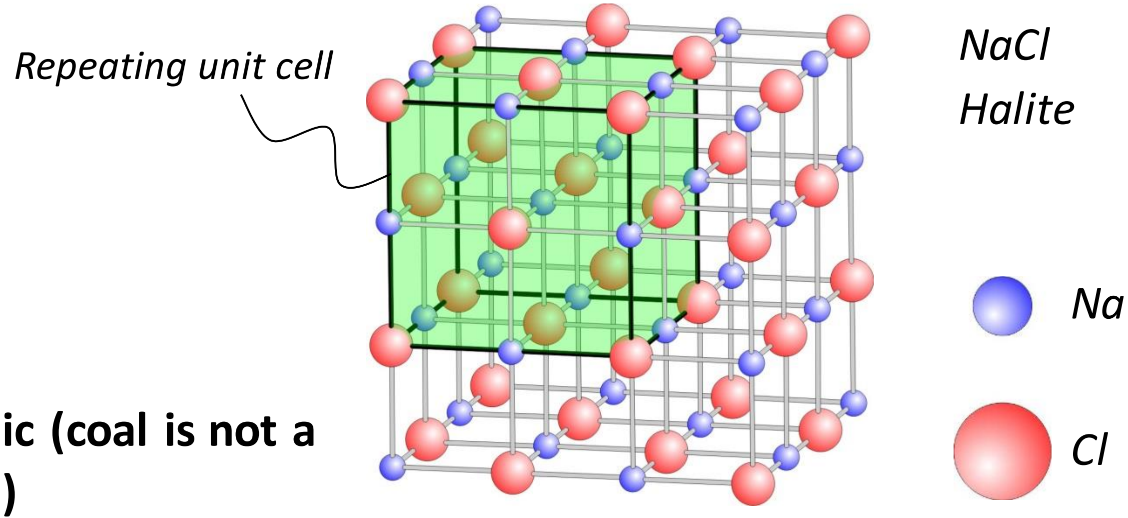
MINERALS

Rock’s elementary building blocks

✶ What is a mineral?

A mineral is

1. **natural**
2. **solid**
3. **inorganic (coal is not a mineral)**

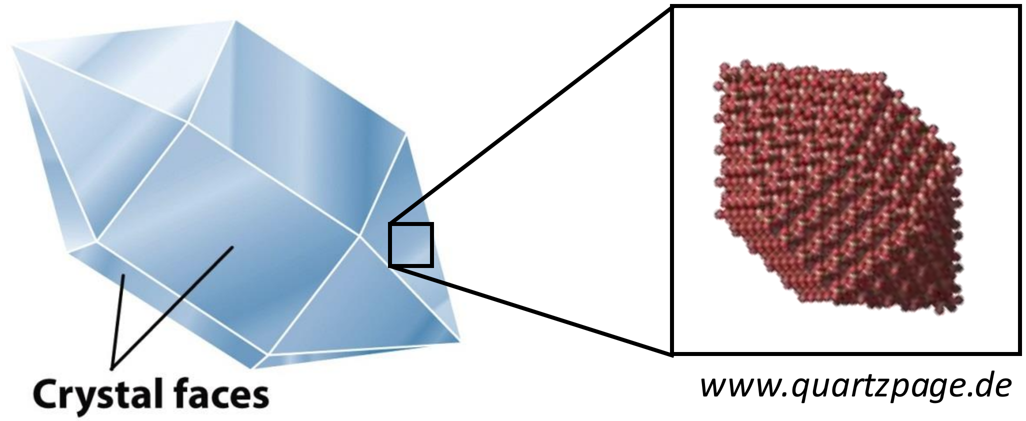


…characterized by

4. **a specific chemical composition**
5. **a regular, repeating 3D arrangement of atoms (crystal structure)**

Understanding Earth

- The regular **shape of crystals** reflects the orderly arrangement of atoms



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- The **structure of a mineral** (how atoms are distributed in 3D) depends on its **chemical composition**, and is also a function of **temperature** and **pressure** (e.g. graphite vs. diamond).

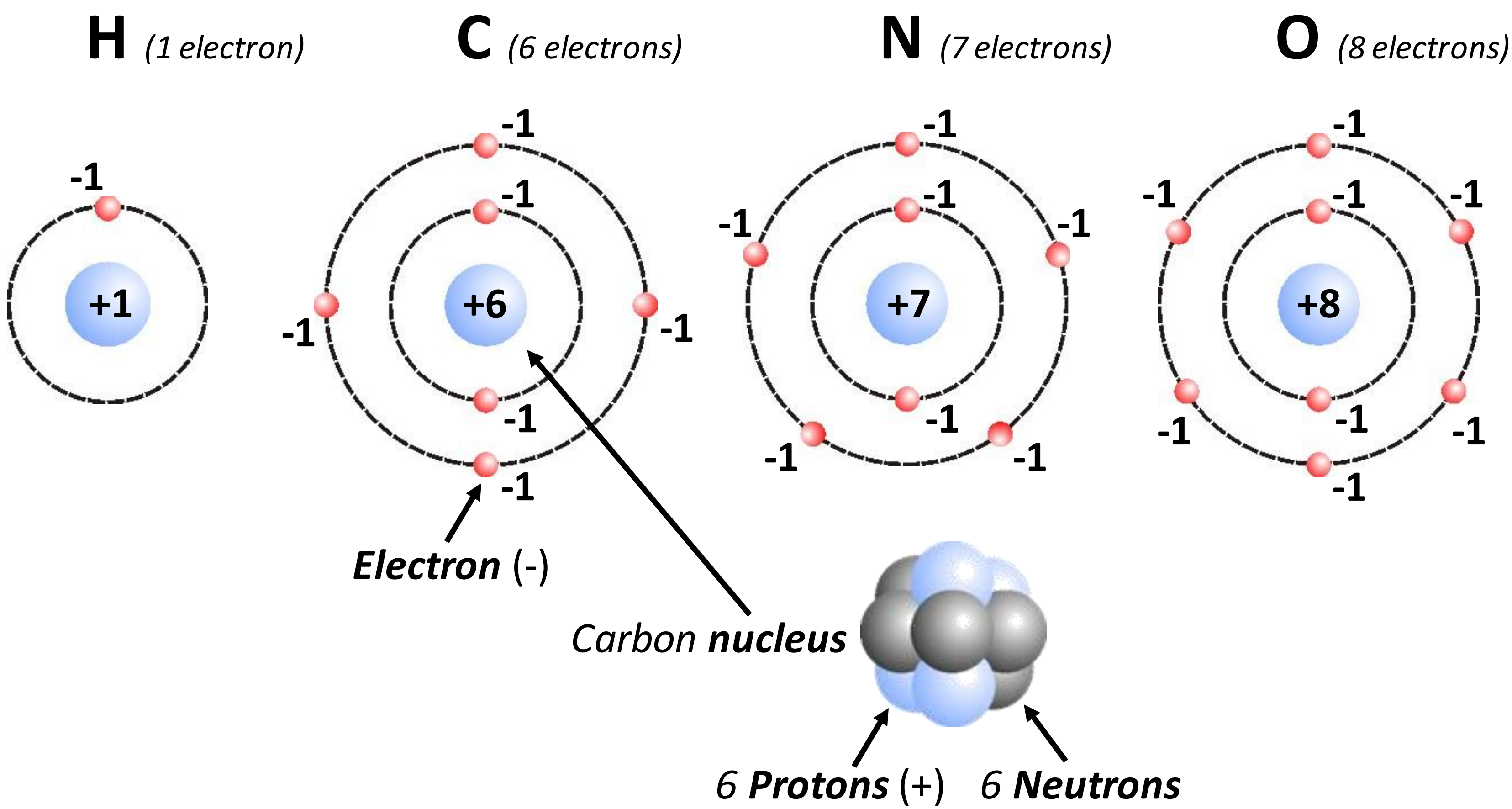
Very high T and P

Diamond

Moderate T and P

Graphite

✶ Atoms, isotopes



Electron = negative electric charge

Proton = positive electric charge

Neutrons = no electric charge

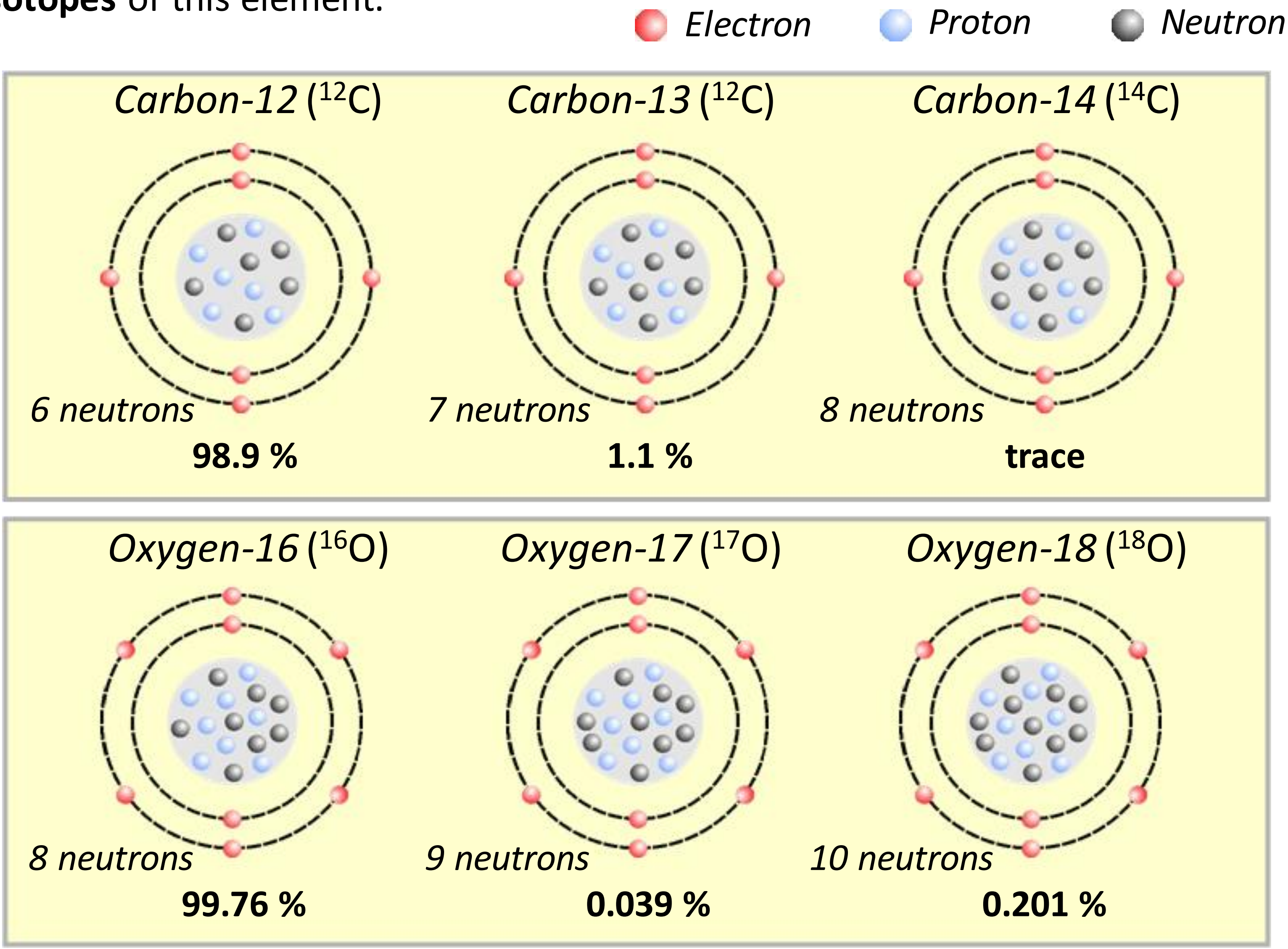
} nucleus

Atoms are electrically neutral

↓

number of e- = number of p+

Atoms of an element with different numbers of neutrons are different **isotopes** of this element.

