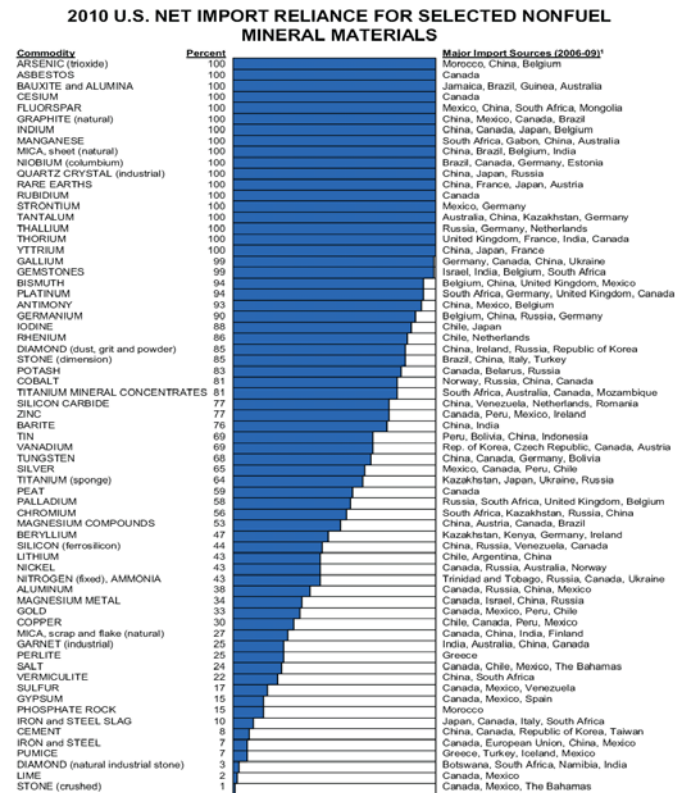


Earth Materials 114 Lecture Notes

Introduction

Read Chapters 1 & 2 of Klein & Philpotts
or Read Chapter 1 of Nesse (2000)

Strategic Minerals and Metals

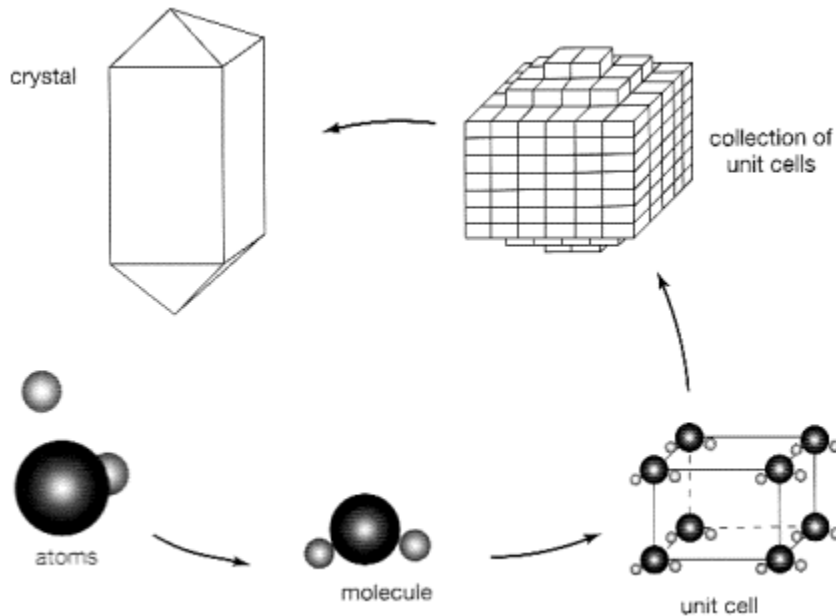


Atoms and Elements

Read Chapter 4 of Klein & Philpotts

or Read Chapter 3 of Nesse (2000)

atoms → molecules → crystals → rocks → Earth



http://darkwing.uoregon.edu/~cashman/GEO311/311pages/L1-Intro_pic_files/image014.gif

Element: A chemical element is a pure chemical substance consisting of one type of atom distinguished by its atomic number, which is the number of protons in its nucleus. (http://en.wikipedia.org/wiki/Chemical_element)

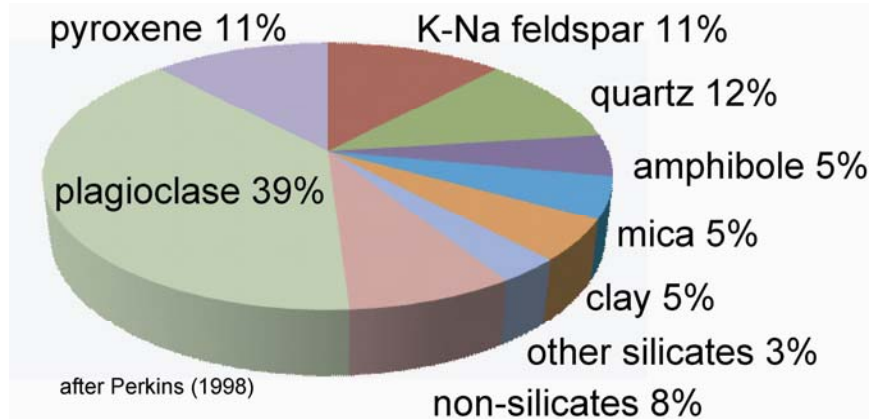
Common mineral-forming elements

Elemental composition of the whole Earth and the crust (the outermost solid layer):

element	whole Earth	crust	mineral
O	29%	46%	most minerals
Si	15%	28%	silicates
Al	1%	8%	feldspar
Fe	35%	6%	pyroxene, amphibole

Ca	1%	4%	plagioclase
Na	<1%	2%	feldspar
Mg	11%	2%	olivine
K	<1%	2%	K-feldspar
S	<3%	<1%	pyrite
Ni	2%	<1%	olivine

mineralogy of Earth's crust

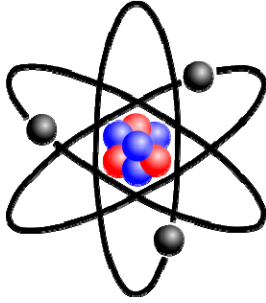


a

Periodic Table of the Elements

Periodic Table of the Elements																		Noble Gases	
atomic number (# protons, electrons)																			
atomic mass (protons + electrons + neutrons)																			
<div><div><div>1 H hydrogen 1.008</div><div>3 Li lithium 6.941</div><div>11 Na sodium 22.99</div><div>19 K potassium 39.10</div><div>37 Rb rubidium 85.47</div><div>55 Cs cesium 132.9</div><div>87 Fr francium (223)</div></div><div><div>+2</div><div>4 Be beryllium 9.012</div><div>12 Mg magnesium 24.31</div><div>20 Ca calcium 40.08</div><div>38 Sr strontium 87.62</div><div>56 Ba barium 137.3</div><div>88 Ra radium 226.0</div></div><div><div>47 Ag 107.9</div><div>+3</div><div>21 Sc scandium 44.96</div><div>39 Y yttrium 88.91</div><div>57 La lanthanum 138.9</div><div>89 Ac actinium (227)</div></div><div><div>+4</div><div>22 Ti titanium 47.90</div><div>40 Zr zirconium 91.22</div><div>58 Ce cerium 140.1</div><div>90 Th thorium 232.0</div></div><div><div>+5</div><div>23 V vanadium 50.94</div><div>41 Nb niobium 92.91</div><div>59 Pr praseodymium 140.9</div><div>91 Pa protactinium 231.0</div></div><div><div>+6</div><div>24 Cr chromium 52.00</div><div>42 Mo molybdenum 95.94</div><div>60 Nd neodymium 144.2</div><div>92 U uranium 238.0</div></div><div><div>+7</div><div>25 Mn manganese 54.94</div><div>43 Tc technetium 98.91</div><div>61 Pm promethium (147)</div><div>93 Np neptunium 237.0</div></div><div><div>+3</div><div>26 Fe iron 55.85</div><div>44 Ru ruthenium 101.1</div><div>62 Sm samarium 150.4</div><div>94 Pu plutonium (244)</div></div><div><div>+2</div><div>27 Co cobalt 58.93</div><div>45 Rh rhodium 102.9</div><div>63 Eu europium 152.0</div><div>95 Am americium (243)</div></div><div><div>+2</div><div>28 Ni nickel 58.71</div><div>46 Pd palladium 106.4</div><div>64 Gd gadolinium 157.3</div><div>96 Cm curium (247)</div></div><div><div>+2</div><div>29 Cu copper 63.55</div><div>47 Ag silver 107.9</div><div>65 Tb terbium 158.9</div><div>97 Bk berkelium (247)</div></div><div><div>+2</div><div>30 Zn zinc 65.37</div><div>48 Cd cadmium 112.4</div><div>66 Dy dysprosium 162.5</div><div>98 Cf californium (251)</div></div><div><div>+3</div><div>31 Ga gallium 69.72</div><div>49 In indium 114.8</div><div>67 Ho holmium 164.9</div><div>99 Es einsteinium (254)</div></div><div><div>+4</div><div>32 Ge germanium 72.59</div><div>50 Sn tin 118.7</div><div>68 Er erbium 167.3</div><div>100 Fm fermium (257)</div></div><div><div>+3</div><div>33 As arsenic 74.92</div><div>51 Sb antimony 121.8</div><div>69 Tm thulium 168.9</div><div>101 Md mendelevium (258)</div></div><div><div>-2</div><div>34 Se selenium 78.96</div><div>52 Te tellurium 127.6</div><div>70 Yb ytterbium 173.0</div><div>102 No nobelium (259)</div></div><div><div>-1</div><div>35 Br bromine 79.90</div><div>53 I iodine 126.9</div><div>71 Lu lutetium 175.0</div><div>103 Lr lawrencium (260)</div></div><div><div>2 He helium 4.003</div><div>10 Ne neon 20.18</div><div>18 Ar argon 39.95</div><div>36 Kr krypton 83.80</div><div>54 Xe xenon 131.3</div><div>86 Rn radon (222)</div></div></div>																			
<div><div>LIL</div><div>HFS</div></div>																			
whole Earth constituents																		crust constituents	
<div>Lanthanides</div>																			
<div>Actinides</div>																			
after Moore and Winkler																			

Atoms



atom: The smallest particle that retains the chemical properties of an element; composed of

proton: electric charge +1, 1.00728 amu

neutron: electric charge 0, 1.00867 amu

electron, e^- : electric charge -1 , 0.00055 amu (insignificant)

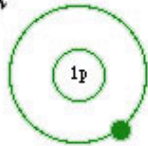
For example, Li has an **atomic number** of 3, meaning 3 protons (and 3 electrons, if neutral); if it is ${}^7\text{Li}$, it has a mass of 7 and thus 4 neutrons.

electrons fill orbital levels around the **nucleus**: 2 in the first level, 8 in the second, and so on

the position of an element in the periodic table relates to the number of electrons in the **outer orbital**

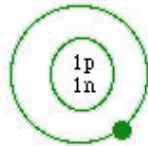
Atomic Orbital Structures

Hydrogen



${}^1_1\text{H}$

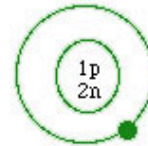
atomic number, $p, e = 1$
atomic mass, $p+n = 1$



${}^2_1\text{H}$

atomic number, $p, e = 1$
atomic mass, $p+n = 2$

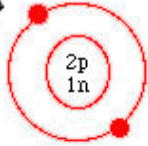
*naturally occurring



${}^3_1\text{H}$

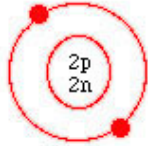
atomic number, $p, e = 1$
atomic mass, $p+n = 3$

Helium



${}^3_2\text{He}$

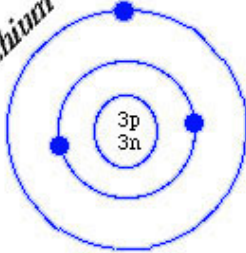
atomic number, $p, e = 2$
atomic mass, $p+n = 3$



${}^4_2\text{He}$

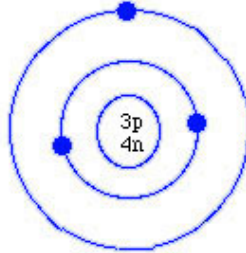
atomic number, $p, e = 2$
atomic mass, $p+n = 4$

Lithium



Li

atomic number, $p, e = 3$
atomic mass, $p + n = 6$



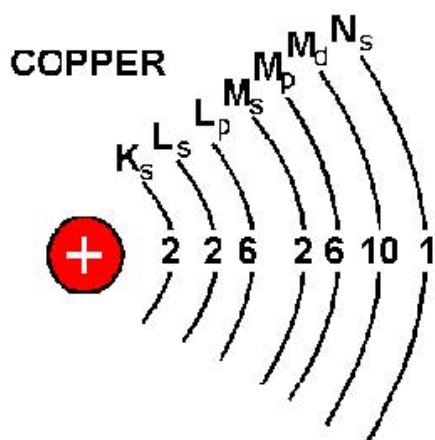
Li

atomic number, $p, e = 3$
atomic mass, $p + n = 7$

after Davidson et al.

Structure of Atoms

The four electron shells surrounding the nucleus are named—with increasing distance and energy—K (or 1), L (or 2), M (or 3), and N (or 4) shells. Each shell is split into subshells, labeled *s*, *p*, *d*, and *f*; the K shell contains an *s* subshell, the L shell has *s* and *p* subshells, M has *s*, *p*, and *d*, and N has *s*, *p*, *d*, and *f*. An *s* subshell consists of one *s* orbital (with 2 electrons), a *p* subshell consists of up to 3 *p* orbitals (6 electrons), and a *d* subshell consists of up to 5 *d* orbitals (10 electrons).



this is written $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^{10}$

electronic configurations

		shell						
(±)		K	L	L	M	M	M	N
Z	element	1s	2s	2p	3s	3p	3d	4s
								4p
1	H	1						
2	He	2						
3	Li	2	1					
4	Be	2	2					
5	B	2	2	1				
6	C	2	2	2				
7	N	2	2	3				
8	O	2	2	4				
9	F	2	2	5				
10	Ne	2	2	6				
11	Na	2	2	6	1			
12	Mg	2	2	6	2			
13	Al	2	2	6	2	1		
14	Si	2	2	6	2	2		
15	P	2	2	6	2	3		
16	S	2	2	6	2	4		
17	Cl	2	2	6	2	5		
18	Ar	2	2	6	2	6		
19	K	2	2	6	2	6		1
20	Ca	2	2	6	2	6		2
21	Sc	2	2	6	2	6	1	2
22	Ti	2	2	6	2	6	2	2
23	V	2	2	6	2	6	3	2

24	Cr	2	2	6	2	6	4	2	
25	Mn	2	2	6	2	6	5	2	
26	Fe	2	2	6	2	6	6	2	
27	Co	2	2	6	2	6	7	2	
28	Ni	2	2	6	2	6	8	2	
29	Cu	2	2	6	2	6	9	2	
30	Zn	2	2	6	2	6	10	2	
31	Ga	2	2	6	2	6	10	2	1
32	Ge	2	2	6	2	6	10	2	2
33	As	2	2	6	2	6	10	2	3
34	Se	2	2	6	2	6	10	2	4
35	Br	2	2	6	2	6	10	2	5
36	Kr	2	2	6	2	6	10	2	6

1 e- in outer s orbital

2 e- in outer s orbital

alkali metals +1

alkaline earth metals +2

1 e- in outer d orbital (& 2 in s)

2 e- in outer d orbital (& 2 in s)

4 e- in outer d orbital (& 2 in s)

2 e- in outer s orbital (outer s orbital lower energy than outer d orbital)

1 e- in outer p orbital

2 e- in outer p orbital

outer p orbital full -1

outer p orbital full -2

outer p orbital full -3

Halogens

Noble Gases

whole Earth constituents

crust constituents

Lanthanides

Actinides

after Housner and Wiersma

Ions

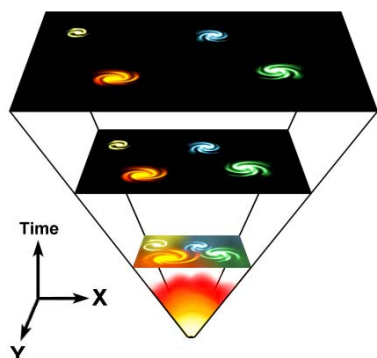
elements tend to gain or lose electrons to acquire the configuration of a noble gas

cation: ion w/ excess + charge

anion: ion w/ excess — charge

typical oxidation states: <http://www.wsu.edu/~wherland/#Radii>

Cosmochemistry and the production of elements



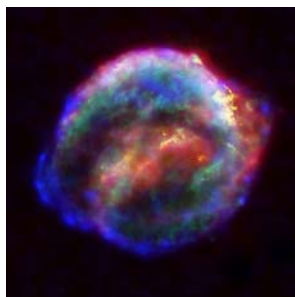
(for more see http://en.wikipedia.org/wiki/Stellar_nucleosynthesis)

The birth of matter in the universe began about 15–20 Ga, judged by tracing expanding galaxies (groups of stars) back to a common origin in the Big Bang. After 1 m.y., the universe had cooled sufficiently (3000K) for H and He to form from subatomic particles.

These elements aggregated to form stars via gravitational attraction; stars are 75 wt% H, 22 wt% He, and 3% heavier elements.

The heat of star aggregation caused particles and elements to accelerate and collide, forming elements as heavy as Fe (atomic number 26).

Elements heavier than Fe are produced by during supernovae explosions, which occur when the gravitational force of the outer layers of a star overcomes the thermal pressure of the fusing inner layers.

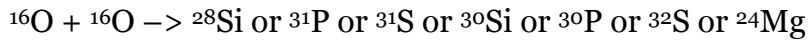


Carbon burning



carbon is consumed and a core of product elements builds up; gravity builds up and the new core collapses sufficiently to burn heavier elements

Oxygen burning

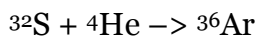


O, Ne, Mg, Si, S burning takes a star 6 months, reaching $3\text{E}9$ Kelvin

The heat of star aggregation causes particles and elements to accelerate and collide, forming elements as heavy as Fe (atomic number 26).

Silicon burning

lasts one day, reaching $5\text{E}9$ Kelvin. This causes a gravitational collapse, forming either a neutron star or a black hole, with the outer layers being blown off in a supernova whose neutron burst forms elements heavier than Fe



Further accretion formed solar systems, meteorites, and planets by about 4.5 Ga
Differentiation of the Earth occurred by gravitational separation of the lightest elements into the atmosphere and the densest elements into the core.

Chemical Bonds

What is a molecule?

Molecule: group of bonded atoms; e.g., H_2O , SiO_2 , [NaCl](#)

What is a mineral?

Mineral: a solid of specific composition with a regular arrangement of atoms

How do atoms **bond** together to form minerals?

Elements bond by sharing or transferring electrons

Why don't elements prefer to remain alone, unbonded?

Elements like to have their outer electron orbital full of electrons, so elements with full orbitals are very stable (e.g., the noble gases He, Ar, Kr, Xe) elements near the left side of the periodic table (e.g., this creates the positively charged ions K^+ , Mg^{2+}) like to give up electrons (the next lower orbital becomes full), while those near the right side like to gain electrons to become full (e.g., this creates the negatively charged ions S^{2-} , Cl^-)

ionic bond: electrostatic attraction between cations and anions;

forms where and when, e.g.,

- one atom that loses an electron to become a more-stable cation is adjacent to second atom that gains an electron to become a more-stable anion (e.g., NaCl);
- one atom that loses two electrons to become a more-stable cation is adjacent to second and third atoms that gain an electron to become a more-stable anion (e.g., $CaCl_2$);

the atoms are attracted and bound to one another by electrostatic charge

nice movie of this at http://en.wikipedia.org/wiki/Ionic_bond

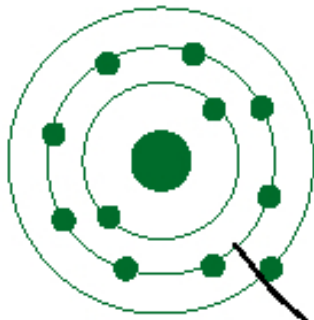
an ionic bond is charge balanced

soluble in H_2O because, e.g., NaOH and HCl are more stable than $NaCl + H_2O$;

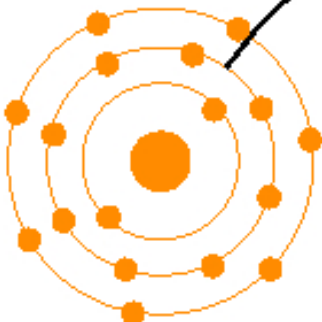
ionic solids are hygroscopic, and can dissolve in H_2O pulled out of the atmosphere; also have low melting point

Na: 1 valence electron

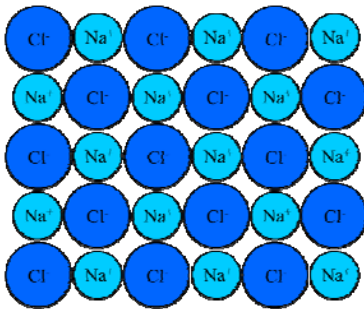
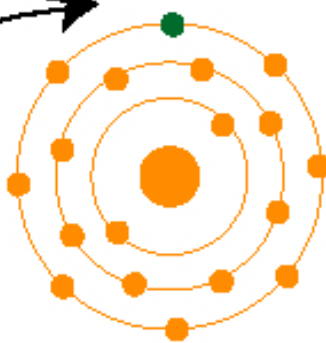
Na⁺: 8 valence electrons



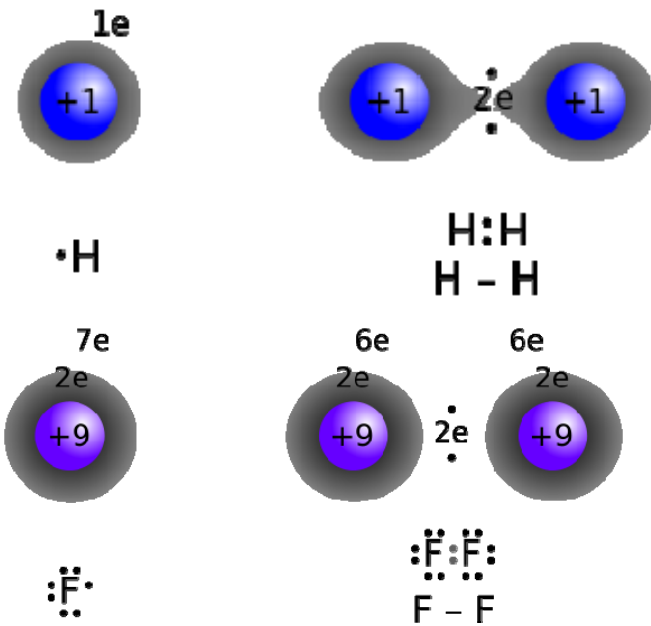
Cl: 7 valence electrons



Cl⁻: 8 valence electrons

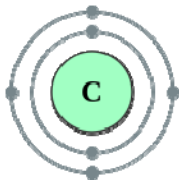


covalent bond: sharing of electrons between atoms when orbitals overlap;
'beneficial' for atoms that can fill their valence shell



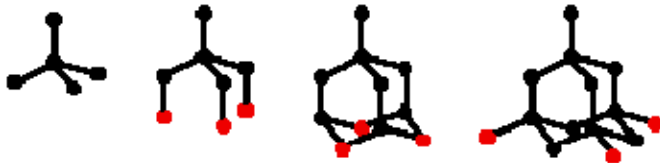
http://en.wikipedia.org/wiki/Covalent_bond

e.g., carbon would “like to have” 6 electrons in its valence shell, but has only 2



from http://en.wikipedia.org/wiki/Covalent_bond

if it can share valence electrons with 3 other C atoms in a 4-fold, 4-coordinated, tetrahedral structure, it can be electrically neutral. This is diamond



<http://www.chemguide.co.uk/atoms/structures/giantcov.html>

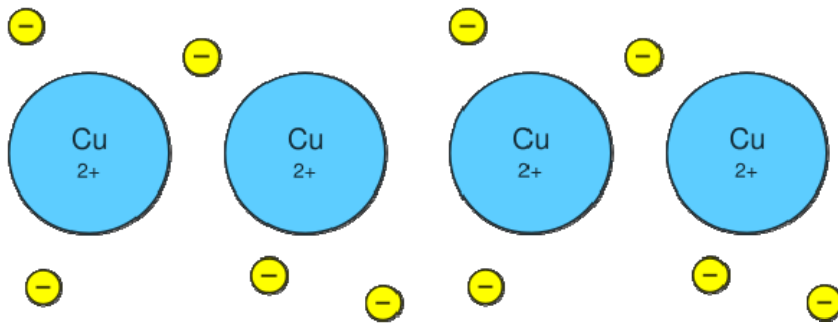
Si is right below C in the periodic table, so also “missing” 4 electrons in its valence shell

so, metallic Si has the same structure as diamond

another configuration for Si is that of quartz, SiO_2 , in which each Si^{4+} cation is charge balanced by four half oxygen atoms, O^{2-}

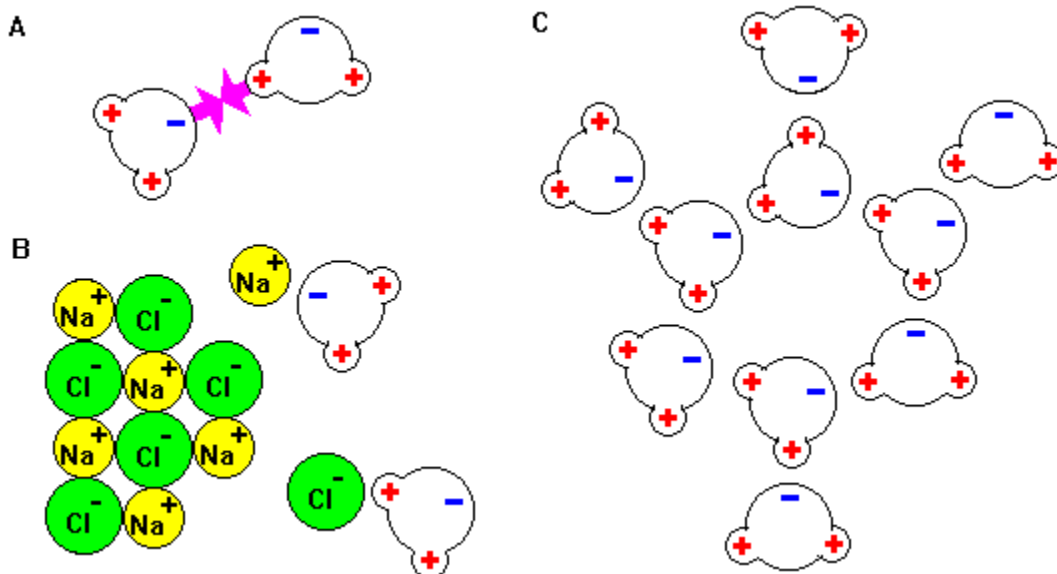
covalently bonded materials are insoluble in H_2O and have high melting temperatures

metallic bond: special type of covalent bond in which valence electrons are freer to migrate around multiple atoms in “multi-atom orbitals”



leads to materials that are electrically conductive, strong yet malleable, and have high melting temperatures (except for the Zn–Cd–Hg group, which are close to noble gases in their electronic configuration)

hydrogen bond: weak electrostatic attraction among individual polar molecules (e.g., H₂O)



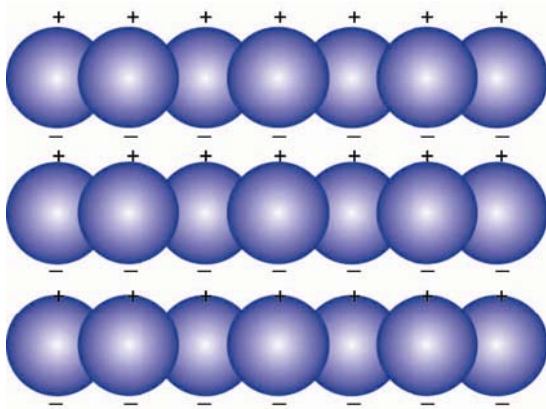
<https://www.uwgb.edu/dutchs/EarthSC202Notes/minerals.htm>

unusually high heat capacity, making H₂O the principal heat reservoir in Earth
 expands when freezing; very weird
 complexes with many ions; great solvent of ionic bonds

van der Waals bond: weak electrostatic attraction between dipoles—or all forces not covered by the aforementioned types of bonding

