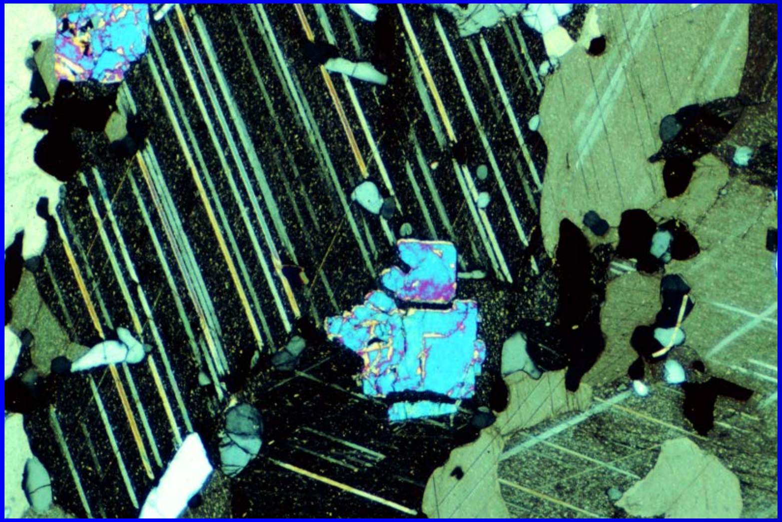
89.325 Geology for Engineers
Minerals



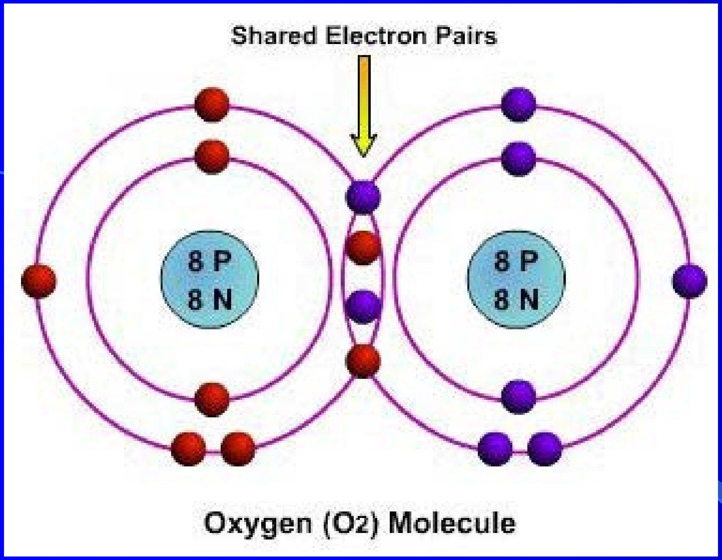
How do we define a mineral?

- Naturally occurring
- Inorganic
- Characteristic Internal Structure
- Chemical composition that is fixed or varies within certain limits

The two characteristics that most useful in the study of minerals are

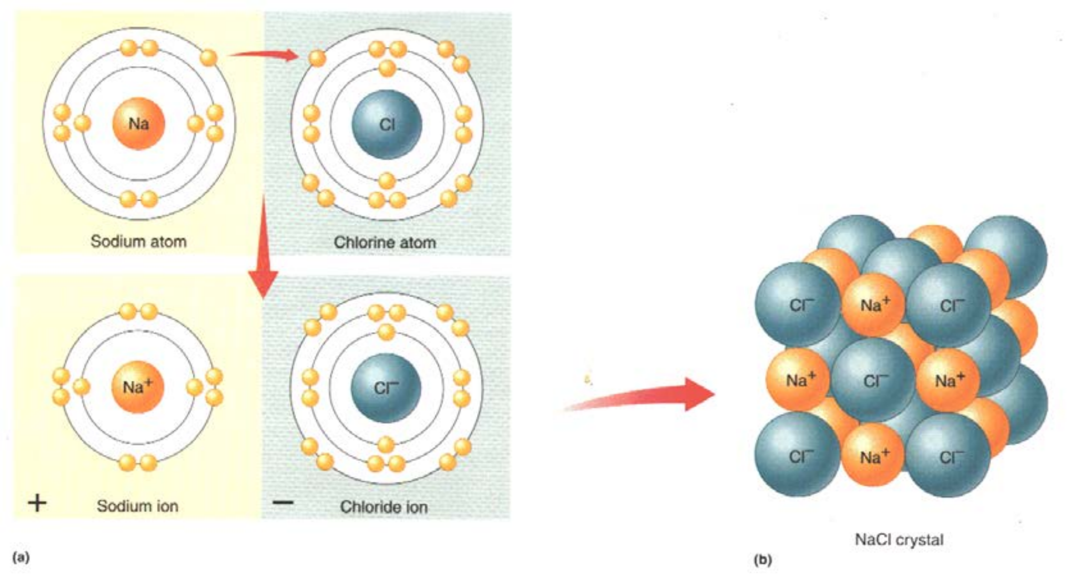
- Crystal structure - the way the atoms of the elements are packed together
- Composition - the major chemical elements that are present and their proportions

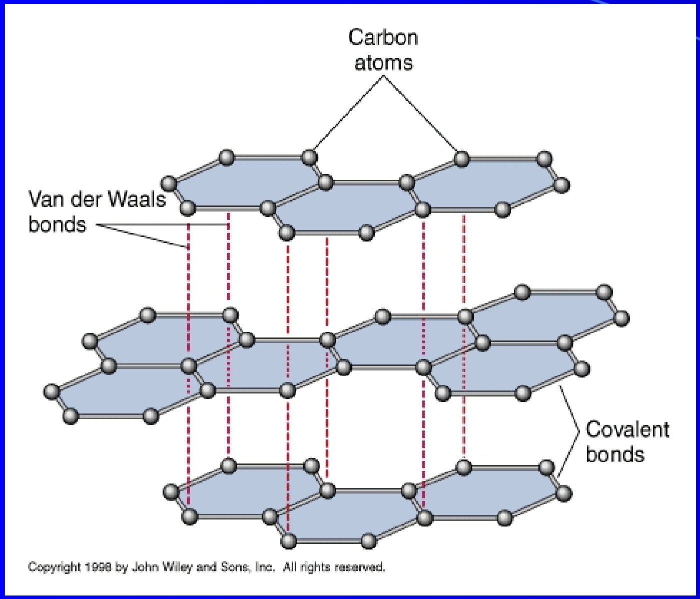
Types of Chemical Bonds



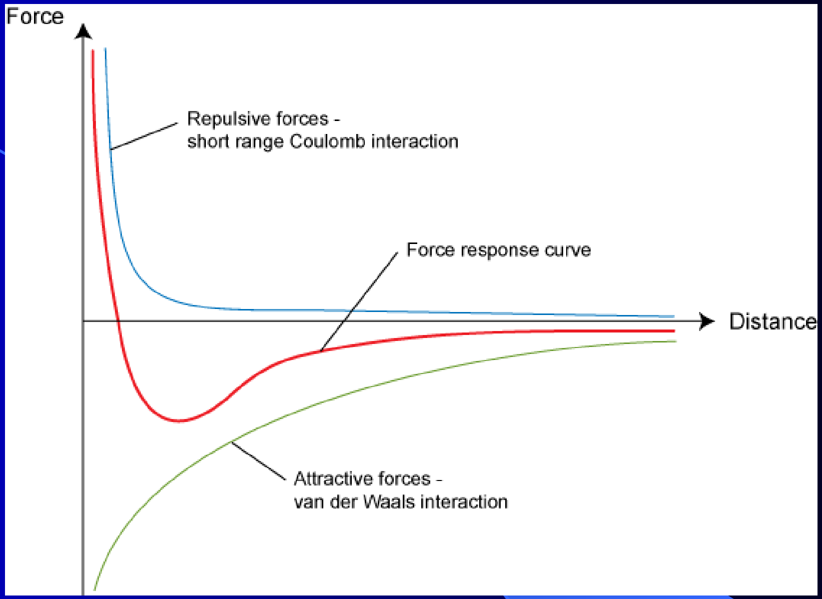
Covalent

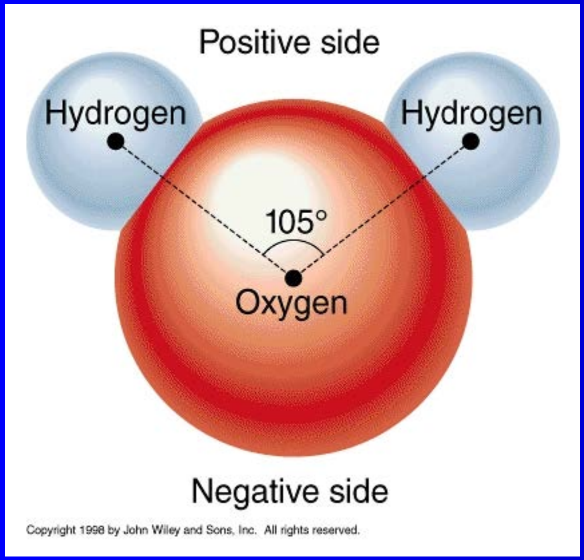
Ionic

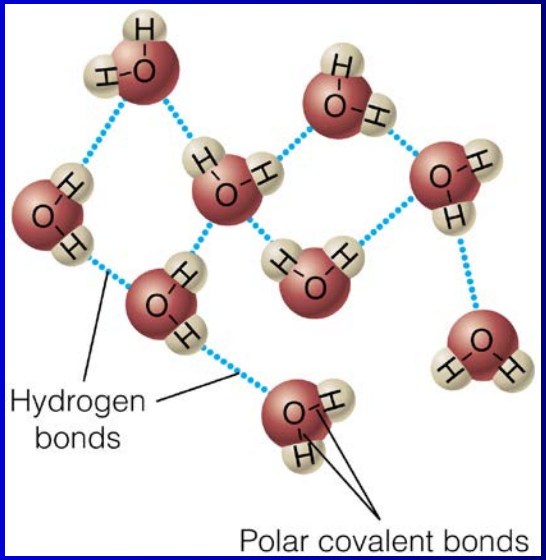




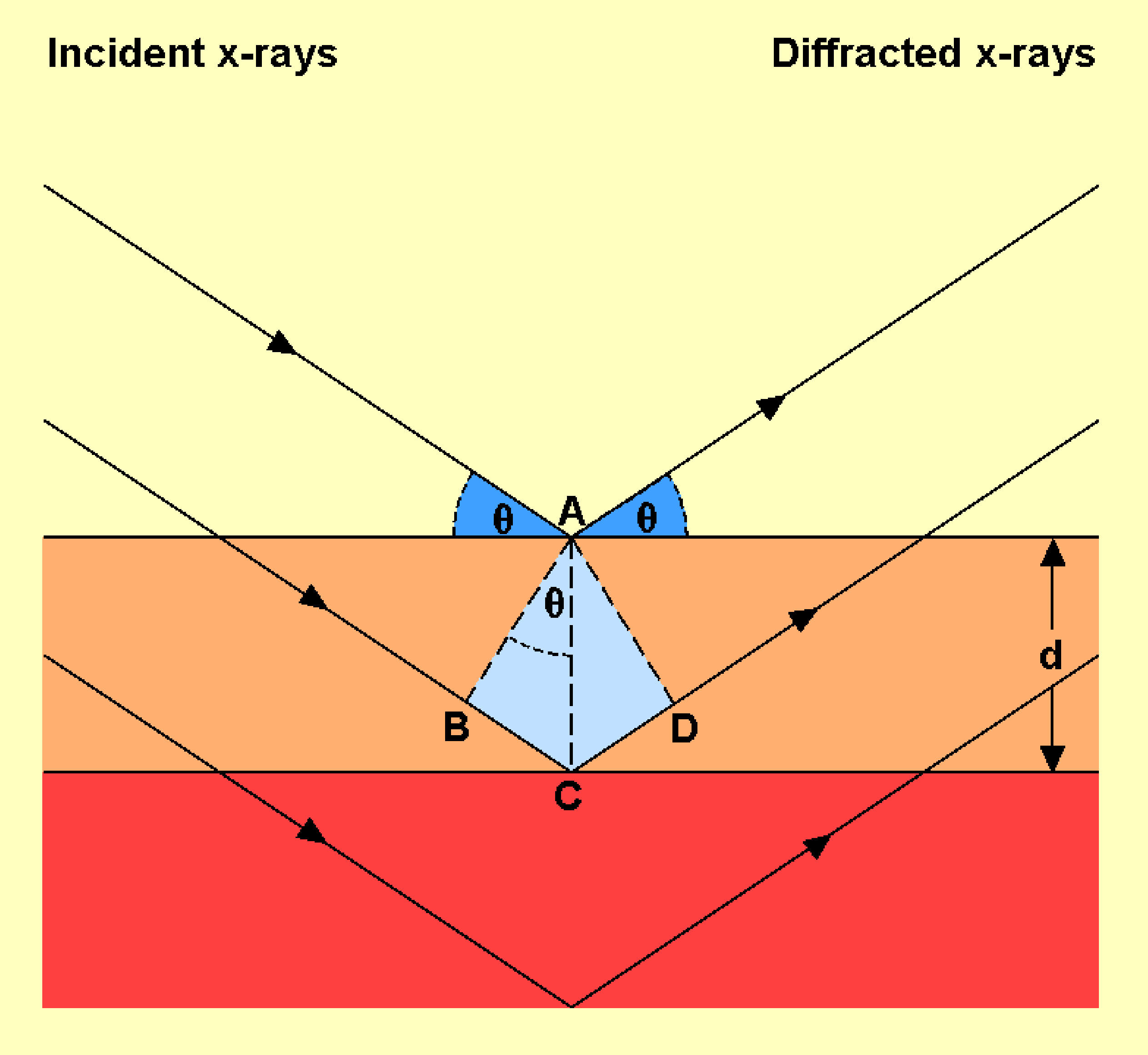
Van der Waals



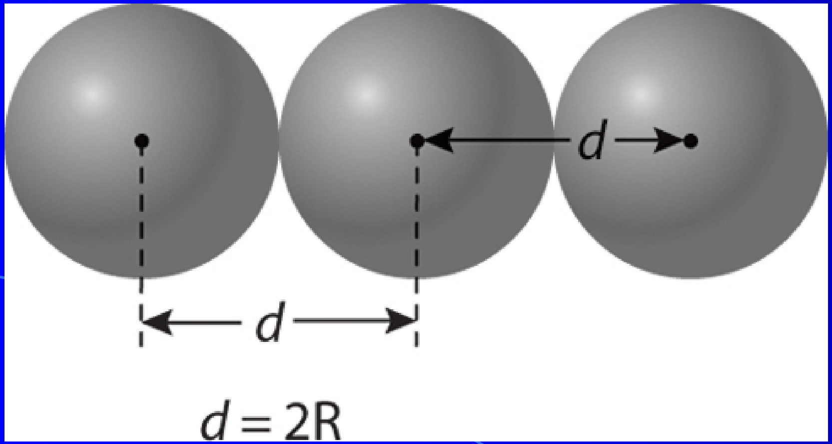




Hydrogen bonding



Bragg's law: $\lambda = 2d \sin\theta$ and $d = \lambda/(2d \sin\theta)$. θ = angle of incidence and diffraction when Bragg's law conditions are met. d = interplanar spacing.