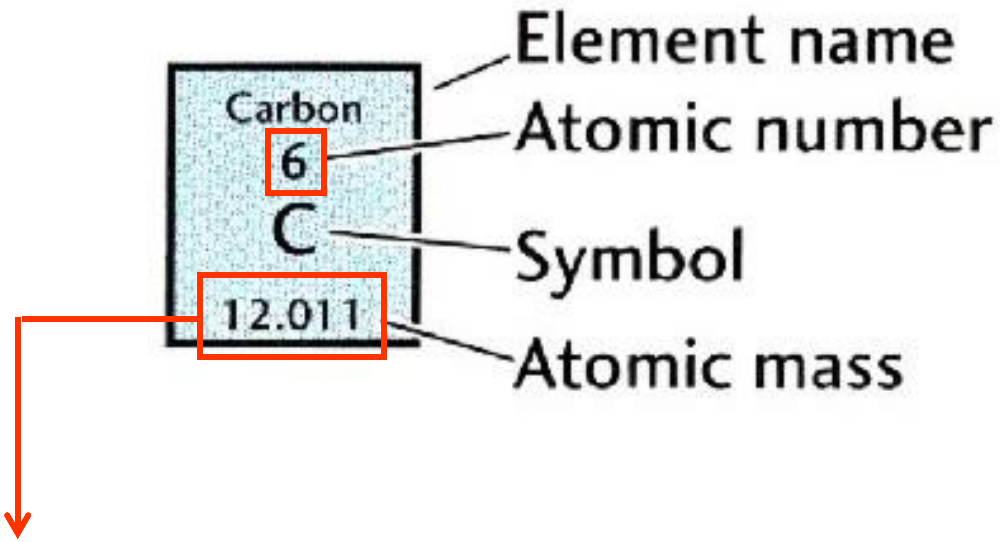


Each element is characterized by its **atomic number**.

Atomic number = number of electrons (protons)

Atomic mass = sum of the masses of protons and neutrons

By convention, one atom of ^{12}C has a mass of 12 amu (**atomic mass unit)**



The atomic mass of an element depends on the relative abundance of its isotopes

Periodic table of elements

Elements of major abundance in Earth's crust

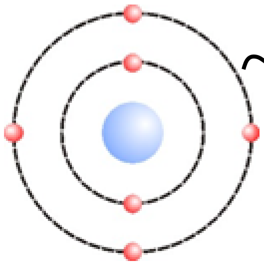
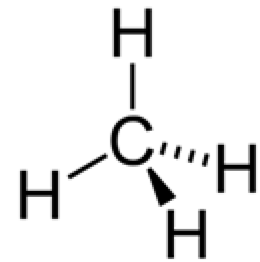
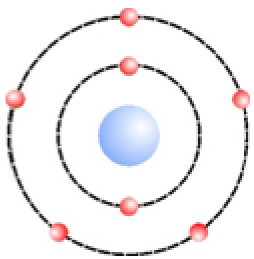
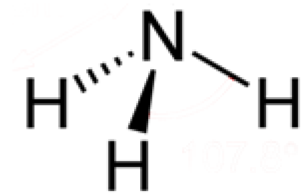
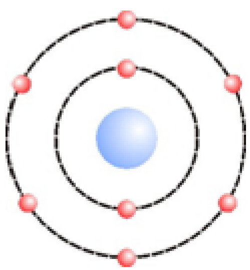
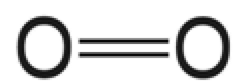
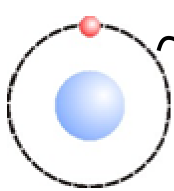
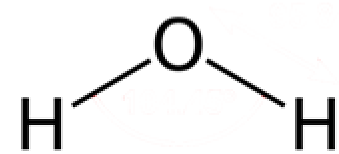
Elements of lesser abundance but of major geologic importance

Carbon 6 C 12.011 — Element name, Atomic number, Symbol, Atomic mass

Hydrogen 1 H 1.0079																	Helium 2 He 4.0026
Lithium 3 Li 6.941	Beryllium 4 Be 9.0122											Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.0067	Oxygen 8 O 15.9994	Fluorine 9 F 18.9984	Neon 10 Ne 20.1797
Sodium 11 Na 22.9898	Magnesium 12 Mg 24.3050											Aluminum 13 Al 26.9815	Silicon 14 Si 28.0855	Phosphorus 15 P 30.9738	Sulfur 16 S 32.066	Chlorine 17 Cl 35.4527	Argon 18 Ar 39.948
Potassium 19 K 39.0983	Calcium 20 Ca 40.078	Scandium 21 Sc 44.9559	Titanium 22 Ti 47.867	Vanadium 23 V 50.9415	Chromium 24 Cr 51.9961	Manganese 25 Mn 54.9380	Iron 26 Fe 55.845	Cobalt 27 Co 58.9332	Nickel 28 Ni 58.6934	Copper 29 Cu 63.546	Zinc 30 Zn 65.39	Gallium 31 Ga 69.723	Germanium 32 Ge 72.61	Arsenic 33 As 74.9216	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.80
Rubidium 37 Rb 85.4678	Strontium 38 Sr 87.62	Yttrium 39 Y 88.9059	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.9064	Molybdenum 42 Mo 95.94	Technetium 43 Tc (97.907)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.9055	Palladium 46 Pd 106.42	Silver 47 Ag 107.8682	Cadmium 48 Cd 112.411	Indium 49 In 114.818	Tin 50 Sn 118.710	Antimony 51 Sb 121.760	Tellurium 52 Te 127.60	Iodine 53 I 126.9045	Xenon 54 Xe 131.29
Cesium 55 Cs 132.9054	Barium 56 Ba 137.327	Lanthanum 57 La 138.9055	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.9479	Tungsten 74 W 183.84	Rhenium 75 Re 186.207	Osmium 76 Os 190.2	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08	Gold 79 Au 196.9665	Mercury 80 Hg 200.59	Thallium 81 Tl 204.3833	Lead 82 Pb 207.2	Bismuth 83 Bi 208.9804	Polonium 84 Po (208.98)	Astatine 85 At (209.99)	Radon 86 Rn (222.02)
Francium 87 Fr (223.02)	Radium 88 Ra (226.0254)	Actinium 89 Ac (227.0278)	Rutherfordium 104 Rf (261.11)	Dubnium 105 Db (262.11)	Seaborgium 106 Sg (263.12)	Bohrium 107 Bh (262.12)	Hassium 108 Hs (265)	Meitnerium 109 Mt (266)			Ununbium 112 Uub (277)						

Cerium 58 Ce 140.115	Praseodymium 59 Pr 140.9076	Neodymium 60 Nd 144.24	Promethium 61 Pm (144.91)	Samarium 62 Sm 150.36	Europium 63 Eu 151.965	Gadolinium 64 Gd 157.25	Terbium 65 Tb 158.9253	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.9303	Erbium 68 Er 167.26	Thulium 69 Tm 168.9342	Ytterbium 70 Yb 173.04	Lutetium 71 Lu 174.967
Thorium 90 Th 232.0381	Protactinium 91 Pa 231.0388	Uranium 92 U 238.0289	Neptunium 93 Np (237.0482)	Plutonium 94 Pu (244.664)	Americium 95 Am (243.061)	Curium 96 Cm (247.07)	Berkelium 97 Bk (247.07)	Californium 98 Cf (251.08)	Einsteinium 99 Es (252.08)	Fermium 100 Fm (257.10)	Mendelevium 101 Md (258.10)	Noblelium 102 No (259.10)	Lawrencium 103 Lr (262.11)

The periodic table.

Atoms		Valency Number of bonds that can be formed	Examples of molecules		
C		Optimal nbr = 8 electrons (octet rule) **4**	CH_4		*METHANE*
N		**3**	NH_3		*AMMONIA*
O		**2**	O_2		*FREE OGYGEN*
H		Optimal nbr = 2 electrons **1**	H_2O		*WATER*

✶ Chemical bonds

3 types of chemical bonds exist in minerals:

1. **Covalent bond** (electrons shared)
   An atom shares one or more electrons with another atom, electrons being attracted by the nucleus of each atom.

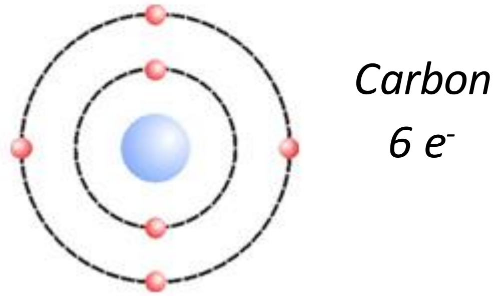
2. **Ionic bon** (electrons transferred)
   An atom gains one or more electrons from another atom (transfer of electrons). The positively charged ion (cation = atom that has lost one or more electrons) is attracted by the negatively charged ion (anion = atom that has gained one or more electrons)

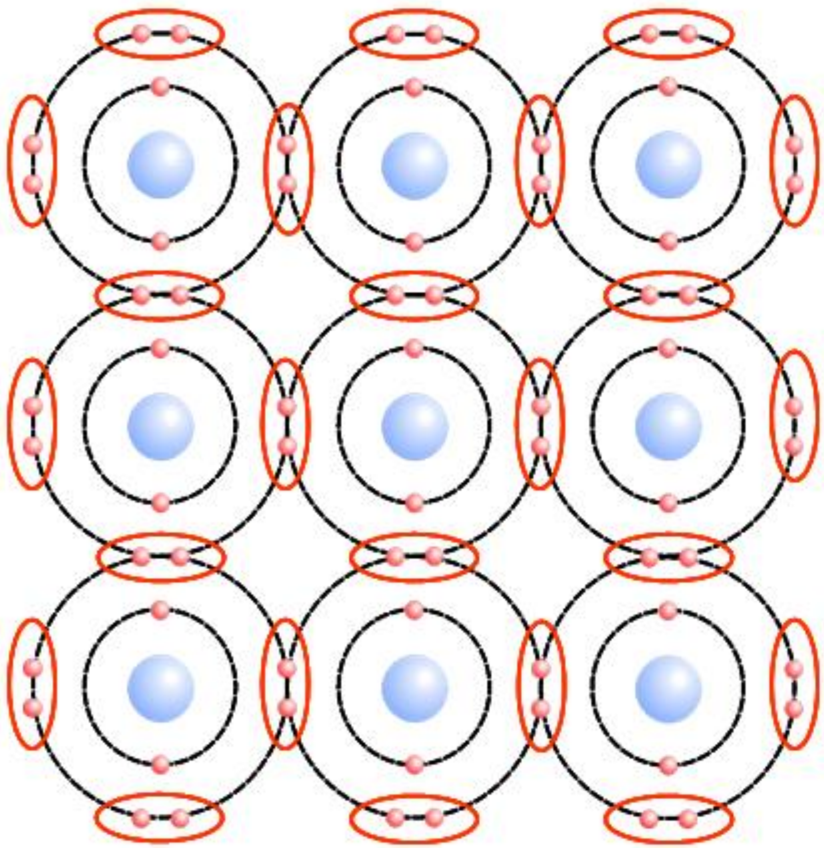
3. **Metallic bond** (electrons freely moving)
   Atoms which have a strong tendency to lose electrons (cations) are held together by their attraction to free (mobile) electrons ("cations in a sea of electrons").