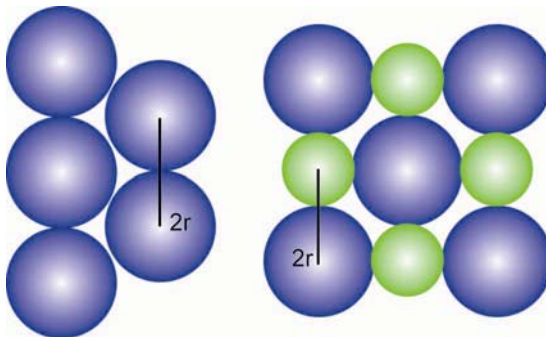


geckos may climb using van der Waals forces



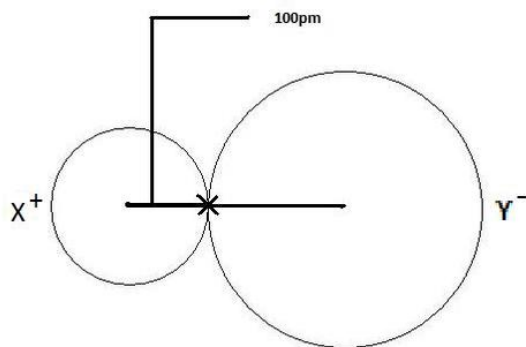
Nesse (2000)

bond length: distance between atoms that are bonded

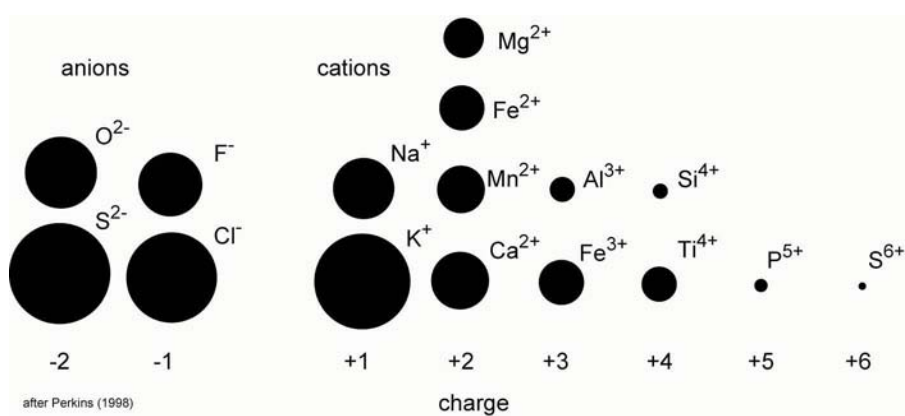


Nesse (2000)

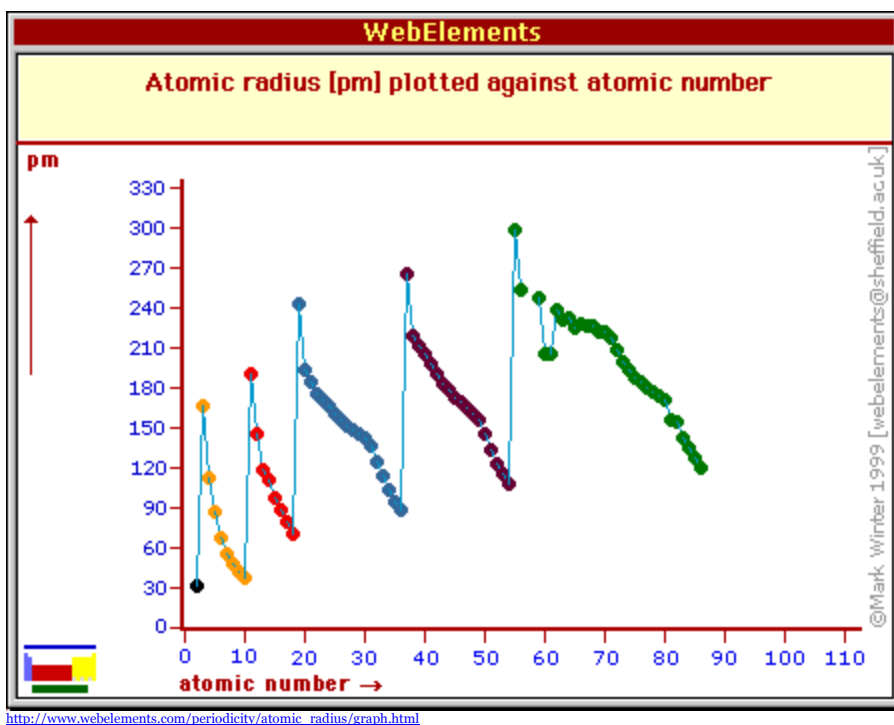
effective radius of an atom is its size within a crystal lattice



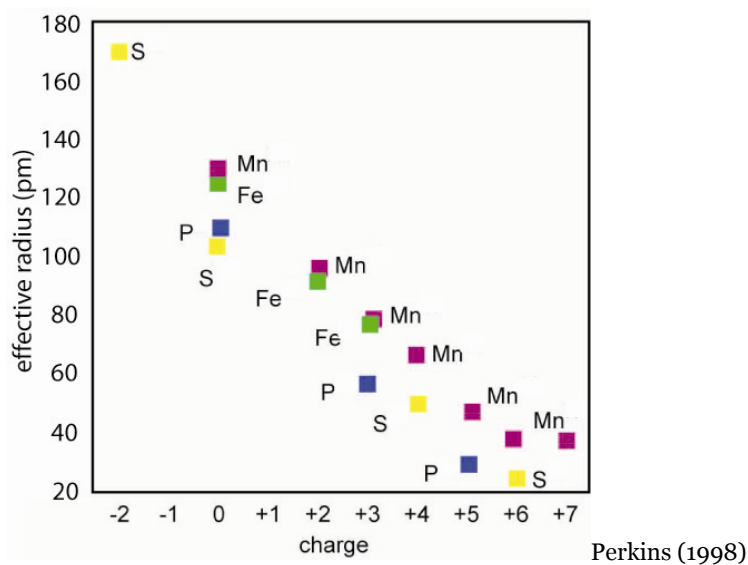
http://chemwiki.ucdavis.edu/Inorganic_Chemistry/Descriptive_Chemistry/Periodic_Table_of_the_Elements/Atomic_Radii



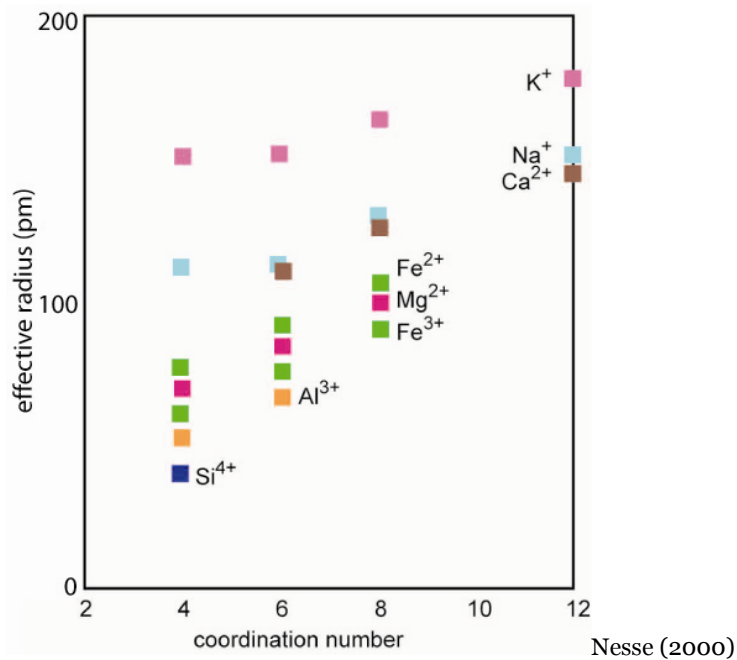
decreases from left to right across periodic table as the number of electrons and protons increase and exert an increasing mutually attractive force
increases down the periodic table (from a noble gas to an alkali metal) due to the addition of another electron shell)



effective radius is affected by oxidation state, with cations smaller than the neutral atom (because of the “missing” electron(s)) and anions larger (because of the “extra” electron(s))



effective radius is affected by density of packing/coordination



this is encapsulated in the Goldschmidt correction:

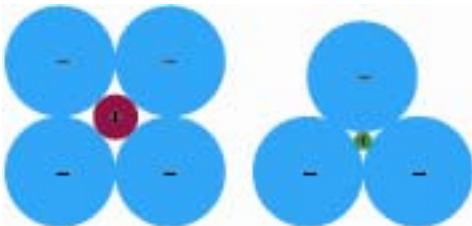
coordination number	radius
XII	1
VIII	0.97
VI	0.96
IV	0.88

high-coordination materials are denser; even though the anions are a *bit* farther from the cation, the number of anions nearer the cation is larger

Pauling's Rule 1 (Radius Ratio Principle)

cation–anion separation = cation radius + anion radius

cation coordination number depends on cation radius / anion radius



coordination number	cation radius / anion radius
XII	1
VIII	0.73–1
VI	0.41–0.73
IV	0.22–0.41
III	0.15–0.22

Pauling's Rule 2 (Electrostatic Valency Principle)

bond strength = ionic charge / coordination number

Crystal Structure

Read Chapters 4 & 5 of Klein & Philpotts

or Read Chapter 4 of Nesse (2000)

If Si and O are the most common elements in the outer part of the Earth, what are common minerals made of?

silicates are the most common minerals because O is the most common anion and Si is the most common cation; hence SiO_4 and variants

How do Si and O bond together to form 3-D structures?

Is SiO_4 a stable compound?

SiO_4 has a net negative charge of 4-; this must be balanced by cations

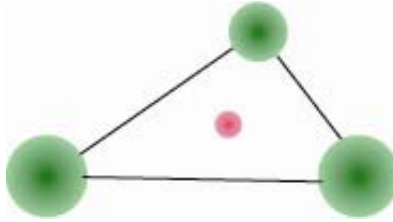
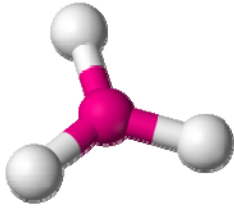
the minimum **coordination number** for an element that is part of a 3D mineral is IV, thus SiO_4 , (cannot form 3-D structures from 3-coordinated things like CO_3)

What structure can be formed from pure Si and O?

Quartz: SiO_2 in a 3-D array of tetrahedra, each of which is joined to other tetrahedra at all 4 corners; quartz is 100% SiO_2 and has a density of 2.65 g/cm³

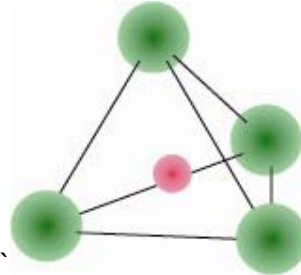
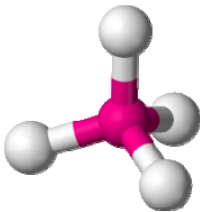
coordination number: number of atoms surrounding another

3-fold, III, planar

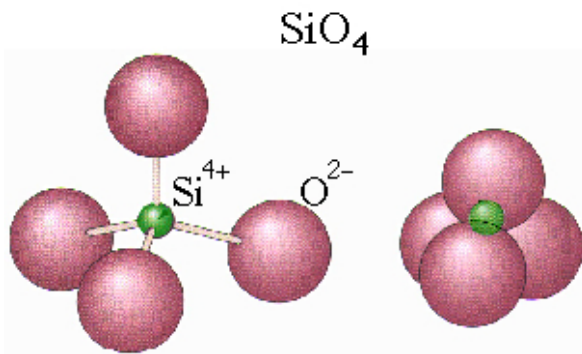


example material: BO_3^{3-} , SO_3 , NO_3^- , CO_3^{2-}

4-fold, IV, tetrahedral; common



tetrahedron, with 3 triangular faces

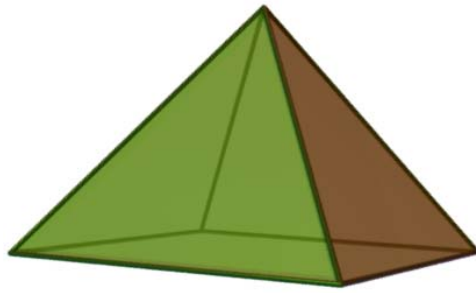


expanded for clarity

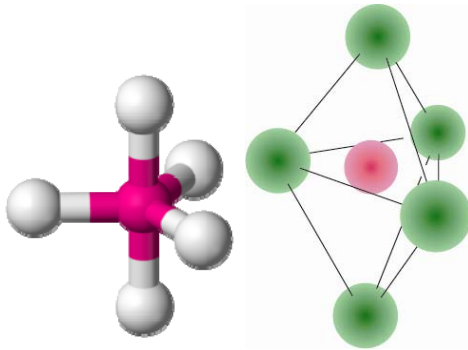
true scale

example mineral: Si in many silicates is surrounded by 4 O

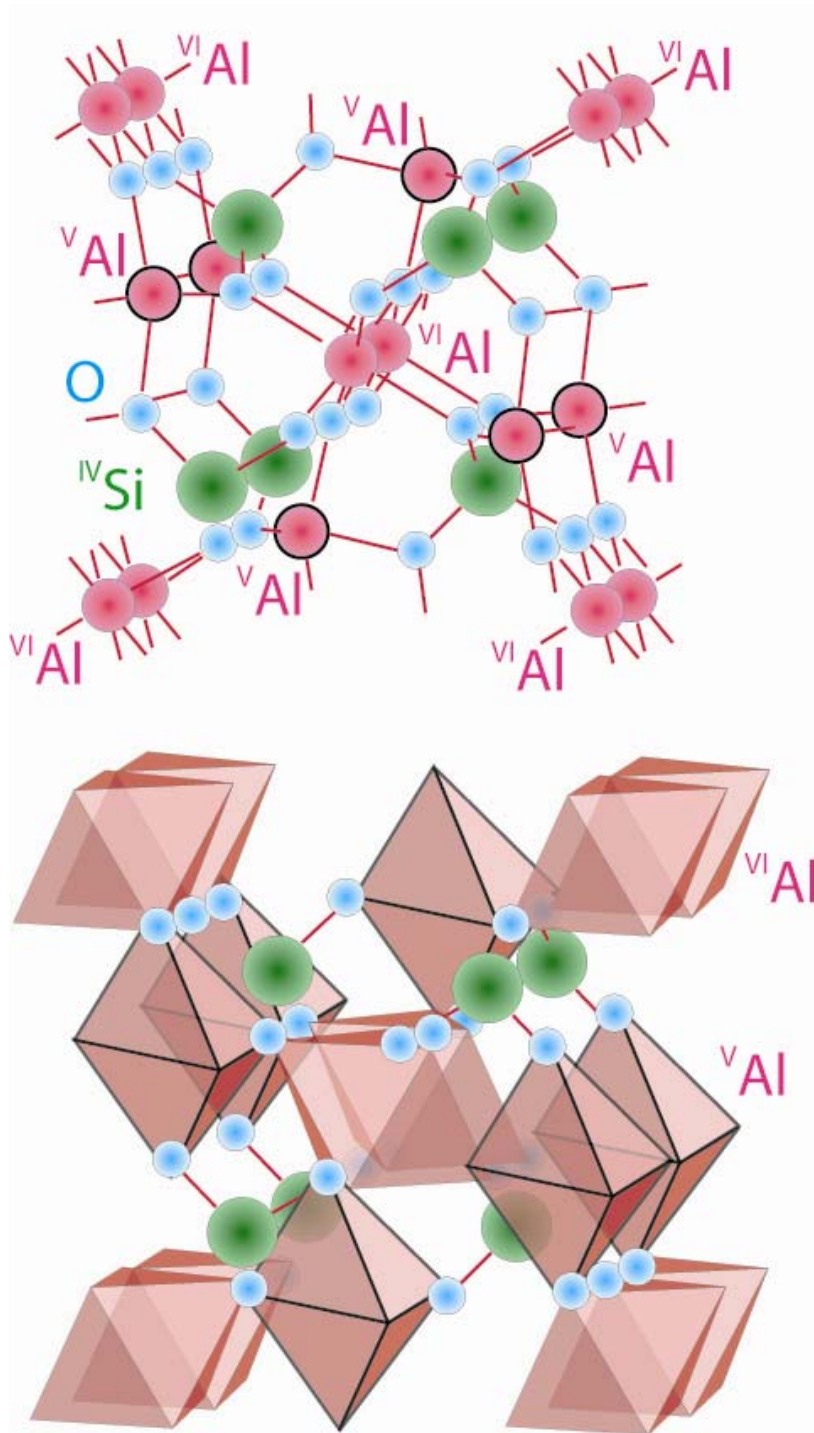
5-fold, V; uncommon



square pyramid, with 4 triangular faces and 1 square face

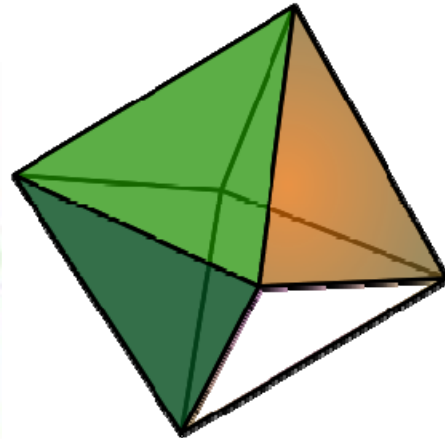
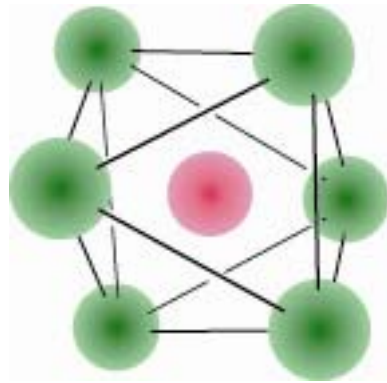
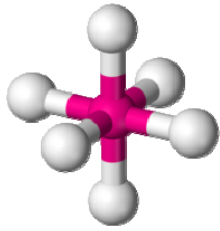


trigonal bipyramid, with 6 triangular faces

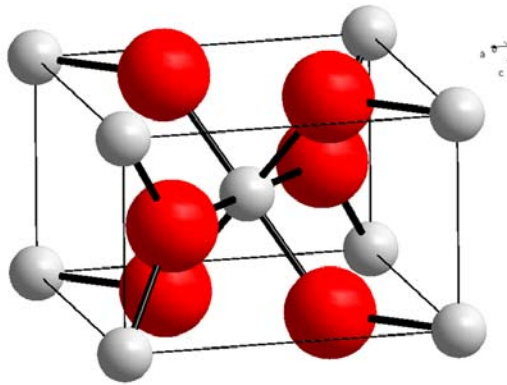


example mineral: half the Al in andalusite is surrounded by 5 O

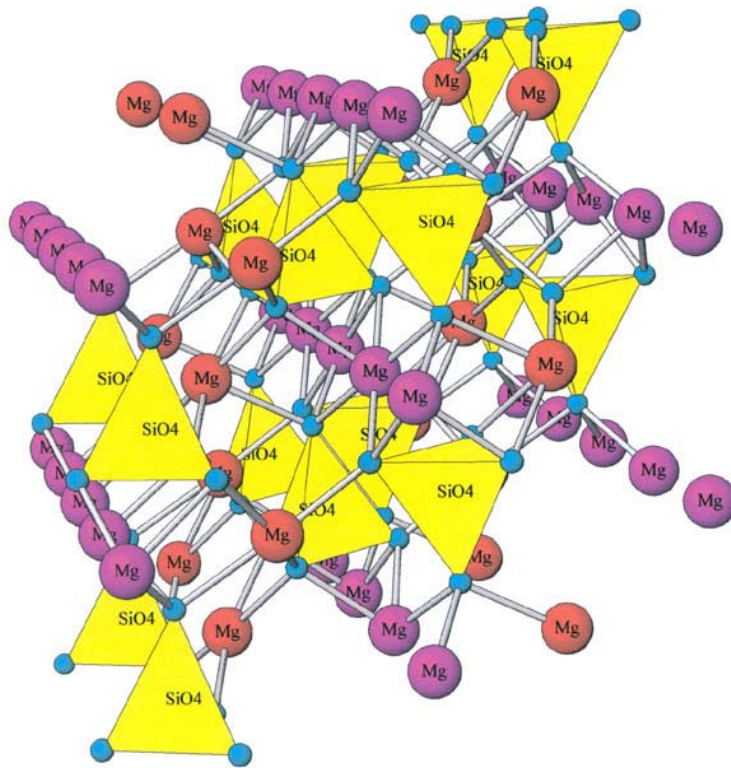
6-fold, VI, octahedral; common



octahedron, with 8 triangular faces

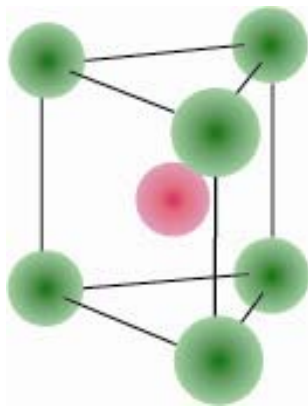


example mineral: Ti in rutile is surrounded by 6 O atoms



http://www3.geosc.psu.edu/courses/Geosc533/LectureMaterials/Lecture11/Olivine_structure_1.html

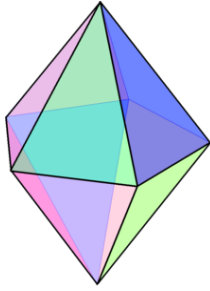
example mineral: Mg or Fe in olivine is surrounded by 6 O atoms



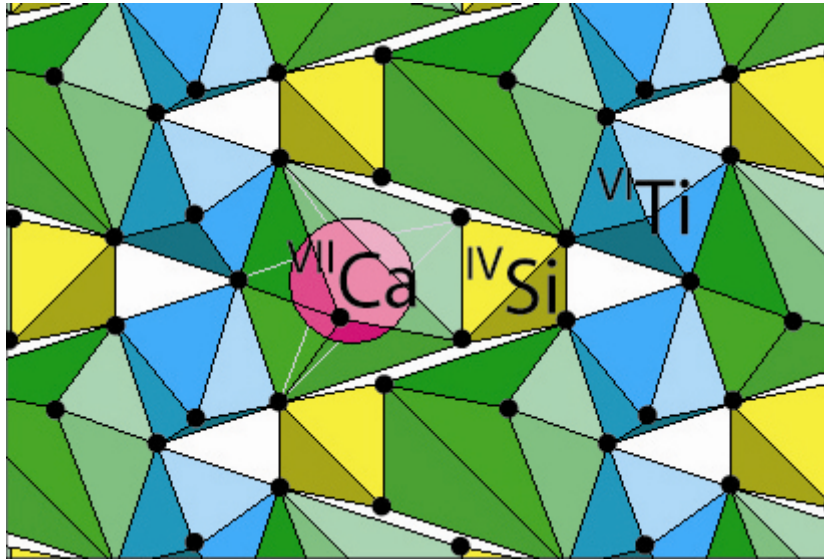
triangular prism, with 2 triangular faces and 3 square faces

example mineral: Mo in molybdenite is surrounded by 6 S atoms

7-fold, VII; uncommon



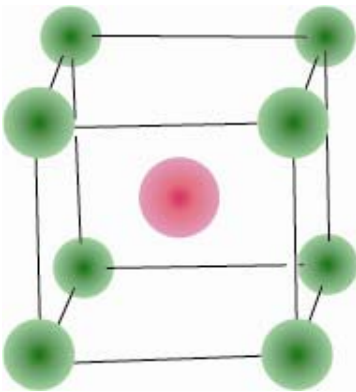
pentagonal bipyramid, with 10 triangular faces



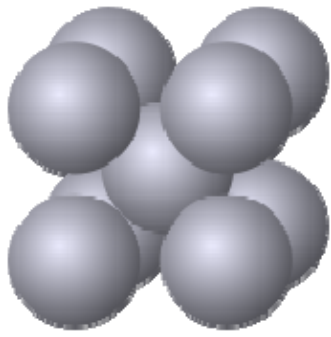
<http://www.uwgb.edu/dutchs/Petrology/Titanite%20Structure.HTM>

example mineral: Ca in titanite is surrounded by 7 O atoms

8-fold, VIII; common



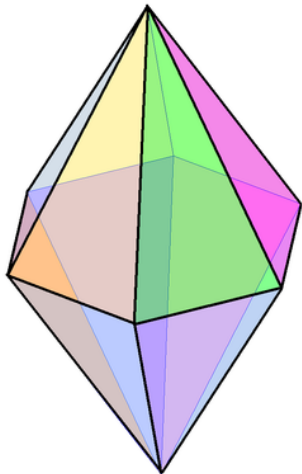
prism, with 6 rectangular faces:



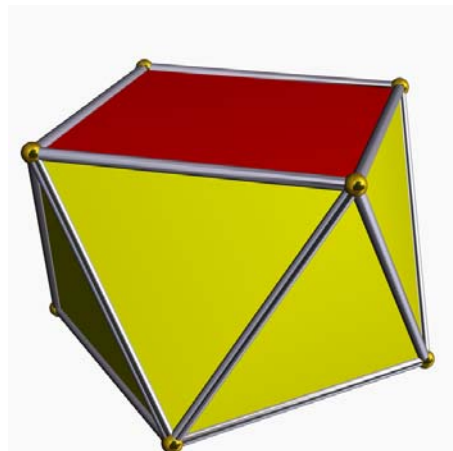
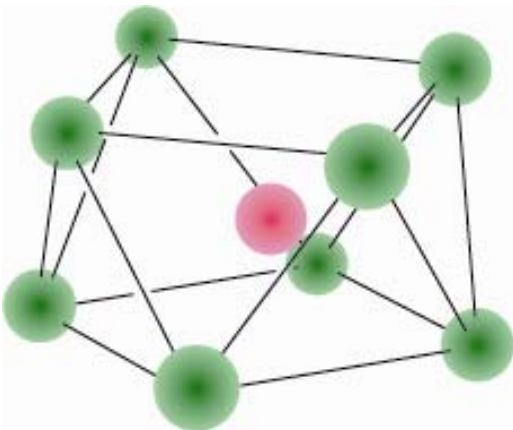
body-centered cubic packing: cube with 6 square faces

example mineral: metallic Fe, Cr, Mo, W, V, Nb, Ta; strong, less ductile

atomic packing factor (volume of atoms/volume of unit cell) = 0.68



hexagonal bipyramid with 12 triangular faces



square antiprism with 8 triangular faces and 2 square faces

example mineral: Ca in scheelite is surrounded by 8 oxygen

12-fold, XII; common

close packing

because metals share electrons freely, they can attain close packing

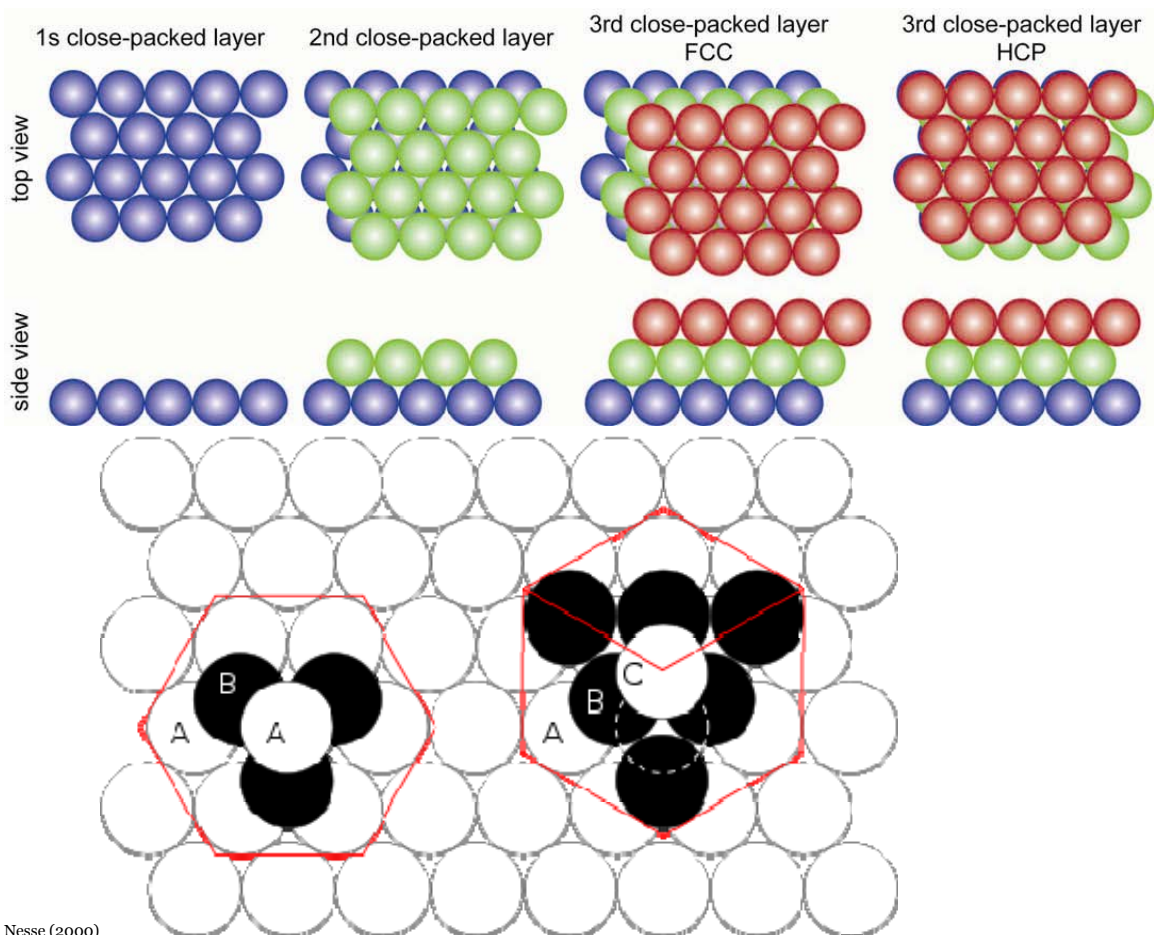
Here's a helpful animation to see how cannonballs stack to make tetrahedra in case you have never served on a pirate ship:

<http://upload.wikimedia.org/wikipedia/commons/3/32/Animated-HCP-Lattice.gif>

hexagonal closest packing 12 neighboring atoms

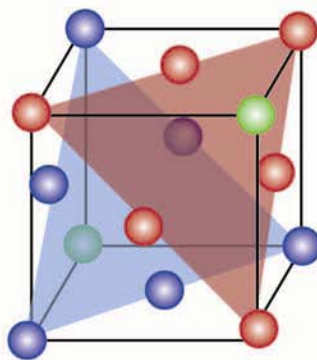
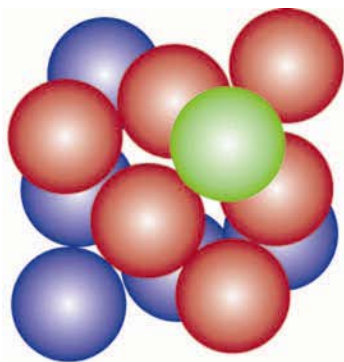
face-centered cubic packing 12 neighboring atoms

atomic packing factor (volume of atoms/volume of unit cell) = 0.74

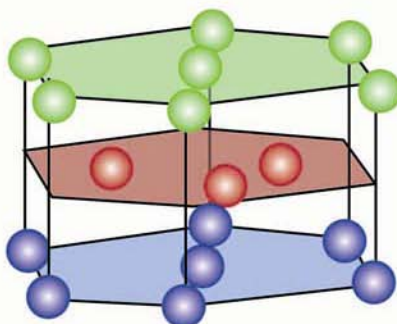
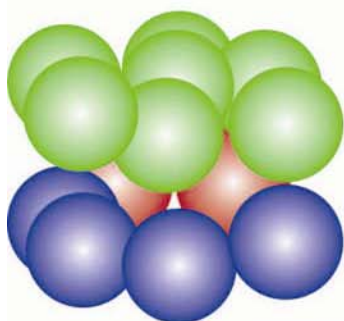


Nesse (2000)

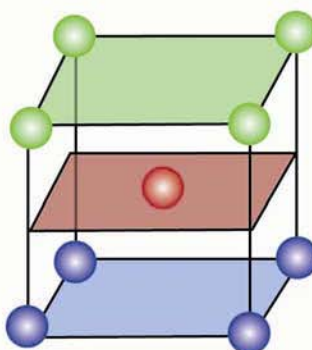
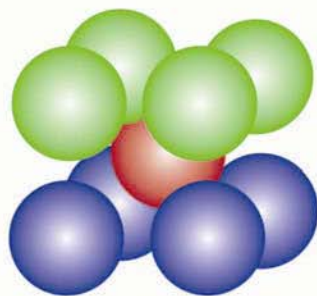
http://en.wikipedia.org/wiki/Close-packing_of_equal_spheres



cubic close packed

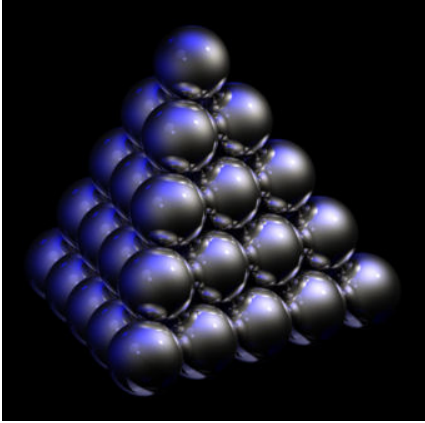


hexagonal close packed

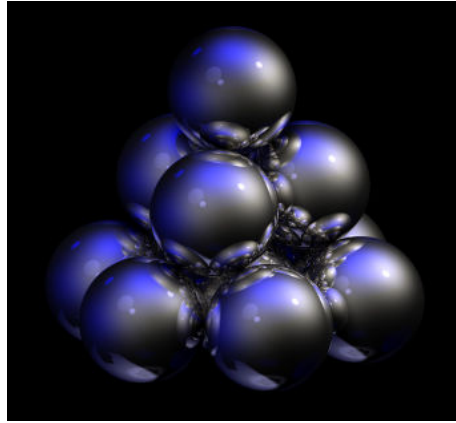


after Perkins (1998)

body-centered cubic



FCC



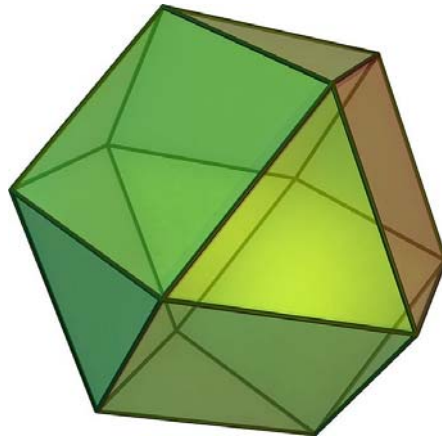
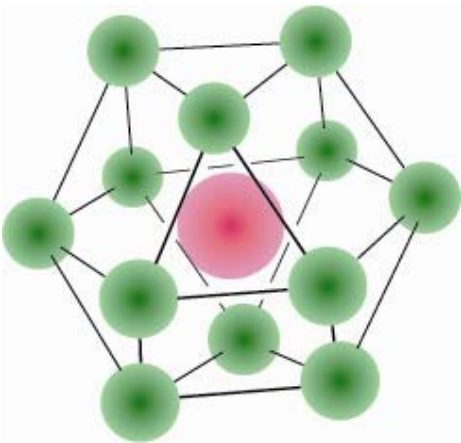
HCP

the key to seeing the difference is that the two balls in the 2nd layer from the top touch different balls in the 3rd layer from the top and that the adjacent balls along each edge of the tetrahedron defined by the stack are (FCC) or are not (HCP) in direct contact with each other

example **FCC** mineral: metallic Cu, Ag, Au, Pb, Co, In, Rh, Pd, Ir, Pt; soft and ductile

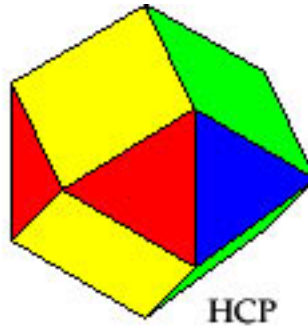
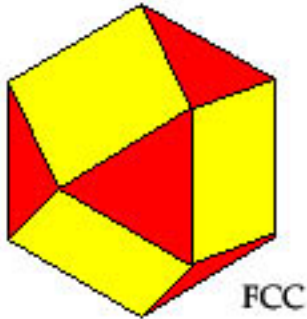
example **HCP** mineral: metallic Sc, Ti, Y, Zr; usually brittle

for **FCC**, the coordination polyhedron is



cuboctahedron, with 8 triangular faces and 6 square faces

for **HCP** the coordination polyhedron is similar to FCC, but with half rotated 60°



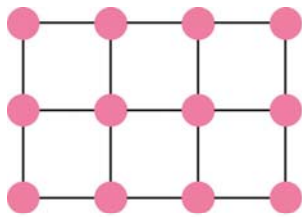
<http://www.uwgb.edu/dutchs/Petrology/coordination.htm>

Lattices, Symmetry, Point Groups, Space Groups

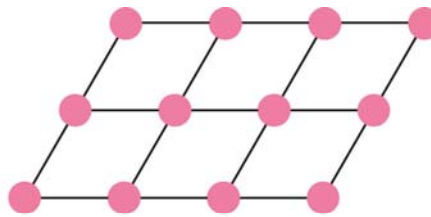
Read Chapter 5 of Klein & Philpotts

or Read Chapter 2 of Nesse (2000)

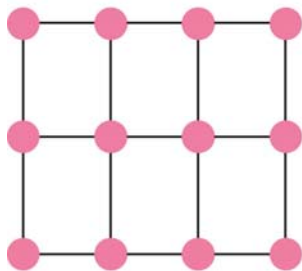
plane lattice: a 2D pattern of atoms (or points or objects) that extends infinitely



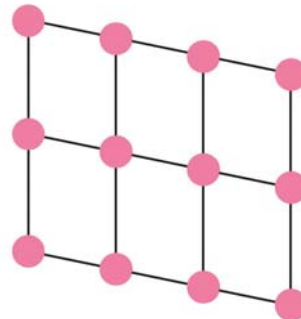
square
 $a = b$
 $\gamma = 90$



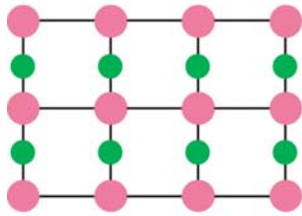
hexagonal
 $a = b$
 $\gamma = 120$



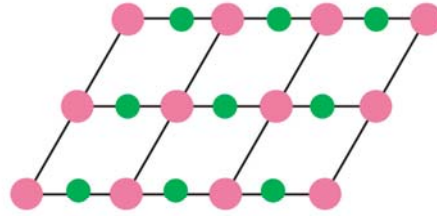
rectangular
 $a \neq b$
 $\gamma = 90$



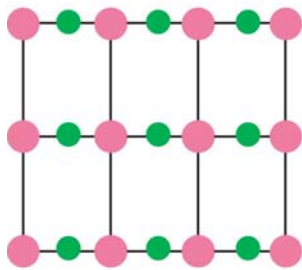
parallelogram
 $a \neq b$
 $\gamma \neq 90$



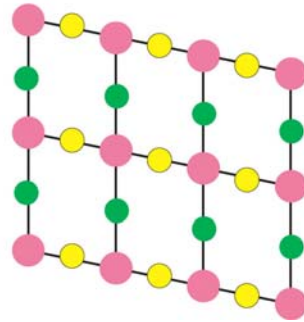
square
 $a = b$
 $\gamma = 90$



hexagonal
 $a = b$
 $\gamma = 120$

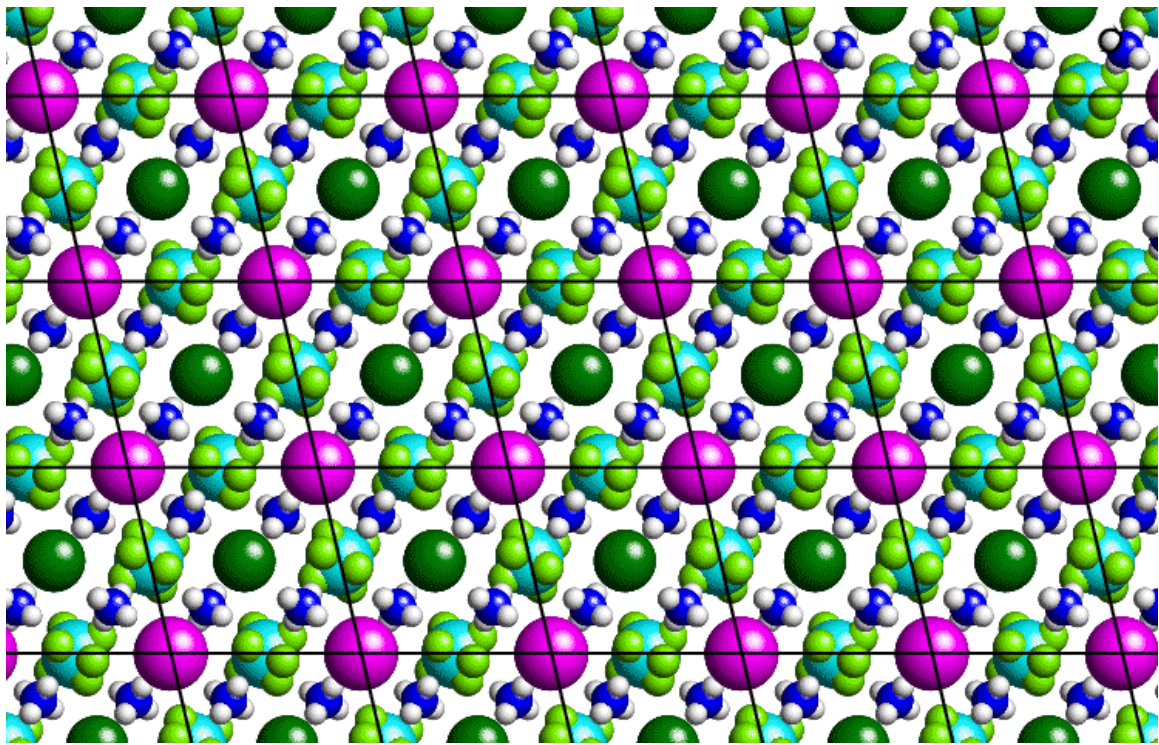


rectangular
 $a \neq b$
 $\gamma = 90$

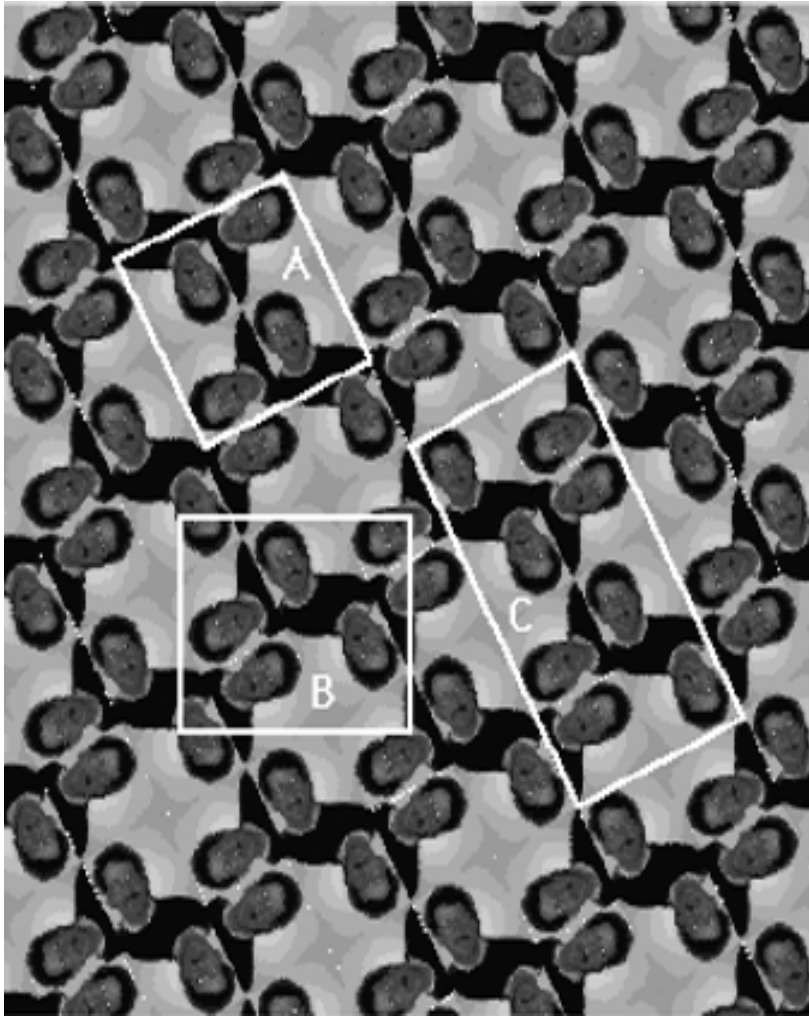


parallelogram
 $a \neq b$
 $\gamma \neq 90$

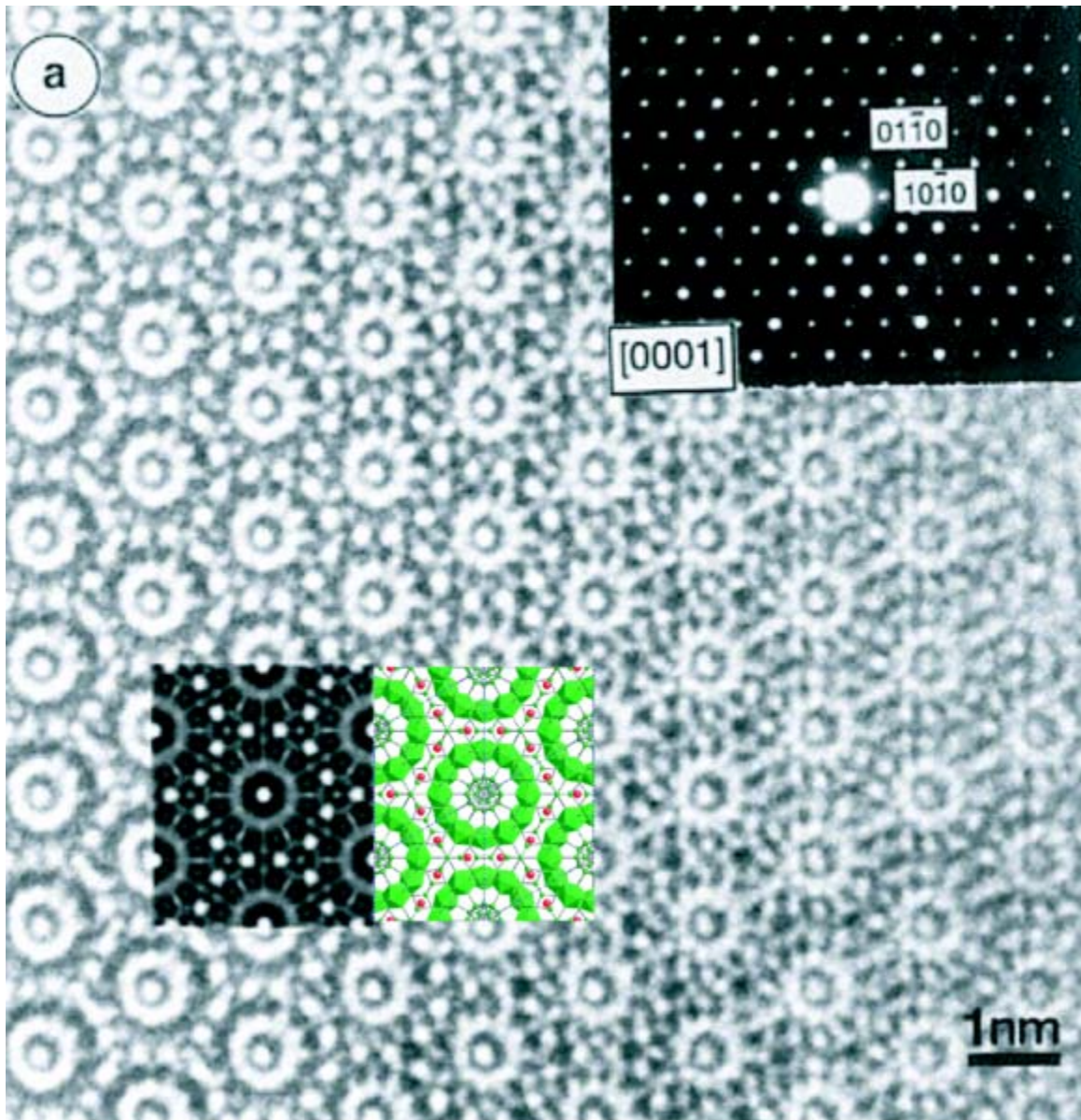
2D 'unit cell': minimum portion of lattice required to describe 'crystal' (may be more than once choice)



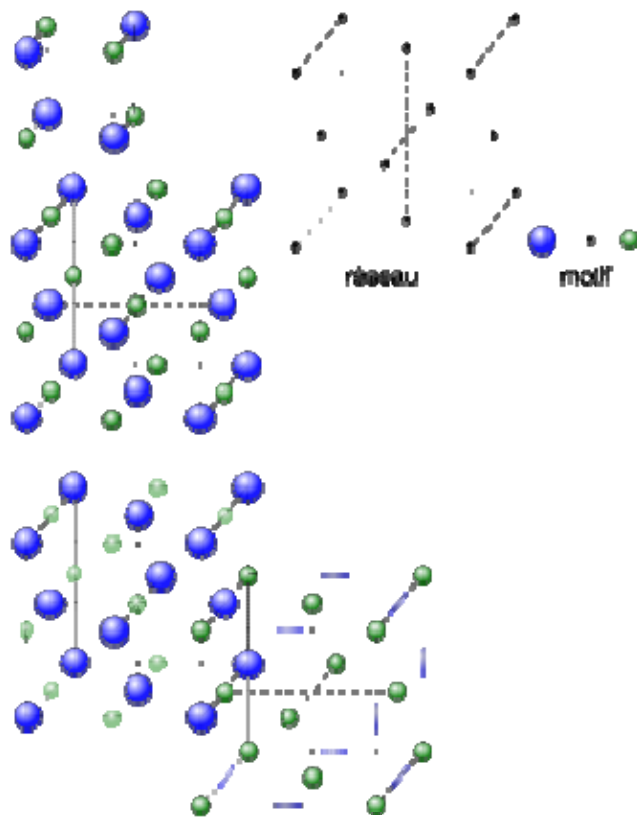
<http://pd.chem.ucl.ac.uk/pdnn/symm1/trans1.htm>



http://depts.washington.edu/chemcrs/bulkdisk/chem484A_spr06/notes_Slides_1_Lattice-2-D_CHEM484Aspr06.pdf

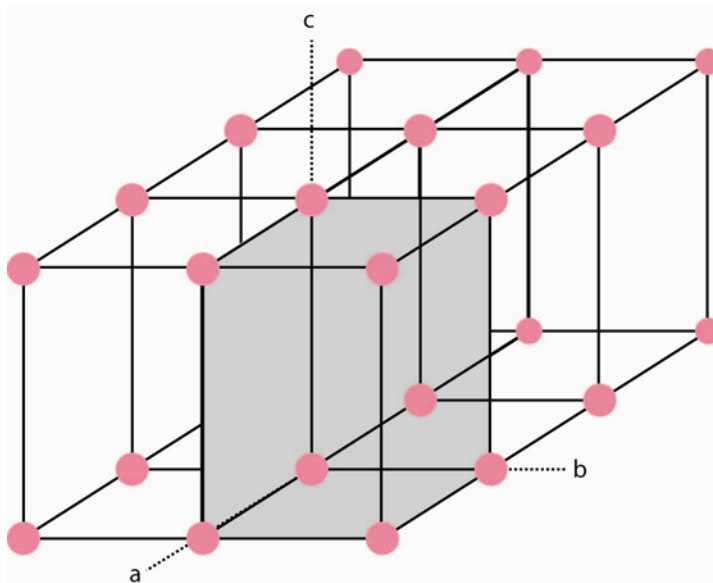


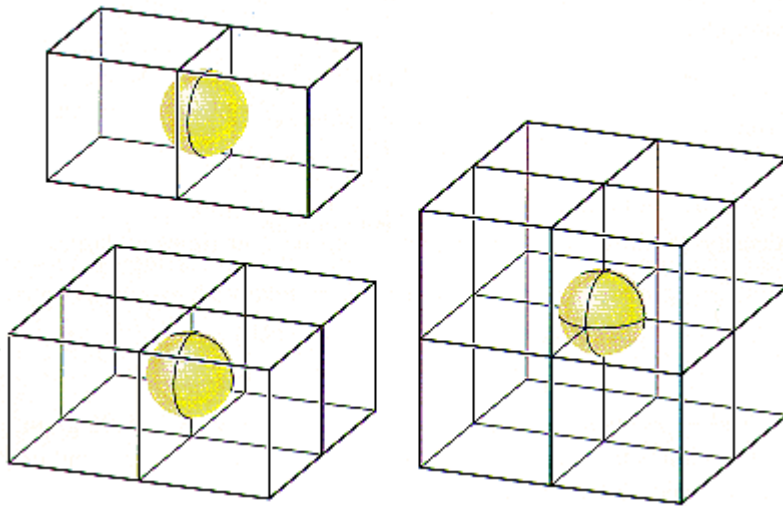
space lattice: a 3D pattern of atoms that extends infinitely



crystal axes: vectors defined by the unit cell

unit cell: minimum portion of space lattice required to describe crystal (may be more than once choice)