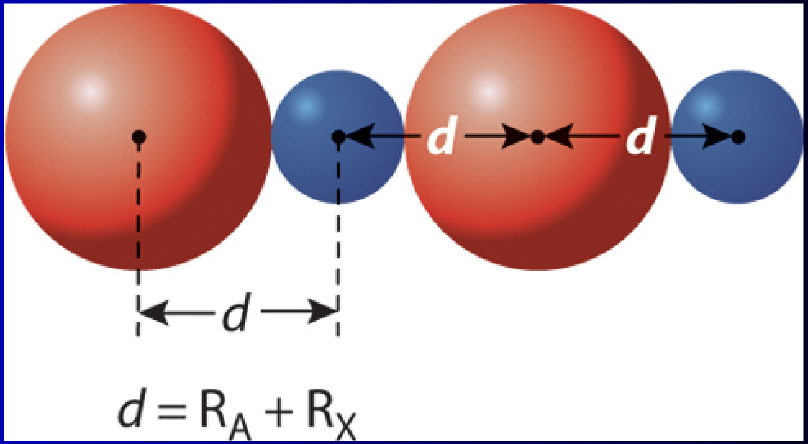


Table 4.3 Atomic radii in Ångstroms for 12-fold coordination.

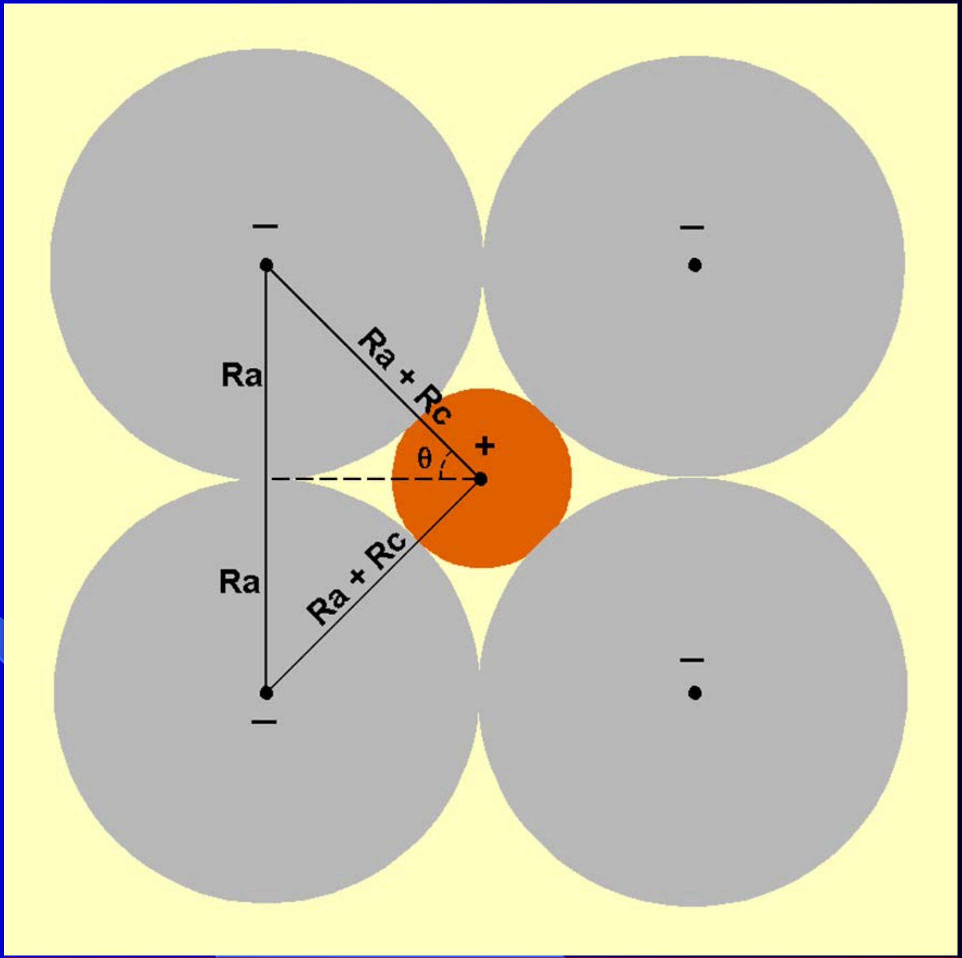
Atom	Radius	Atom	Radius
Li	1.57	Cr	1.29
Be	1.12	Mn	1.37
Na	1.91	Fe	1.26
Mg	1.60	Cu	1.28
Al	1.43	Ag	1.44
K	2.35	Sn	1.58
Ca	1.97	Pt	1.39
Ti	1.47	Au	1.44

Source: Wells (1991)

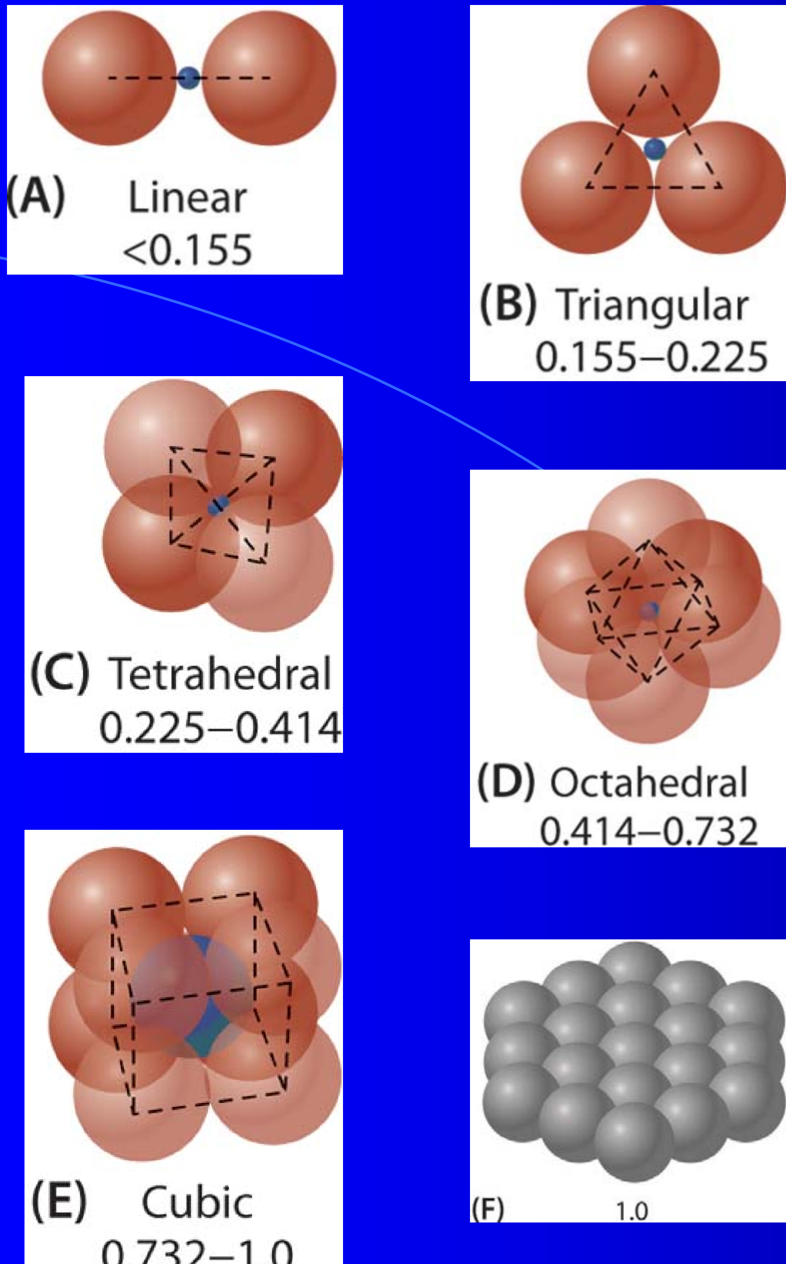
Coordination Principle

Radius Ratio = Radius cation/Radius Anion

This ratio determines how many anions can be packed around a cation.



Packing of anions around a cation for a coordination number of 4. The minimum radius ratio can be calculated from the geometry of the packing. R_a and R_c are the radii of the anion and cation, respectively. In this case, $\theta = 45^o$.



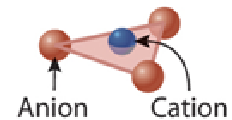
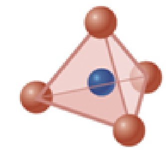
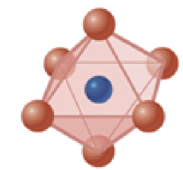
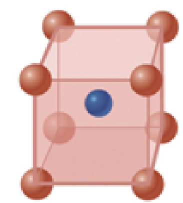
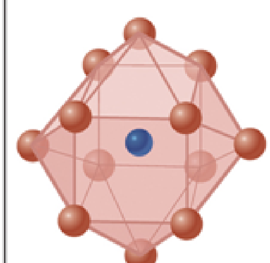
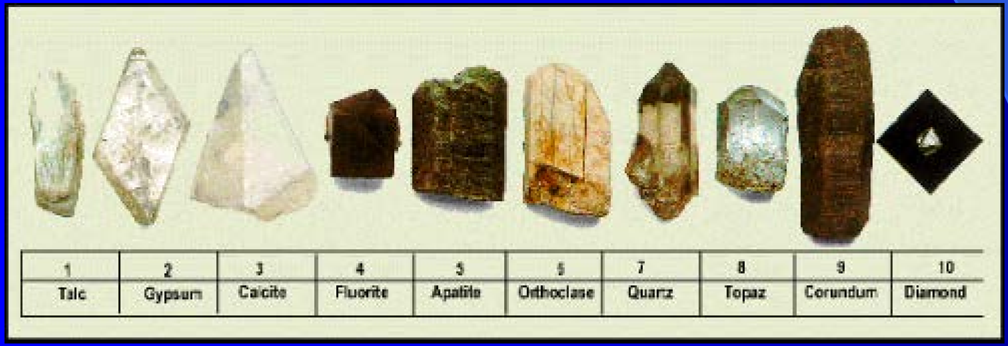
Radius ratio R_A/R_X limits	C.N.	Geometric shape	
0.155 to 0.225	III		Corners of an equilateral triangle (triangular coordination)
0.225 to 0.414	IV		Corners of a tetrahedron (tetrahedral coordination)
0.414 to 0.732	VI		Corners of an octahedron (octahedral coordination)
0.732 to 1.0	VIII		Corners of a cube (cubic coordination)
1.0	XII		Corners of a cuboctahedron (close packing)

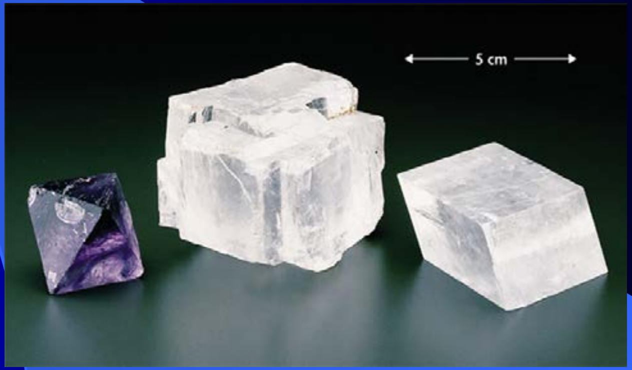
Table 4.4 Radii of common ions (in Ångstroms) as a function of coordination number.

