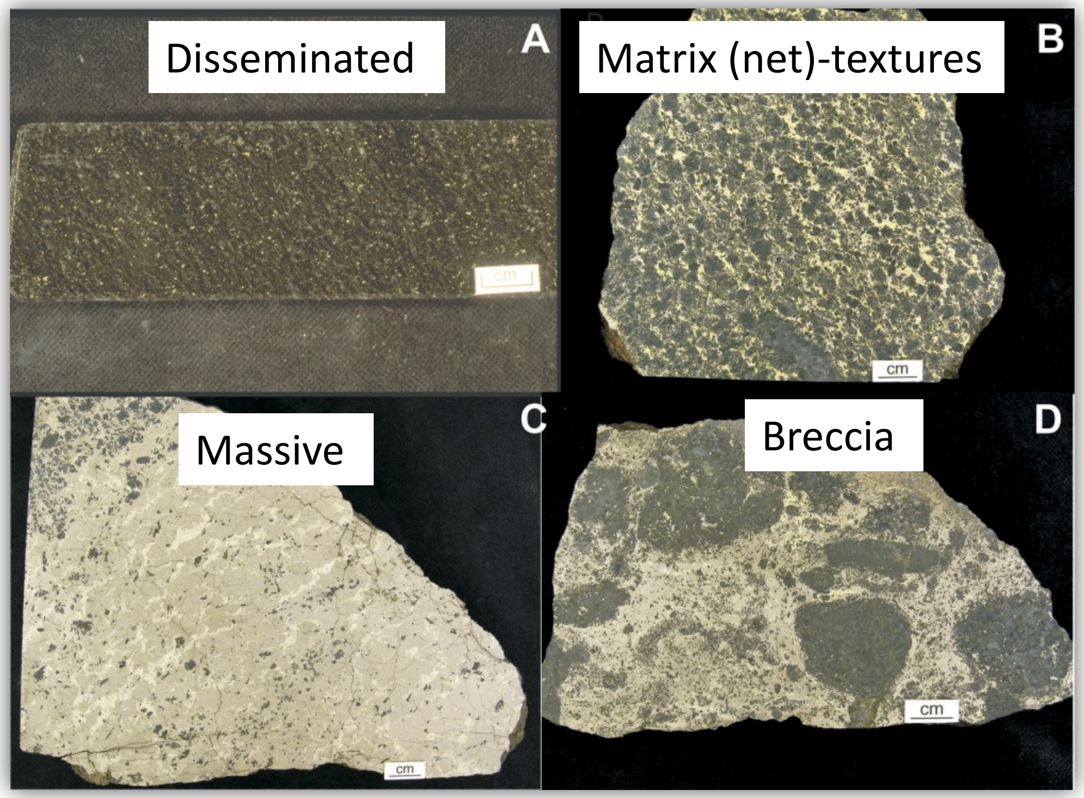
Zeolites are colourless, white, grey and occur in low-grade metamorphic rocks (zeolite facies, 50-150C) and in volcanic rocks as secondary fillings in vesicles.

Sulfides

- Many of the minerals in this group are economically important and provide metals for our technologies.
- They all contain sulfur in their formula and form during hydrothermal or magmatic processes.
- Many sulfides have a metallic lustre (-glanz) and their density is typically >4g/cm^3 . H between 2-5.
- They are not ‘rock-forming’ and occur disseminated in the rocks, in veins or more massive patches.