<http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch13/unitcell.php>

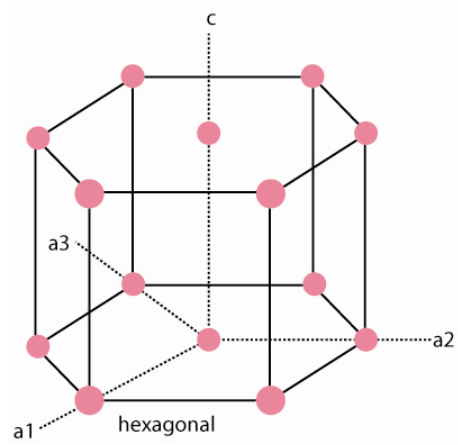
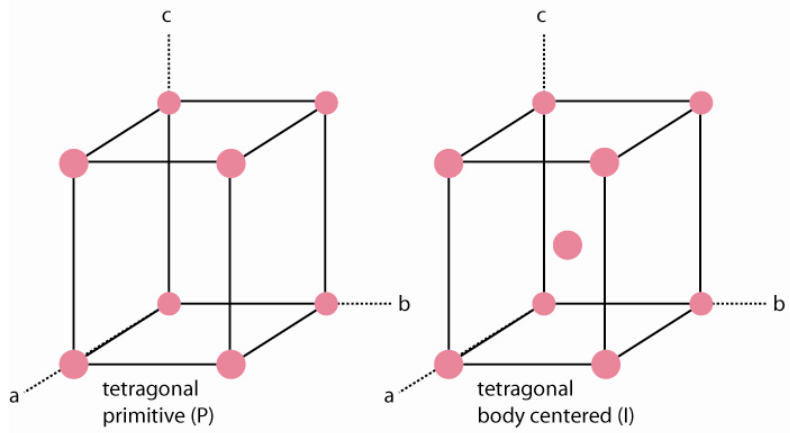
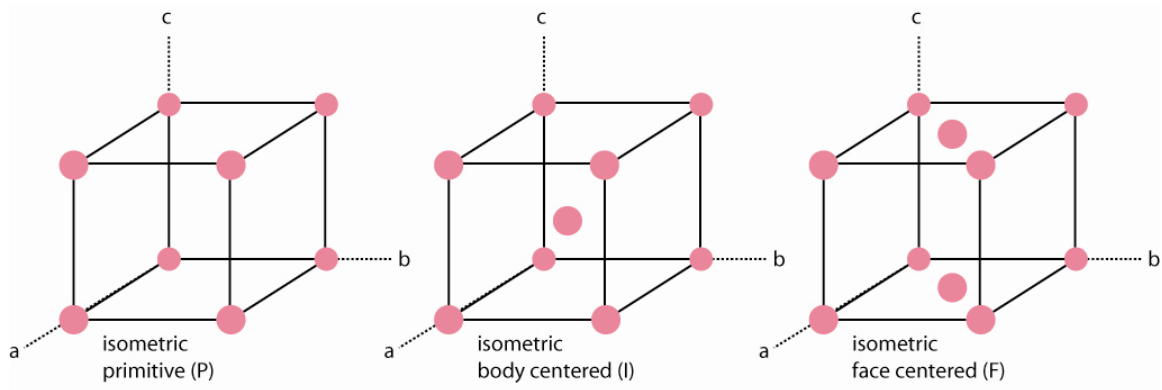
atoms at corners of cells are shared among cells

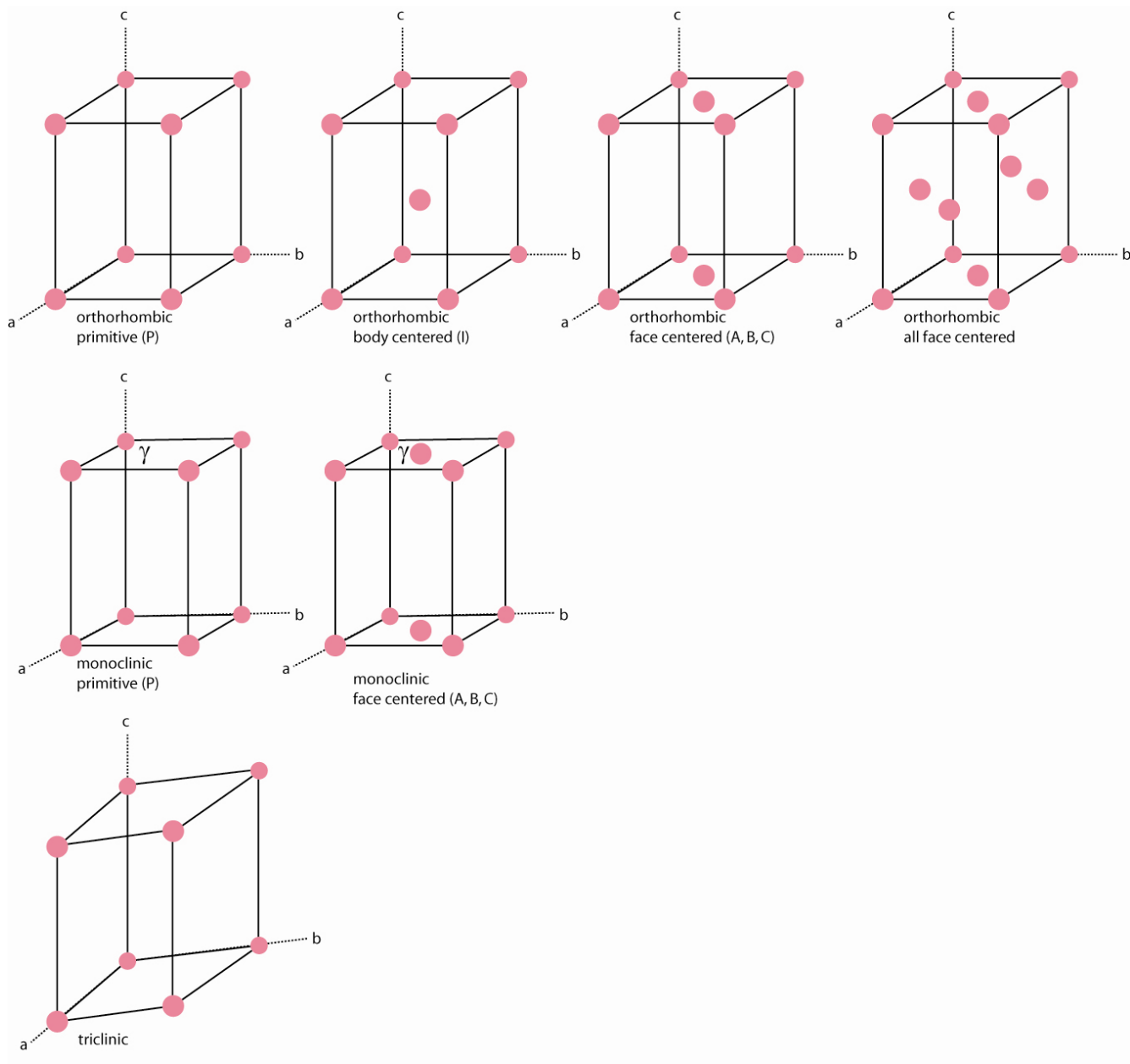
There are six types of unit cell:

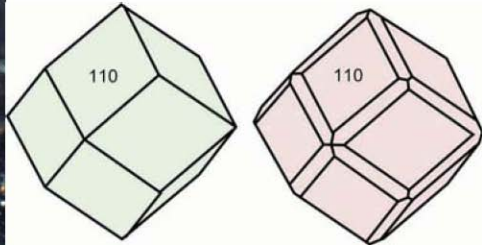
isometric	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$
hexagonal	$a \neq c$	$\alpha = 90^\circ \gamma = 120^\circ$
tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$
orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$
monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90^\circ \neq \beta$
triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma$

The distribution of atoms in the unit cell (P, primitive; F, face centered; I, body centered or Innenzentrierte) gives rise to the 14 **Bravais lattices**

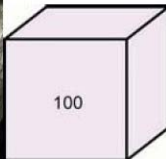
see http://commons.wikimedia.org/wiki/Crystal_structure



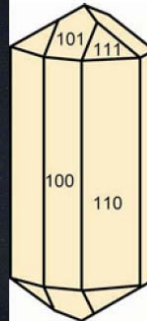




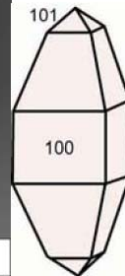
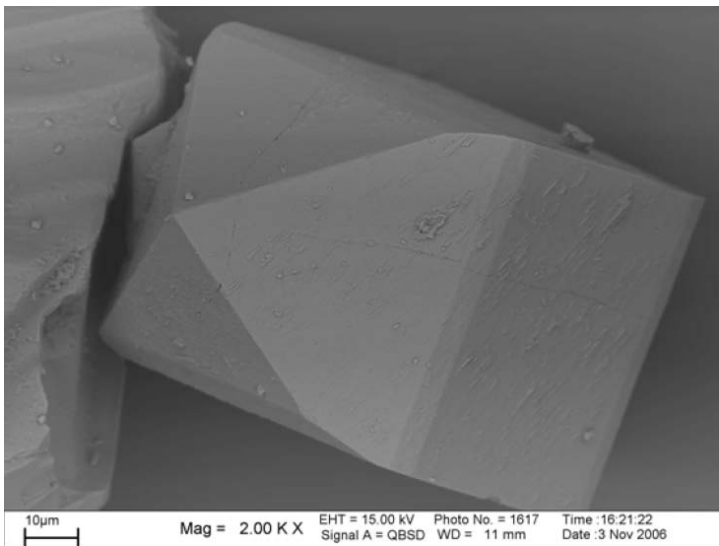
cubic example: garnet



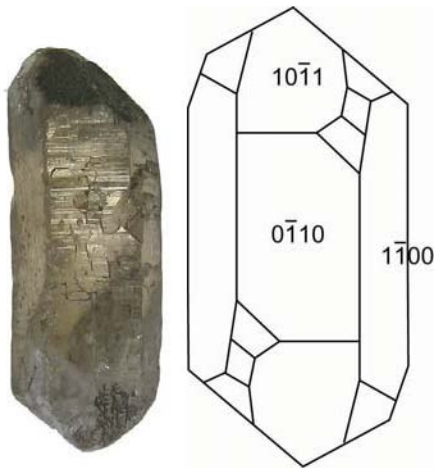
cubic example: fluorite



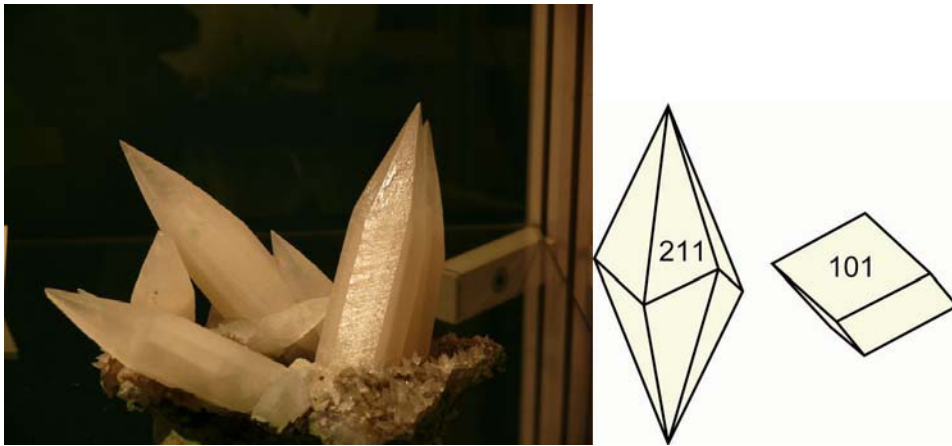
tetragonal example: rutile



tetragonal example: zircon



hexagonal example: quartz

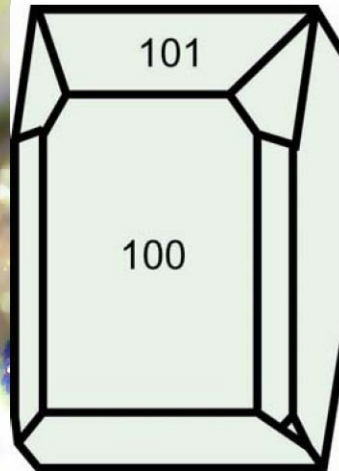


hexagonal example: calcite

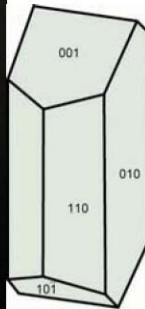


orthorhombic example: olivine (from www.mineralminers.com/.../mins/perm111.jpg)

Barahona Micromounts



monoclinic example: diopside



triclinic example: albite

see

<http://www.uwsp.edu/geo/projects/geoweb/participants/dutch/symmetry/unitcell.htm> for some nice examples of how crystal forms are made up of unit cells

Crystal Faces

crystal faces tend to be close-packed planes of atoms

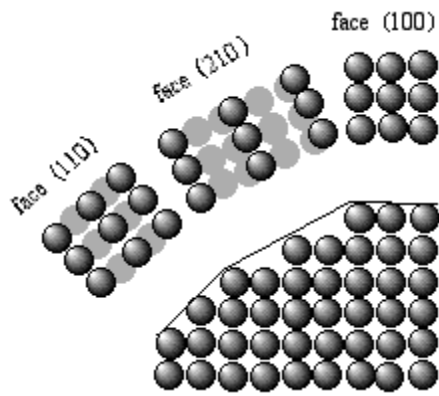


Fig 2.21

prism

set of faces parallel to one direction

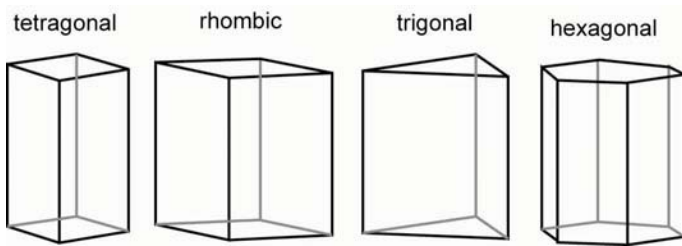
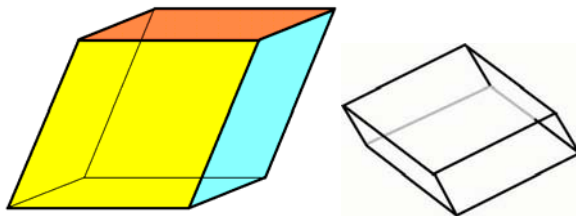


Fig 2.32

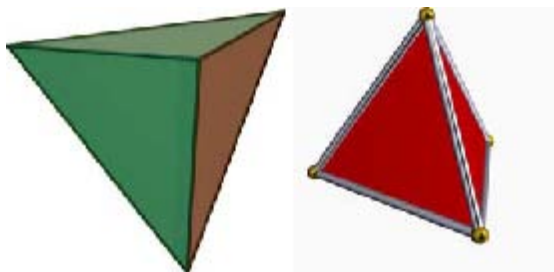
rhombohedron

6 rhomb-shaped faces like a stretched or squashed cube
part of F2.33

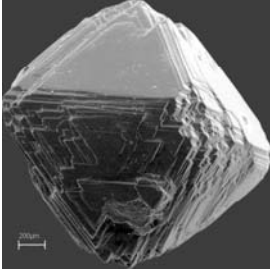


tetrahedron

4 triangular faces



octahedron



for more crystal forms see

<http://www.uwsp.edu/geo/projects/geoweb/participants/dutch/symmetry/xlforms.htm>

Point symmetry and Point Groups

Point symmetry operations in 2D are

reflection

like a mirror



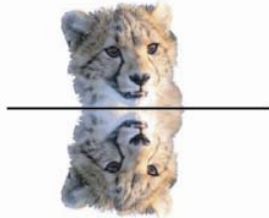
rotation

around an axis; number identifies degrees of rotation as $360^\circ/n$

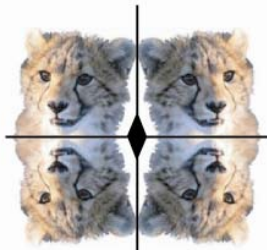
reflection and rotation produce the 10 2D **point groups**, each of which consists of a rotation axis or a rotation axis plus a mirror parallel to that axis (i.e., the mirror normal is perpendicular to the rotation axis)



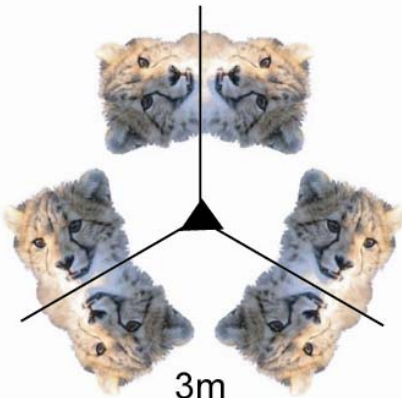
1



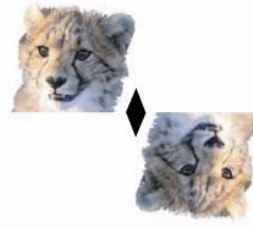
1m



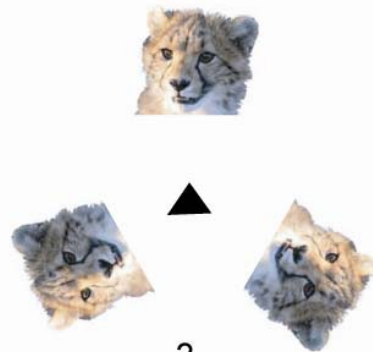
2m



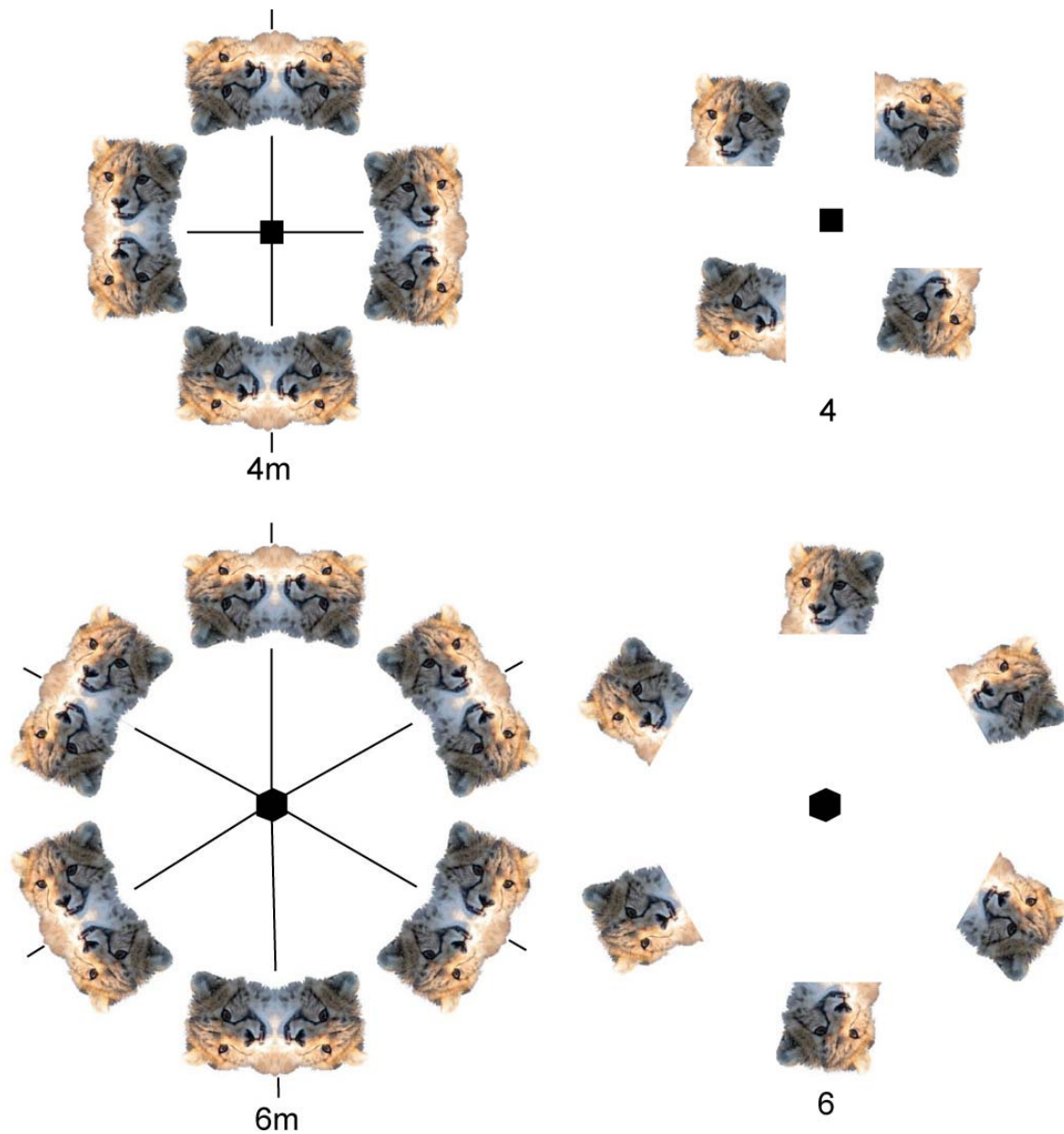
3m



2



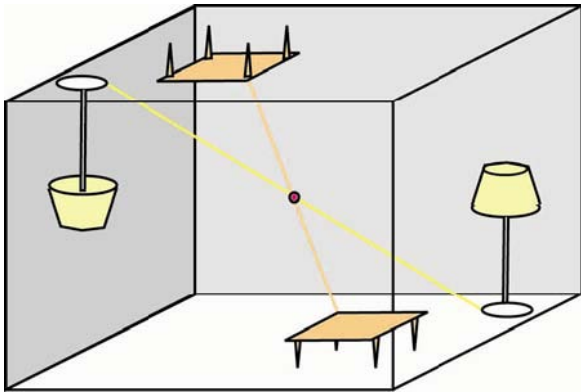
3



Adding a 3rd dimension permits a 3rd symmetry operation:

rotoinversion (rotation + inversion)

rotoinversion axes have a bar over the top of the number to distinguish them from ordinary rotation axes; axis of rotation is perpendicular to mirror plane

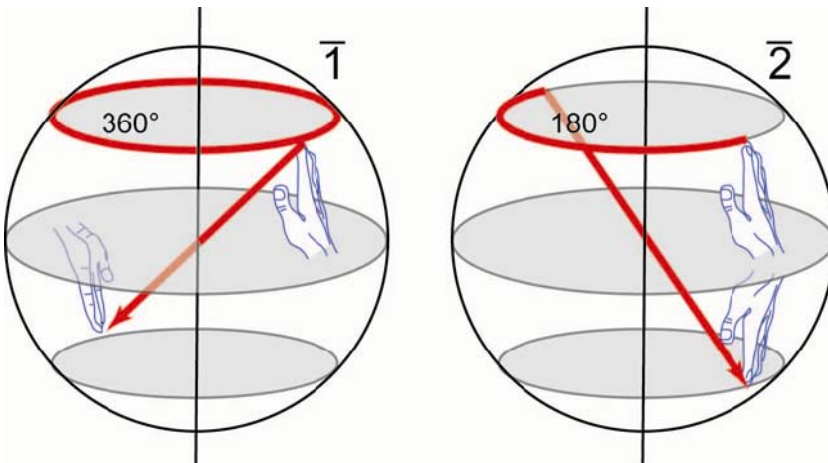


after Bloss (1971)

$\bar{1}$ rotoinversion is a simple **center of symmetry** like the room drawing above.

$\bar{2}$ is equivalent to a mirror plane.

$\bar{6}$ is equivalent to a 3-fold rotation plus a mirror plane



this leads to the 32 **space groups** or **crystal classes**, with their **Hermann–Mauguin** symbols

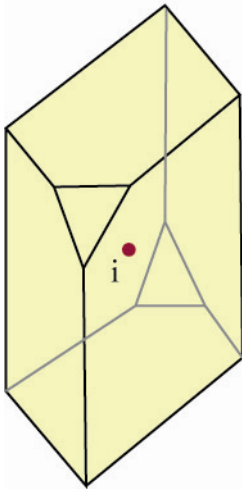
HM symbols show non-redundant symmetry operations

There are 3 “digit” positions, each of which indicates the orientation of a symmetry element (if a mirror and rotation have the same orientation, they are denoted “ n/m ”, meaning that the mirror is perpendicular to the rotation axis—or the mirror normal is parallel to the rotation axis):

crystal system	1st symbol	2nd symbol	3rd symbol
cubic	4, 4/m, $\bar{4}$, 2, 2/m	3, $\bar{3}$	2, 2/m, m

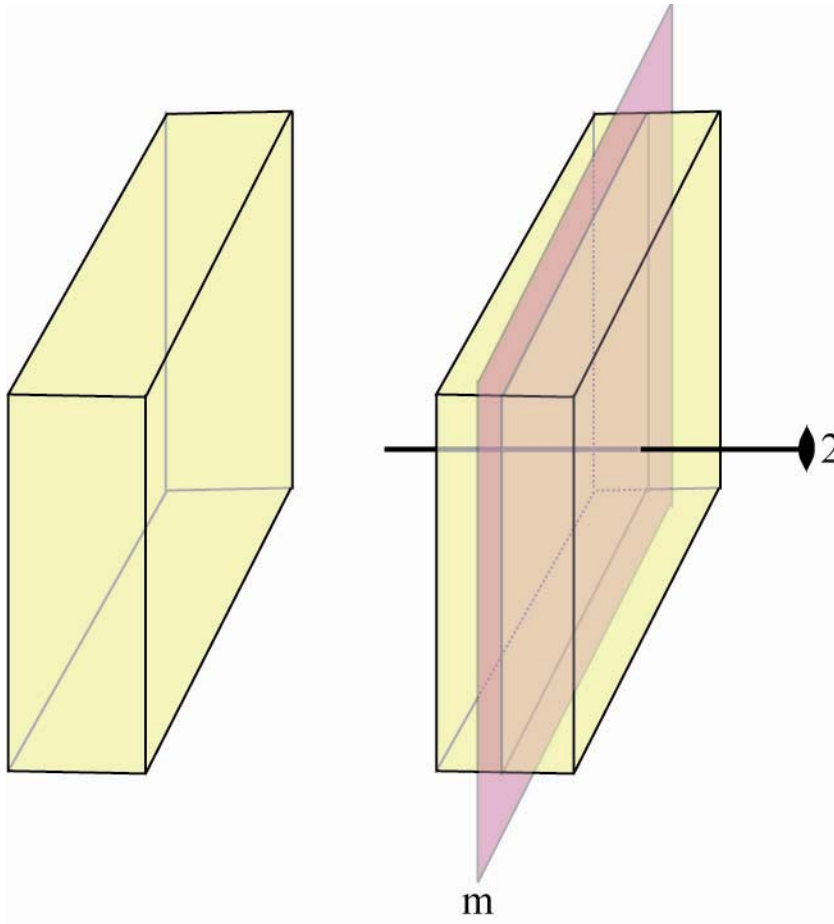
hexagonal	6, 6/m, $\bar{6}$, 3, 3	2/m, m	2, 2/m, m
tetragonal	4, 4/m, $\bar{4}$	2, 2/m, m	2, 2/m, m
orthorhombic	2, 2/m, m	2, 2/m, m	2, 2/m, m
monoclinic	2, 2m, m		
triclinic	1, 1		

Triclinic (e.g., $\bar{1}$)

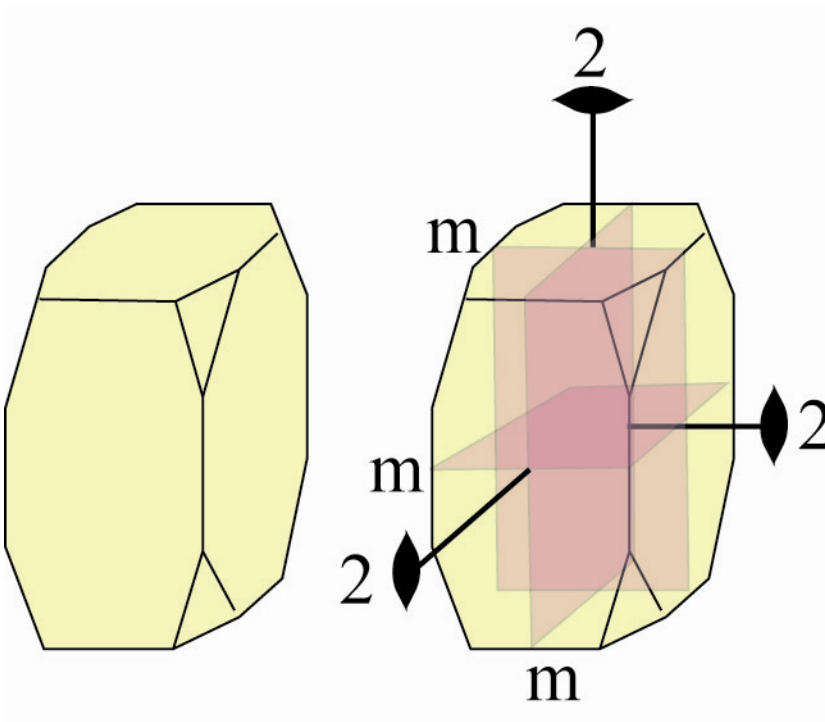


after <http://www.tulane.edu/~sanelson/cens211/32crystalclass.htm>

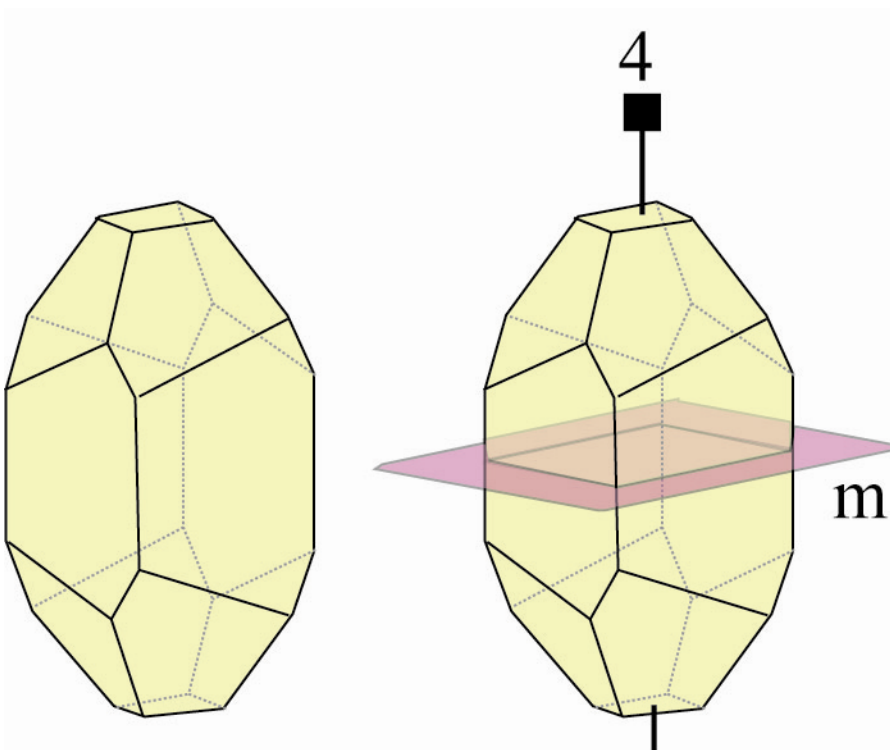
Monoclinic (e.g., 2/m)