1. Covalent bond

EXAMPLES: *diamond, graphite*

*Each carbon atom **shares** 4 electrons with its neighbors (1 with each surrounding atom of C)*



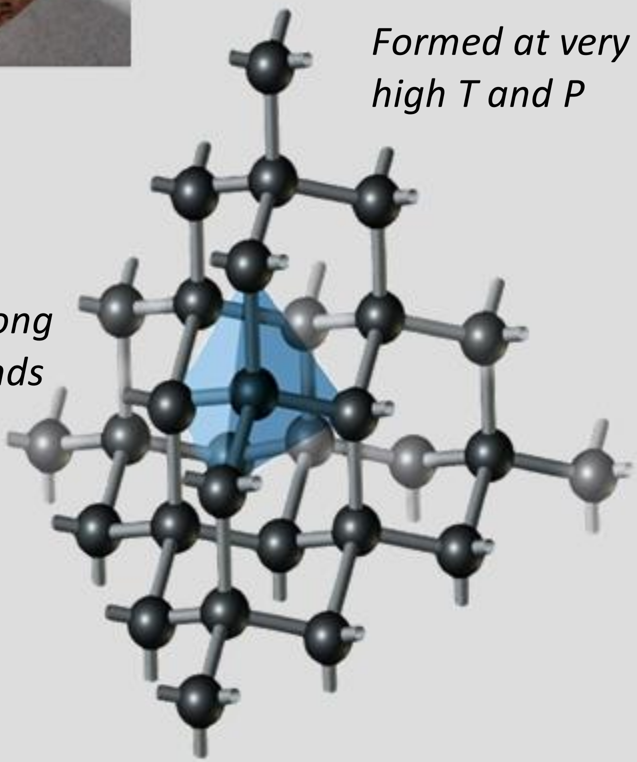


Electron sharing in Diamond (2D projection)

POLYMORPHS

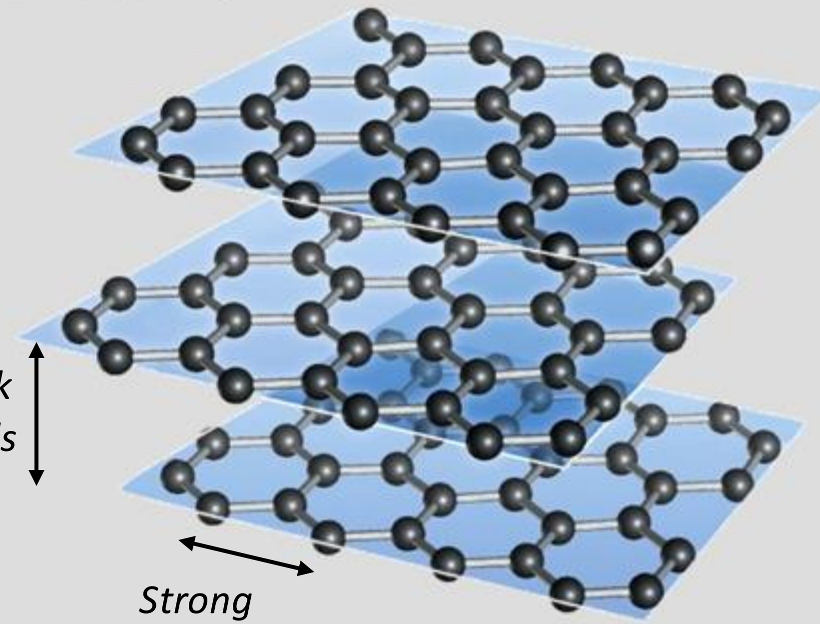
Carbon atoms closely packed
Each atom shares 4 electrons with 4 other atoms

Formed at very high T and P



Carbon atoms arranged in sheets
Each atom shares 3 electrons with 3 other atoms

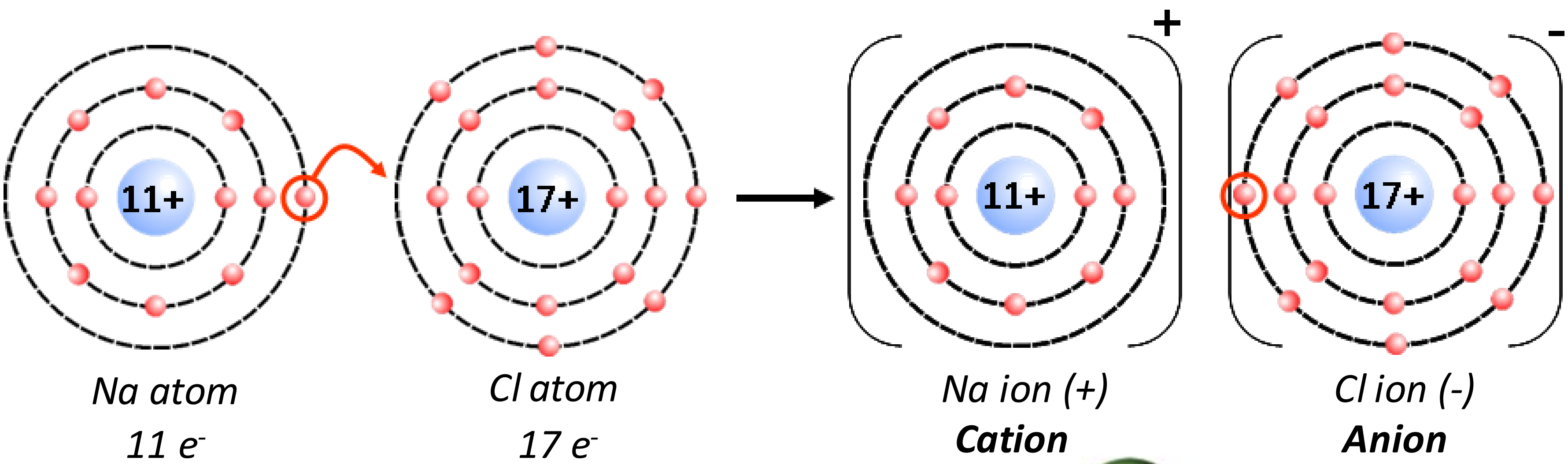
Formed at moderate T and P

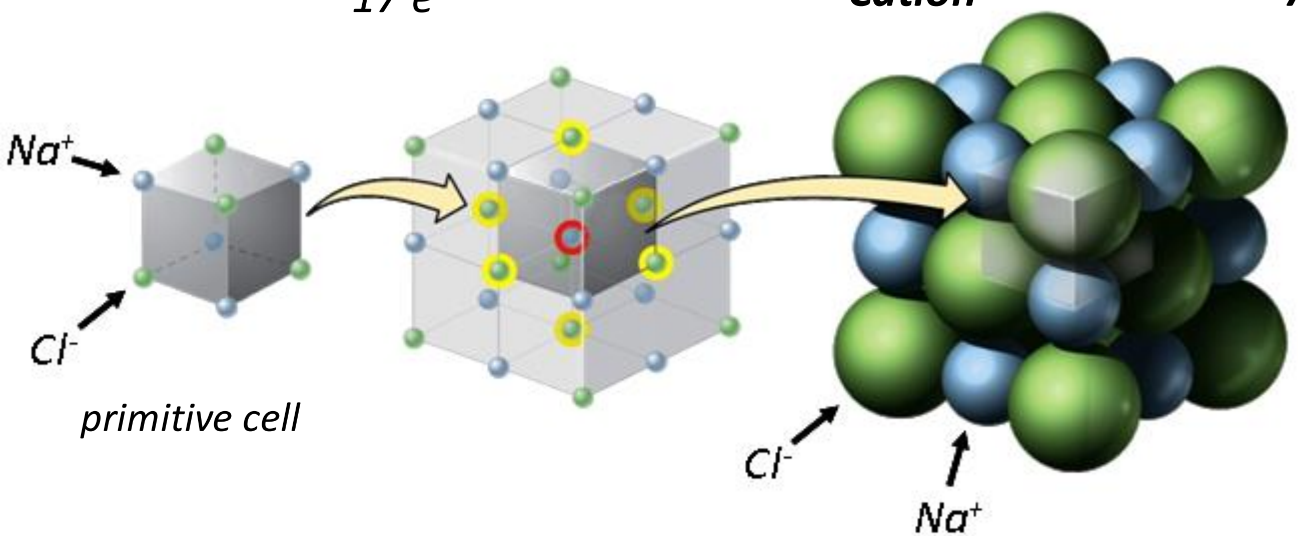


2. Ionic bond

***EXAMPLE**: halite (NaCl, sodium chloride, “table salt”)*

The sodium atom **loses** one electron (cation) and the chlorine atom **gains** one (anion)