Atomic number	Element	Ion	Radius as a function of coordination number				
			III	IV	VI	VIII	XII
3	Lithium	Li^{+}		0.73	0.90	1.06	
4	Beryllium	Be^{2+}	0.30	0.41	0.59		
5	Boron	B^{3+}	0.15	0.25	0.41		
6	Carbon	C^{4+}	0.06	0.29	0.30		
8	Oxygen	O^{2-}	1.22	1.24	1.26	1.28	
9	Fluorine	F^{-}	1.16	1.17	1.19		
11	Sodium	Na^{+}		1.13	1.16	1.32	1.53
12	Magnesium	Mg^{2+}		0.71	0.86	1.03	
13	Aluminum	Al^{3+}		0.53	0.68		
14	Silicon	Si^{4+}		0.40	0.54		
15	Phosphorus	P^{3+}			0.58		
		P^{5+}		0.31	0.52		
16	Sulfur	S^{2-}			1.70		
		S^{4+}			0.51		
		S^{6+}		0.26	0.43		
17	Chlorine	Cl^{-}			1.67		
19	Potassium	K^{+}		1.51	1.52	1.65	1.78
20	Calcium	Ca^{2+}			1.14	1.26	1.48
22	Titanium	Ti^{4+}		0.56	0.65	0.88	
24	Chromium	Cr^{3+}			0.76		
25	Manganese	Mn^{2+}		0.80	0.97	1.10	
		Mn^{4+}		0.53	0.67		
26	Iron	Fe^{2+}		0.77	0.92	1.06	
		Fe^{3+}		0.63	0.78	0.92	
27	Cobalt	Co^{2+}		0.72	0.88	1.04	
28	Nickel	Ni^{2+}		0.69	0.83		
29	Copper	Cu^{+}		0.74	0.91		
		Cu^{2+}		0.71	0.87		
30	Zinc	Zn^{2+}		0.74	0.88	1.04	
38	Strontium	Sr^{2+}			1.32	1.40	1.58
40	Zirconium	Zr^{4+}		0.73	0.86	0.98	
47	Silver	Ag^{+}		1.14	1.29	1.42	
56	Barium	Ba^{2+}			1.49	1.56	1.75
82	Lead	Pb^{2+}			1.33	1.43	1.63
92	Uranium	U^{3+}			1.17		
		U^{4+}			1.03	1.14	1.31
		U^{6+}		0.66	0.87	1.00	

Note: These data represent the crystal radii reported by Shannon (1976). In textbooks such as Klein and Dutrow (2008) and Dyar et al. (2008), the traditional radii (based on the radius of oxygen = 1.40 Å) are reported. The difference between crystal radii and traditional radii is a constant factor of 0.14 Å.

Mineral Identification





Physical Properties:

- Habit
- State of aggregation
- Color
- Luster
- Cleavage
- Hardness
- Specific gravity (density)
- Fluorescence
- Magnetism

Habit – visible external shape of a mineral

A. Prismatic – elongate with the bounding faces forming a prism-like shape

B. Columnar – rounded columns

C. Acicular – “needle-like”

D. Tabular – flat like a board

E. Bladed – elongate and flat

F. Fibrous – threadlike masses

G. Dendritic – leaflike branching

H. Foliated – stack of thin leaves or plates

I. Capillary – hairlike or threadlike thin crystals

J. Massive – specimen totally devoid of crystal faces

Color and Luster

Luster – interaction of white light with the surface of a mineral

- Metallic – most of the light is reflected or scattered from the surface of the mineral. The mineral is opaque.

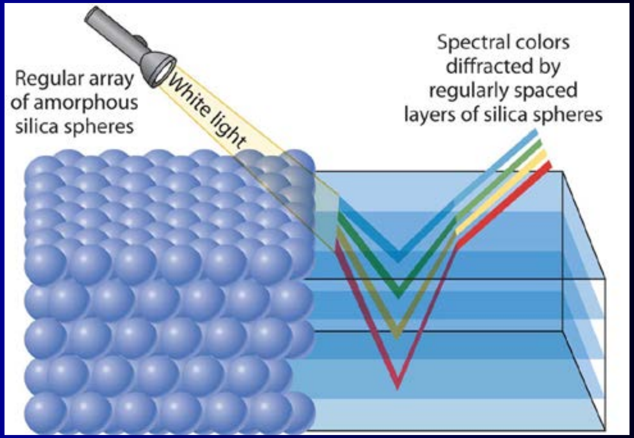


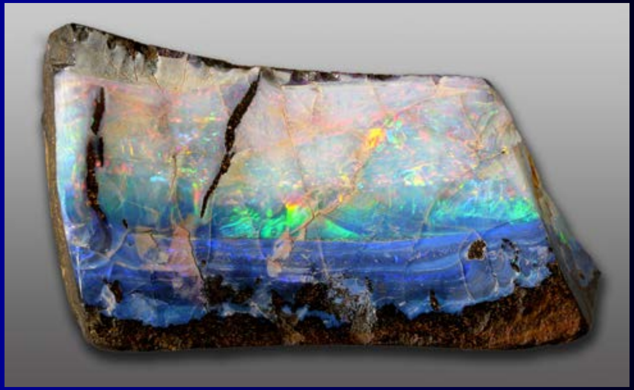
- Nonmetallic – most of the light passes through the mineral. The mineral is translucent.
  - Vitreous – luster of glass
  - Resinous – luster of resin

Vitreous

Resinous

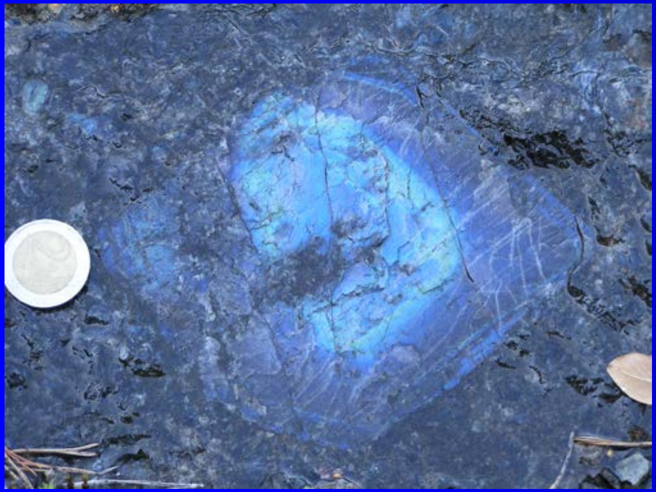
Play of color – example Opal ($SiO_2 \cdot nH_2O$) - stacked 3000 Å amorphous silica spheres causes diffraction. This leads to the display of colors.





Chatoyancy – as the mineral is tilted light moves from side to side. This is due to the presence of closely spaced fibers, inclusions or cavities.

Labradorescence – presence of closely spaced, parallel planar lamellae (exsolution lamellae). Scattered light diffracts from the microstructures producing colors.



Spectrolite

Asterism – six-rayed optical phenomenon due to the alignment of inclusions along crystallographic directions. Seen in star rubies and star sapphires when cut perpendicular to *c*. The inclusions are fine needles of rutile (TiO_2).

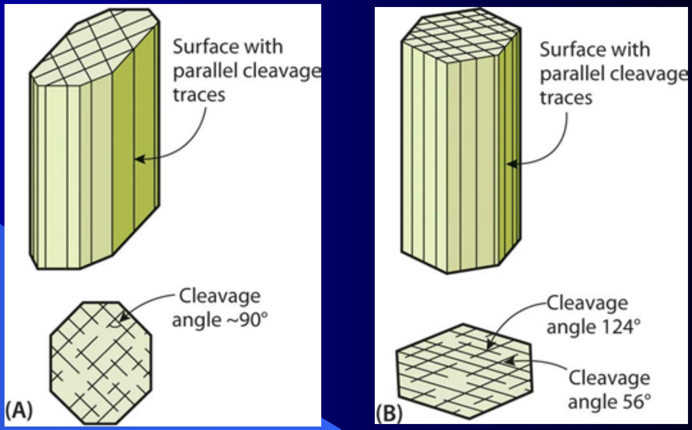
Fluorescence – occurs when UV light promotes electrons to higher energy levels. When the electrons return to an intermediate energy level the emitted photon is in the visible region of the spectrum.

Streak – color of powdered mineral. The color is usually more consistent. Most useful for metallic minerals.

Cleavage – breaking of minerals long planes of weakness. These planes are crystallographic planes. The cleavage planes are controlled by weak bonds or large interplanar spacings across atomic planes in a crystal structure.

Types of cleavage:

- Planar – cleavage along a single planar direction
- Prismatic – two different cleavage directions whose lines of intersection are commonly parallel to a specific crystallographic direction. In hand specimen, the distinction between an amphibole and a pyroxene is largely based on the intersection of the cleavage planes (~90^{o} for pyroxene, 56^{o} and 124^{o} for amphibole). Feldspars also show approximately right-angle cleavage intersections.



- Cubic – three cleavages at right angles. Isometric minerals such as halite and galena.
- Rhombohedral – three cleavage directions not at right angles. Example calcite
- Octahedral – breaking along four different directions. Example fluorite
- Conchoidal fracture – no specific directions. Irregular fracture pattern. Quartz and glasses show this type of fracture.


Cubic


Rhombohedral


Conchoidal


Octahedral

Hardness – resistance to abrasion or indentation.

Absolute hardness – weight in grams required to produce a standard scratch. This is done using an instrument known as a sclerometer. Note that grams are a unit of mass, not force. The correct measurement would be in dynes cm^{-2}. On the scale to the right the values should be multiplied by 980 to get the force in dynes cm^{-2}.

The Turner-sclerometer test consists of microscopically measuring the width of a scratch made by a diamond under a fixed load, and drawn across the face of the specimen under fixed conditions.

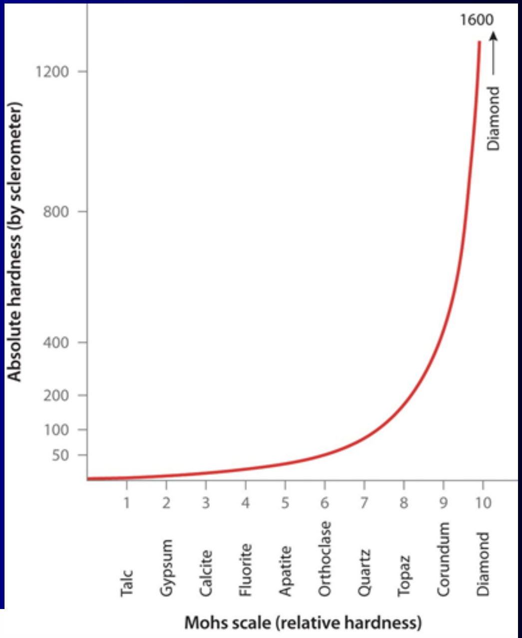


Table 3.1 Mohs hardness scale minerals.

Hardness number (**H**)	Mineral name	Chemical formula	Remarks
1	Talc	$Mg_3Si_4O_{10}(OH)_2$	Soft, greasy feel; flakes are left on the fingers
2	Gypsum	$CaSO_4{\cdot}2H_2O$	Can be easily scratched by the fingernail *fingernail hardness ~2.2*
3	Calcite	$CaCO_3$	Can be easily scratched with a knife and just scratched by a copper penny *copper penny hardness ~3.2*
4	Fluorite	CaF_2	Less easily scratched by a knife than calcite
5	Apatite	$Ca_5(PO_4)_3(F, Cl, OH)$	Is scratched by a knife with difficulty *pocket knife hardness ~5.1* *glass plate hardness ~5.5*
6	Orthoclase	$KAlSi_3O_8$	Not scratched by a knife and will scratch ordinary glass
7	Quartz	SiO_2	Scratches glass easily *porcelain streak plate hardness ~7*
8	Topaz	$Al_2SiO_4(F, OH)_2$	Scratches glass very easily[a]
9	Corundum	Al_2O_3	Cuts glass[a]
10	Diamond	C	Used as a glass cutter[a]

[a] There are few minerals that are as hard as, or harder than, quartz, and these include several of the highly prized gems.

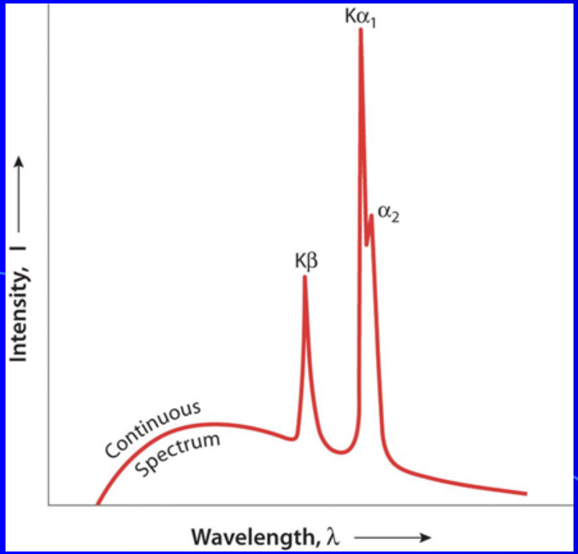
Specific Gravity – the density of a mineral compared to the density of water. Specific gravity is non-dimensional.