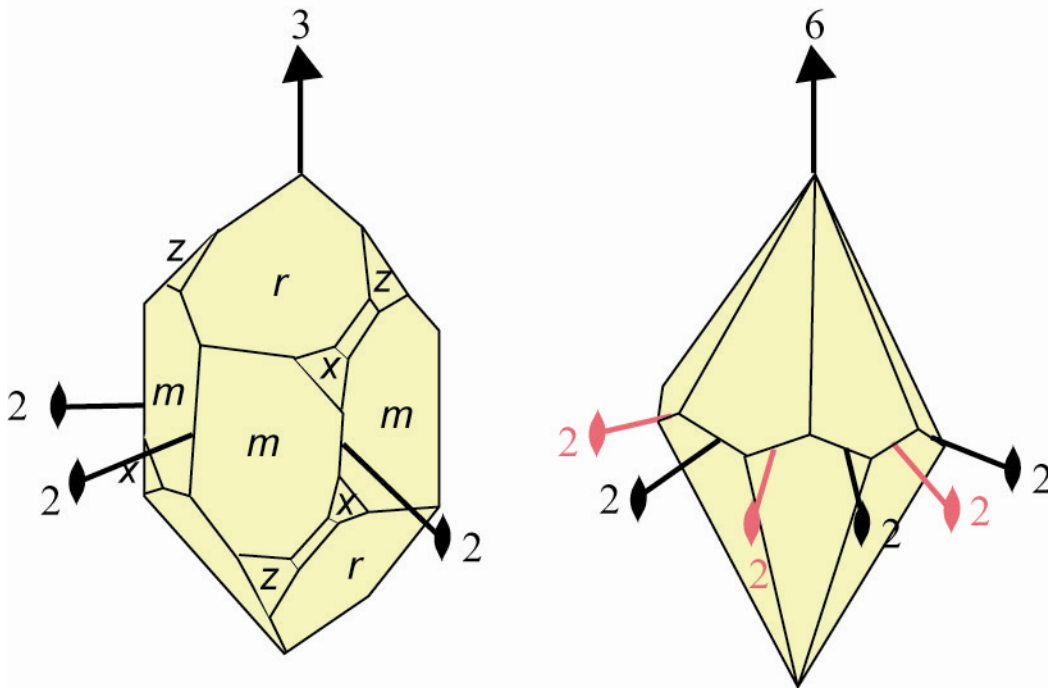
Orthorhombic (e.g., $2/m \ 2/m \ 2/m$)



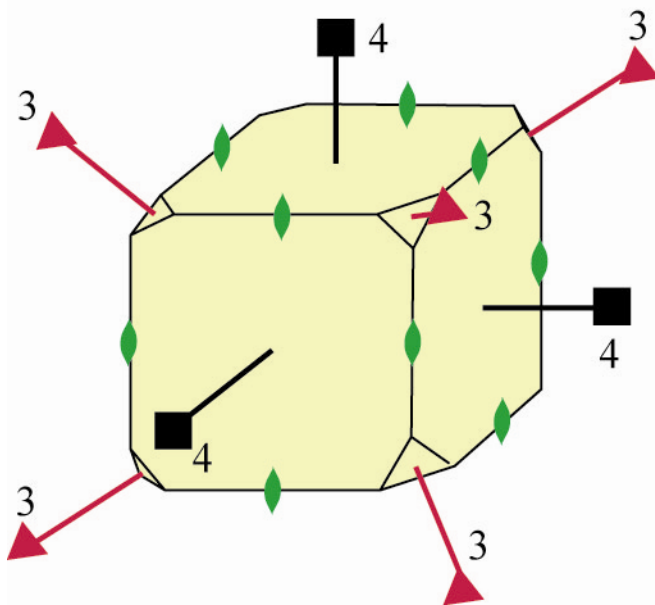
Tetragonal (e.g., 4/m)



Trigonal (e.g., $3\ 2$; α quartz) and hexagonal (e.g., $6\ 2\ 2$; β quartz)



Cubic (e.g., $4/m\ \bar{3}\ 2/m$)

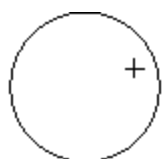


Crystal System	Crystal Class, H-M	Name of Class
Triclinic	1	pedial
	$\bar{1}$	pinacoidal
Monoclinic	2	sphenoidal

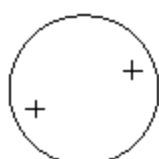
	m	domatic
	2/m	prismatic
Orthorhombic	222	rhombic-disphenoidal
	mm2 (2mm)	rhombic-pyramidal
	2/m2/m2/m	rhombic-dipyramidal
Tetragonal	4	tetragonal- pyramidal
	$\bar{4}$	tetragonal-disphenoidal
	4/m	tetragonal-dipyramidal
	422	tetragonal-trapezohedral
	4mm	ditetragonal-pyramidal
	$\bar{4}2m$	tetragonal-scalenohedral
	4/m2/m2/m	ditetragonal-dipyramidal
Hexagonal	3	trigonal-pyramidal
	$\bar{3}$	rhombohedral
	32	trigonal-trapezohedral
	3m	ditrigonal-pyramidal
	$\bar{3}2/m$	hexagonal-scalenohedral
	6	hexagonal-pyramidal
	$\bar{6}$	trigonal-dipyramidal
	6/m	hexagonal-dipyramidal
	622	hexagonal-trapezohedral
	6mm	dihexagonal-pyramidal
	$\bar{6}m2$	ditrigonal-dipyramidal
	6/m2/m2/m	dihexagonal-dipyramidal
Isometric	23	tetaroidal
	2/m $\bar{3}$	diploidal
	432	gyroidal
	$\bar{4}3m$	hextetrahedral
	4/m $\bar{3}2/m$	hexoctahedral

<http://www.tulane.edu/~sanelson/eens211/32crystalclass.htm>

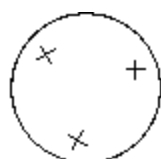
the 32 **space groups** or **crystal classes** can be represented by stereonets



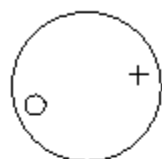
1.



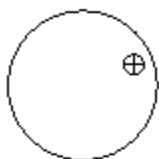
2



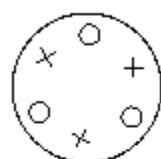
3



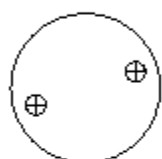
$\bar{1}$



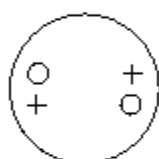
$\bar{2} = m$



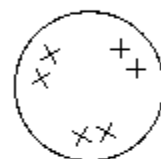
$\bar{3}$



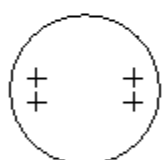
$2/m$



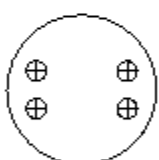
222



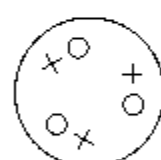
$3m$



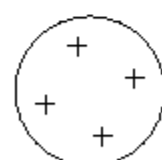
$mm2$



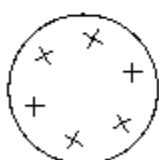
mmm



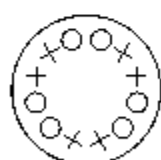
32



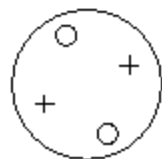
4



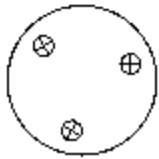
6



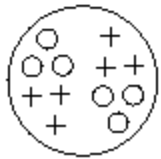
$\bar{3}m$



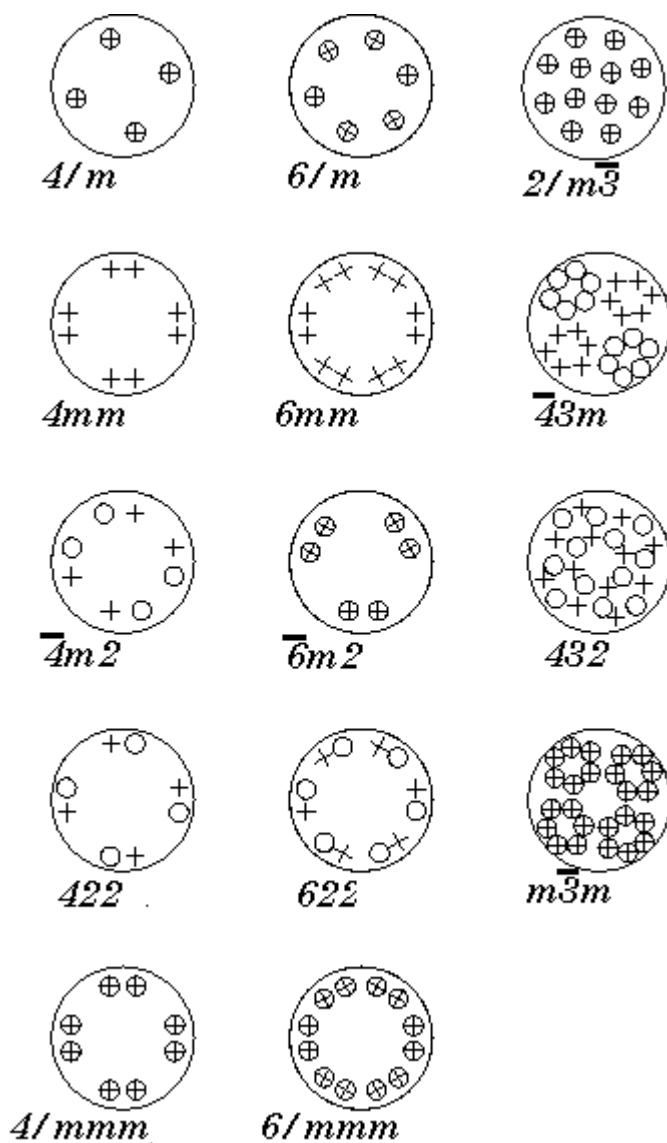
$\bar{4}$



$\bar{6}$



23

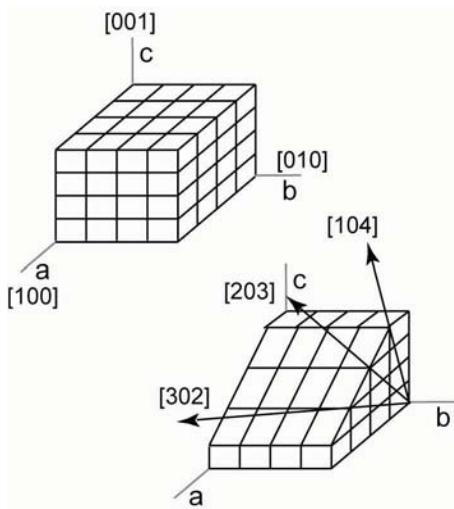


(from <http://xrayweb.chem.ou.edu/images/ptgroups1.gif>)

Miller indices are used to describe crystal faces and directions

Directions

Miller indices for directions are integers that describe the vector representation of the direction; e.g., $[104]$ is the direction that points 1 unit cell in the a direction and 4 unit cells in the c direction and is parallel to the b axis. $[uvw]$ describes a specific direction; $\langle uvw \rangle$ is a family of crystallographically equivalent directions

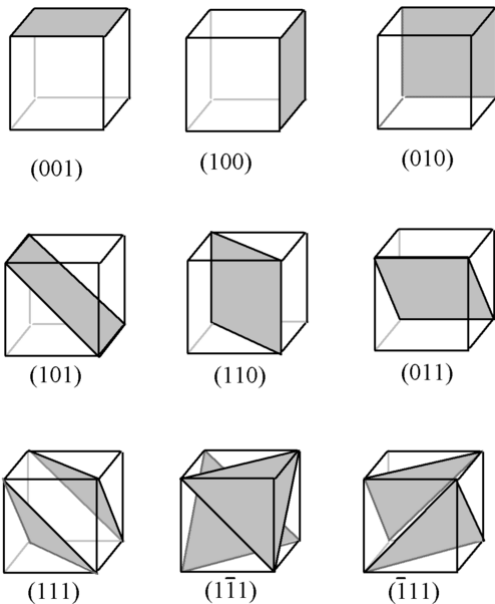


Perkins (1998)

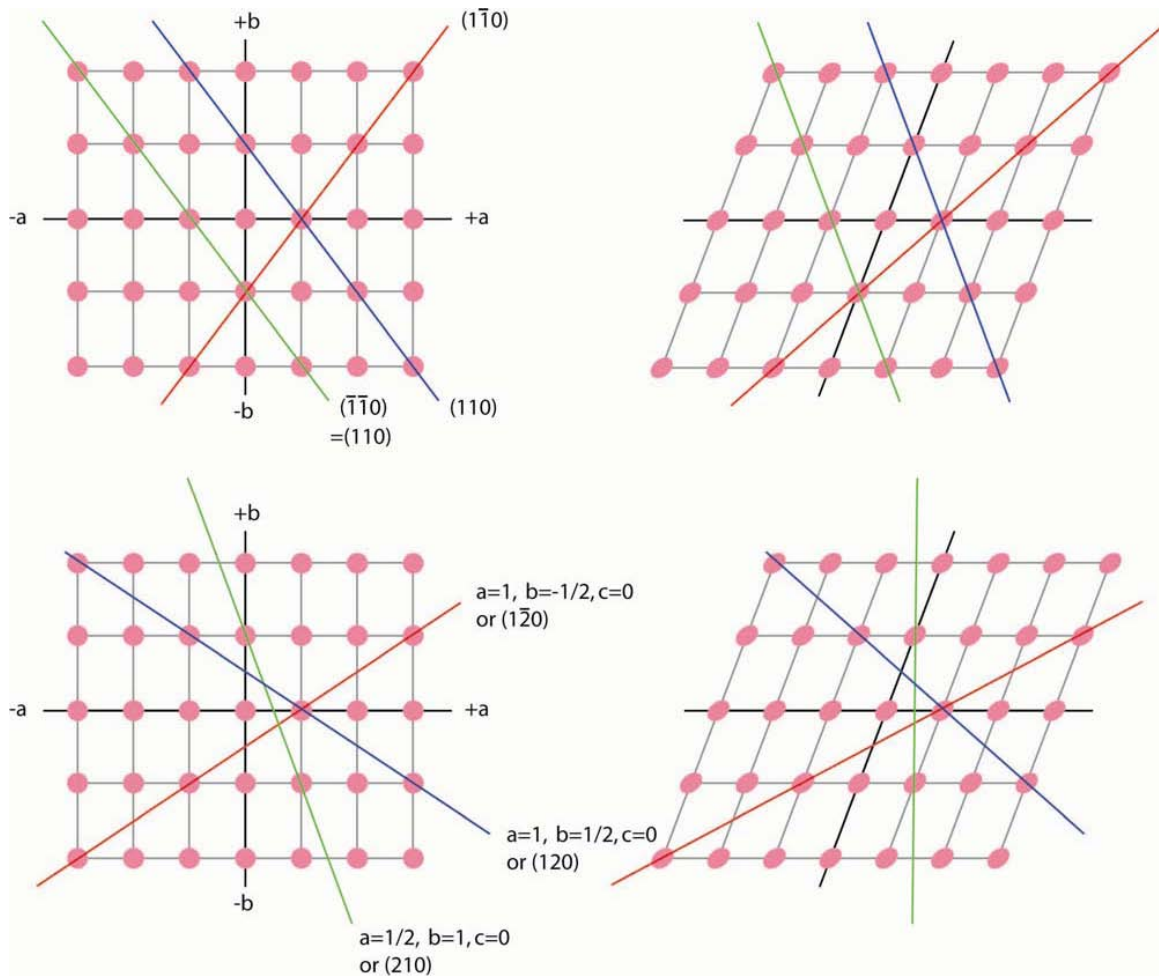
Planes

Miller indices for planes are integers that are the *reciprocal* of the intersection with each axis; e.g., (104) is the plane that intersects the *a* axis at 1 unit-cell spacing and the *c* axis at 1/4 unit-cell spacing and is parallel to the *b* axis.

Like H–M symbols, a bar is used to indicate a negative number.



(hkl) describes a specific plane; {hkl} is a family of crystallographically equivalent planes



somewhat more painful in the hexagonal system

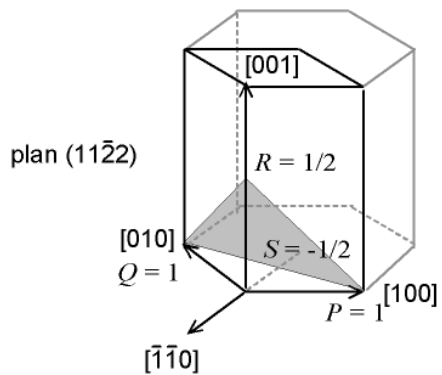


Fig 2.24

$[uvw]$ describes a specific direction; $\langle uvw \rangle$ is a family of crystallographically equivalent directions $t = -(u+v)$

(hkl) describes a specific plane; {hkl} is a family of crystallographically equivalent planes $i = - (h+k)$

Crystal Structures

Read Chapter 20, Chapters 11–19 of Nesse (2000)

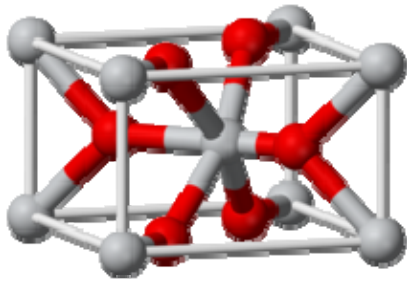
Hydroxides

'bauxite' (several minerals)	Al hydroxide	source of Al
goethite	Fe hydroxide	rust



$X^{4+}O_2$ group

rutile	$^{VI}TiO_2$	tetragonal	source of Ti
cassiterite	$^{VI}SnO_2$	tetragonal	source of Sn
uraninite	$^{VIII}UO_2$	cubic	source of U



<http://en.wikipedia.org/wiki/Rutile>

rutile (cassiterite) has a body-centered tetragonal structure with ^{VI}Ti (^{VI}Sn)



$^{VI}\text{X}^{3+}_2\text{O}_3$ group

trigonal

oxygen in approximately hexagonal closest packing, with cations in 2/3 of the 'holes'

hematite	$\text{Fe}^{3+}_2\text{O}_3$	rust; source of Fe
corundum	$\text{Al}^{3+}_2\text{O}_3$	source of Cr (ruby)
ilmenite	$\text{Fe}^{2+}\text{Ti}^{4+}\text{O}_3$	source of Fe



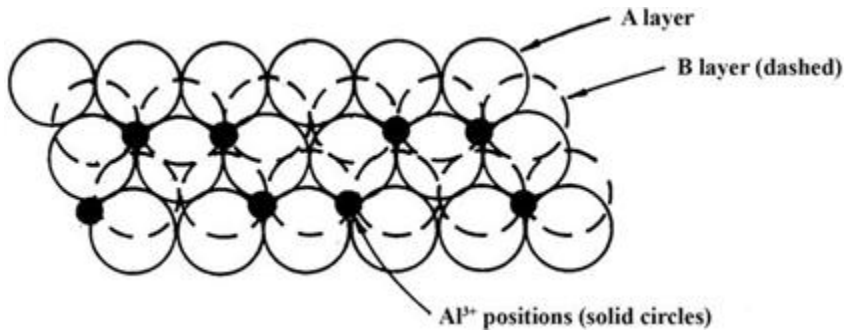
hematite



corundum



ilmenite



<http://www.chegg.com/homework-help/questions-and-answers/corundum-crystal-structure-al2o3-consists-hcp-arrangement-o2-ions-al3-ions-occupy-octahedr-q1339249>

Spinel Group $^{IV}X^{2+} ^{VI}Y^{3+}_2 O_4$

cubic

spinel	$MgAl_2O_4$	
chromite	$FeCr_2O_4$	source of Cr
magnetite	$Fe^{2+}Fe^{3+}_2O_4$	source of Fe



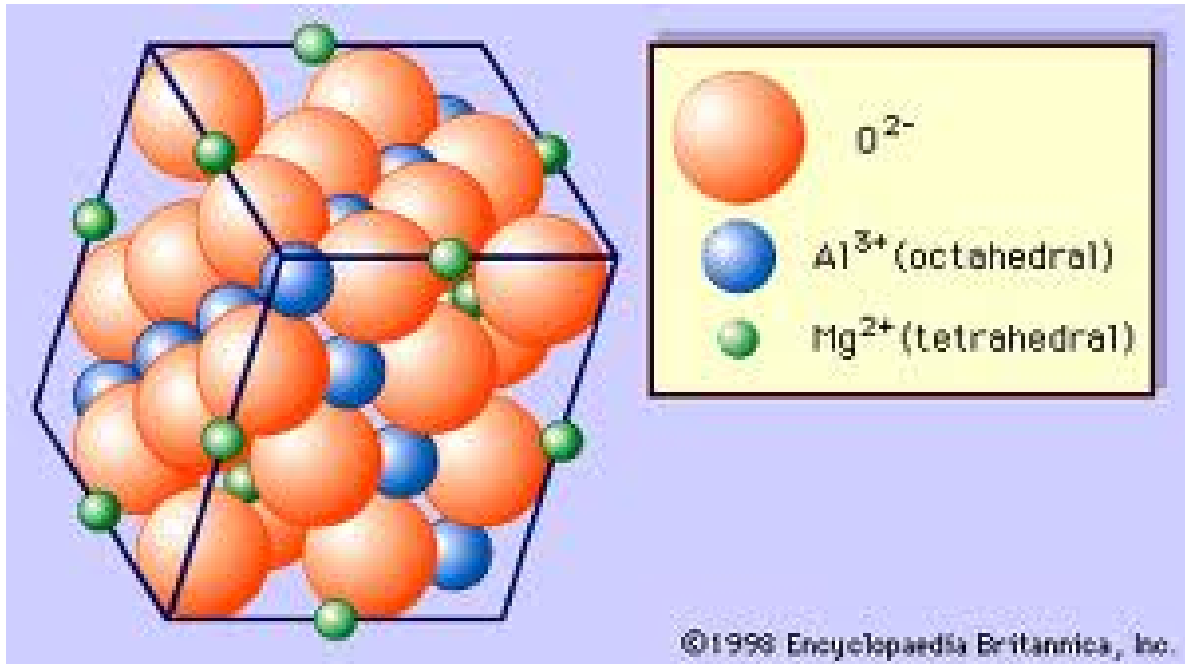
spinel



chromite



magnetite



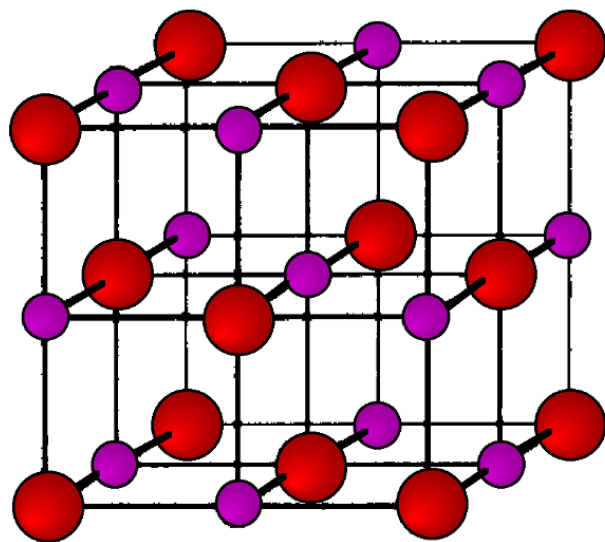
spinel structure consists of cubic close packed oxygen

Halide Minerals

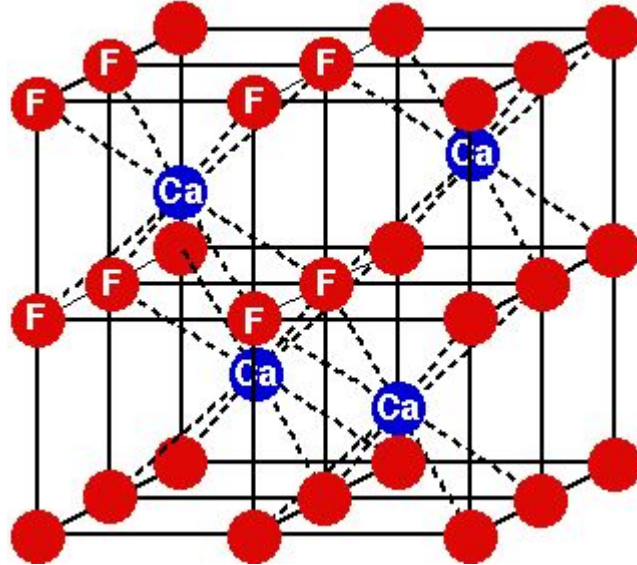
halite	NaCl	cubic
sylvite	KCl	cubic; source of K
fluorite	CaF_2	cubic; source of F



<http://cnx.org/content/m16927/latest/>



halite (Na^+ (green) coordinated with six Cl^- (orange); Na and Cl alternate in a face-centered cubic arrangement



<http://www.seas.upenn.edu/~chem101/sschem/ionicsolids.html#fluorite>

fluorite structure; face-centered cubic structure with half of the cubic sites filled.