Sulfide in veins

Sulfides: Textures



Sudbury Ni-Cu-PGE

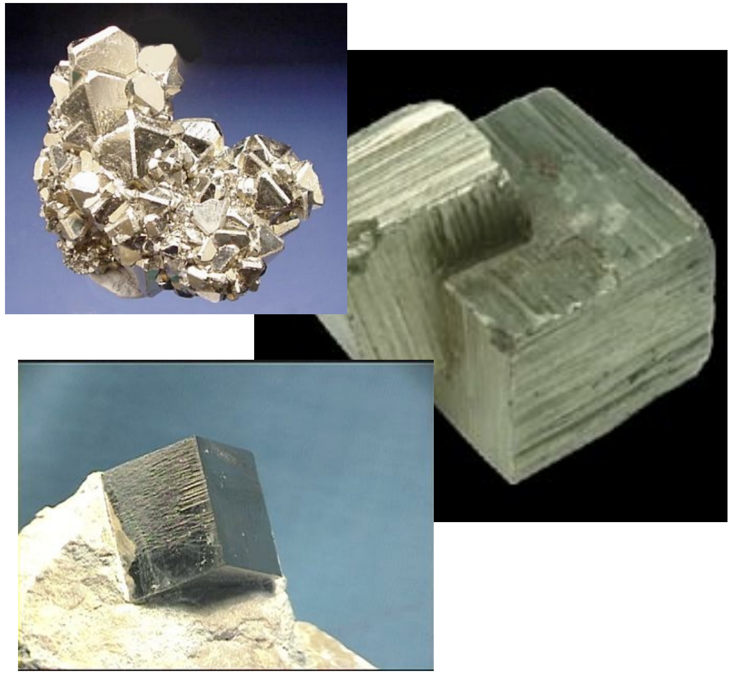
Podolsky Mine - 2450 Level drift intersecting massive Cu-Ni-Pt-Pd-Au mineralization with estimated grade of 20-25% Cu, 1-2% Ni, 0.25-0.75 opt TPM

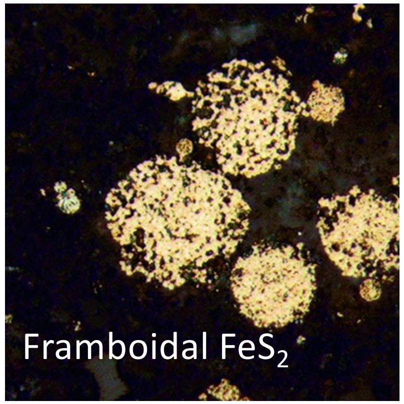
Sulfides: pyrite, markasite

- **Pyrite (FeS_2):** cubic, yellow, (fool's gold).

- Most common sulphide, occurs in many different rock types. It is not used to extract iron, but S for sulfuric acid. Can contain gold.

- **Markasite (FeS_2)** orthorhombic, low T (<300C) polymorph of pyrite. Less common than pyrite, hydrothermal or sedimentary.





Sulfides: pyrrhotite, cinnabar

- **Pyrrhotite (FeS):** dark/dull yellow, light bronze, magnetic. Often together with pentlandite in Ni deposits. Rarely used as iron ore.

- **Cinnabar (HgS):** red, red-brown, D = 8, most important quicksilver ore, famous mine in Almadén (Spain), toxic, occurs in volcanic areas.

Sulfides: galena, sphalerite

- **Galena (PbS):** cubic, light grey/silver, high density (heavy), forms often cubes. Can contain high concentrations of silver (Ag)

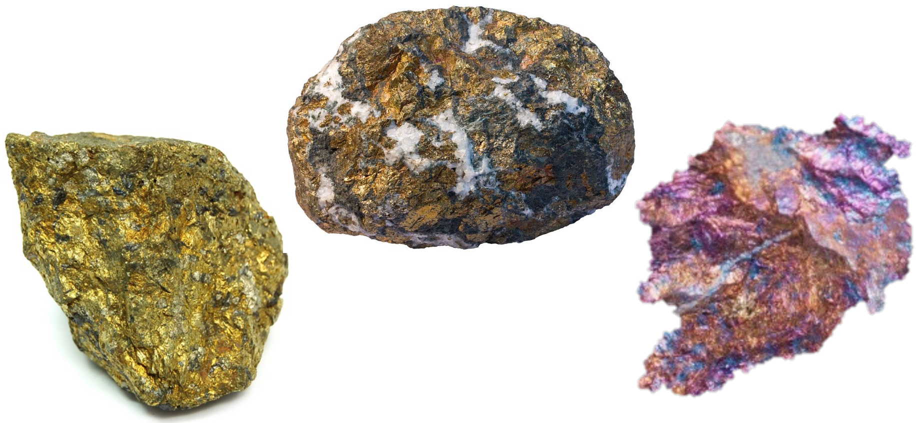
- **Sphalerite (ZnS):** cubic, yellow-brown to dark brown. High lustre, good cleavage