Each Na^+ is surrounded by 6 Cl^-, and vice versa

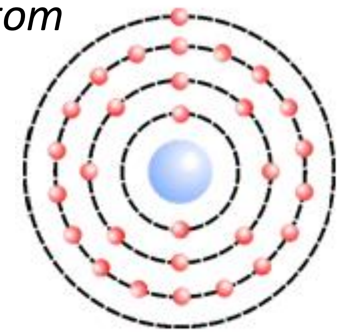
Understanding Earth

3. Metallic bond

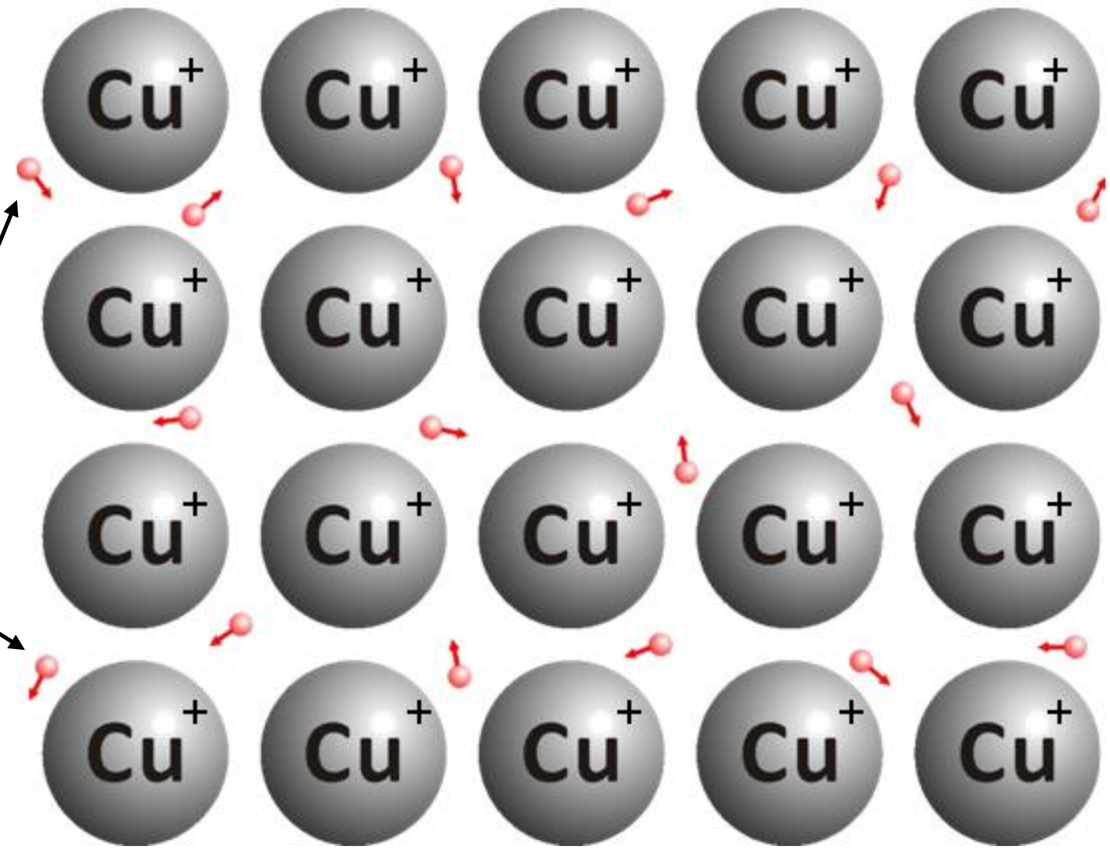
***EXAMPLES**: gold, silver, copper, some sulfides…*

Copper atom

29 e^-



Copper mineral structure

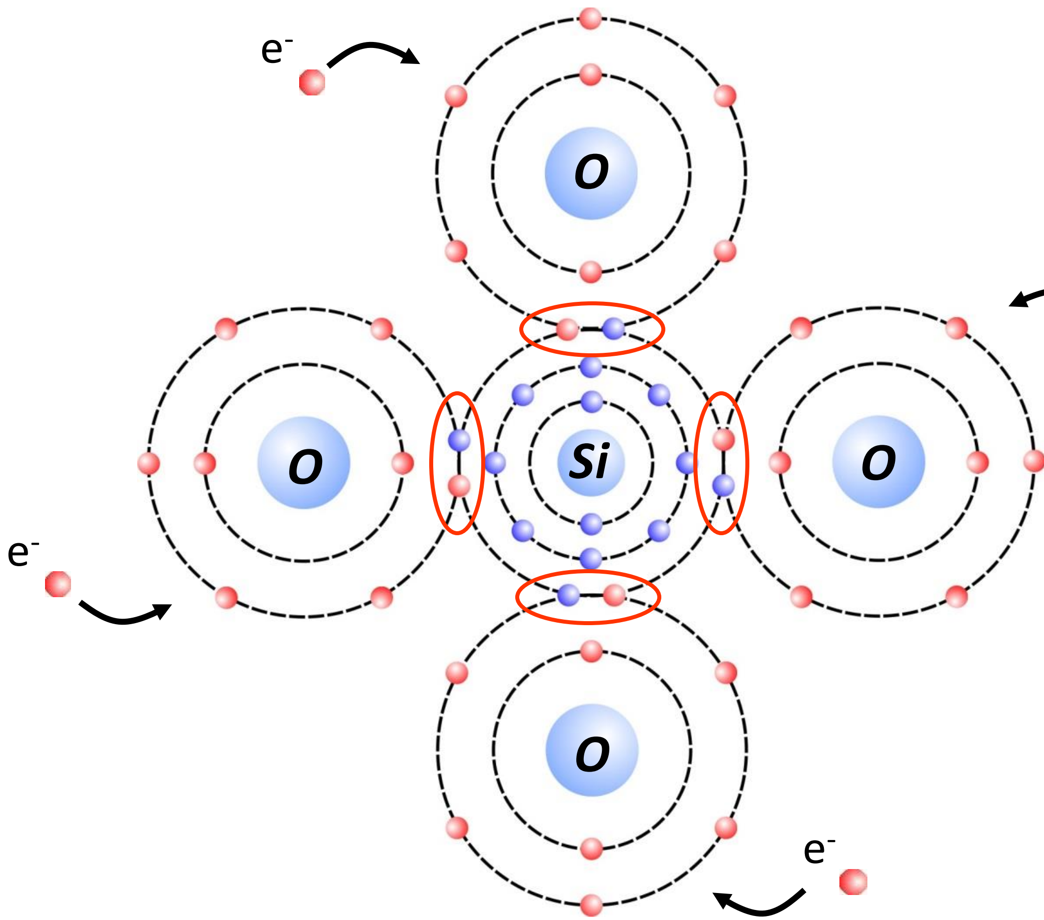


Delocalized (free) electrons

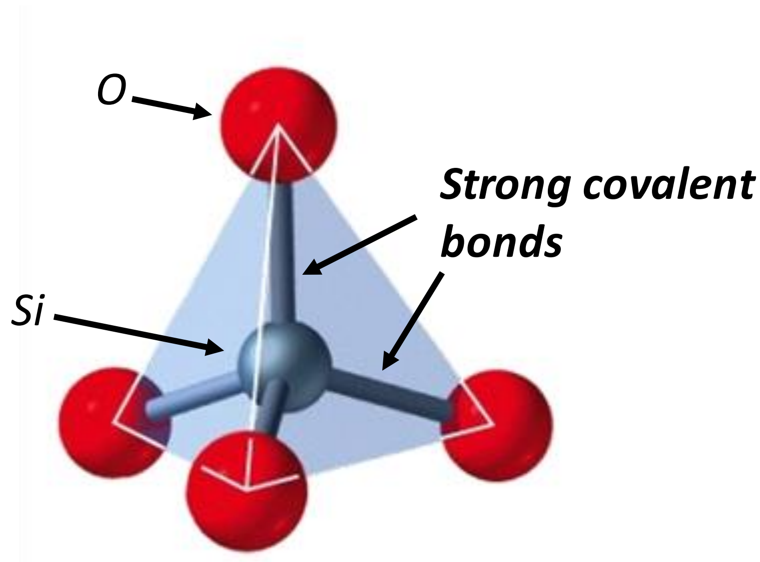
✶ Silicate minerals

BASIC STRUCTURAL UNIT: **silicon-oxygen tetrahedron = $[SiO_4]^{4-}$ = silicate anion**

Each O can share one e- with another Si (**covalent bonds**) or bind to a cation (**ionic bonds**) → possibility of combining covalent and ionic bonds



$[SiO_4]^{4-}$

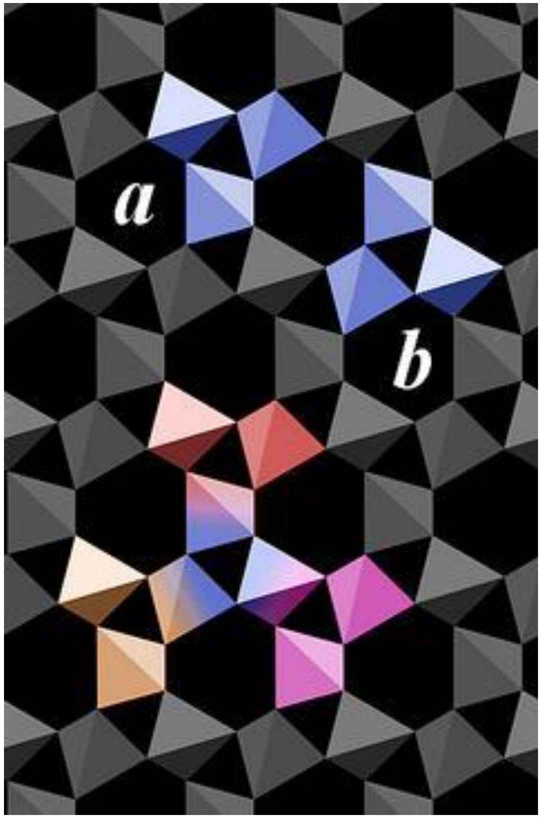


EXAMPLES of silicate minerals

***1**. Quartz (SiO_2)*

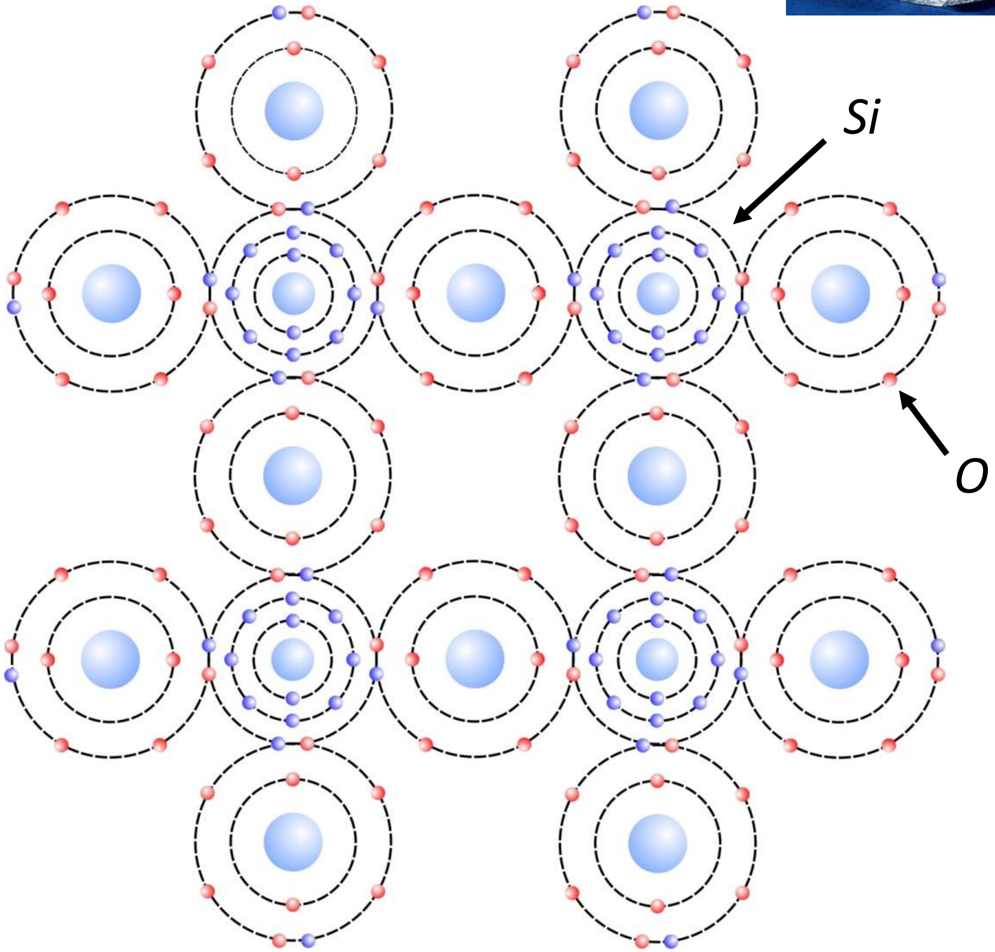
Each Si surrounded by 4 O, and each O linked to 2 Si