Ca^{2+} (grey) coordinated with eight F^- (yellow)

Sulfide Minerals

sphalerite	IVZnS	cubic; source of Zn
galena	VIPbS	cubic; source of Pb
pyrite	VIFeS	cubic
cinnabar	VIHgS	source of Hg
molybdenite	VIMoS_2	hexagonal; source of Mo



sphalerite



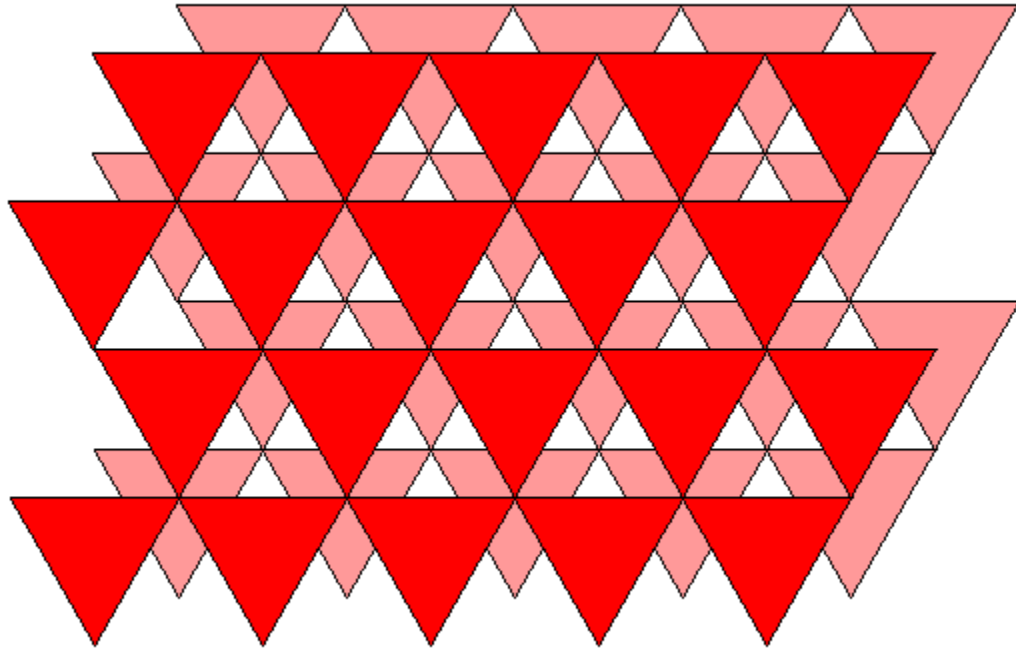
galena



pyrite

pyrite structure similar to that of NaCl

molybdenite structure consists of pairs of triangular S sheets with Mo in between in triangular prisms with 6-fold coordination; weak van der Waals bonds hold the sheets together



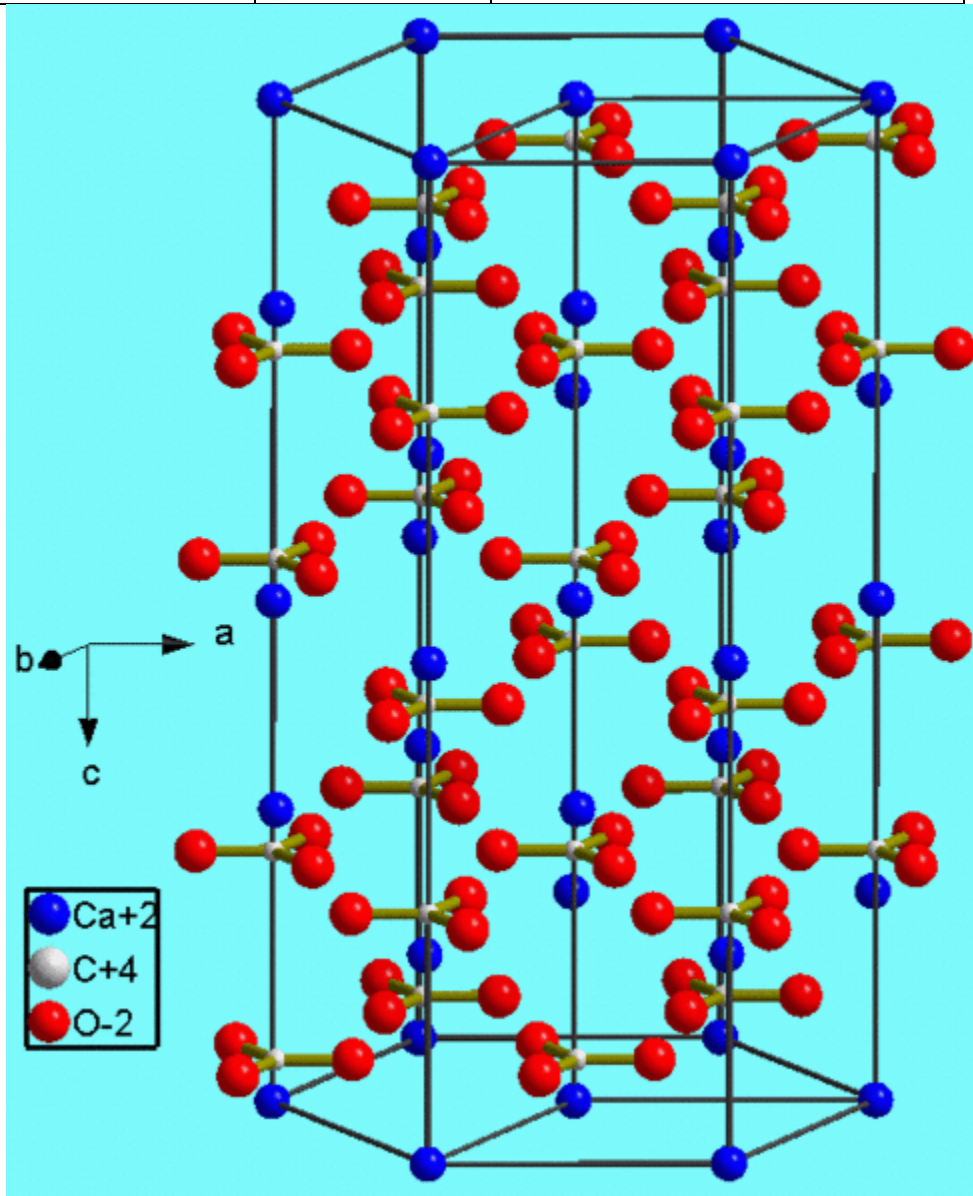
<https://www.uwgb.edu/dutchs/Petrology/MolybdeniteStructure.HTM>

Carbonate Minerals



calcite	CaCO ₃	hexagonal	2.71 g/cm ³
aragonite	CaCO ₃	orthorhombic	2.94 g/cm ³
magnesite	MgCO ₃	source of Mg	

dolomite	$\text{CaMg}(\text{CO}_3)_2$	source of Mg	
siderite	FeCO_3		
rhodochrosite	MnCO_3	source of Mn	



<https://commons.wikimedia.org/wiki/File:Calcite.GIF>

calcite structure is similar to $\text{VI}X_2\text{O}_3$ **group**, with the oxygen in approximately hexagonal closest packing and the Ca cations in 1/3 of the 'holes'

Sulfate Minerals

evaporites

gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$		wallboard
anhydrite	CaSO_4	orthorhombic	
barite	BaSO_4		source of Ba



gypsum



anhydrite

Phosphate Minerals

apatite	$\text{Ca}_5(\text{PO}_4)_3 (\text{OH}, \text{Cl}, \text{F})$	hexagonal	source of P
monazite	$\text{Ce}(\text{PO}_4)$	monoclinic	source of P



$\text{Ce}(\text{PO}_4)$

source of Th

Tungstate Minerals

scheelite	$\text{CaW}^{6+}\text{O}_4$	source of W
------------------	-----------------------------	-------------



(from

<http://www.wrightsrockshop.com/gallery/wulfenitemimetite/wulfenitemimetitemiscellaimages/scheelite022504.JPG>)

Borate Minerals

borax hydrous Na borate (including borax, colemanite, kernite, ulexite)

source of B

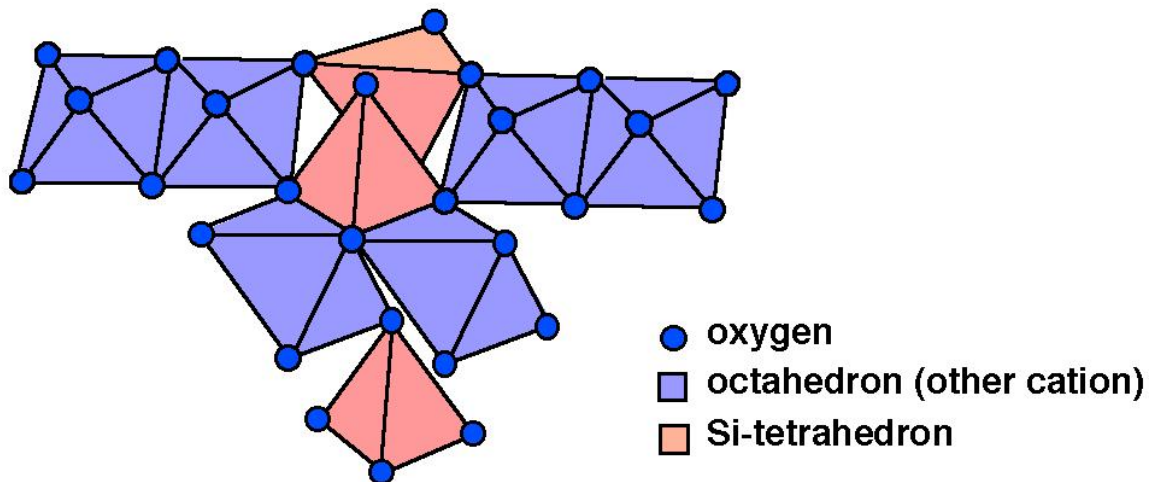
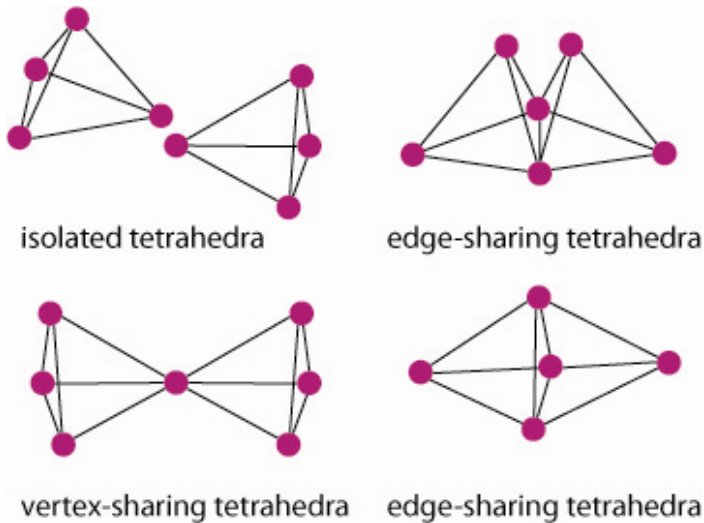


Silicate Minerals

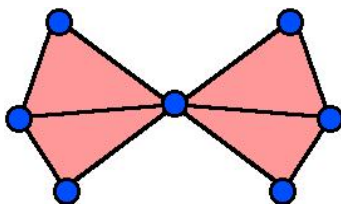
type	-silicate	no of O shared between tetrahedra
orthosilicates	neso	0
disilicates	soro	1
ring silicates	cyclo	2
chain silicates	ino	2 or 3
sheet silicates	phyllo	3
framework silicates	tecto	4

Pauling's Rule 3

two cations prefer to share one anion (e.g., Si–O–Si), rather than two (which creates a polyhedra/polyhedra edge), and definitely rather than three (which creates a polyhedra/polyhedra face)

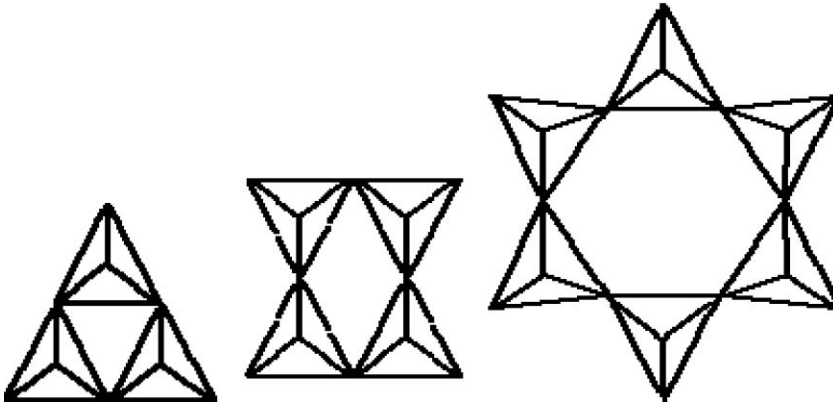


nesosilicate isolated tetrahedra (from <http://classes.colgate.edu/rapril/geol201/summaries/silicates/neso.htm>)



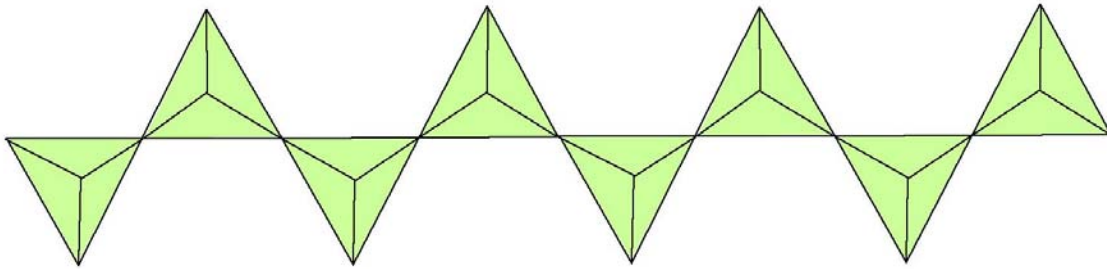
sorosilicate tetrahedra pairs/sisters (from

<http://classes.colgate.edu/rapril/geol201/summaries/silicates/soro.htm>)



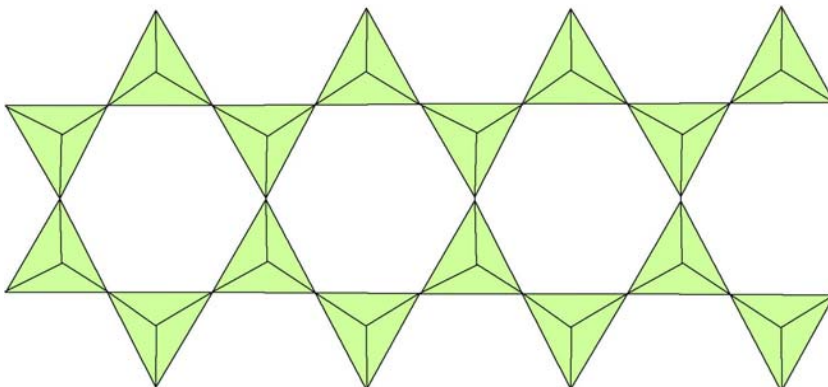
cyclosilicate share 2 oxygen per tetrahedron (from

<http://classes.colgate.edu/rapril/geol201/summaries/silicates/cyclo.htm>)



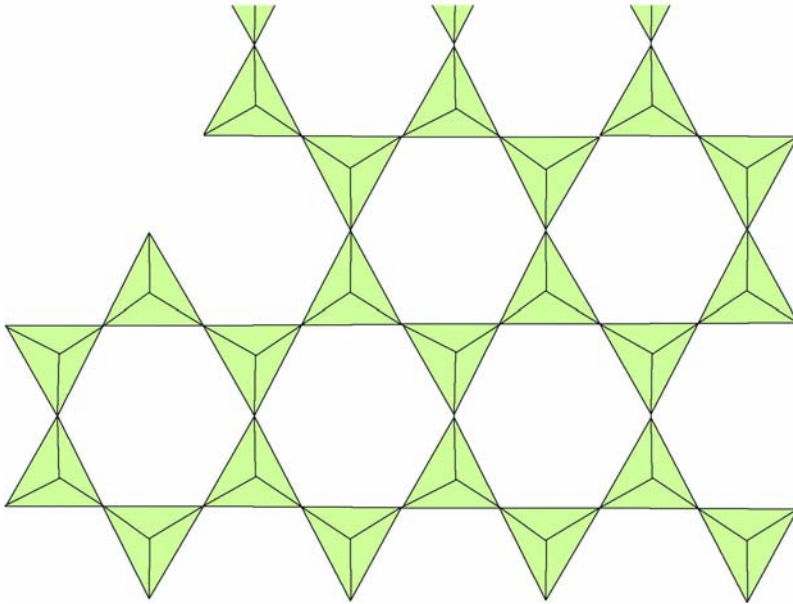
single-chain inosilicate share 2 oxygen per tetrahedron (from

<http://classes.colgate.edu/rapril/geol201/summaries/silicates/ino.htm>)



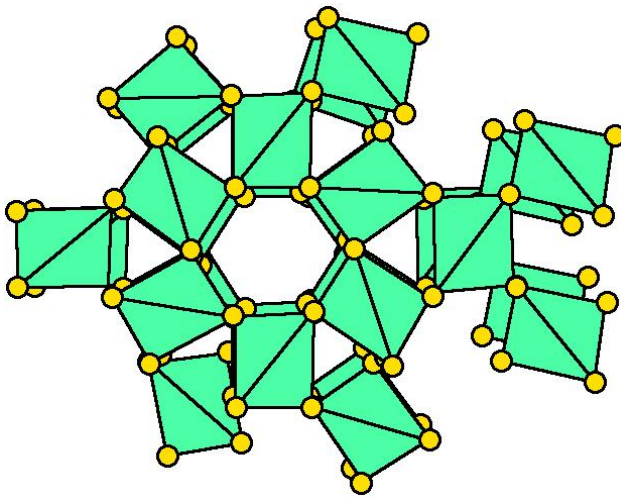
double-chain inosilicate share 2–3 oxygen per tetrahedron (from

<http://classes.colgate.edu/rapril/geol201/summaries/silicates/amphib.htm>)



phyllosilicate share 3 oxygen per tetrahedron (from

<http://classes.colgate.edu/rapril/geol201/summaries/silicates/phyllo.htm>)



tectosilicate share 4 oxygen per tetrahedron (from

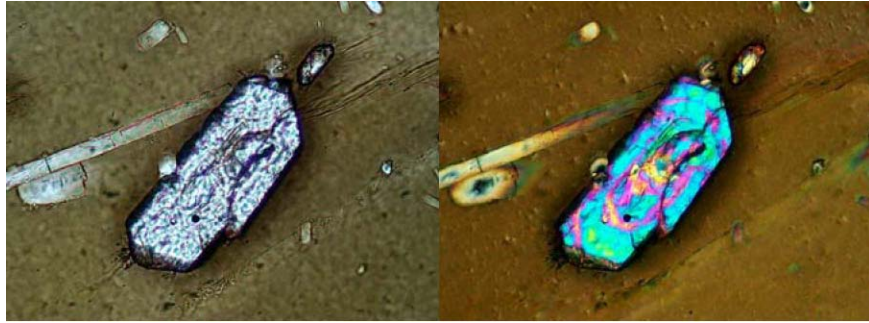
<http://classes.colgate.edu/rapril/geol201/summaries/silicates/tecto.htm>)

Orthosilicates (Nesosilicates)

SiO_4 + cations

zircon

ZrSiO_4



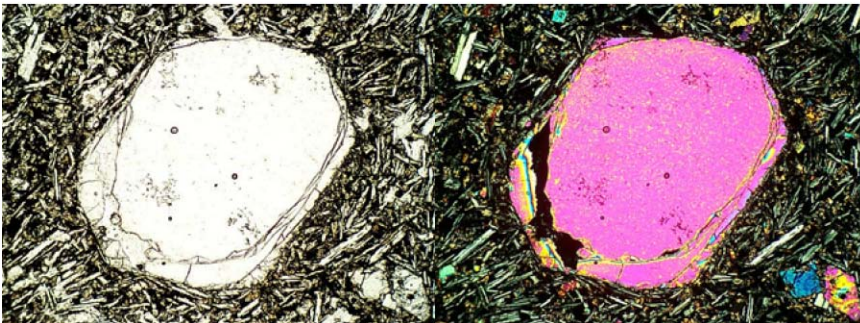
(from

http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)

crystal structure movie:

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/zircon.mov> (SiO₄ tetrahedra blue, Zr⁴⁺ 8-fold sites green)

olivine



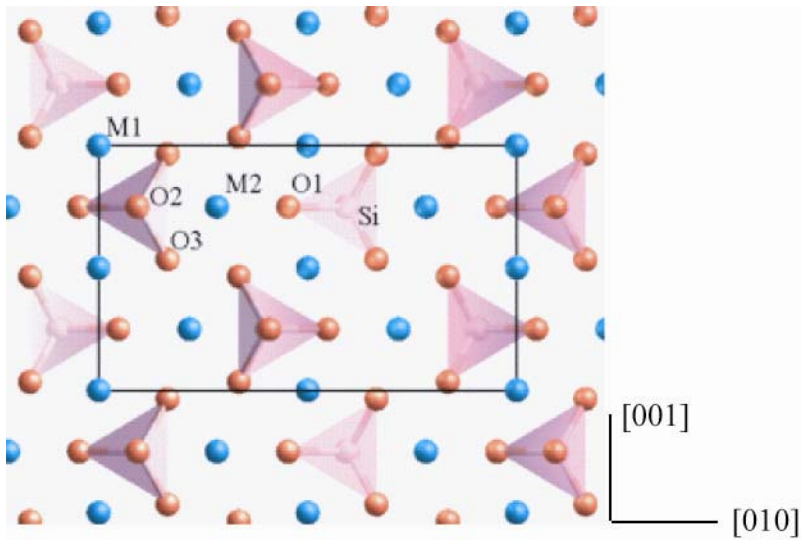
(from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)

orthorhombic

forsterite Mg₂SiO₄

in ultramafic rocks

fayalite Fe₂SiO₄

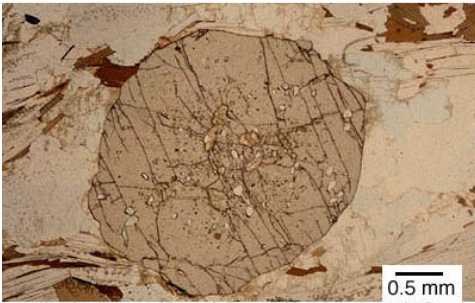
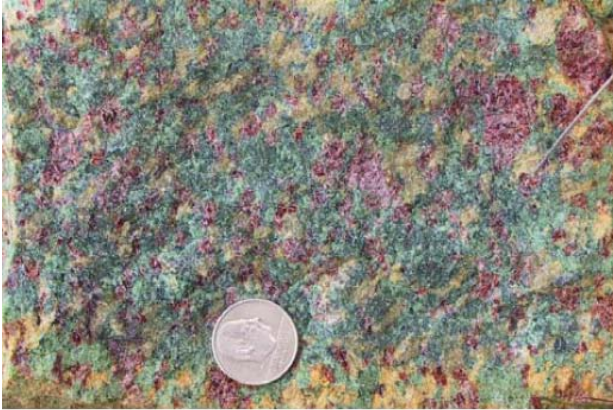


crystal structure movie:

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/olivine.mov>

(SiO₄ tetrahedra blue, Fe & Mg distorted octahedral sites yellow, Fe & Mg octahedral sites orange)

garnet $X_3Y_2Si_3O_{12}$



(from <http://www.geolab.unc.edu/Petunia/IgMetAtlas/mainmenu.html>)



(from <http://www.geolab.unc.edu/Petunia/IgMetAtlas/mainmenu.html>)

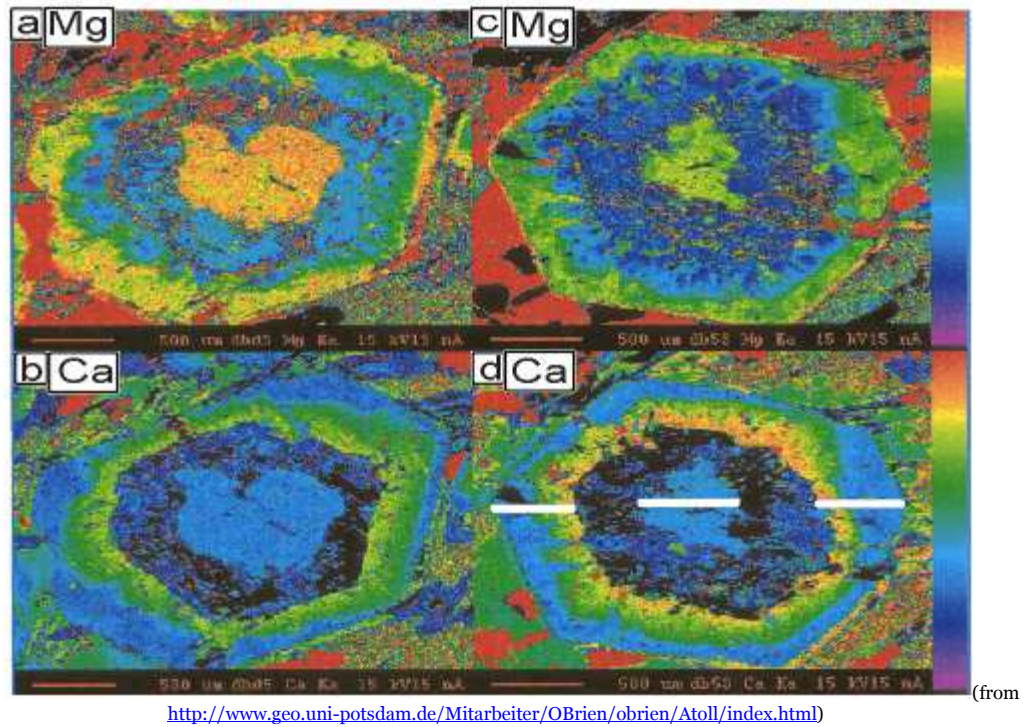
almandine Fe

pyrope Mg

grossular Ca

spessartine Mn

Y-garnet $Y_3Al_2Si_3O_{12}$



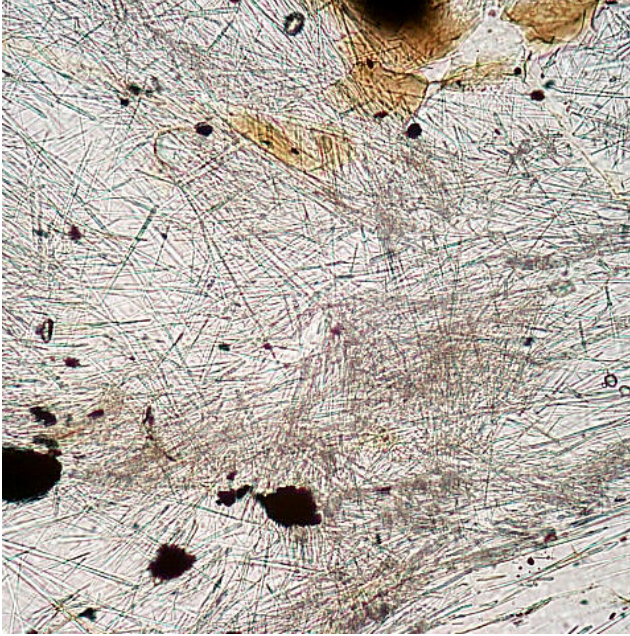
crystal structure movie:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/garnet.mov> (SiO₄ tetrahedra blue, Al octahedra red, M²⁺ distorted 8-fold sites cyan)

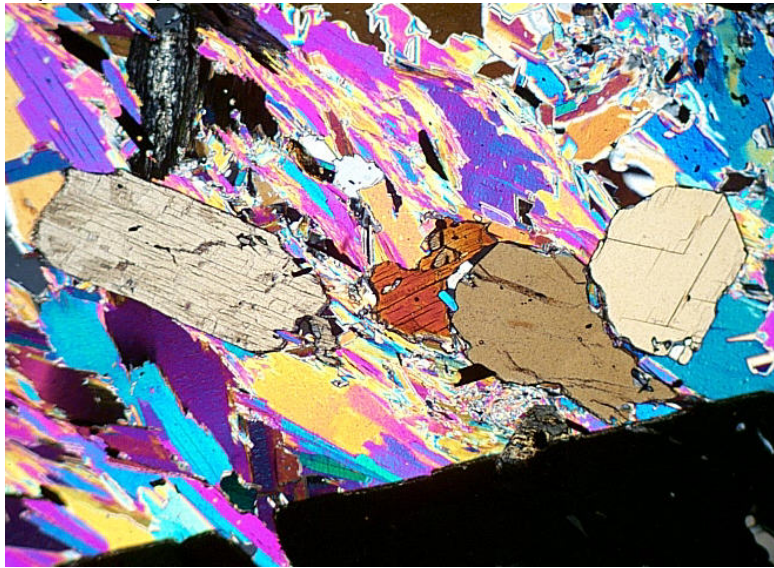
Aluminosilicates (also orthosilicates)