These two sulphides occur often together

Sulfides: chalcocite, chalcopyrite

- **Chalcocite (Cu_2S):** grey, Cu ore, hydrothermal or most commonly as secondary mineral in copper deposits such as the Kupferschiefer and supergene enrichment zones.

- **Chalcopyrite ($CuFeS_2$):** dark yellow, surface tarnishes quickly, most important Cu ore, hydrothermal or magmatic. Weathering products are azurite/malachite



Sulfides: Molybdenite, Stibnite

- **Molybdenite (MoS_2):** grey, silver, soft, flacky, hydrothermal and major Mo ore

- **Stibnite (Sb_2S_3):** light-grey, easily tarnished. Important Sb ore, hydrothermal, prismatic crystals

Sulfides: Pentlandite

- **Pentlandite $(Ni,Fe)_9S_8$):** bronze, important Ni ore. Forms commonly magmatic, often together with pyrrhotite

Oxides

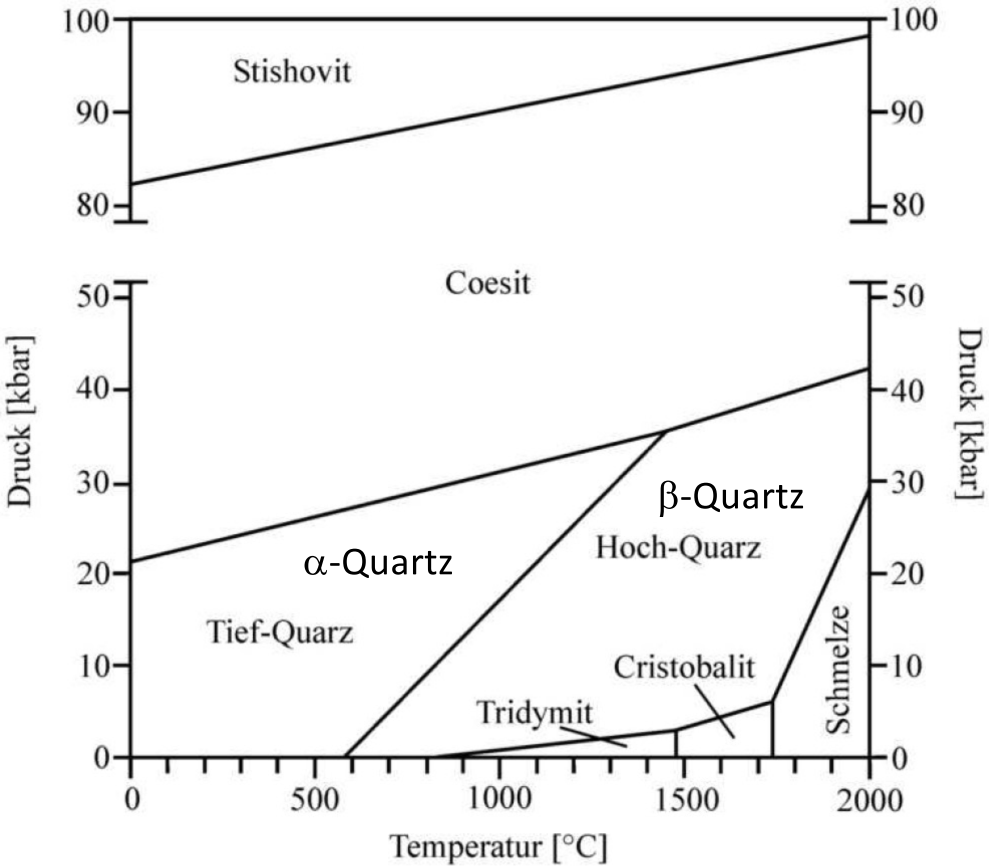
- **Oxides** are a large group of minerals. They form minerals with formulas such as XO_2, X_2O_3, XY_2O_4
- Several minerals in the oxide group are economically important and include, hematite, magnetite, chromite, pyrolusite, rutile, ilmenite, cassiterite, wolframite, uraninite, high-purity quartz