Silicate tetrahedra linked by **covalent bonds**



www.quartzpage.de

3D structure of Quartz



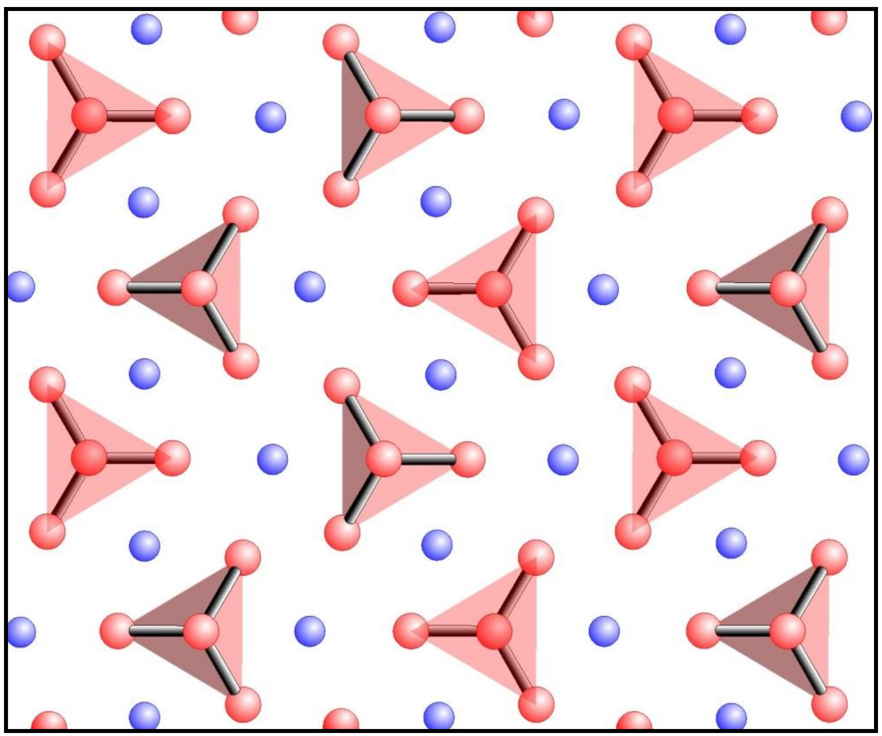
Electron sharing in SiO_2 (2D projection)

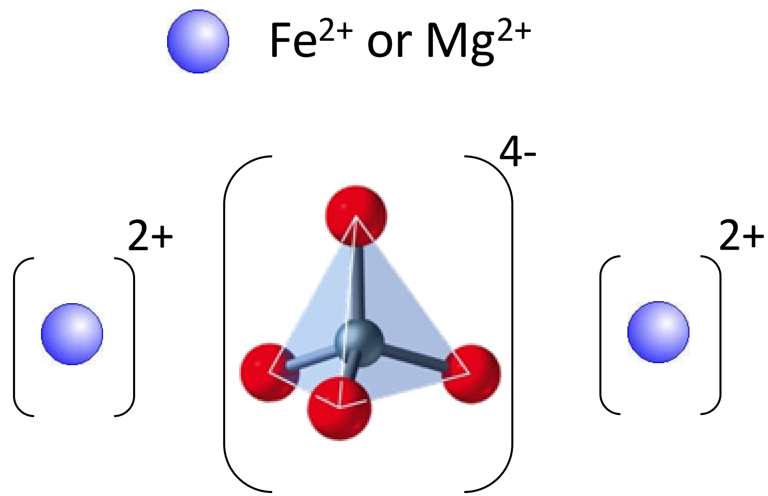
Combination of covalent and ionic bonds

2. Olivine [$(Mg, Fe)_2SiO_4$]

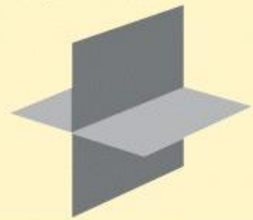
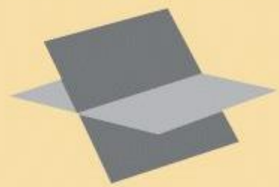
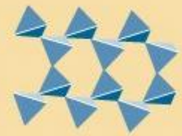
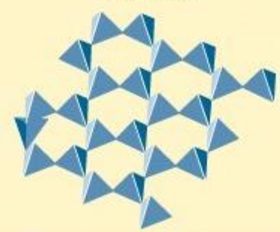
Silicate anions ($[SiO4]^{4-}$) are linked to cations (Fe^{2+} or Mg^{2+}) by ionic bonds

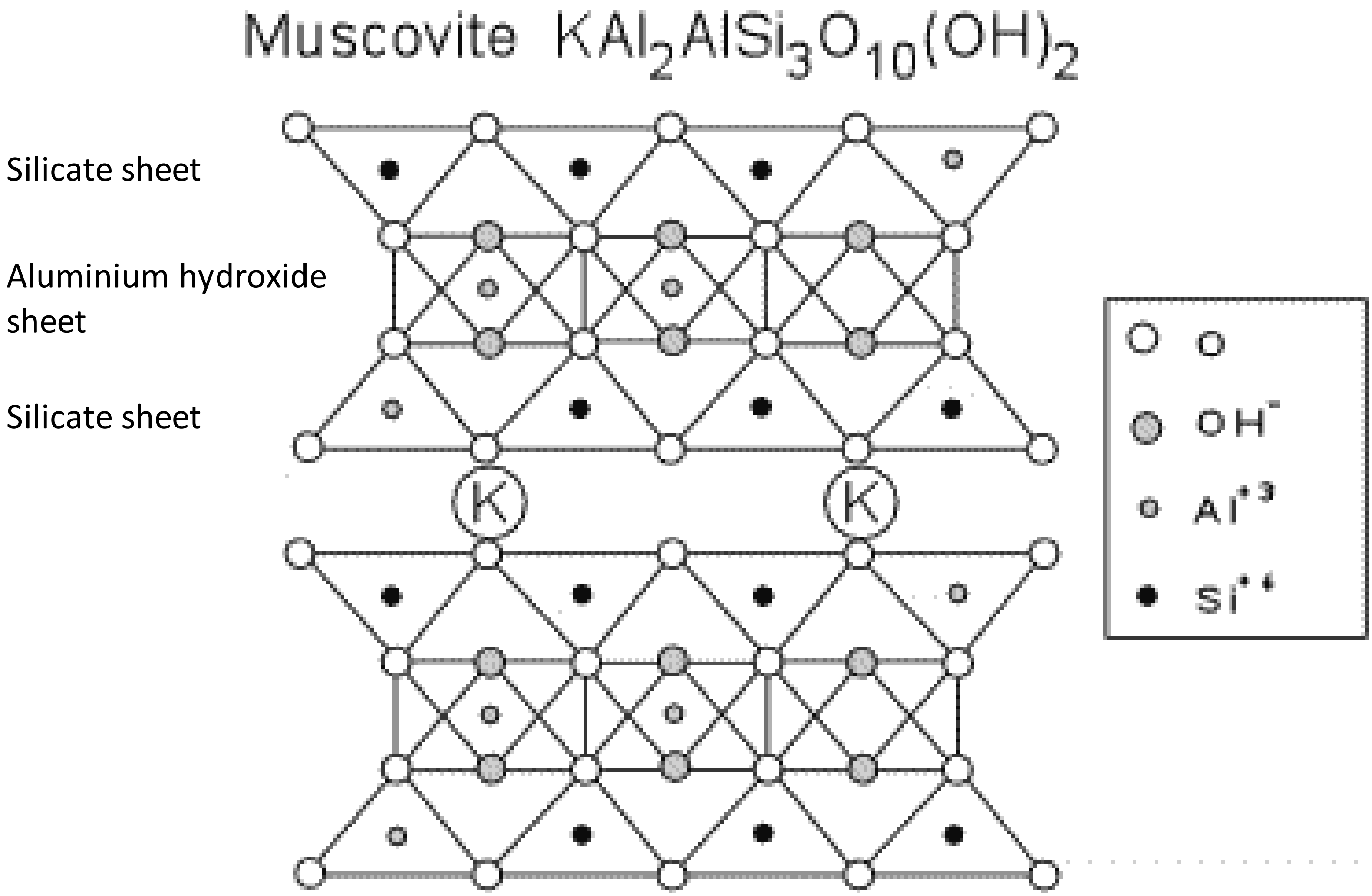
Fosterite: Mg_2SiO_4 ↕ Solid solution
Fayalite: Fe_2SiO_4





The silicate anions are held together by metallic cations (Fe^{2+} or Mg^{2+}). The -4 charge of each silicate anion is balanced by 2 metallic cations of charge +2 (Fe^{2+} or Mg^{2+})

Mineral	Chemical formula	Cleavage planes and number of cleavage directions	Structure	Specimen
(a) Olivine	$(Mg,Fe)_2SiO_4$	1 plane 	Isolated tetrahedra 	
(b) Pyroxene	$(Mg,Fe)SiO_3$	2 planes at 90° 	Single chains 	
(c) Amphibole	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	2 planes at 60° and 120° 	Double chains 	
(d) Mica	Muscovite: $KAl_2(AlSi_3O_{10})(OH)_2$	1 plane 	Sheets 	
(e) Feldspar	Orthoclase feldspar: $KAlSi_3O_8$ Plagioclase feldspar: $(Ca,Na)\ AlSi_3O_8$	2 planes at 90° 	Three-dimensional frameworks 	



http://www.tulane.edu/~sanelson/eens211/weathering&clayminerals.htm

✶ Formation of minerals

- **Crystallization**: process by which atoms in a gas or a liquid assemble in an orderly 3D pattern (lattice) to form a solid substance (mineral crystal).

- **Contexts in which new minerals can form**:

1. **Saturation** of brines – as water is removed by evaporation and/or dissolved ions are added to the solution, the solution becomes saturated and salt precipitate into crystals)

2. **Phase change** – liquid-solid, gas-solid

3. **Biomineralization** – biologically-induced precipitation of minerals – biominerals – (e.g. corals, mollusks…)

4. **Chemical weathering** – transformation of a preexisting rock at/near Earth's surface (e.g., chemical reactions with rainwater ›› $2\ KAlSi_3O_8 + 2\ H_2CO_3 + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4\ SiO_2 + 2\ K^+ + 2\ HCO_3^-$)

5. **Metamorphism** – recrystallization of a preexisting rock at the solid-state resulting from variations in T, P or in contact with hydrothermal fluids deep inside the crust.

1. **Saturation** of brines

Sebkha El Melah is a 150-km^2 **evaporite** basin located Along Tunisia's southeastern coast. Sea water rich in dissolved minerals is occasionally discharged into the lake and quickly evaporates once the lake becomes isolated from the sea.

Major ions precipitating in the lake are Na^+, K^+, Mg^{2+}, Cl^-, and SO_4^{2-}.