Specific gravity for minerals is determined by

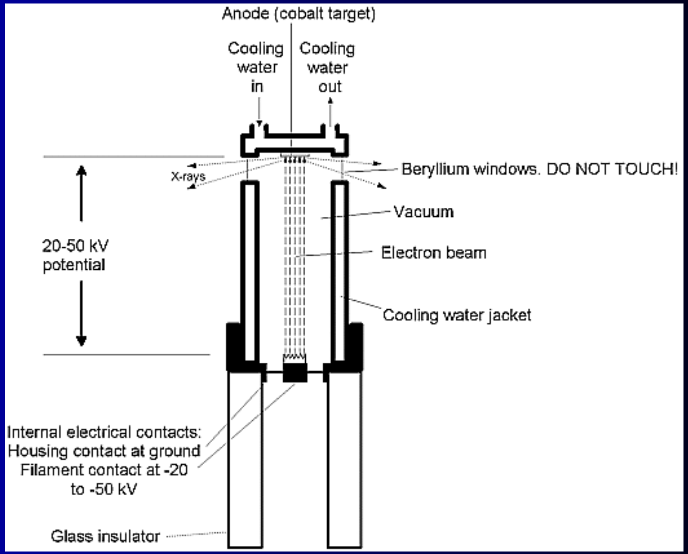
- The atomic weight of the elements that comprise the mineral
- Atomic packing - the way in which the atoms are packed in the crystal structure

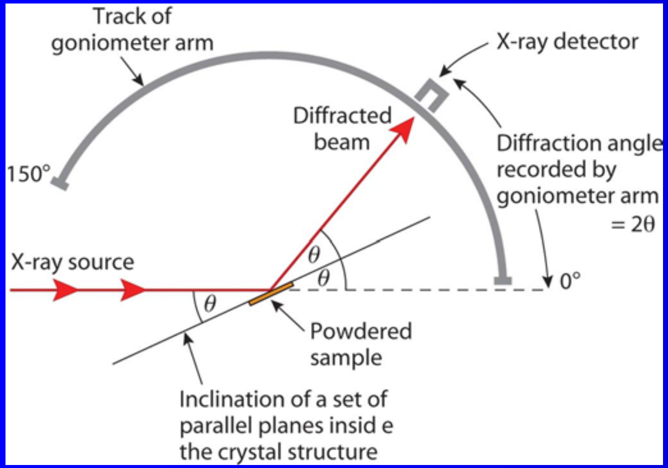
Other Physical Properties:

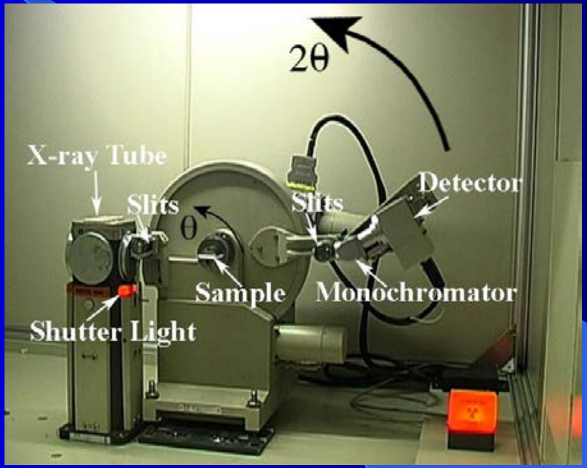
- Magnetism – magnetite (Fe_3O_4) and pyrrhotite ($Fe_{1-x}S$)
- Solubility in acid – carbonates – aragonite and calcite ($CaCO_3$) versus dolomite [$CaMg(CO_3)_2$] , magnesite ($MgCO_3$), siderite ($FeCO_3$) , and rhodochrosite ($MnCO_3$) .
- Radioactivity – Uraninite (UO_2), Carnotite [$K_2(UO_2)_2(VO_4)_2$- 1-3H_2O], Thorite [(Th, U)SiO_4]

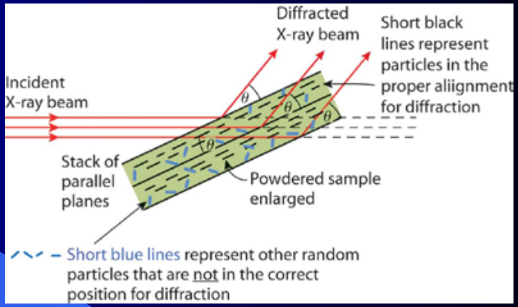


X-rays generated by an X-ray tube. Common tubes are Cu, Fe, and Mo.

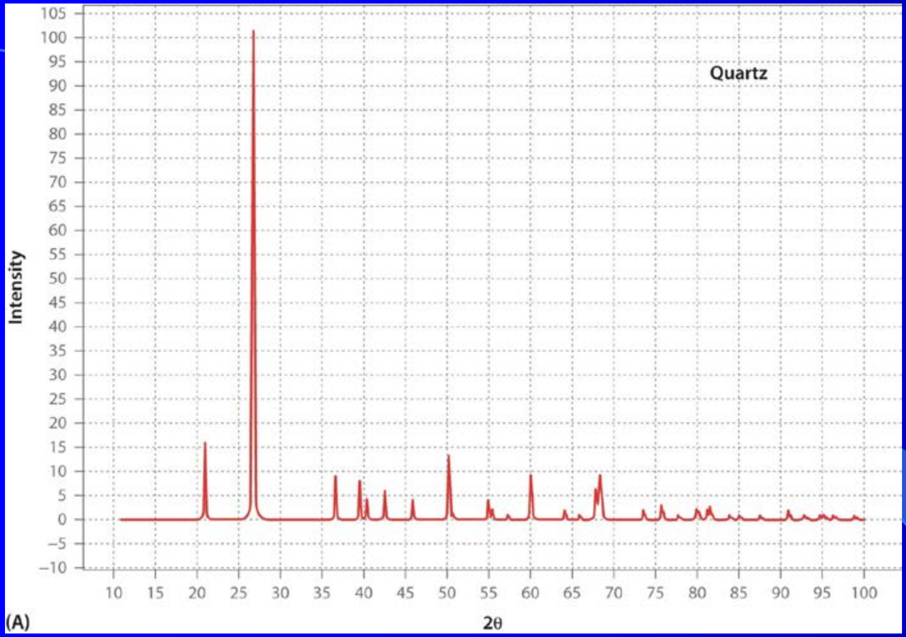


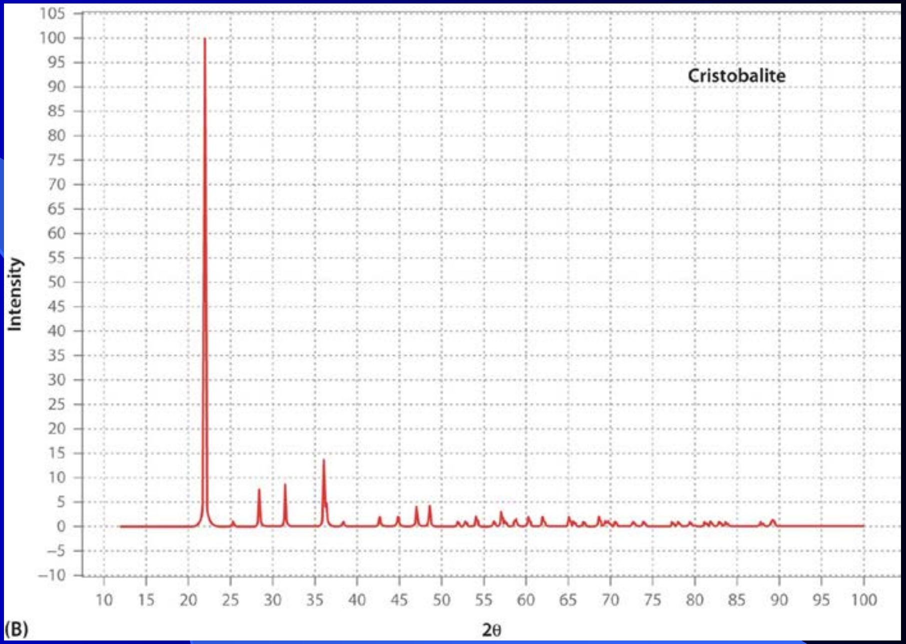




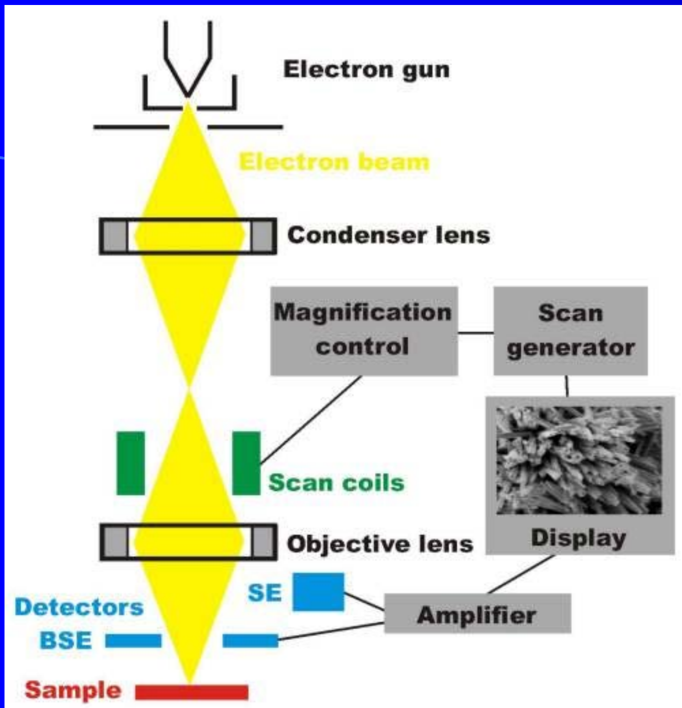


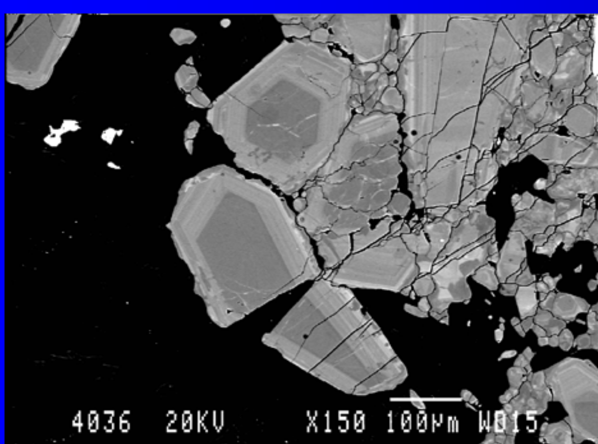
X-ray diffraction patterns for the silica polymorphs – quartz and cristobalite

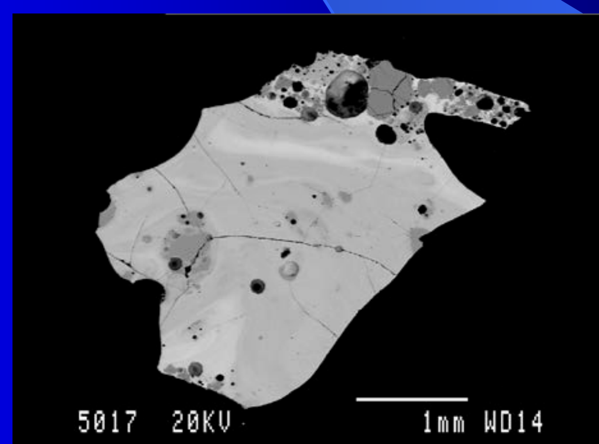


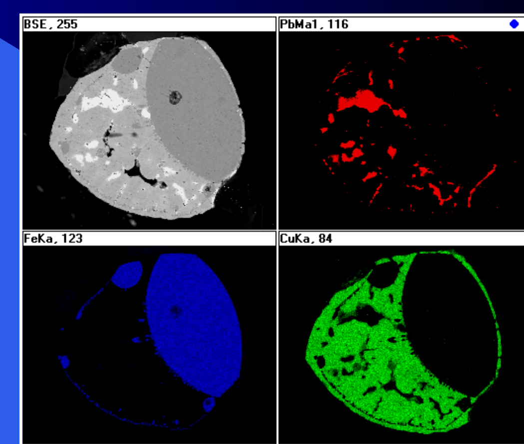


Scanning Electron Microscope (SEM)

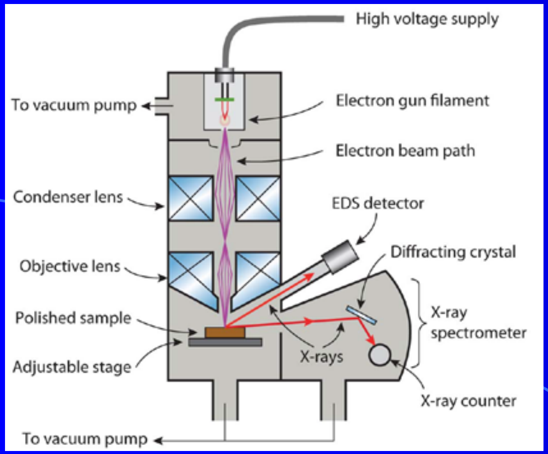


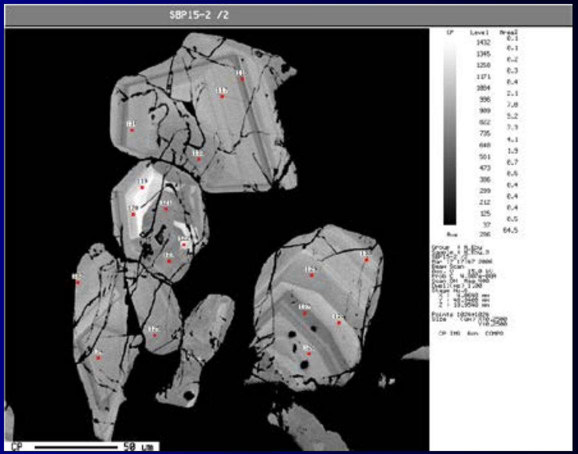






Electron Microprobe Analyzer (EMPA)