Oxides: Quartz

- **Quartz (SiO_2)** is one of the most abundant minerals in the Earth's crust (remember the abundance of Si and O).

- Quartz is found in all different rock types (magmatic, metamorphic, sedimentary and in hydrothermal veins).
- Quartz is in the oxide group, but the structure is made up of SiO_4^{4-} tetraheder and belongs to the tectosilicates (framework).
- Quartz occurs in many colours and crystallinity varies from microcrystalline to large single crystals.
- Quartz has many polymorphs, depending under which P-T conditions it forms.

Oxides: Quartz polymorphs



Modifikation	Kristallsystem	Dichte (g/cm^3)
Tief-Quarz α-Quartz	trigonal	2,65
Hoch-Quarz β-Quartz	hexagonal	2,53
Tief-Tridymit	monoklin	2,27
Hoch-Tridymit	hexagonal	2,26
Tief-Cristobalit	tetragonal	2,32
Hoch-Cristobalit	kubisch	2,20
Coesit	monoklin	3,01
Stishovit	tetragonal	4,35
Opal ($SiO_2 \cdot nH_2O$)	amorph	2,1 – 2,2

Oxides: Quartz polymorphs

The high temperature polymorphs tridymite and cristobalite are rare and occur in some volcanic rocks and sediments.

The high pressure polymorphs coesite and stishovite occur in some metamorphic rocks and rocks that experienced meteorite impact.

The polymorphs α-quartz and β-quartz have a reversible phase transition at 573C. There occurs a slight volume increase in β-quartz.

Many microcrystalline quartz varieties such as agate, chalcedony, onyx, flint, opal are not polymorphs.

Oxides: Quartz varieties

CARNELIAN - red chalcedony

CHRYSOPRAS - green chalcedony

FLINT

AGATE

ONYX

OPAL

Oxides: Quartz varieties

The coloured varieties are due to crystal lattice defects and in-cooperation of trace elements

Smokey quartz

Citrine

Berg crystal

Rose quartz

Amethyst

Oxides: Rutile, Cassiterite

- **Rutile (TiO_2)**: red-brown, yellowish, is an accessory phase in magmatic and metamorphic rocks. Occurs as small, stubby or needle-shaped crystals. Forms secondary ore deposits (heavy sands). After ilmenite most important Ti ore. Polymorphs are called brookite and anatas.

- **Cassiterite (SnO_2)**: light to dark brown, heavy. Occurs in hydrothermal veins in magmatic rocks, pegmatites. Found also in heavy sands. Most important Sn ore.

Oxides: Pyrolusite, Uraninite

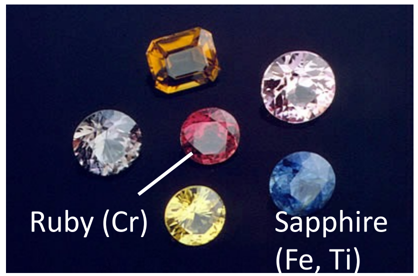
- **Pyrolusite (MnO_2)**: dark grey, occurs in weathered zones together with iorn-hydroxides. Forms also on the seafloor (Mn nodules). Most important Mn ore.

- **Uraninite (UO_2)**: black, radioactive, heavy. Occurs in hydrothermal veins, but commonly in sediments where it is precipitated due to redox change (U^{6+} (soluble) to U^{4+} (insoluble)). Found also in heavy sands. Most important U ore.