Minerals formed:

NaCl	*Halite*
KCl	*Sylvite*
$MgSO_4.H_2O$	*Kieserite*
…	

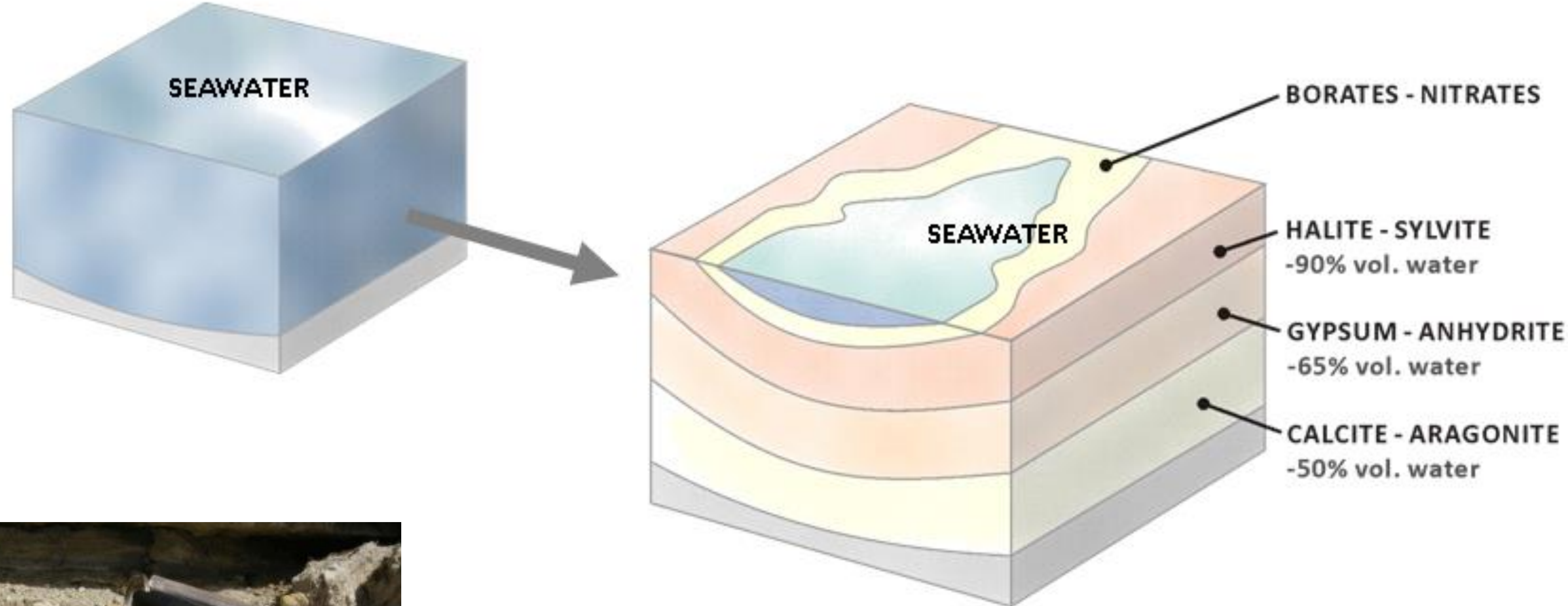
Landsat images (http://earthobservatory.nasa.gov)

Lake Urmia (Iran)

US DEPARTMENT OF THE INTERIOR/USGS

"The three rivers that supply nearly 90% of the water flowing into Urmia have all been dammed for irrigation and hydropower. And groundwater recharge to those rivers has tapered thanks to an estimated 40,000 illegal wells that have lowered the water table, Iranian experts say."

Science, Stone 2015



Messinian (~5.5 Ma) evaporite composed of gypsum
Source: F. Boulvain (University of Liege)

Calcite-aragonite	$CaCO_3$
Gypsum	$CaSO_4.2H_20$
Anhydrite	$CaSO_4$
Halite	*NaCl*
Sylvite	*KCl*
Borates	*Ex:* $Na_2B_4O_7{\cdot}5H_2O$
Nitrates	*Ex:* KNO_3

Messinian salinity crisis*: period during which the Mediterranean Sea partly or nearly completely evaporated periodically around 5.5 Ma ago until the Atlantic Ocean re-flooded the basin.*

IRL
GBR
NLD
BLR
POL
KAZ
ATLANTIC
OCEAN
Celtic Sea
English Channel
BEL
DEU
LUX
CZE
UKR
RUS
SVK
AUT
MDA
Sea of Azov
CHE
HUN
FRA
Bay of Biscay
SVN
HRV
ROU
BIH
Black Sea
GEO
Ligurian Sea
Adriatic Sea
SRB
AND
ITA
BGR
PRT
ESP
MKD
Sea of Marmara
Balearic Sea
Tyrrhenian Sea
ALB
Thracian Sea
TUR
GRC
Aegean
Mediterranean
Strait of Gibraltar
Alboran Sea
Ionian Sea
Myrtoan Sea
Sea
Cilician Sea
SYR
CYP
Sea of Crete
MLT
LBN
IRQ
MAR
Libyan Sea
Sea
TUN
ISR
JOR
DZA
SAU
LBY
EGY
Red Sea
Tropic of Cancer
MRT
MLI
0°
10°E
20°E
30°E
40°E
30°N

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Formation of natural gypsum megacrystals in Naica, Mexico

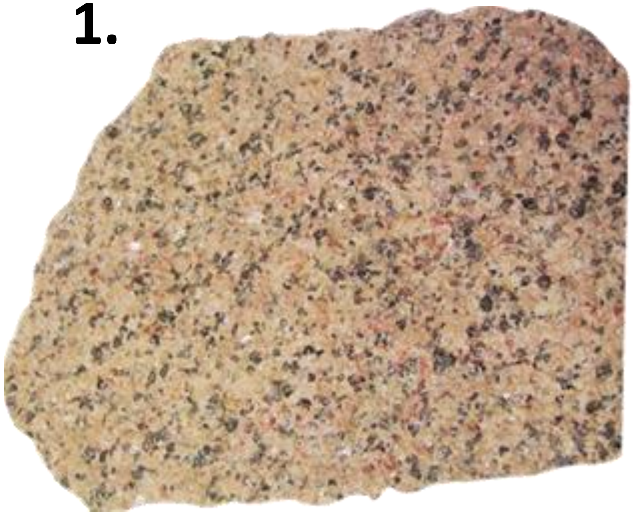
Garcia-Ruiz et al., 2007. Geology, vol. 35, p. 327-330

Very large crystals of gypsum ($CaSO_4.2H_2O$) precipitated out of a hydrothermal fluid saturated in calcium and sulfate ions. A nearly stable temperature (~54ºC) and a constant supply of calcium and sulfate ions explain the formation of these very large crystals, which probably have been growing for more than a million years.

©Wikipedia

2. **Phase change** (e.g. solid formed by cooling of a liquid)

1.



3.

2.

Rocks formed by **cooling of a magma/lava** are called **igneous rocks**.

GENERAL PROPERTY OF CRYSTALLIZATION:

The **size of crystals** depends on the **crystallization rate** and the **space** available for crystal growth.

ROCK TEXTURE AS A FUNCTION OF CRYSTALLIZATION RATE

www.beg.utexas.edu

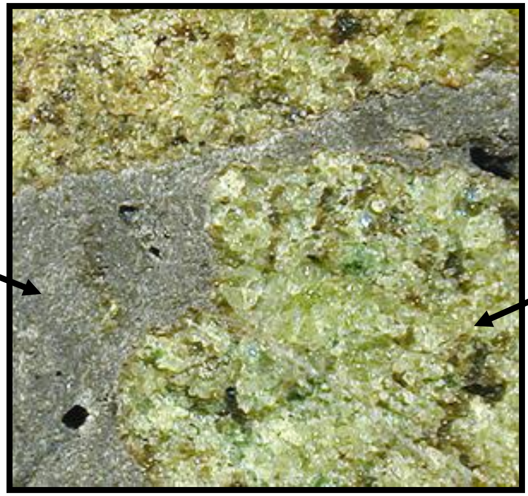
www.es.ucl.ac.uk

www.geology.com

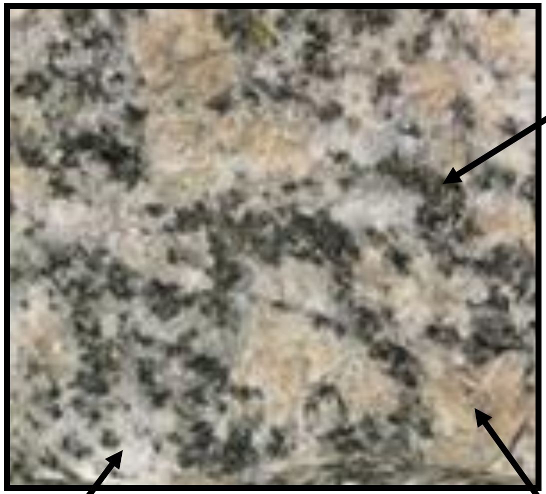
Slowly *cooling magma*	***Rapidly*** *cooling magma*	***Very rapidly*** *cooling magma*
Large crystals	***Small crystals***	***Amorphous***

EXAMPLES: ***Granite*** — ***Basalt*** — ***Volcanic glass*** *(no crystalline structure)*

Igneous rocks are mainly composed of silicate minerals.



Olivine inclusions (mantle xenoliths) in basalt



Granite

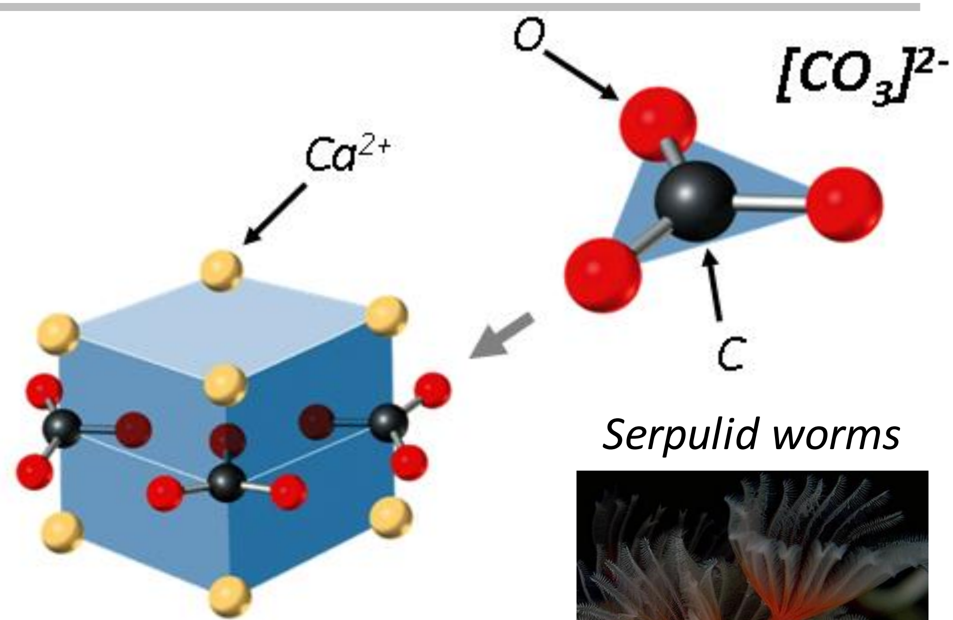
Quarz	SiO_2
Feldspar-K (orthoclase)	$KAlSi_3O_8$
Plagioclase	$(Ca,Na)AlSi_3O_8$
Mica (biotite / muscovite)	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ / $KAl_2(AlSi_3O_{10})(OH)_2$
Amphibole	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
Pyroxene	$(Mg,Fe)SiO_3$
Olivine	$(Mg,Fe)_2SiO_4$