No.	SiO2	TiO2	Al2O3	FeO	MnO	CaO	P2O5	V2O3	La2O3	Ce2O3	Pr2O3	Nd2O3	Sm2O3
116	1.9	0	0.004	0	0	0.195	27.559	0	14.72	31.043	3.12	10.051	0.974
117	2.078	0	0	0	0	0.174	27.147	0	13.95	30.607	3.09	10.537	1.116
118	1.065	0	0.019	0.015	0	0.178	28.744	0	14.704	33.228	3.372	10.905	0.998
119	4.321	0	0.015	0.004	0	0.238	23.928	0	11.036	26.526	2.775	10.056	1.319
120	4.9	0	0	0.058	0	0.221	22.894	0	11.211	25.178	2.742	9.962	0.996
121	1.499	0	0.004	0.027	0	0.325	28.174	0	13.629	31.073	3.103	10.644	1.225
122	3.627	0	0.011	0.044	0	0.265	24.925	0	11.756	27.256	2.932	10.618	1.231
123	1.451	0	0	0	0.014	0.176	28.232	0	15.186	32.484	3.095	10.142	1.006
124	1.661	0	0	0.008	0	0.129	27.924	0	15.045	32.451	3.197	10.447	0.861
125	1.433	0	0.004	0.011	0.025	0.153	28.19	0	14.987	32.457	3.289	10.557	0.806
126	1.907	0	0.001	0.04	0.004	0.147	27.454	0	14.344	31.682	3.187	10.534	1.102
127	0.857	0	0.006	0	0.01	0.182	29.241	0	15.73	33.814	3.268	10.563	1.144
128	2.343	0	0	0	0	0.158	26.773	0	14.964	30.944	2.904	9.904	0.87
129	1.54	0	0	0	0	0.186	27.958	0	15.017	32.512	3.169	10.347	0.826
130	2.06	0	0	0.061	0	0.232	27.154	0	14.523	31.369	3.085	10.002	0.861
131	1.818	0	0.007	0.039	0	0.349	27.781	0	14.702	31.238	3.299	10.411	1.119
132	1.839	0	0	0.019	0	0.327	27.376	0	14.735	31.676	3.28	10.54	1.125
133	1.349	0	0.001	0.007	0	0.121	28.336	0	14.824	33.301	3.138	10.859	1.108

No.	Eu2O3	Gd2O3	Tb2O3	Dy2O3	Ho2O3	Er2O3	Tm2O3	Yb2O3	Lu2O3	Y2O3	Nb2O5	PbO	ZrO2	ThO2	UO2
116	0.088	1.183	0.073	0.344	0	0.031	0.046	0	0.06	1.191	0	0.126	0.043	7.589	0.296
117	0.086	1.274	0.125	0.271	0.032	0.123	0.141	0.066	0.065	1.418	0.057	0.112	0.017	8.45	0.33
118	0.089	1.177	0.105	0.434	0	0.097	0.129	0.141	0.169	1.746	0.007	0.096	0.064	3.936	0.325
119	0.195	1.062	0.089	0.329	0.107	0.091	0.007	0.009	0.056	1.573	0.007	0.293	0.039	17.49	0.588
120	0.075	1.042	0.04	0.405	0.017	0.198	0.042	0.078	0.018	1.373	0.042	0.318	0.088	19.277	0.679
121	0.087	1.348	0.176	0.429	0	0.16	0.079	0.204	0.133	1.749	0	0.113	0.047	6.842	0.232
122	0.048	1.303	0.056	0.47	0.246	0.142	0.134	0	0	1.572	0.003	0.253	0.003	14.541	0.514
123	0.068	1.098	0.076	0.354	0.1	0.014	0.048	0.02	0.109	1.078	0.057	0.085	0.007	5.817	0.2
124	0.072	1.019	0.153	0.255	0.135	0.122	0.168	0.09	0	1.235	0.01	0.106	0.04	6.629	0.247
125	0	1.181	0.121	0.259	0.063	0.197	0.118	0	0	1.102	0	0.088	0.027	5.704	0.197
126	0.162	1.082	0.105	0.304	0	0.039	0.006	0.03	0.094	1.269	0.02	0.117	0	7.444	0.278
127	0.094	1.134	0.145	0.379	0.195	0.073	0	0.035	0.065	1.464	0	0.052	0.104	3.06	0.299
128	0.051	1.03	0.081	0.304	0.106	0	0.115	0	0	1.162	0	0.13	0.03	9.334	0.304
129	0.13	1.015	0.154	0.378	0.144	0.146	0.029	0.009	0	1.337	0	0.096	0.09	6.07	0.313
130	0	1.111	0	0.334	0	0.126	0.073	0.14	0.059	1.098	0.05	0.129	0	8.094	0.232
131	0.015	1.317	0.153	0.514	0.139	0.142	0.089	0.08	0.002	1.255	0	0.111	0.11	7.014	0.264
132	0.096	1.237	0.154	0.395	0.037	0.096	0.03	0	0.082	1.304	0	0.11	0.053	7.174	0.272
133	0.135	1.079	0.093	0.306	0.004	0.043	0	0.039	0.167	1.175	0.084	0.082	0.06	5.364	0.192

The analyzed mineral is monazite

monazite-Ce (Ce, La, Pr, Nd, Th, Y)PO_4

Class	Chemical characteristics	Examples
Borates	Various elements in combination with boron	Borax [$Na_2B_4O_7$ $10H_2O$]
Carbonates	Metals in combination with carbonate (CO_3^{2-})	Calcite [$CaCO_3$] Cerrusite [$PbCO_3$]
Halides	Alkali metals or alkaline earths in combination with halogens (F, Cl, Br, I)	Halite [NaCl] Fluorite [CaF_2]
Hydroxides	Metals in combination with hydroxyls (OH-)	Brucite [$Mg(OH)_2$]
Native elements	Pure compound of a metallic or nonmetallic element	Gold [Au] Graphite [C]
Oxides	Metals in combination with oxygen	Hematite [Fe_3O_4]
Phosphates, arsenates, vanadates, chromates, tungstates & molybdates	Various elements in combination with the ZO_4 radical where Z = P, As, V, Cr, W, Mo	Apatite [$Ca_5(PO_4)_3(F,Cl,OH)$] Carnotite [$K_2(UO_2(VO_4)_2$ $3H_2O$] Scheelite [$CaWO_4$]
Silicates	Metals in combination with silica tetrahedra (SiO_4^{4-}) forming three dimensional networks, sheets, chains and isolated tetrahedra	Quartz [SiO_2] Forsterite [$MgSiO_4$] Orthoclase [$KAlSi_3O_8$]
Sulfates	Alkaline earths or metals in combination with sulfate (SO_4^{2-})	Barite [$BaSO_4$] Epsomite [$MgSO_4$ $7H_2O$]
Sulfides	One or more metals in combination with reduced sulfur or chemically similar elements (As, Se, Te)	Pyrite [FeS_2] Galena [PbS] Skutterudite [$CoAs_3$]

Silica and oxygen are the two most abundant elements in the Earth's crust (and mantle). They combine to form the silica tetrahedron which is the basic building block of the silicate minerals. The silicate minerals comprise 92% of the Earth's crust.

Table 7.1 The eight most common elements in the Earth's crust.

	Weight[a] percentage	Atom[b] percentage	Ionic radius[c] (Å)	Volume[d] percentage
O	46.60	62.55	1.26	~86
Si	27.72	21.22	0.40[IV]	
Al	8.13	6.47	0.53[IV]	
Fe	5.00	1.92	0.92[VI]	~14
Ca	3.63	1.94	1.14[VI]	in total
Na	2.83	2.64	1.32[VIII]	
K	2.59	1.42	1.65[VIII]	
Mg	2.09	1.84	0.86[VI]	
	98.59	100.00		

[a] Data from Mason and Moore, 1982.
[b] Values obtained by dividing the numbers in the first column by the appropriate atomic weights, then normalized to 100.
[c] Radii taken from Table 4.4.
[d] These values fluctuate somewhat depending on the radii used in the calculation of the ionic volume ($V = \frac{4}{3}\pi r^3$).

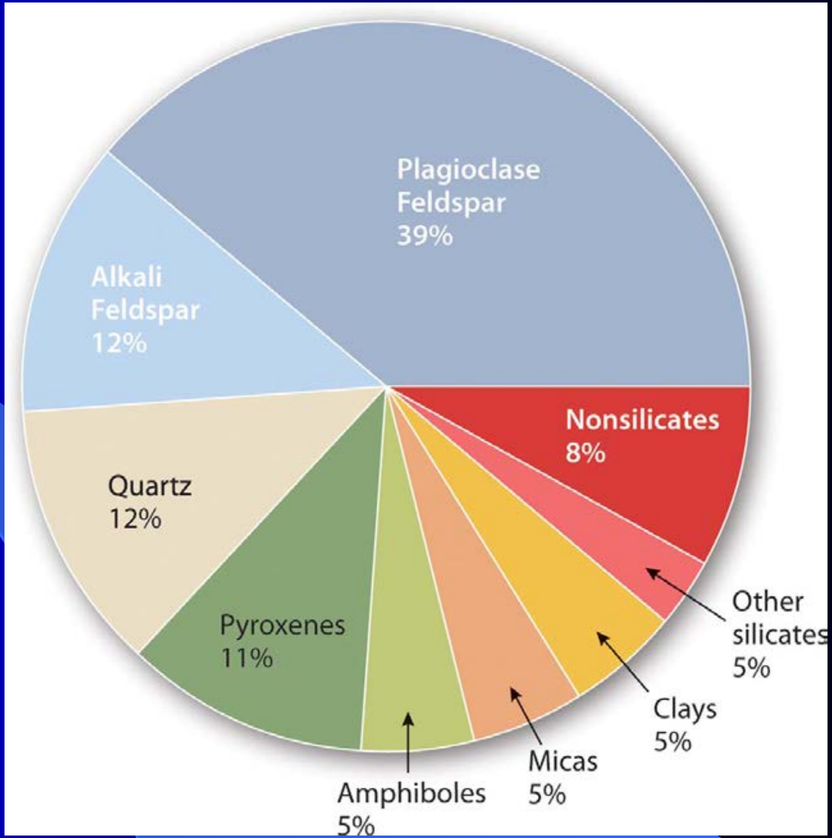
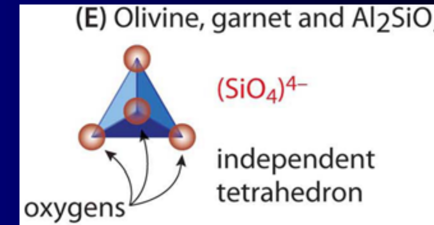
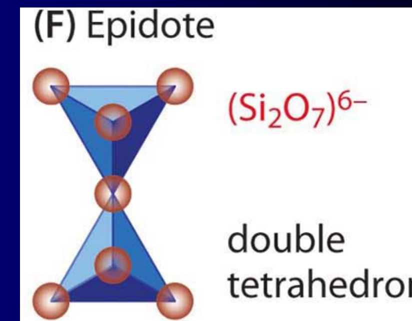
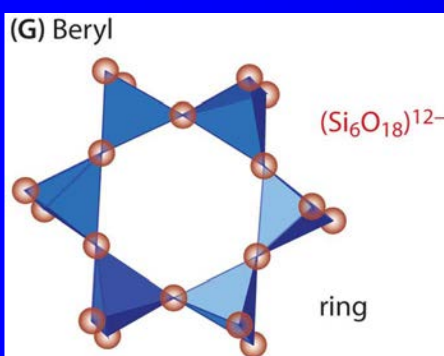


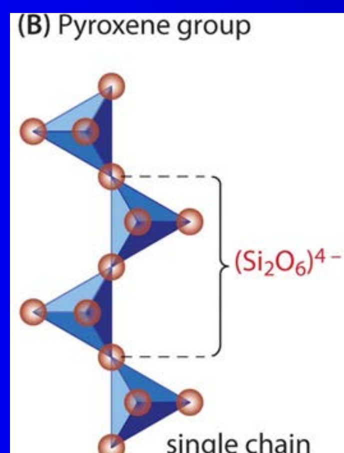
Table 7-4. Properties of the silicate crystal classes

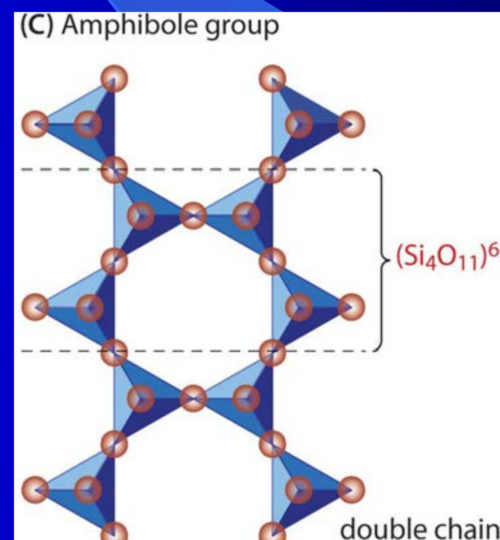
Class	Tetrahedral arrangement	# shared corners	Chemical unit	Si:O	Example
Nesosilicate	Independent tetrahedra	0	$SiO_4^{4\&}$	1:4	Olivine
Sorosilicate	Two tetrahedra sharing a corner	1	$Si_2O_7^{6\&}$	1:3.5	Melilite
Cyclosilicate	Three or more tetrahedra sharing two corners, forming a ring	2	$SiO_3^{3\&}$	1:3	Beryl
Inosilicate	Single chain of tetrahedra sharing two corners	2	$SiO_3^{3\&}$	1:3	Augite
	Double chain of tetrahedra alternately sharing two or three corners	2.5	$Si_4O_{11}^{6\&}$	1:2.75	Hornblende
Phyllosilicate	Sheet of tetrahedra sharing three corners	3	$Si_2O_5^{2\&}$	1:2.5	Kaolinite
Tektosilicate	Framework of tetrahedra sharing all four corners	4	SiO_2	1:2	K-feldspar