Oxides: Wolframite, Corundum

- **Wolframite ($(Fe,Mn)WO_4$)**: black, heavy. Important W ore. Occurs in hydrothermal veins together with cassiterite (+/- molybdenite, pyrite). Also in heavy sands.

- **Corundum (Al_2O_3)**: colourless, red (ruby), blue (sapphire), hard (9). Occurs in metamorphic and magmatic (pegmatites) rocks. Requires high content of Al in the rocks.



Oxides: Hematite, Ilmenite

- **Hematite (Fe_2O_3)**: red, red-brown, grey. Stroke: red. Most important Fe ore. Occurs in in sedimentary rocks (banded iron formations), hydrothermal veins and in skarns (metasomatized limestone). Gives a red hue to many rocks/minerals.

- **Ilmenite ($FeTiO_3$)**: brown-black. Most important Ti ore. Occurs in magmatic rocks and secondary in heavy sands.

Oxides: Spinel, Chromite, Magnetite

- **Spinel ($MgAl_2O_4$)**: different colours, hard. Occurs mainly in metamorphic rocks

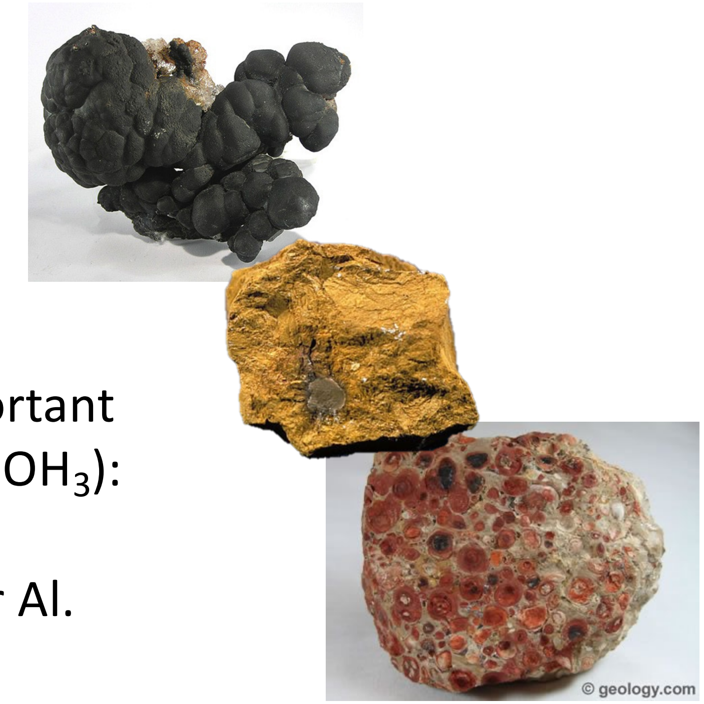
- **Chromite ($FeCr_2O_4$)**: black, semi-metallic lustre. Most important Cr ore. Occurs in ultramafic magmatic rocks and secondary in heavy sands.

- **Magnetite (Fe_3O_4)**: black, magnetic. Important Fe ore. Occurs in hydrothermal veins and in magmatic rocks and secondary in heavy sands. Occurs also together with hematite in BIFs and skarns.

Hydroxides: Goethite, Limonite, Bauxite

Hydroxides are typically weathering products of former oxides or sulphides when they get in contact with water and oxidized conditions. They occur often together with other secondary minerals and clay minerals.

- **Goethite (FeOOH):** yellow-brown, dark brown, dull lustre.
- **Limonite (FeOOH):** yellow-brown, dull lustre. A mineral mix of Fe-hydroxides and clay
- **Bauxite :** yellow-red-brown, dull lustre. Most important ore for Al. A mixture of different Al-hydroxides ($Al(OH_3)$: Gibbsite, AlOOH: Diaspore, Boehmite). Strong weathering and leaching of ‘all’ elments except for Al.