3. Biomineralization

***EXAMPLE**: aragonite and calcite*

$CaCO_3$

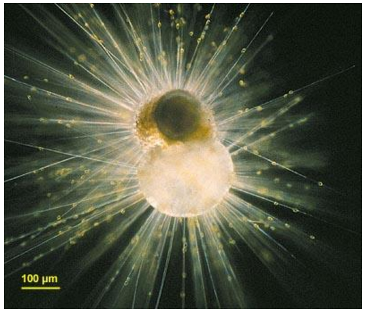
Many marine organisms produce hard parts made of $CaCO_3$



Serpulid worms

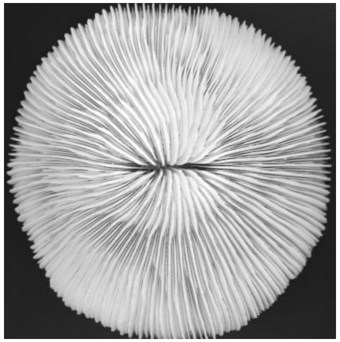
www.discoverlife.org

Foraminifera



O. R. Anderson (serc.carleton.edu)

Corals



Molluscs

www.physorg.com

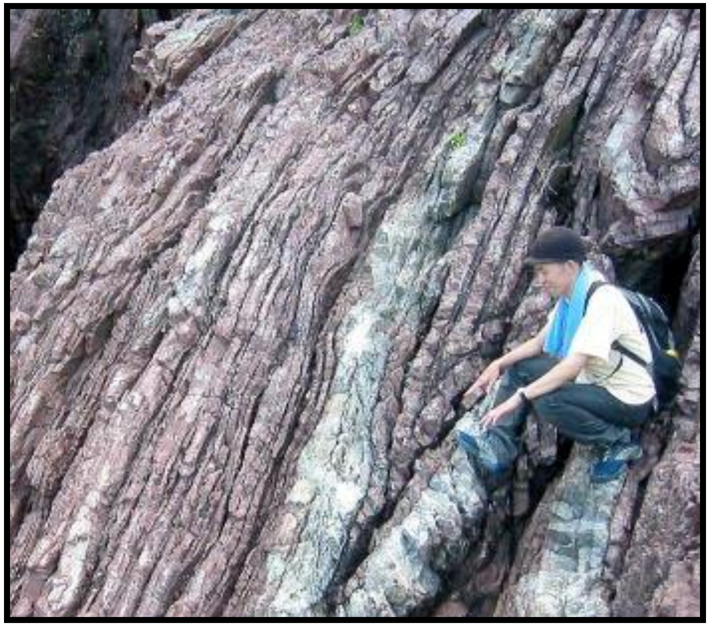
Calcareous algae

Photo: P. Edmunds

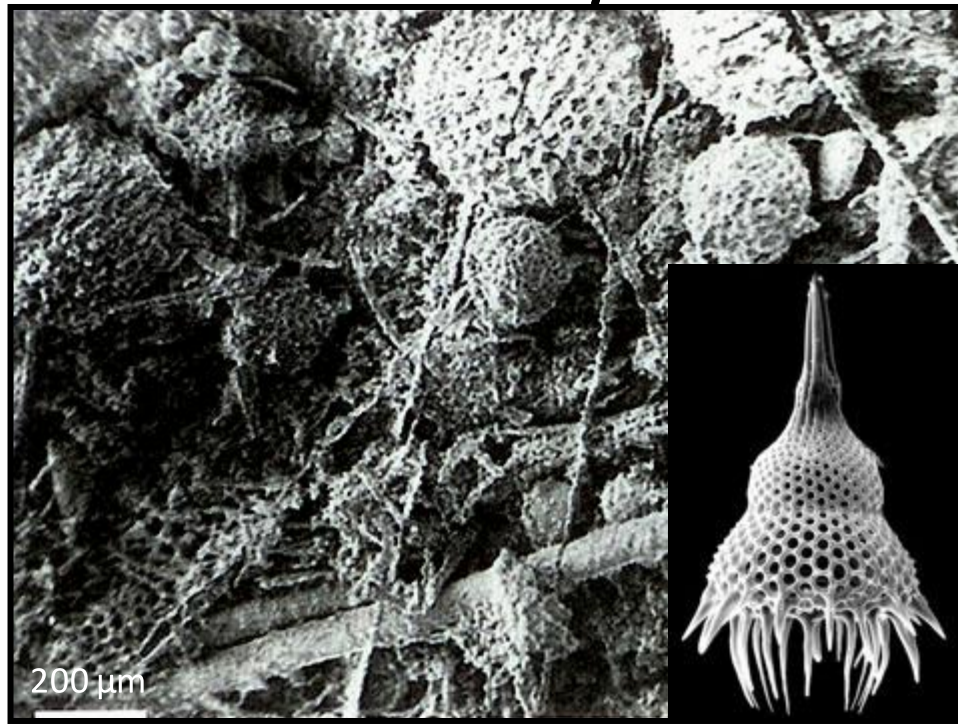
EXAMPLE: radiolarians, diatoms

SiO_2

Radiolarite (Japan)



Radiolarian



www.radiolaria.org

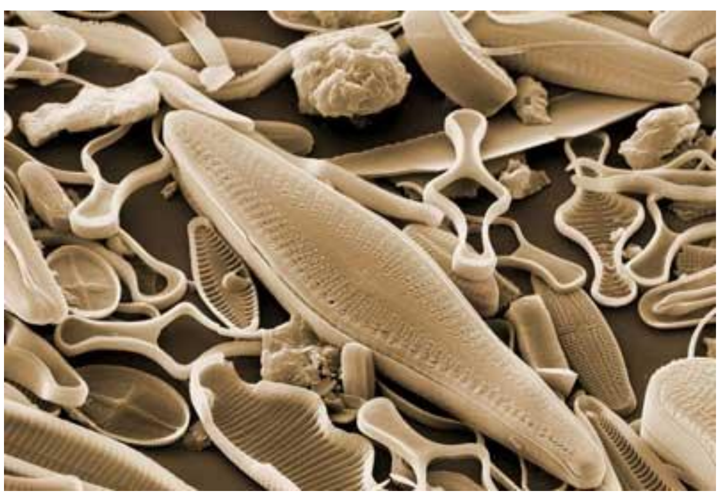


Photo: Sarah Spaulding

→ *Diatoms*

Like foraminifers and radiolarians, diatoms are single-celled organisms. However, diatoms can sometimes form colonies of attached individuals.

4. Chemical weathering

$$4KAlSi_3O_8 + 4H^+ + 2H_2O \rightarrow 4K^+ + Al_4Si_4O_{10}(OH)_8 + 8SiO_2$$

Orthoclase — Kaolinite — Quartz

Kaolinite ↓ Remobilized and transported by rain water and deposited in depressions

Hydrolysis of granite

Kaolin quarry (Japan)

http://www.eacrh.net/ojs/index.php/crossroads/article/view/14/Vol3_Seyock_html

NB: Kaolinite is primarily used in the paper industry (paper coating)

5. Metamorphism

- Process by which a rock experiences at the solid state a transformation of one or a combination of the following characteristics:
  - Chemical composition
  - Mineralogical composition
  - Texture

- One or a combination of the following 3 factors are involved in metamorphism:
  - Change in temperature
  - Change in pressure
  - Contact with hydrothermal fluids

- Most metamorphic rocks form at depths of 10 to 30 km (middle to lower half of continental crust)

SEE CHAPTER ON METAMORPHIC ROCKS

✶ Common classes of minerals

TABLE 3.1 ***Some Chemical Classes of Minerals***

Class	Defining Anions	Example
Native elements	None: no charged ions	Copper metal (Cu)
● Oxides	Oxygen ion (O^{2-})	Hematite (Fe_2O_3)
Halides	Chloride (Cl^-), fluoride (F^-), bromide (Br^-), iodide (I^-)	Halite (NaCl)
● Carbonates	Carbonate ion (CO_3^{2-})	Calcite ($CaCO_3$)
● Sulfates	Sulfate ion (SO_4^{2-})	Anhydrite ($CaSO_4$)
● Silicates	Silicate ion (SiO_4^{4-})	Olivine $(Mg,Fe)_2SiO_4$
● Sulfides	Sulfide ion (S^{2-})	Pyrite (FeS^2)

Understanding Earth

● *Main rock-forming minerals*

Sulfides

EXAMPLES*: pyrite (FeS_2)*

Pyrite

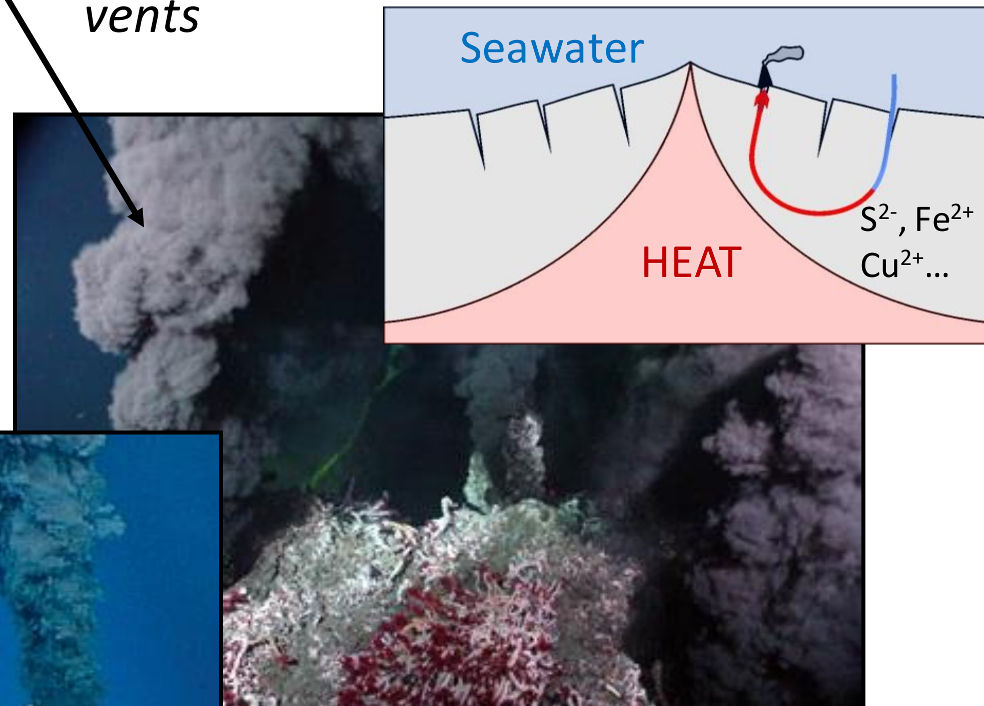
Understanding Earth

WHOI

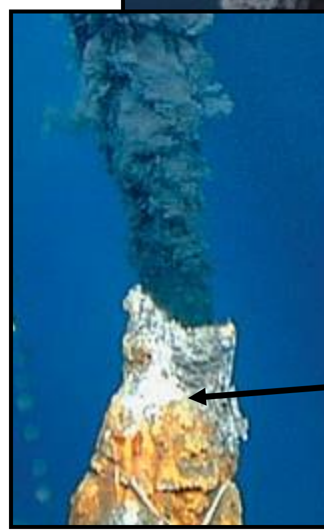
Rich in metal sulfides and oxides (Zn, Fe, Cu, Mn)