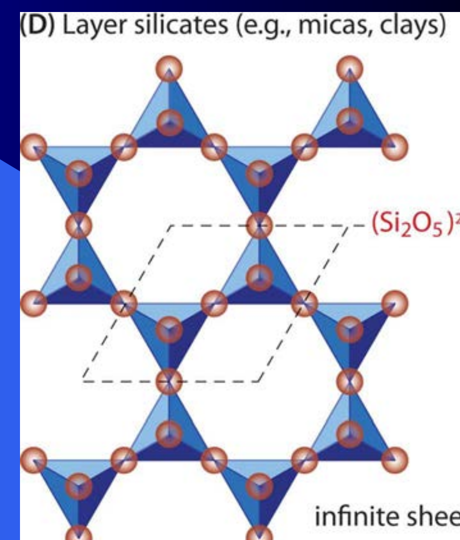






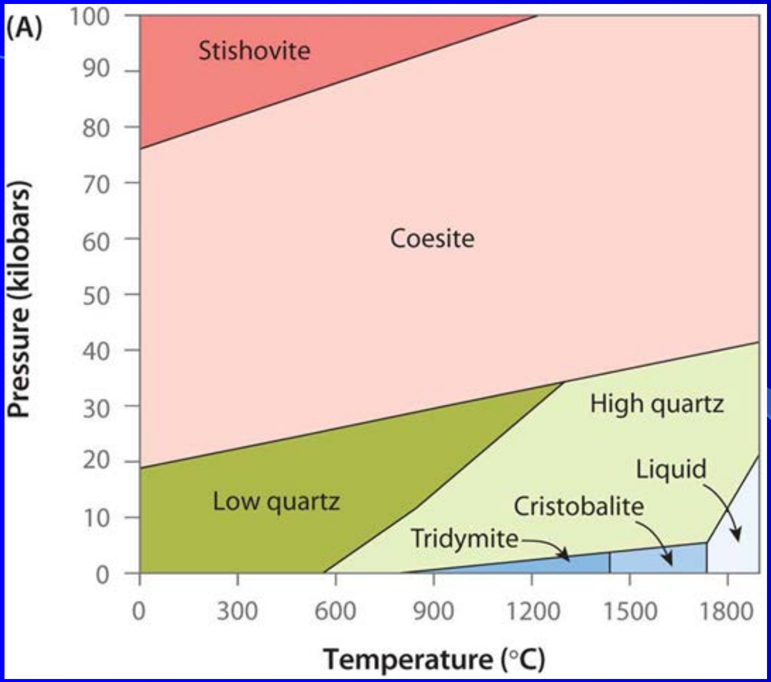


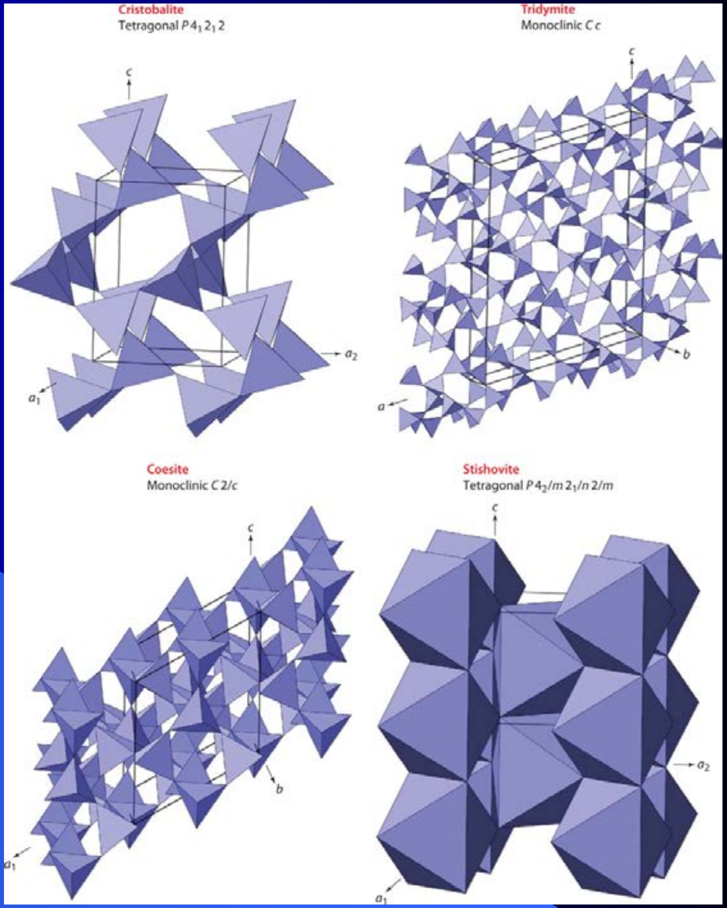


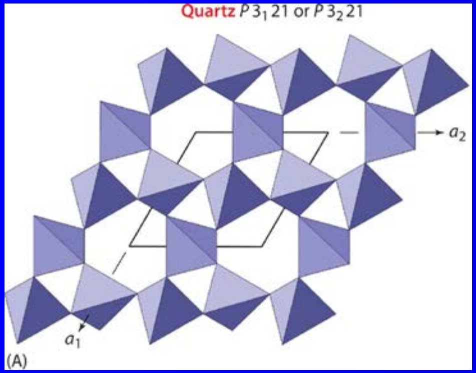


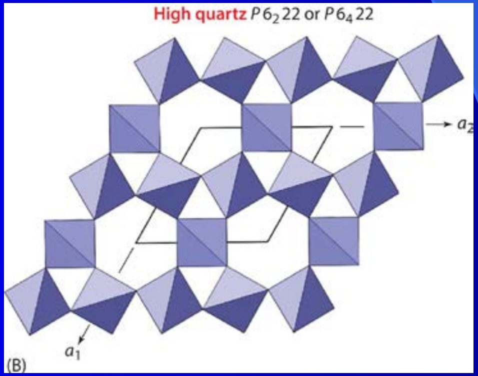
Quartz – SiO_2

P-T conditions and polymorphs







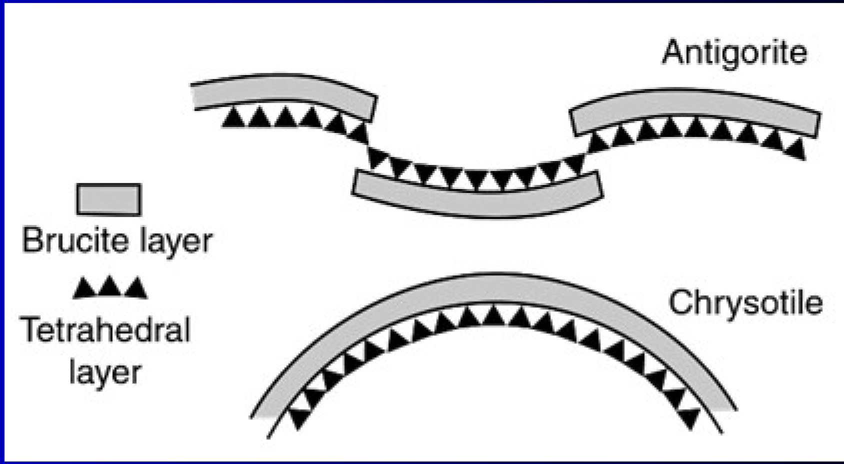


Metamorphic Rock-Forming Minerals

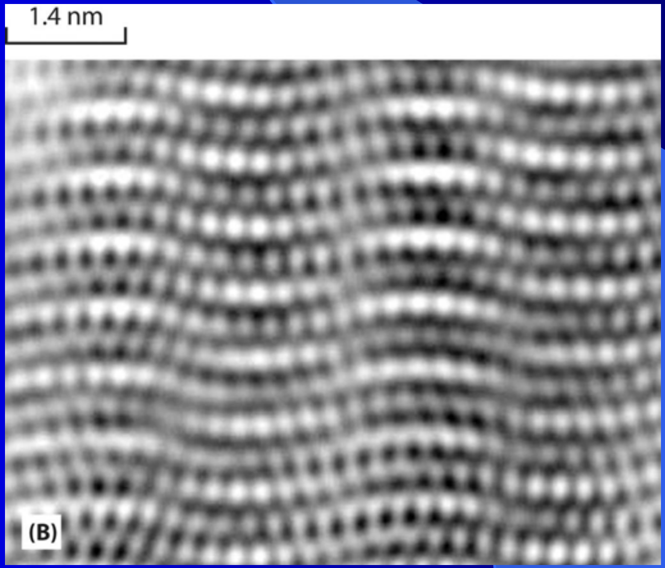
Serpentine minerals – antigorite, chrysotile, and lizardite

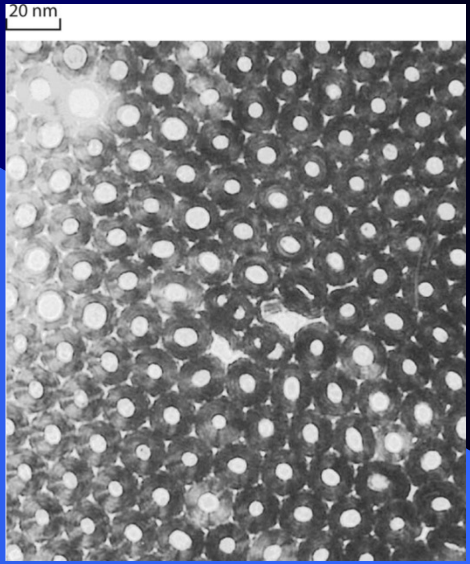
All are polymorphs of $Mg_3Si_2O_5(OH)_2$

Antigorite



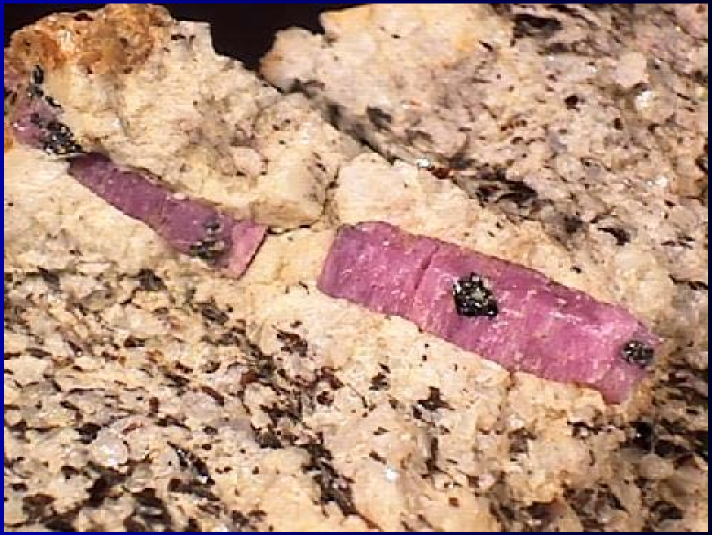
Chrysotile

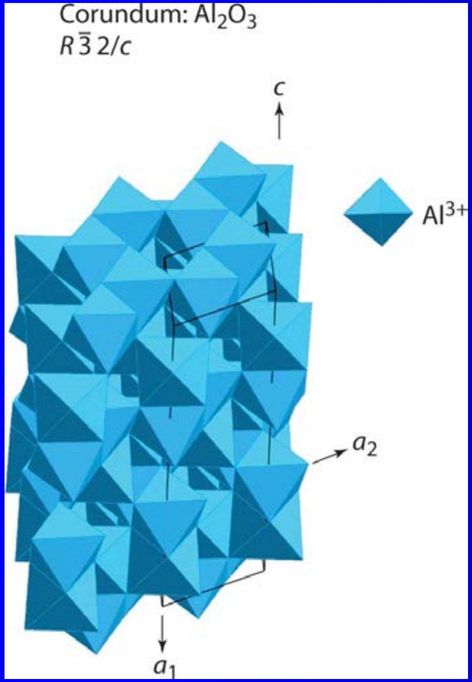




Corundum

Extremely high-grade contact metamorphism of aluminous (pelitic) rocks.