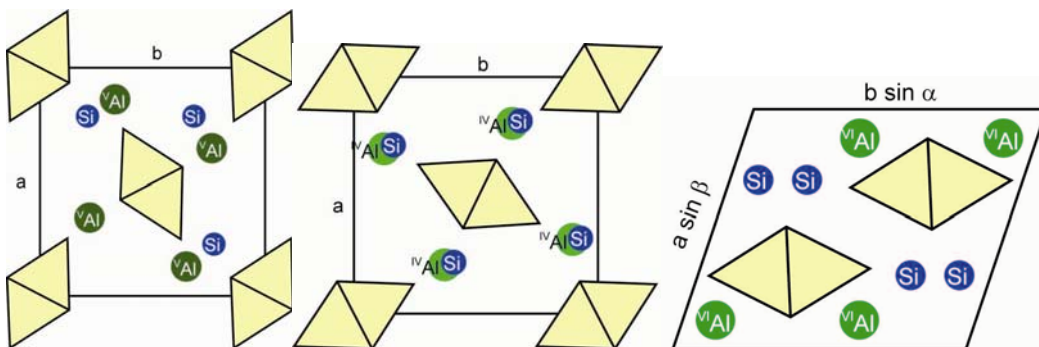
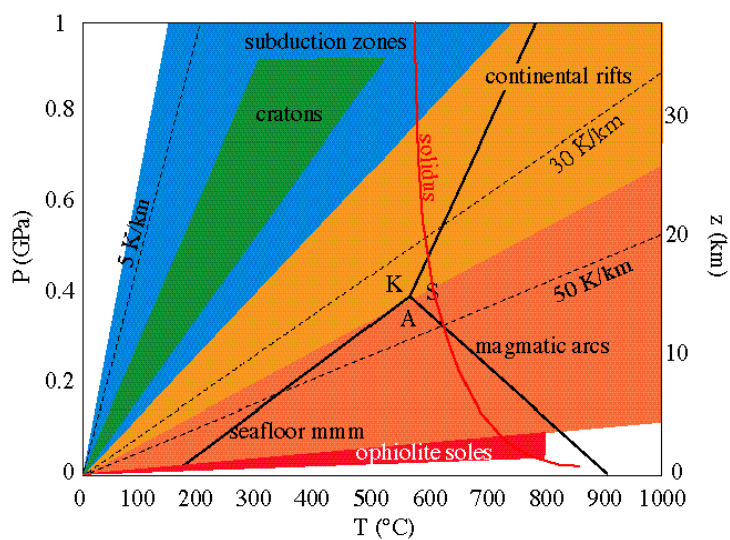
sillimanite ^{VI} Al ^{IV} Al	orthorhombic	high temperature
andalusite ^{VI} Al ^{IV} Al	orthorhombic	low pressure
kyanite ^{VI} Al ^{VI} Al	triclinic	high pressure



sillimanite (fibrolite) (from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)



kyanite (from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)



andalusite

sillimanite

kyanite (after Putnis, 1992)

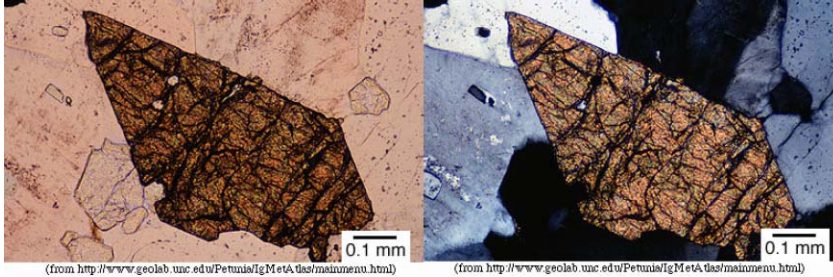
(^{VI}Al shown octahedra shown in yellow)

crystal structure movies:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/andalusite.mov> (SiO_4 tetrahedra blue, $^{\text{VI}}\text{Al}$ pale blue, $^{\text{V}}\text{Al}$ green)

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/sillimanite.mov> (SiO_4 tetrahedra blue, $^{\text{VI}}\text{Al}$ pale blue, $^{\text{IV}}\text{Al}$ yellow)

titanite



$\text{CaTiSiO}_4(\text{OH}, \text{Cl}, \text{F})_4$

staurolite

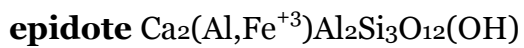


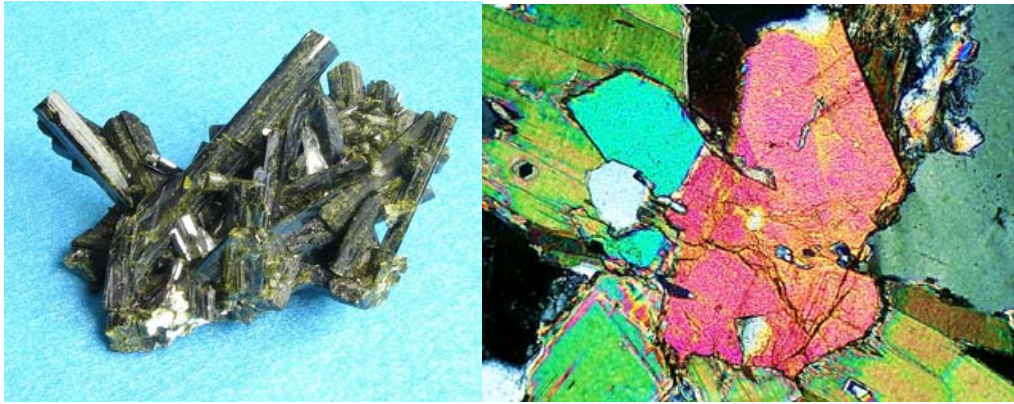
(from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)



Disilicates (Sorosilicates)

paired SiO_4 tetrahedra, Si_2O_7 (Si_2O_8 with each tetrahedron sharing one O with one other tetrahedron)





http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates

(from

monoclinic

has 7 and 11-fold coordinated sites

structure movie:

+<http://nature.berkeley.edu/classes/eps2//wisc/geo360/epidote.mov> (Ca 7- and 11-fold sites green, Si tetrahedra chains blue, Al M2 octahedral site cyan, Al-Fe M1 octahedral site yellow)

zoisite $\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$

orthorhombic

lawsonite $\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$

indicates high pressure

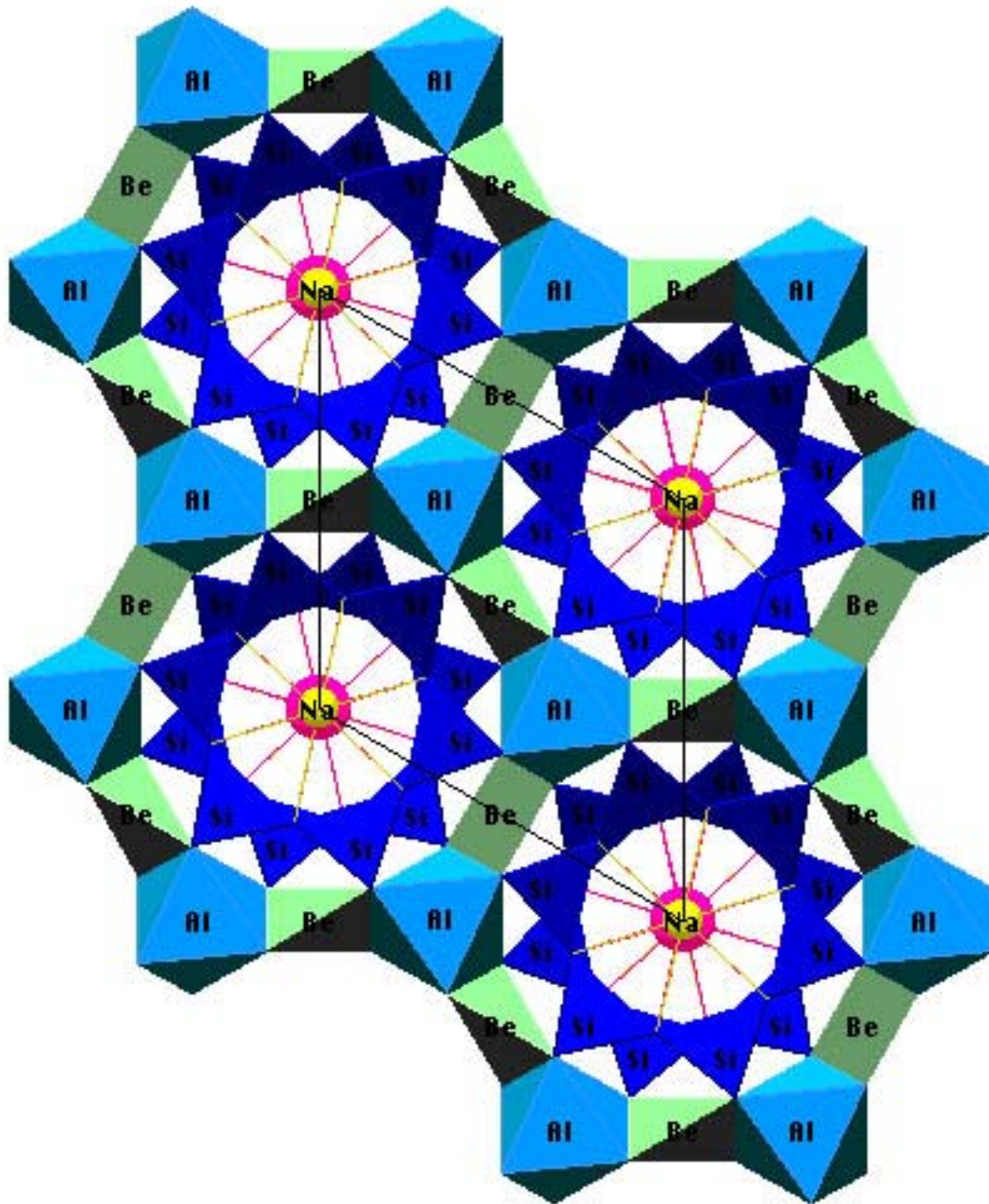
Ring Silicates (Cyclosilicates)

six-fold rings of SiO_4 tetrahedra, Si_6O_{18} (Si_6O_{24} with each tetrahedron sharing two O with two other tetrahedra)

beryl $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$

hexagonal





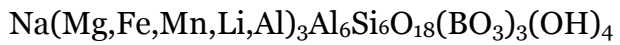
(SiO₄ tetrahedra dark blue, Al 6-fold sites cyan, Be 4-fold sites green)

crystal structure movie: +

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/beryl.mov> (SiO₄ tetrahedra blue, Al 6-fold sites green, Be 4-fold sites pale green; ignore the yellow and pink)

(cordierite structure nearly the same)

tourmaline Li–B silicate



crystal structure movie:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/tourmaline.mov> (SiO₄ tetrahedra cyan, Na⁺ or OH⁻ yellow, Al cyan, Li & Mg and Al purple, BO₃ pale green)



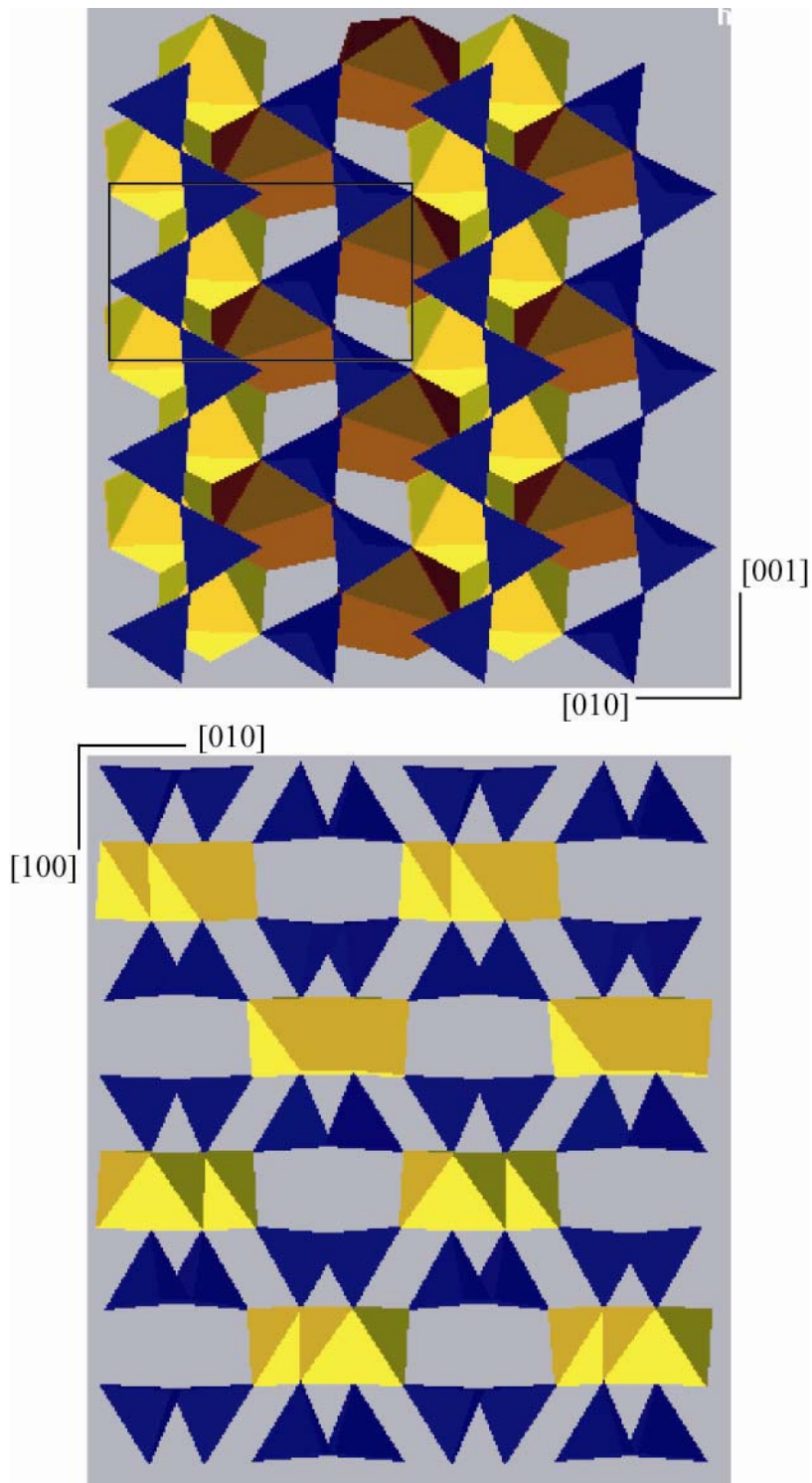
http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates

(from

Chain Silicates (Inosilicates)

Pyroxene

single chains of SiO₄ tetrahedra, Si₂O₆ (Si₂O₈ with each tetrahedron sharing two O with two other tetrahedra)



crystal structure movies: orthopyroxene, showing tetrahedral chains:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/diopibeam.mov> (SiO_4

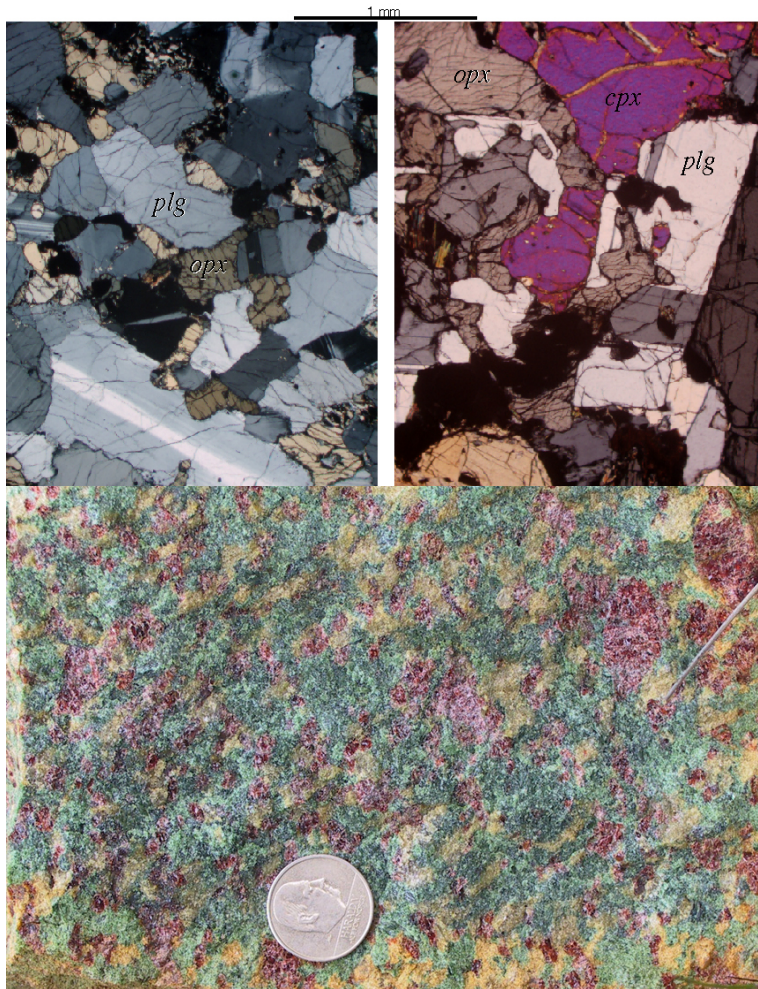
tetrahedra blue, Mg & Ca octahedra yellow)

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/opx.mov> (SiO_4

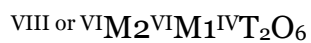
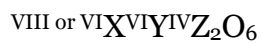
tetrahedra blue, Mg & Ca octahedra yellow)

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/diopside.mov> (SiO₄

tetrahedra blue, Mg octahedra yellow, Ca octahedra orange)



orthorhombic and monoclinic



enstatite



ferrosilite



wollastonite

CaSiO_3 common in skarns



diopside



hedenbergite

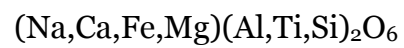


jadeite

$\text{NaAlSi}_2\text{O}_6$ indicates high pressure



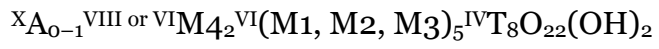
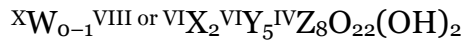
augite

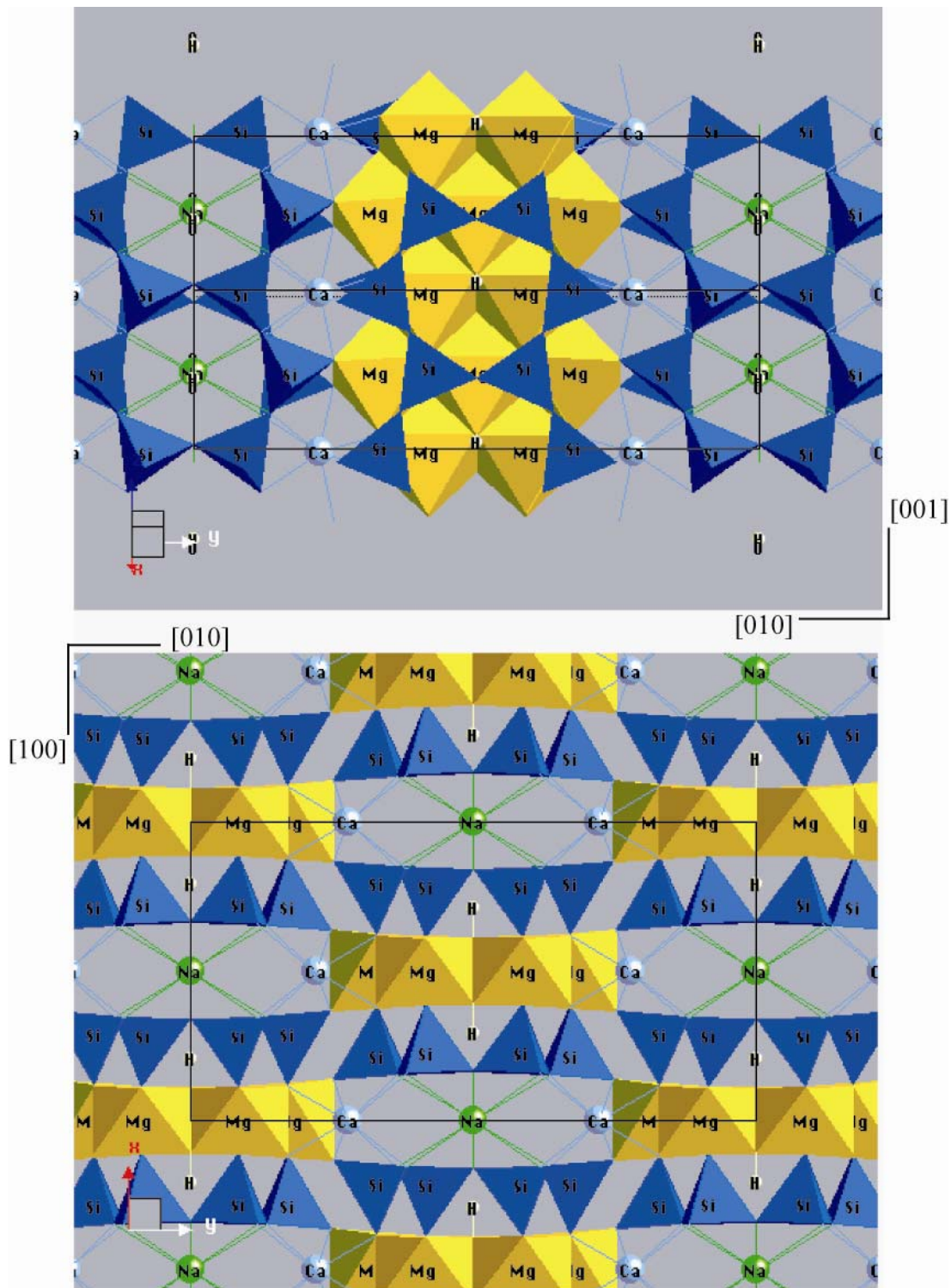


Amphibole

double chains of SiO_4 tetrahedra, Si_8O_{22} (Si_8O_{32} with each tetrahedron sharing two or three O with other tetrahedra)

orthorhombic and monoclinic





crystal structure movies:

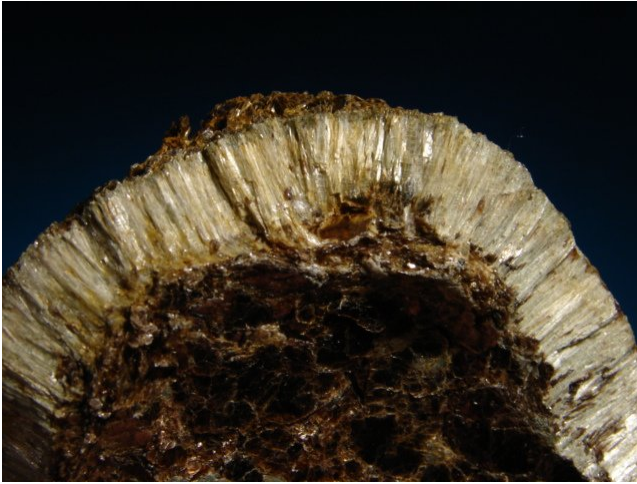
+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/tremolite.mov> (SiO₄ tetrahedra blue, Mg octahedra yellow, Ca 8- or 6-fold sites pale blue, Na 10-fold site green) <http://ist->

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/glaucophane.mov> (SiO₄ tetrahedra blue, Mg octahedra yellow, Al 8- or 6-fold sites pale blue, Na 10-fold site green)

anthophyllite $[\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2]$

Mg–Fe orthoamphibole

Mg-rich rocks: ultramafic



tremolite–actinolite $[\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2]$

Ca–Mg–Fe clinoamphibole

tremolite is Mg endmember; skarns

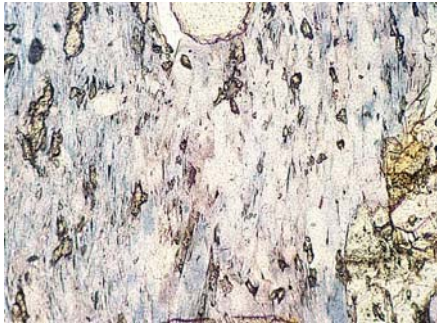
actinolite is Fe endmember; blackwall rinds



glaucophane $[\text{Na}_2(\text{Mg}_3\text{Al}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2]$

Na clinoamphibole

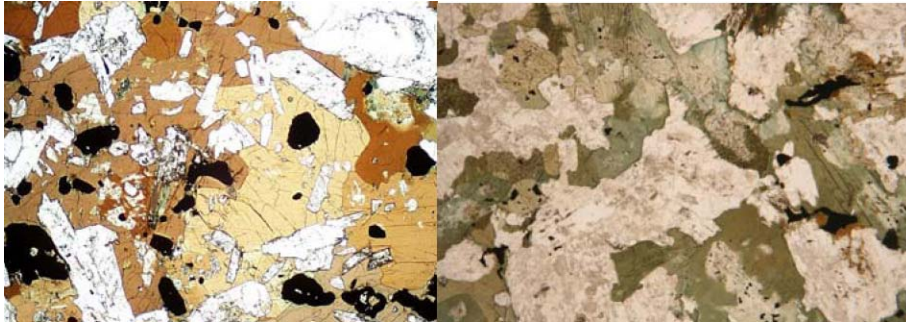
indicates high pressure



(from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)

hornblende $(\text{Na, K})\text{Ca}_2(\text{Mg, Fe}^{2+}, \text{Fe}^{3+}, \text{Al, Ti})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

K, Na, K, Mg, Fe, Al clinoamphibole



(from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)

Sheet Silicates (Phyllosilicates)

brucite: $\text{Mg}(\text{OH})_2$

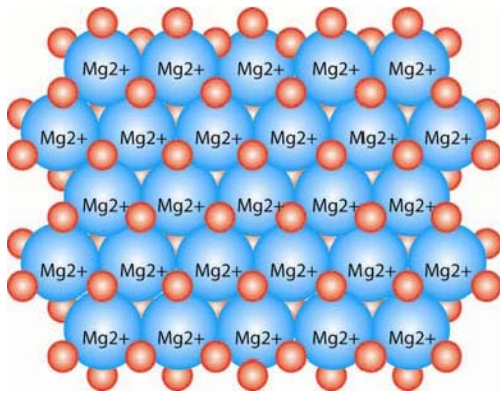
Mg atoms sit in octahedral sites between two planes of OH; the resulting

$\text{Mg}(\text{OH})_2$ sheets are held together by van der Waals bonds

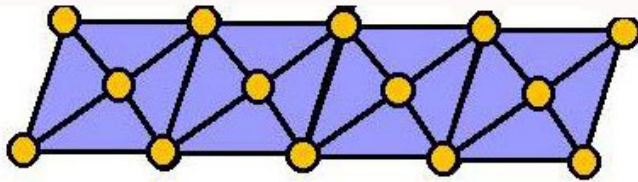
the 6- charge of the anions is satisfied by three 2+ cations, so no sites are vacant,

leading to a tri-octahedral sheet in which all 3 of the octahedral sites are

occupied; each OH (orange in figure) is bonded to three Mg^{2+}



(after Nesse (2000), 2000)