Hydrothermal vents

Mid-Ocean Ridge



NOAA



WHOI

Chimney of a black smoker rich in copper-iron sulfides.

e.g. $CuFeS_2$ (chalcopyrite)

Oxides and hydroxides

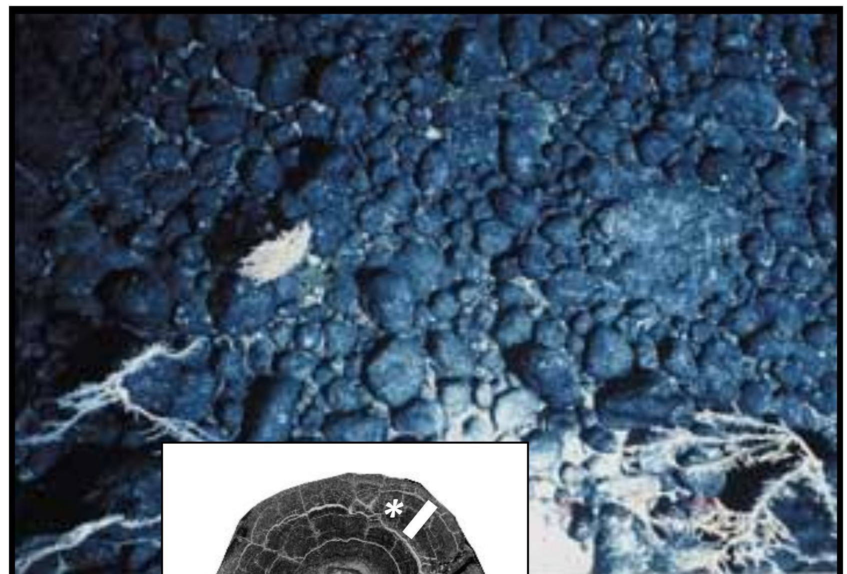
EXAMPLES: *hematite (Fe_2O_3), goethite ($FeO(OH)$), pyrolusite (MnO_2)*
*Important **iron ore***

Banded Iron Formations

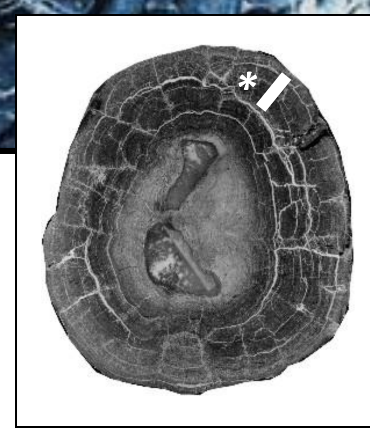
www.britannica.com

Layer rich in iron oxide

***Ferromanganese nodules** on seafloor*



JAMSTEC



NOAA

Growth rate:
1 cm per million years

✶ Physical properties of minerals

1. HARDNESS

TABLE 3.2 ***Mohs Scale of Hardness***

Mineral	Scale Number	Common Objects
Talc	1	
Gypsum	2	Fingernail *
Calcite	3	Copper coin
Fluorite	4	
Apatite	5	Knife blade
Orthoclase	6	Window glass
Quartz	7	Steel file
Topaz	8	
Corundum	9	
Diamond	10	

- Depends on **crystal structure**

  Silicates with sheet structure (mica) softer than silicates composed of isolated tetrahedra (olivine)

- Depends on **chemical bonds**

  Harder minerals are those with:

  - Covalent bonds
  - Smaller atoms/ions**
  - Ions with large charges
  - More closely packed atoms/ions**

* Gypsum can be scratched by the fingernail

** Control distance between opposite charges
The closer, the stronger the bonds

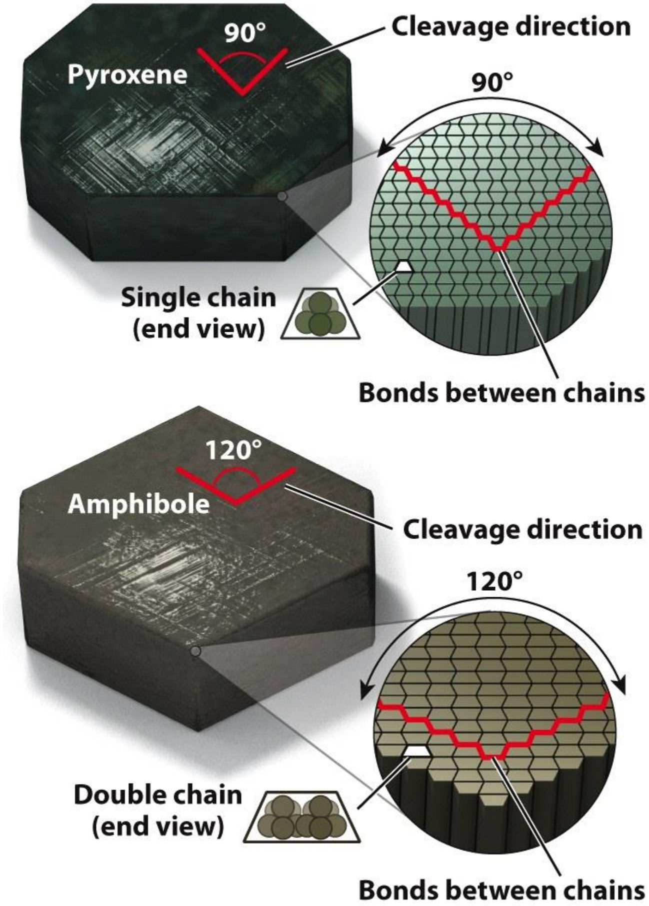
2. CLEAVAGE

- Chemical bond strength varies along different planes within a crystal. A cleavage defines a planar surface along which the crystal tends to split because **bonds** are **weaker** along this surface.

Mica:

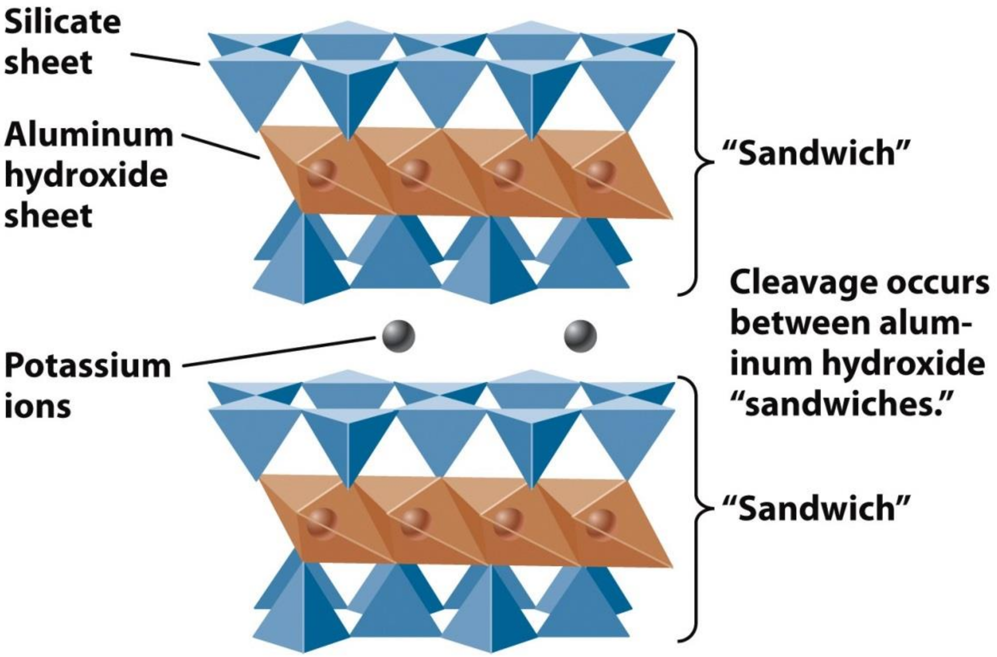
Calcite:

Pyroxene and amphibole:



Understanding Earth 6th ed.

Cleavage in mica:



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3. FRACTURE

- Breakage that is not flat, and occurring along **irregular surfaces** different from cleavage planes

Conchoidal *fracture (quartz)*

Splintery *fracture (Asbestos = fibrous silicates minerals)*

www.consrv.ca.gov

4. LUSTER

= the way minerals reflect light

- *Metallic (pyrite)*
- *Vitreous (quartz)*
- *Pearly (muscovite)*
- *Silky (asbestos)*
- …

Muscovite

www.mindat.org

5. COLOR

- The color of a mineral depends on how light behaves after it reaches the surface of the mineral (some is reflected; some is transmitted through; some is absorbed). It is related to the **composition of the mineral** (including the presence of trace elements).

Citrine *(quartz containing traces of Fe)*

Debra Wilson (www.carnegiemnh.org)

- ***Streak*** *= color of the fine deposit left when a mineral is scraped across an abrasive surface.*

Hematite *(brownish red streak)*

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6. DENSITY

- **Mass per unit of volume** (g/cm^3)

- **Specific gravity**: weight of a volume of a mineral divided by the weight of an equal volume of pure water at a given T and P

  Examples:

  Pyrite (5)

  Calcite (2.71)

  Quartz (2.65)

  Halite (2.16)

- Density depends on atoms' mass and atoms' packing

- Increase in pressure and temperature affects mineral structure and density.

  Example: diamond/graphite, $(Mg, Fe)_2SiO_4$ (olivine)

Olivine structure → (410 km) → Spinel structure → (660 km) → Perovskite structure

↓

Different polymorphs of olivine stable at different depth intervals in Earth's mantle

7. CRYSTAL HABIT

- Crystal habit is the **shape of individual crystals**.

- The crystal shape reflects the **internal arrangement** of atoms/ions, and also the **speed and direction of crystal growth**.

Prism pyramidal extremity (quartz)

www.mindat.org

Pyramidal (calcite)

www.mindat.org

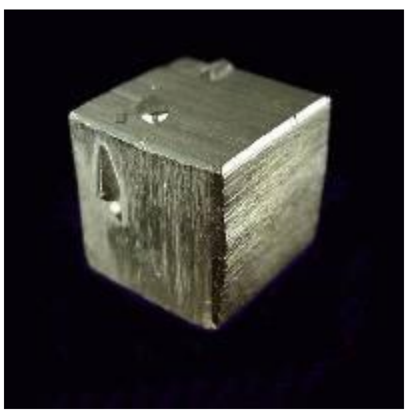
Fibrous (asbestos)

www.consrv.ca.gov

Cubic (halite)

Understanding Earth 6th ed

Cubic (pyrite)



www.mindat.org