Sedimentary Rock-Forming Minerals and Materials

Calcite

Kaolinite

Montmorillonite

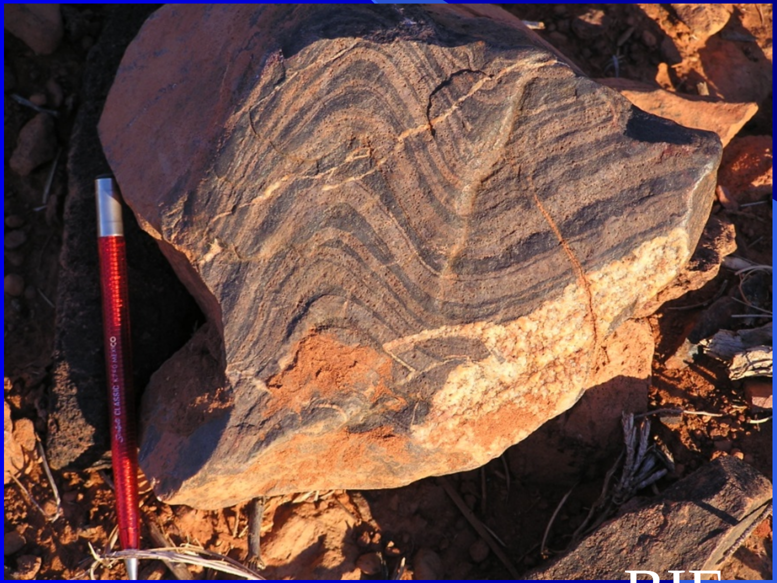
Siderite

Gypsum

Sylvite

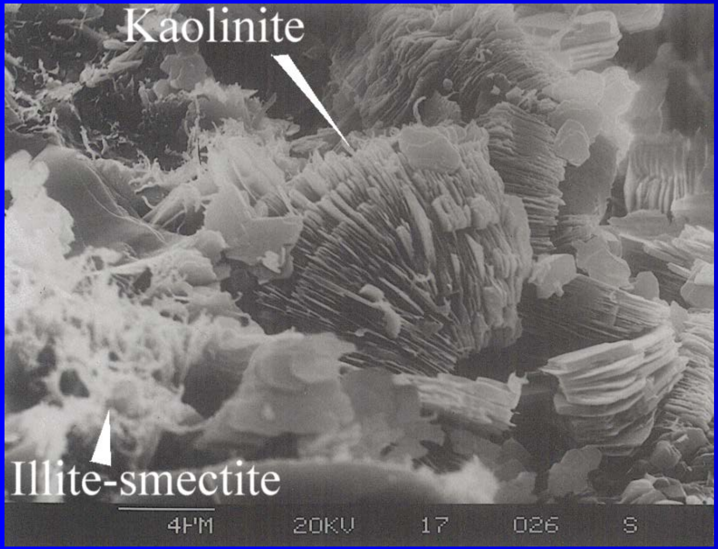
Minerals of Sedimentary Rocks

- Formed by chemical weathering of minerals that are unstable under surface conditions – clay minerals, oxides (hematite, magnetite), hydroxides (goethite, brucite, gibbsite)
- Minerals that precipitate from solution – carbonates, evaporites (halite, sylvite, gypsum), Precambrian iron formation (BIF)
- Detrital minerals – survive physical and chemical weathering processes – e.g. quartz, garnet, rutile, ilmenite, magnetite

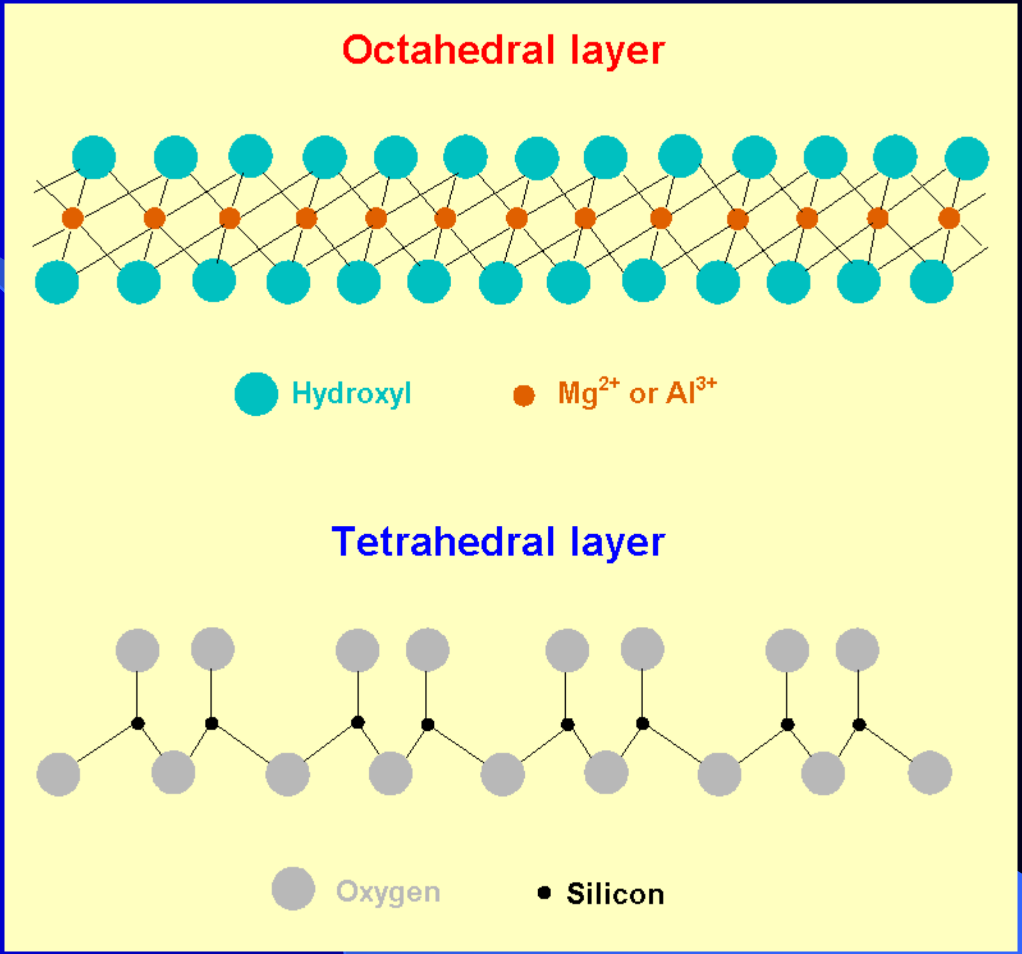


BIF

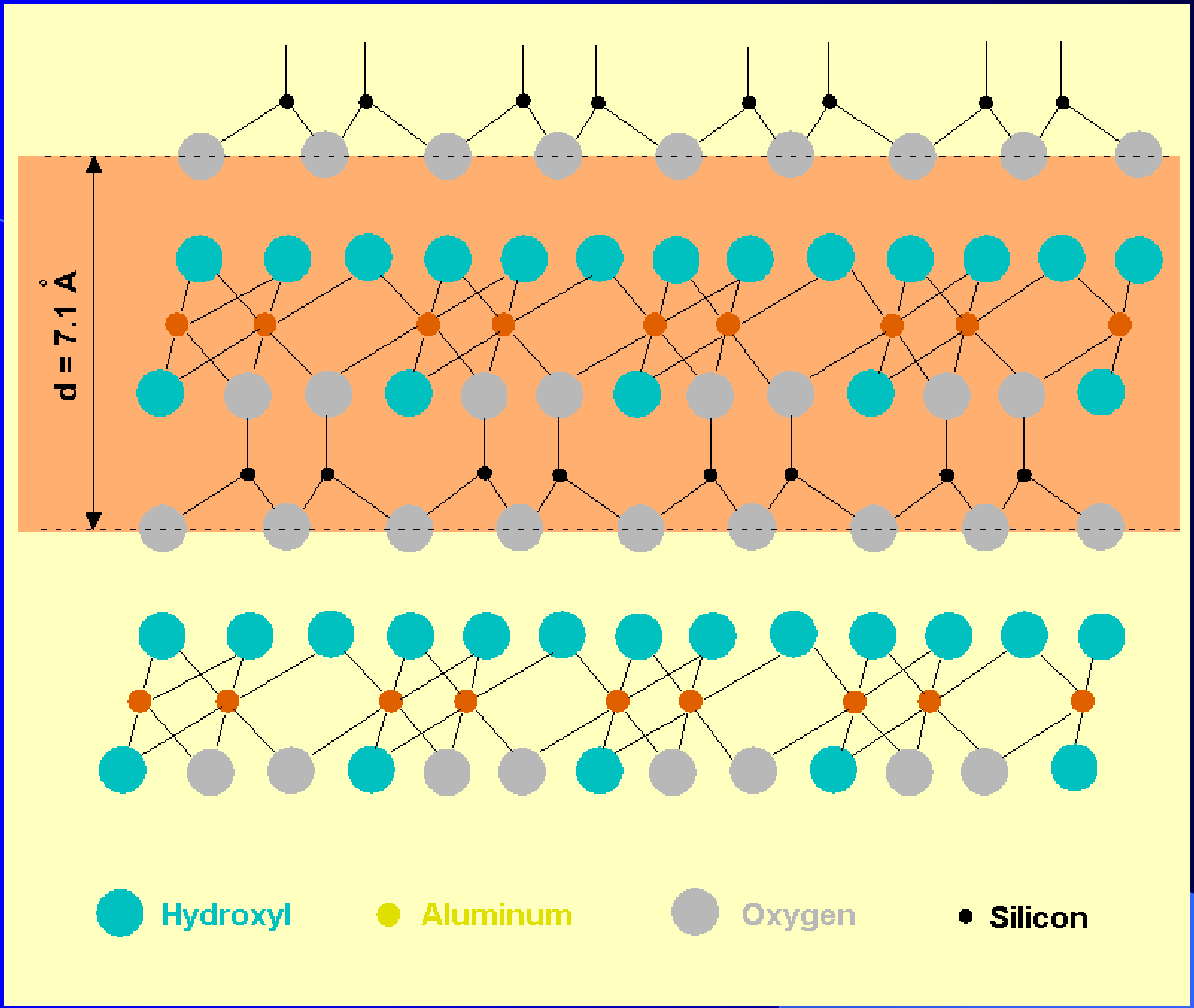
Clay Minerals



The basic building blocks of the clay minerals are tetrahedral layers and octahedral layers {Brucite [$Mg(OH)_2$] or Gibbsite [$Al(OH)_3$]}

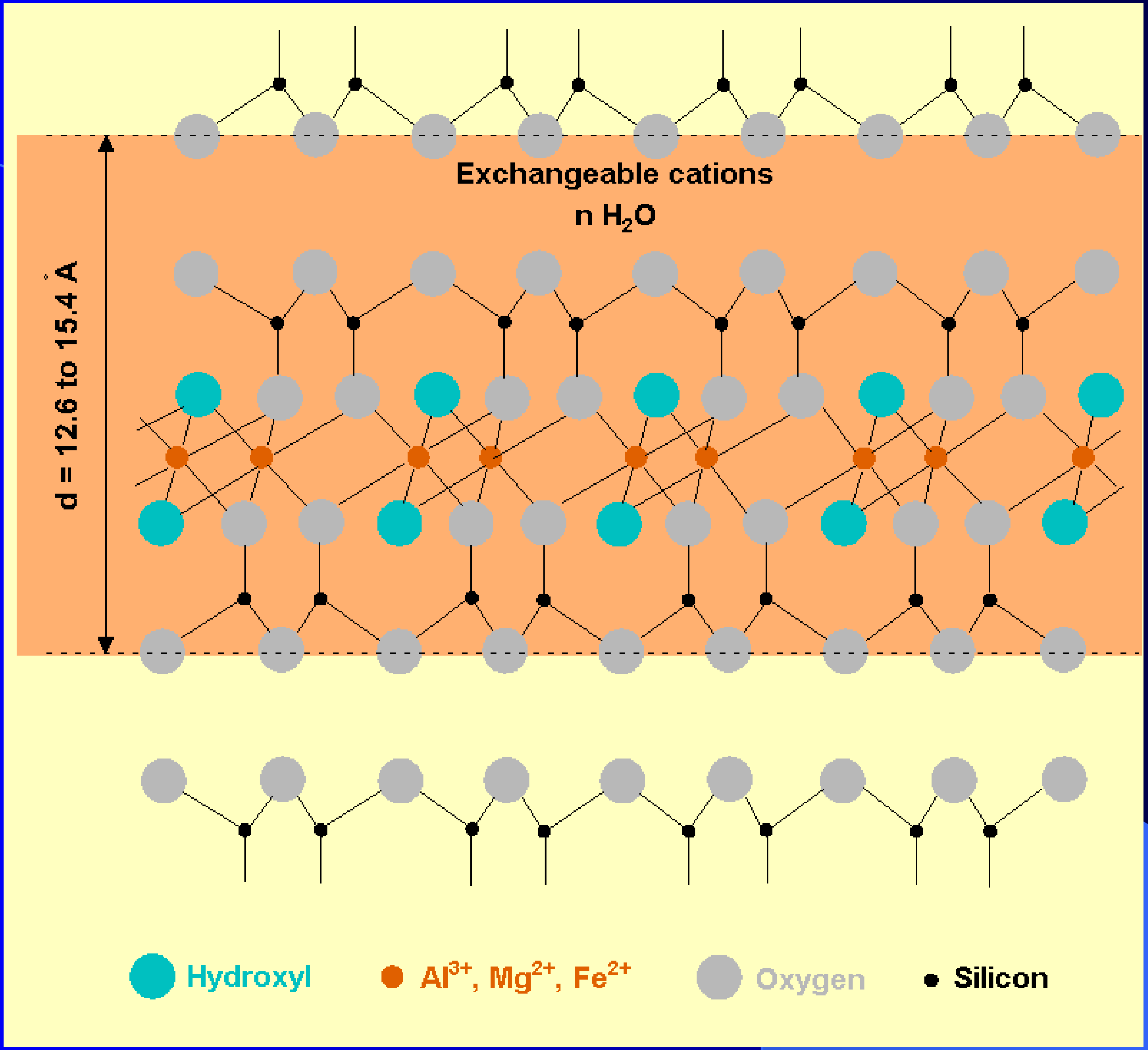


1:1 layer clays (e.g. Kaolinite)