Halogenides: Halite, Sylvite, Carnallite

Halogenides have highly ordered structures and their bonding is typically ionic. Often cubic and good cleavage. Their density is generally low.

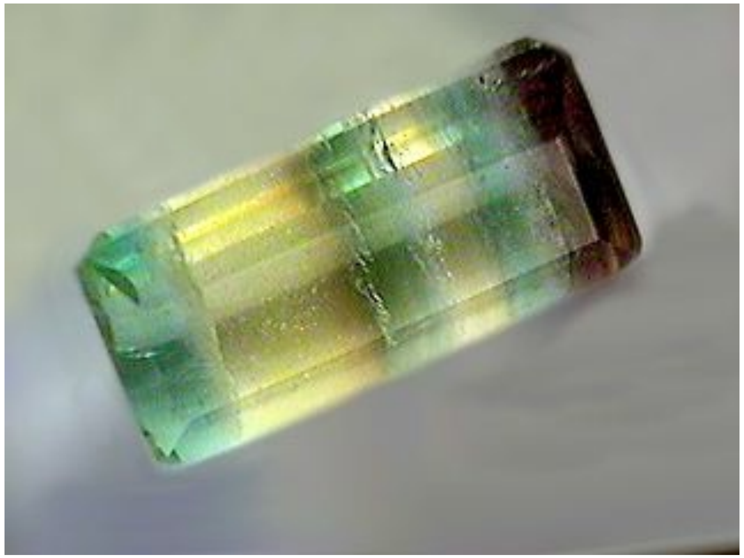
- **Halite (NaCl):** cubic, white, but also other colours. Soluble in water and crystallizes due to evaporation (Evaporites)

- **Sylvite (KCl):** cubic, white, very similar to halite, occurs also in evaporites. Important potassium source

- **Carnallite ($KMgCl_3$ .H2O):** white, grey, red. Easy dissolvable, Important potassium ore. Evaporites and salt deposits.

Halogenides: Fluorite

- **Fluorite (CaF_2):** cubic, different colours, H = 4, perfect cleavage (octahedral) occurs in hydrothermal and pegmatitic veins and rocks. Also in sediments.



Carbonates

This mineral group is making up mostly sedimentary rocks (limestones) and in rarer cases magmatic rocks (carbonatites). They occur as metamorphic rocks (marble).

The minerals contain CO_3^{2-} in their formula, and many of them have a trigonal crystal system.

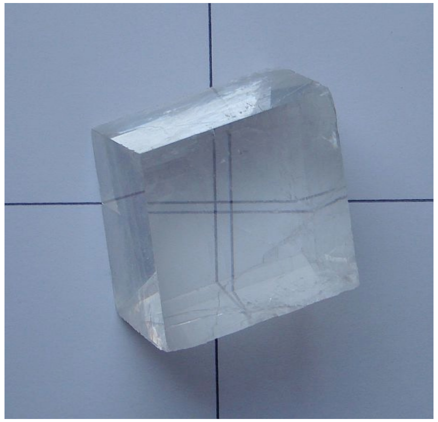
			Ionenradius
Calcit	$CaCO_3$	Ca^{2+}	**1,06 Å**
Rhodochrosit	$MnCO_3$	Mn^{2+}	**0,91 Å**
Siderit	$FeCO_3$	Fe^{2+}	**0,83 Å**
Smithsonit	$ZnCO_3$	Zn^{2+}	**0,83 Å**
Magnesit	$MgCO_3$	Mg^{2+}	**0,78 Å**
Aragonit	$CaCO_3$	Ca^{2+}	**1,06 Å**
Dolomit	$CaMg(CO_3)$	Mg^{2+}	**0,78 Å**




Carbonates: Calcite, Aragonite

- **Calcite ($CaCO_3$):** white, colourless, H = 3, it is the most common carbonate mineral. Aragonite is less stable, but slightly harder. It is the high-pressure polymorph, and is also mother of pearl. Occurs in vesicles of volcanic rocks.

Calcite has high birefringence and reacts with hydrochloric acid.