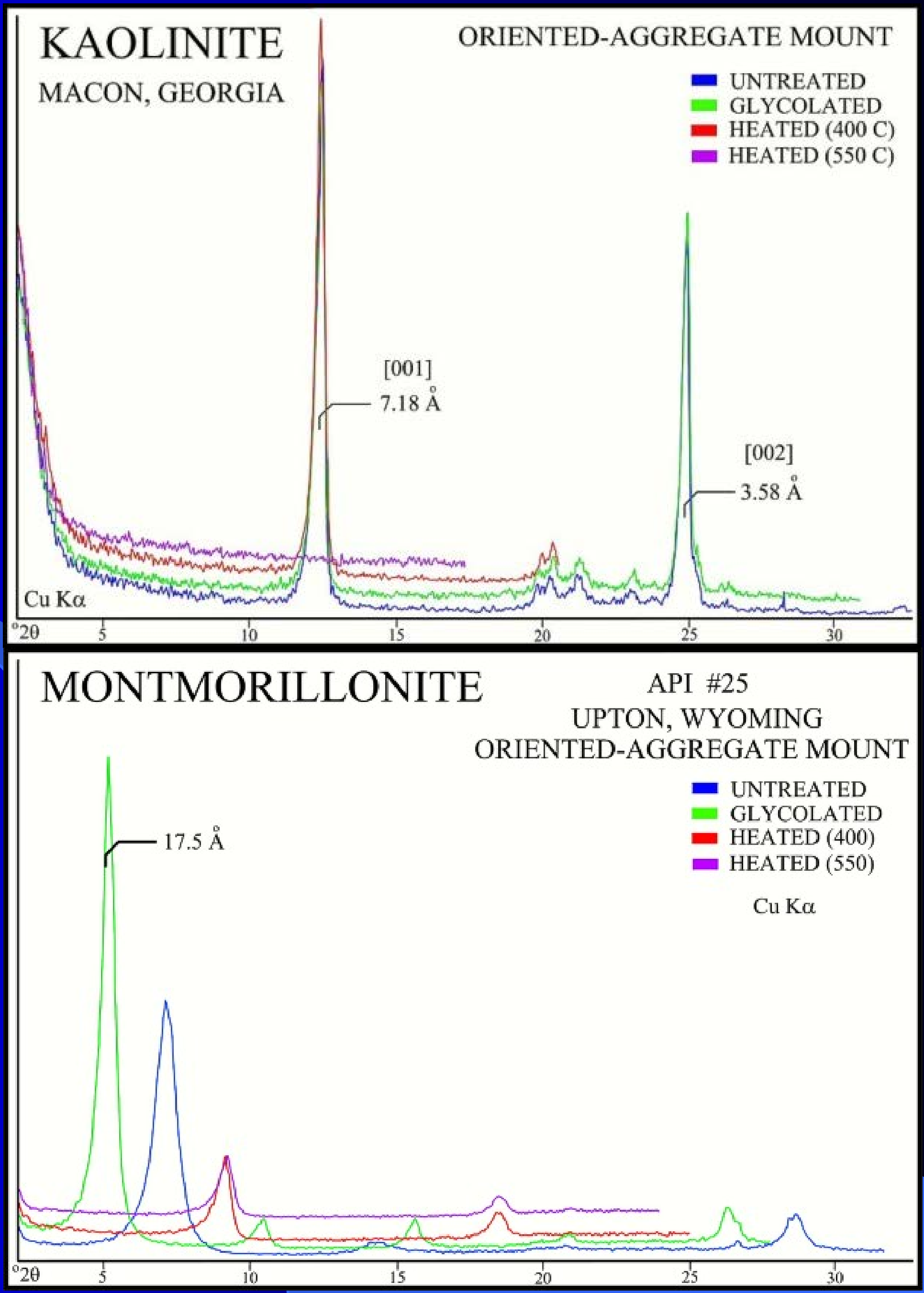


2:1 layer clays (e.g. Montmorillonite)

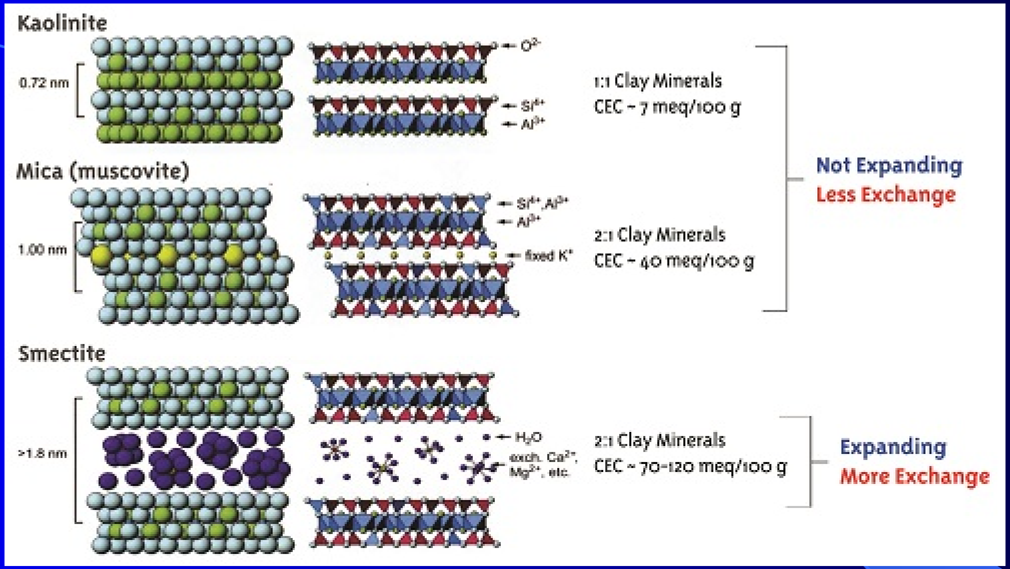
The general term for this group is smectites and they are expandable (swelling) clays



It is difficult to distinguish between clay minerals either in hand specimen or in thin section (there are 220 varieties). The method of choice is X-ray diffraction (XRD).

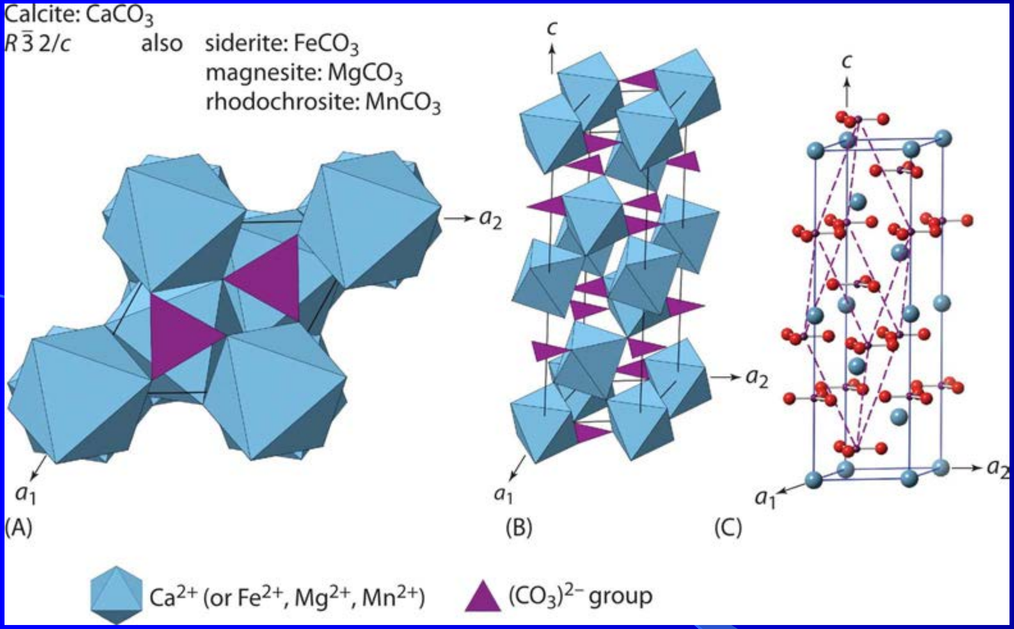


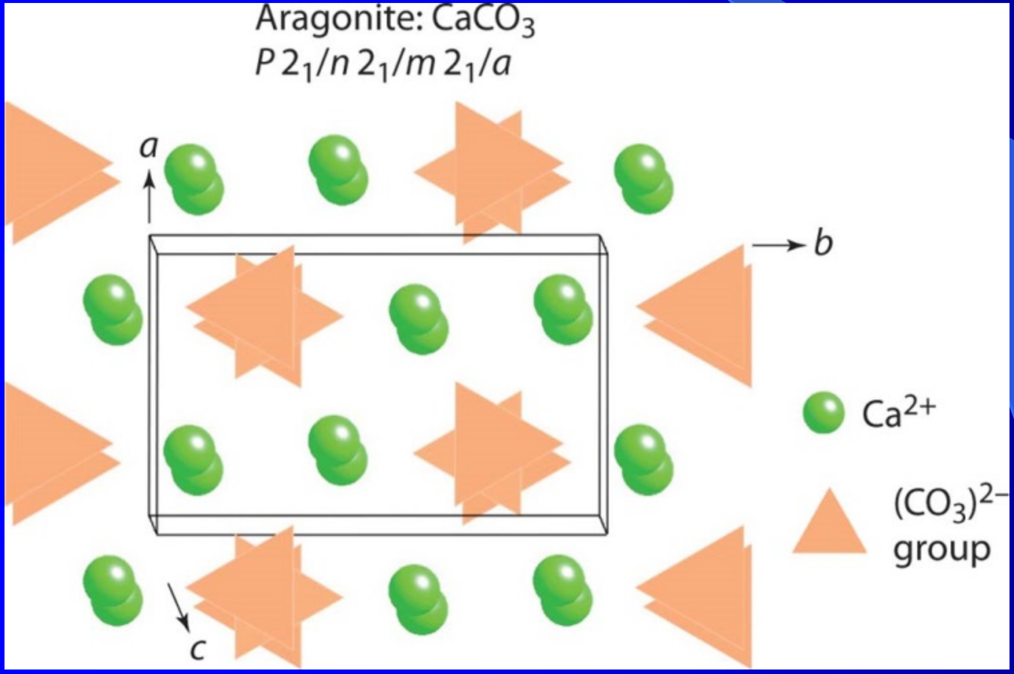
Cation Exchange Capacity (CEC) of various minerals

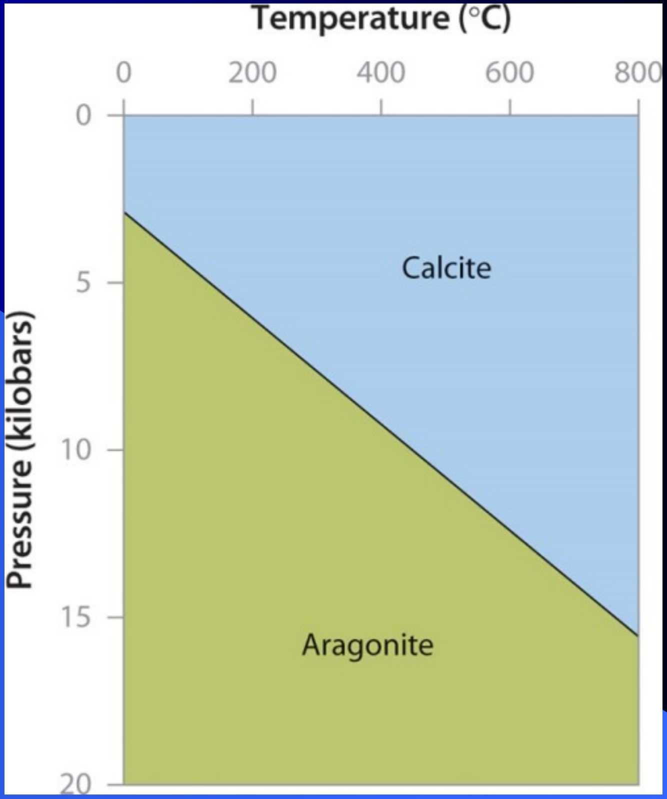


Mineral	Formula	CEC (cmol Kg^{-1})
Kaolinite		2-15
Montmorillonite		80-150
Chlorite		10-40
Vermiculite (Trioctahedral)		100-200
Vermiculite (Dioctahedral)		10-150
Allophane		3-250
Gibbsite		4
Goethite		4

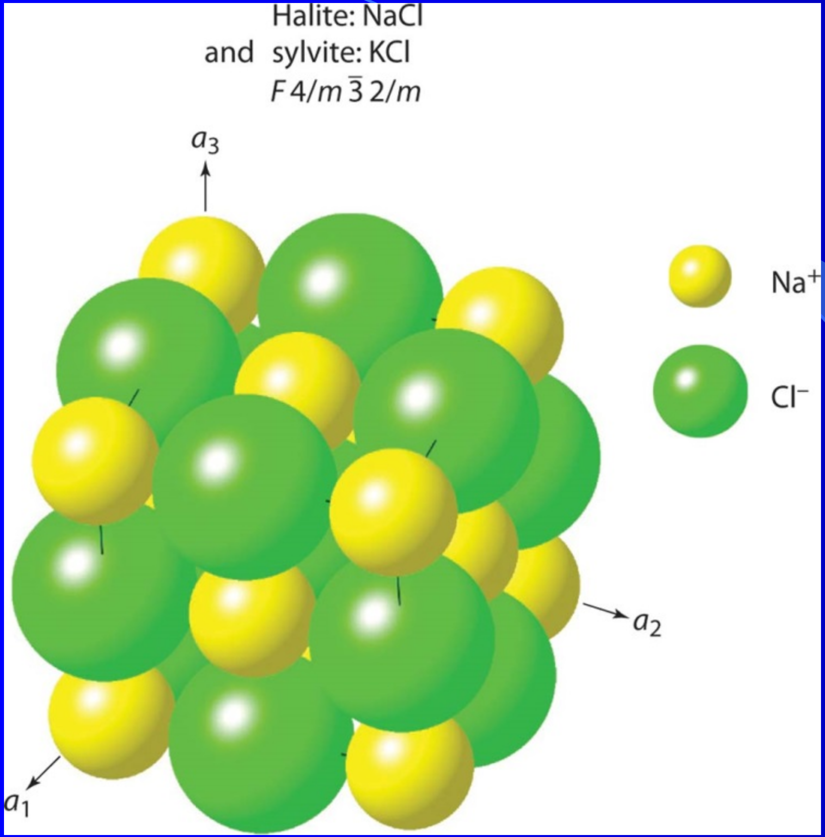
Carbonate minerals – $CaCO_3$ polymorphs - aragonite and calcite







Evaporite Minerals – Halite and Sylvite



Halite

Sylvite

Gypsum (monoclinic) and Anhydrite (orthorhombic)