Calcite occurs as gangue material in hydrothermal veins. Carbonatites (magmatic carbonates) contain calcite. Limestone consists of either biogenic (shells of microorganism) or chemically precipitated calcite.

http://www.itp.uni-hannover.de/~zawischa/ITP/kalcal.h

Carbonates: Rhodochrosite, Siderite, Magnesite

- **Rhodochrosite ($MnCO_3$):** red, pink, forms in hydrothermal systems. Also in weathering zones. In place used as Mn ore.

- **Siderite ($FeCO_3$):** brown, grey-yellow, occurs hydrothermal, metamorphic and sedimentary. Can be used as Fe ore.

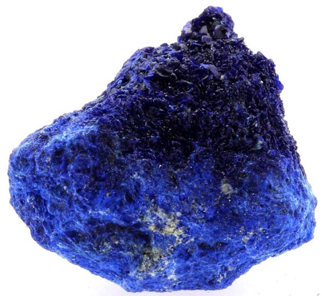
- **Magnesite ($MgCO_3$):** grey, white. Occurs sedimentary and metamorphic. When fired to 1800C it becomes MgO (periclase), used as insulation in high-T ovens.

Carbonates: Dolomite, Malachite, Azurite

- **Dolomite ($CaMg(CO_3)_2$):** grey, white, forms in metasomatized rocks (dolomitization) and under diagenetic conditions where Mg is available.

- **Malachite ($Cu_2(CO_3)(OH)_2$):** green, secondary Cu ore, often together with azurite. Occurs in supergene enrichment zones. Locally, Cu ore

- **Azurite ($Cu_3(CO_3)_2(OH)_2$):** blue, secondary Cu ore, often together with malachite when more water is added and oxidation happnes. Occurs in supergene enrichment zones.



Sulfates/Wolframites/Phosphates: Baryte, Anhydrite, Gypsum

These minerals have either SO_4^{2-} , WO_4^{2-} or PO_4^{2-} units in their formula

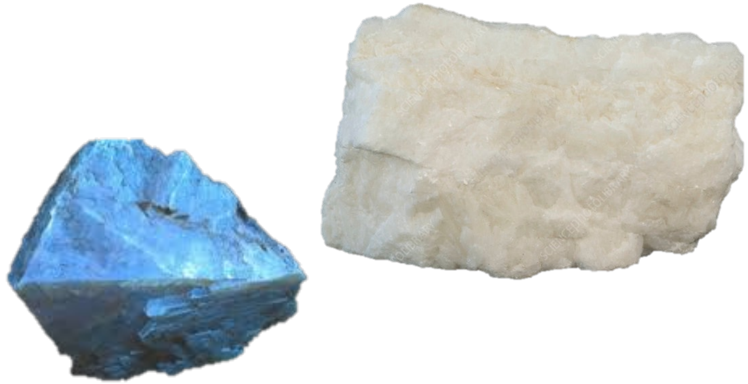
- **Baryte ($BaSO_4$):** grey, white, ‘heavy’ D = 4.5g/cm^3 . Forms in low-temperature hydrothermal systems and sedimentary

- **Anhydrite ($CaSO_4$):** colorless, grey, lila, light blue. Occurs together with halite in evaporites and also hydrothermal.

- **Gypsum ($CaSO_4 . H_2O$):** white, colourless, soft H = 2. Forms in evaporites and from anhydrite by taking up water (volume increase). Hydrothermal.

Sulfates/Wolframites/Phosphates: Scheelite, Apatite

- **Scheelite ($CaWO_4$):** grey-white, light yellowish, heavy. Blueish under UV light. Occurs in magmatic-hydrothermal systems and in skarns. Together with cassiterite. Important W ore after wolframite.



under UV light

- **Apatite ($Ca_5(PO_4)_3(OH,F,Cl)$):** different colours or colourless. H = 5. Occurs as accessory phase in many rocks. Larger crystals in pegmatites. Enriched in heavy sands, source of phosphorous.