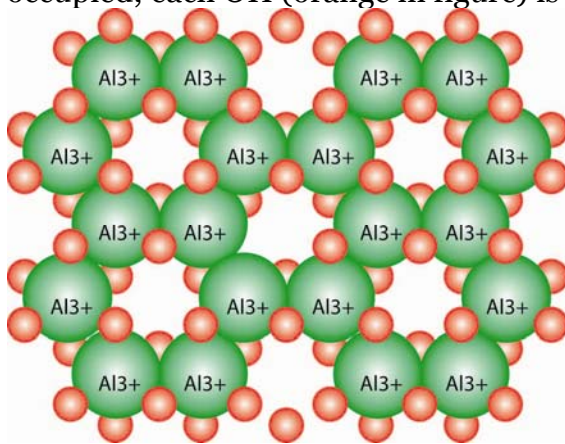
Octahedral Sheet

gibbsite: $\text{Al}(\text{OH})_3$

Al atoms sit in octahedral sites between two planes of OH; the resulting $\text{Al}(\text{OH})_3$

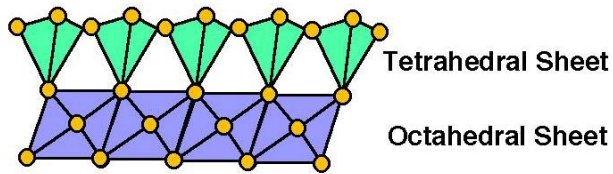
OH sheets are held together by van der Waals bonds

the 6- charge of the anions is satisfied by two 3+ cations, so 1/3 of the sites are vacant, leading to a di-octahedral sheet in which 2/3 of the octahedral sites are occupied; each OH (orange in figure) is bonded to two Al^{3+}



(after Nesse (2000), 2000)

serpentine: $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$



(from <http://classes.colgate.edu/rapril/geol201/summaries/silicates/phyllo.htm>)

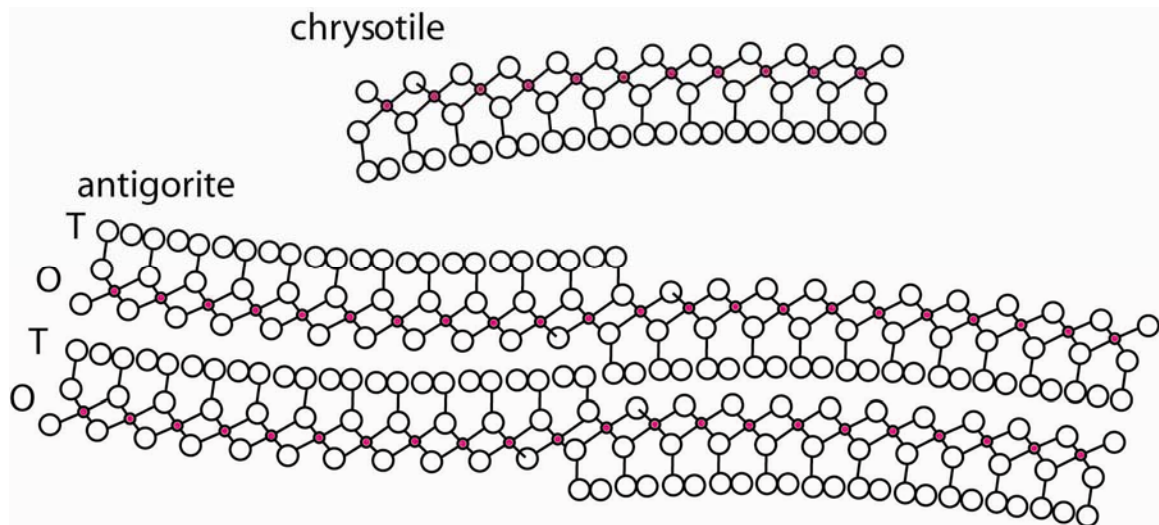
'TO' structure composed of 'brucite', $\text{Mg}(\text{OH})_2$ octahedral layers, and Si_2O_5 tetrahedral sheets

there is a mismatch between the octahedral and tetrahedral layers, which is 'solved' by the various polymorphs of serpentine in different ways:

chrysotile crystals form rolls parallel to $[100]$ (asbestos)

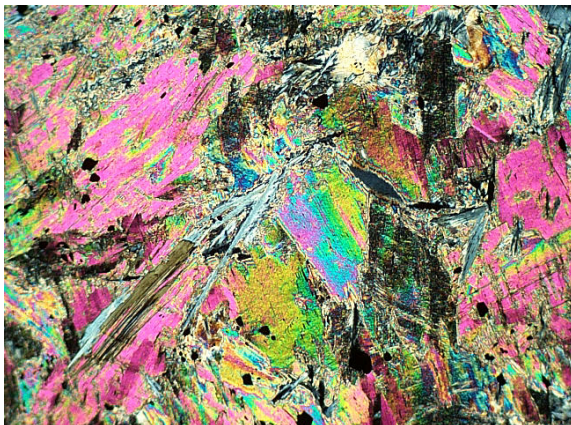
antigorite tetrahedra positions change to keep sheets relatively planar

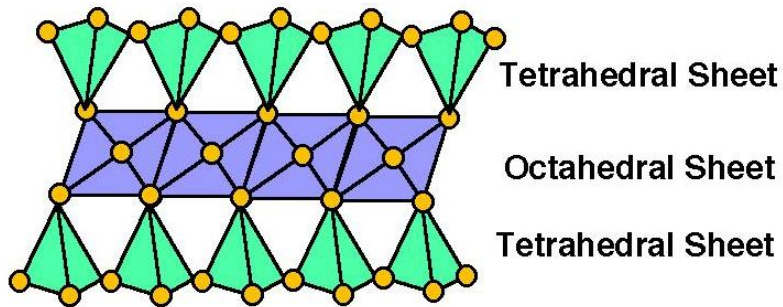
lizardite tetrahedra are distorted to keep sheets relatively planar



(after Nesse (2000), 2000)

talc: $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$





(from <http://classes.colgate.edu/rapril/geol201/summaries/silicates/phyllo.htm>)

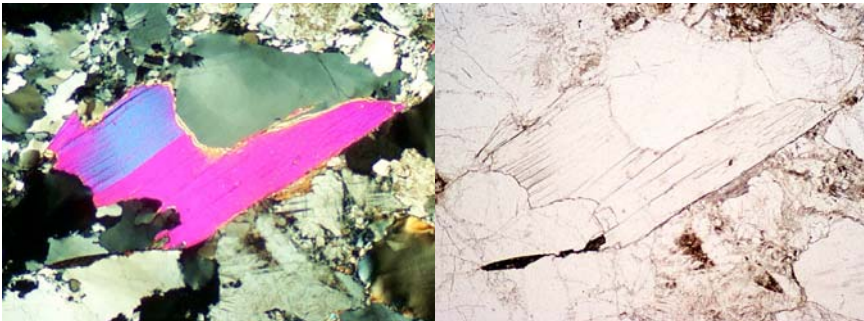
TOT structure, composed of two tetrahedral sheets of Si_2O_5 and an octahedral sheet of $\text{Mg}(\text{OH})_2$; successive TOT layers are held together by van der Waals bonds

crystal structure movie:

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/talc.mov>

muscovite: $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$

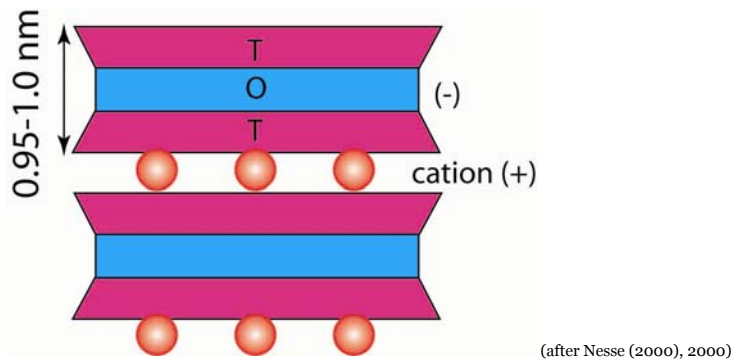
lepidolite: $\text{LiAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$



http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates

(from

TOT + interlayer cation

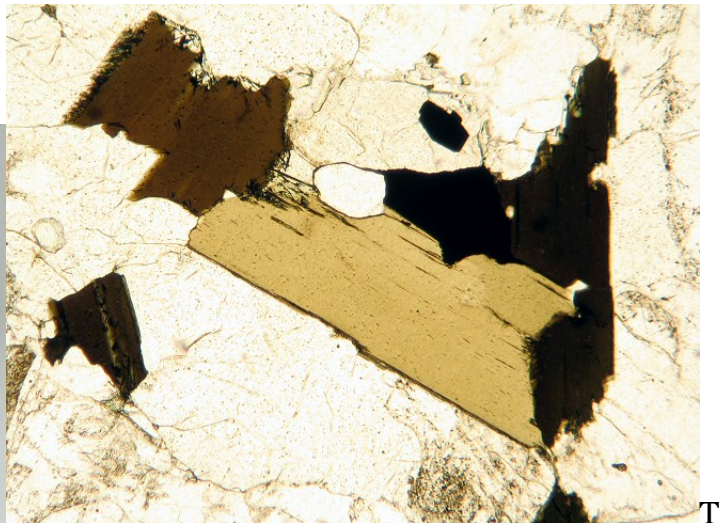


crystal structure movie:

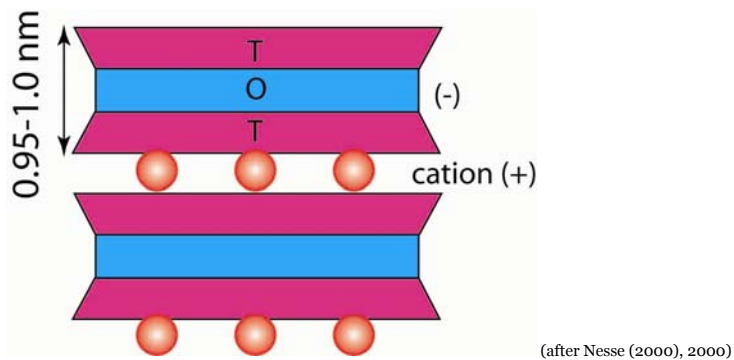
+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/muscovite.mov>

biotite: $\text{K}(\text{Mg, Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$

phlogopite is Mg endmember; found in mantle



OT + interlayer cation like muscovite



crystal structure movie:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/phlogopite.mov>

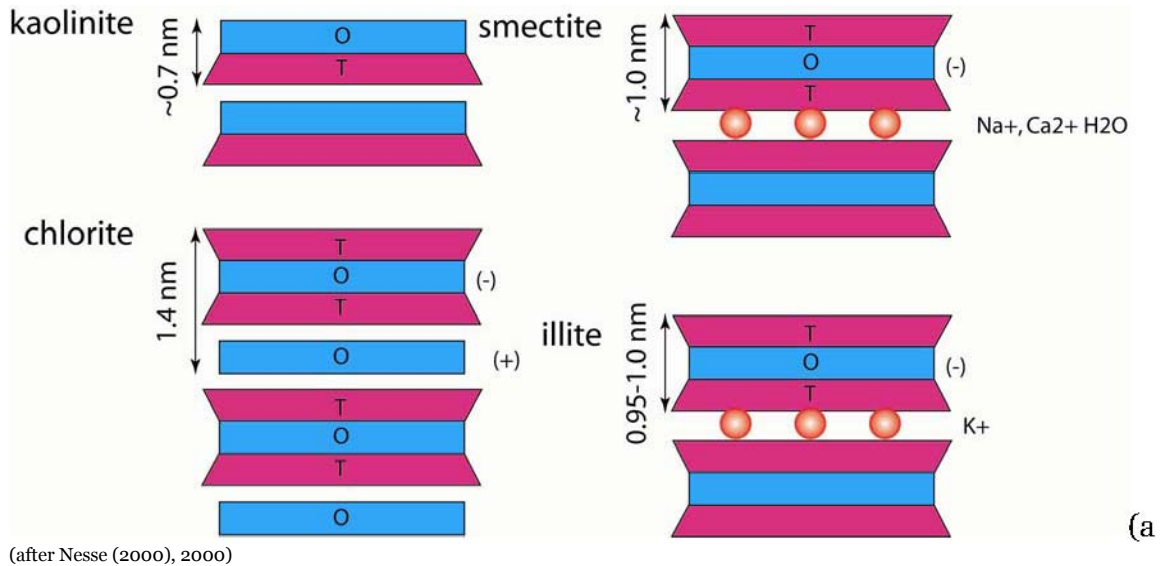
clay minerals

paper, drilling mud, ceramics, cosmetics, absorbents, food

kaolinite TO, $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, interlayer spacing ~ 0.7 nm

smectite TOT, $(\text{Na}, \text{Ca}, \text{Mg}, \text{Fe})_x(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$

illite TOT, $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$



<http://nature.berkeley.edu/classes/eps2//wisc/geo360/kaolinite.mov>

chlorite: $(\text{Mg}, \text{Fe})_3(\text{Al}, \text{Si})_4\text{O}_{10}(\text{OH})_2$

TOT + interlayer octahedral site = talc + brucite

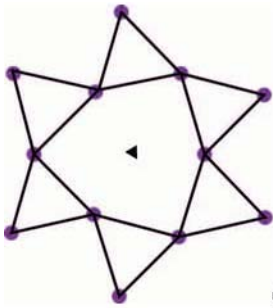
crystal structure movie:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/chlorite.mov>

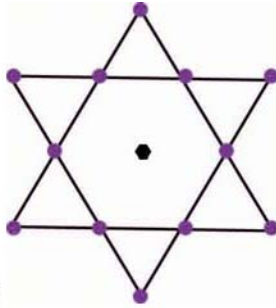


Framework Silicates (Tectosilicates)

Quartz



α quartz

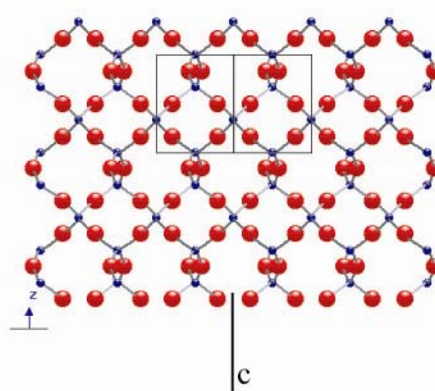
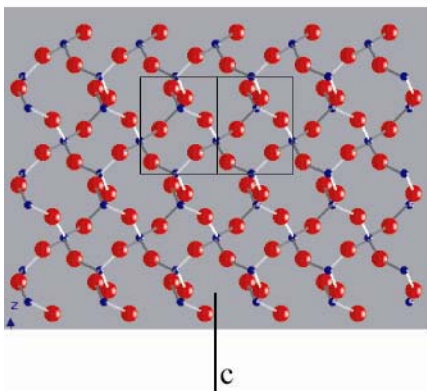
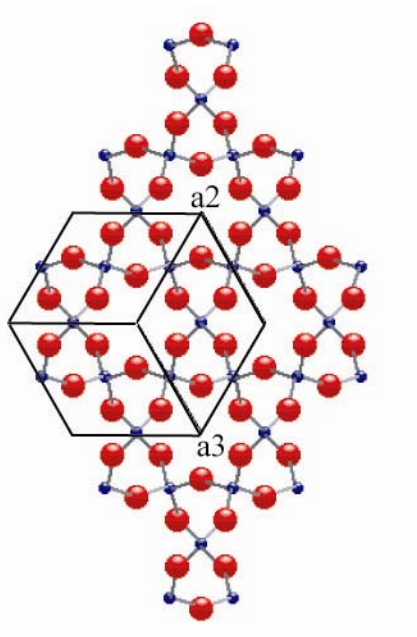
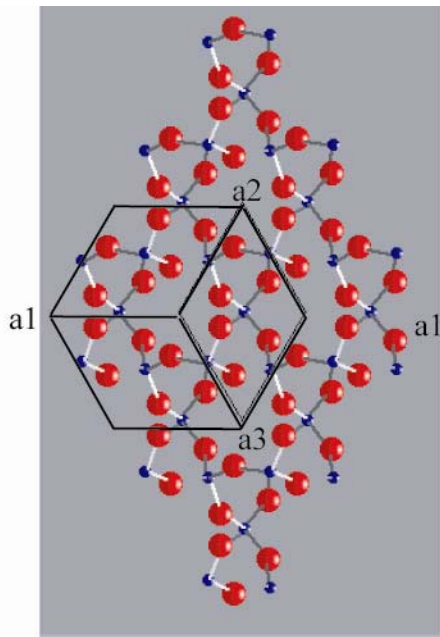


β quartz, showing positions of Si

atoms (after Putnis, 1992)

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/Quartz.mov>

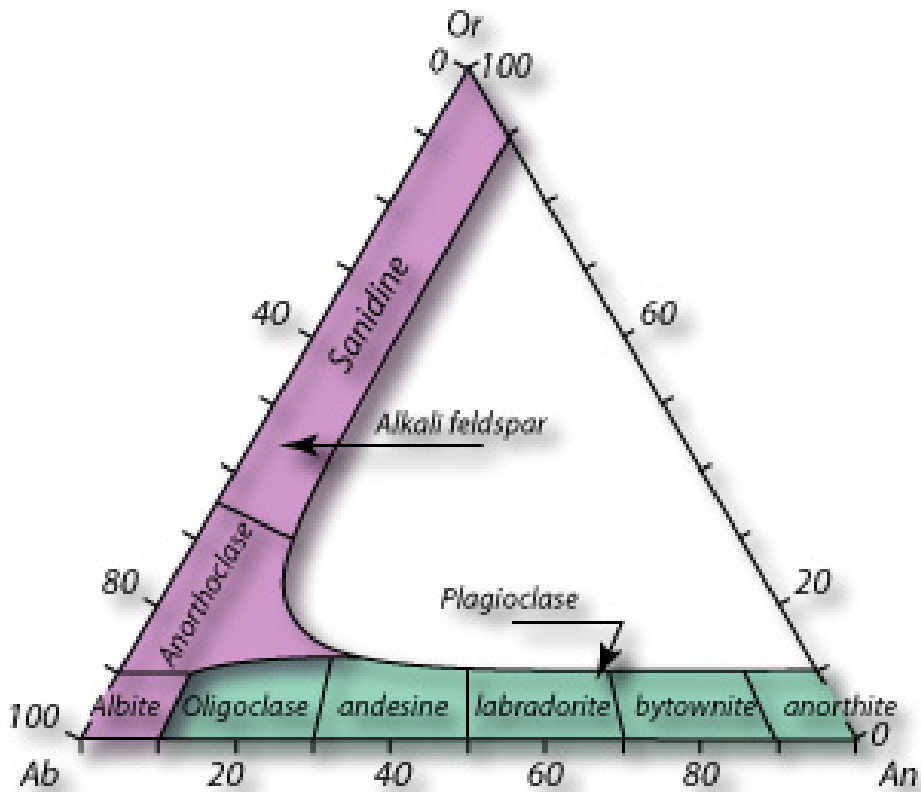
<http://nature.berkeley.edu/classes/eps2//wisc/geo360/Bquartz.mov>



Feldspar



monoclinic and triclinic



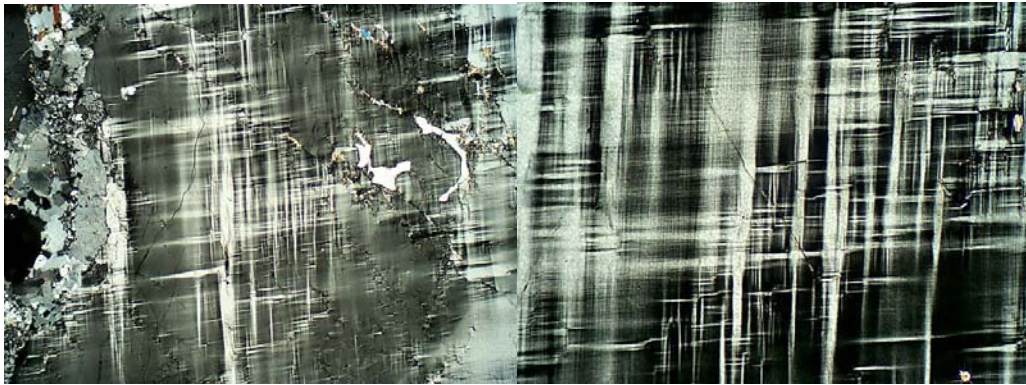
<http://www.geosci.usyd.edu.au/users/prey/FieldTrips/SouthCoastExc02/DayThree.html>

K-feldspar KAlSi_3O_8

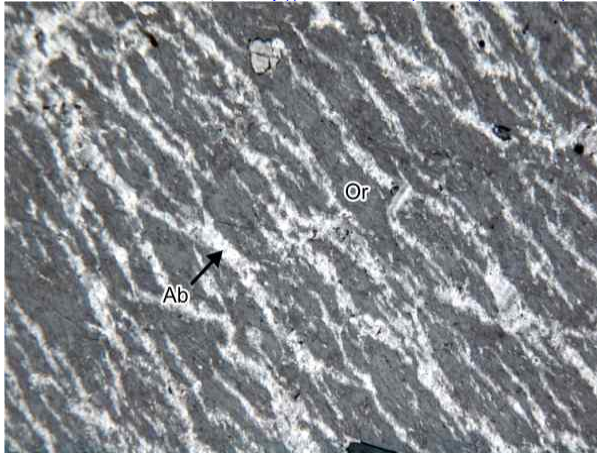
crystal structure movie:

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/Sanidine.mov> (SiO₄ and AlO₄ tetrahedra blue, 9-fold K sites red)

sanidine	monoclinic	high T, rapid cooling	complete Al/Si disorder
orthoclase	monoclinic	moderate T, cooling	partial Al/Si disorder
microcline	triclinic	low T, slow cooling	complete Al/Si order



(from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)



(from http://www.geo.auth.gr/212/6_tekto/fds_perthite/perthite_06x.jpg)

perthite: albite exsolution lamellae in K-feldspar host

plagioclase $\text{NaAlSi}_3\text{O}_8$ – $\text{CaAl}_2\text{Si}_2\text{O}_8$



amazonite (albite)

high albite	triclinic	high T, rapid cooling	complete Al/Si disorder
intermediate albite	triclinic	moderate T, cooling	partial Al/Si disorder
low albite	triclinic	low T, slow cooling	complete Al/Si order

crystal structure movie:

+<http://nature.berkeley.edu/classes/eps2//wisc/geo360/Albitem.mov>

(SiO₄ and AlO₄ tetrahedra blue, Na 9-fold sites yellow)

this is the best of the feldspar movies

<http://nature.berkeley.edu/classes/eps2//wisc/geo360/Anorthite.mov>

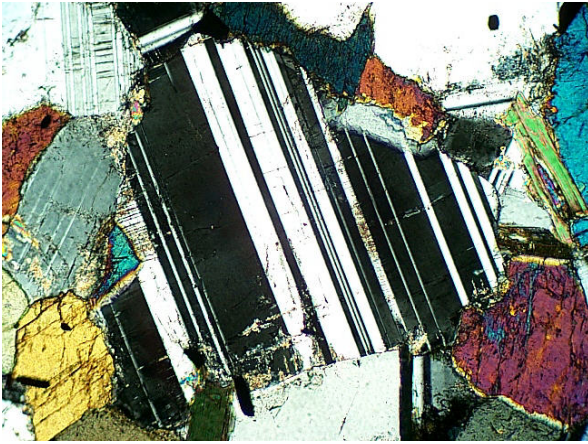
(SiO₄ tetrahedra blue, AlO₄ tetrahedra grey, Ca 9-fold sites blue)

albite–anorthite

albite–An₁₀–oligoclase–An₃₀–andesine–An₅₀–labradorite–An₇₀–bytownite–An₉₀–anorthite

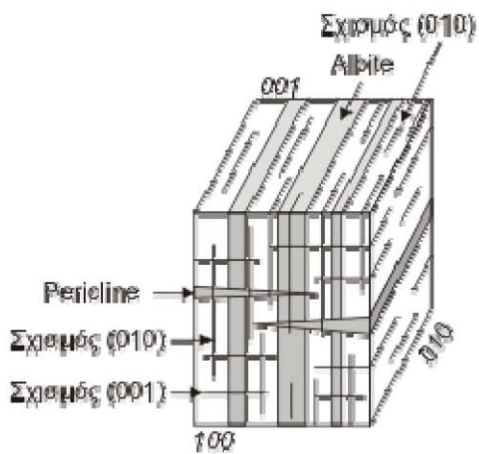
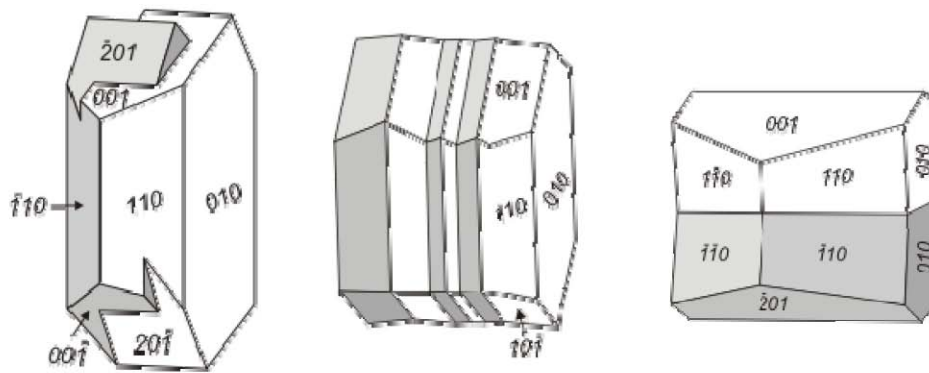


(from <http://www.geolab.unc.edu/Petunia/IgMetAtlas/mainmenu.html>)



(from http://www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/met_minerals.htm#Al-silicates)

feldspar twinning



http://www.geo.auth.gr/212/6_tekto/fds_twin.htm

(from

Carlsbad $[001](010)$

Albite $\perp(010)(010)$

Pericline $[010](hol)$

Albite and Pericline

Zeolites

$'(Na, K)(Ca, Mg)(AlSiO)' \cdot mH_2O$

important filtering agents crystal structure movie:

+ <http://nature.berkeley.edu/classes/eps2//wisc/geo360/Analcime.mov> (SiO₄ & AlO₄ tetrahedra purple, Na pink, H₂O yellow)

Igneous Petrology

Read Chapters 8 & 9 of Klein & Philpotts

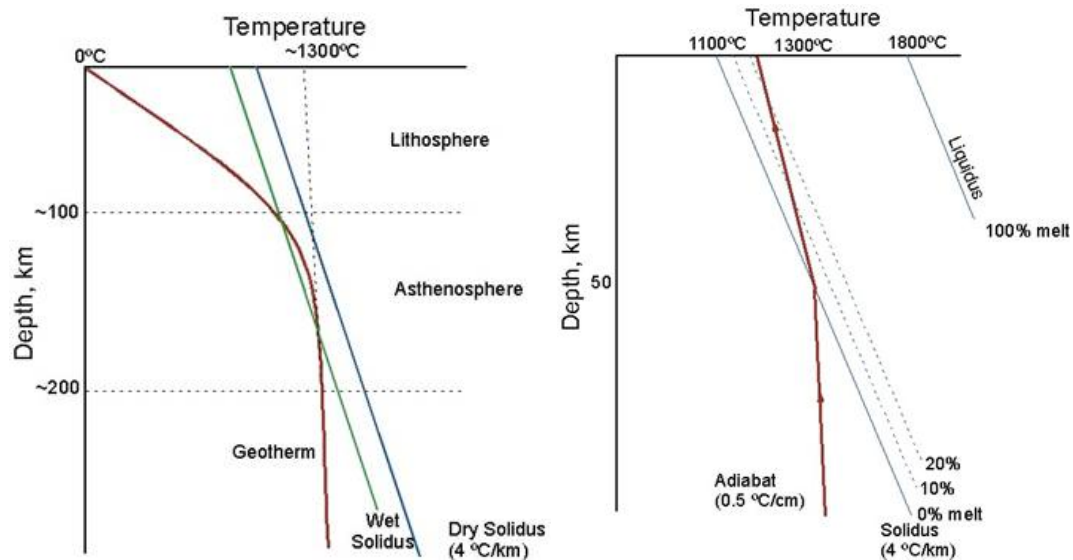
Mid-Ocean Ridge Magmatism

Earth's is differentiated into core, mantle crust.

Mantle is undergoing convection because of core crystallization, radiogenic heat etc.

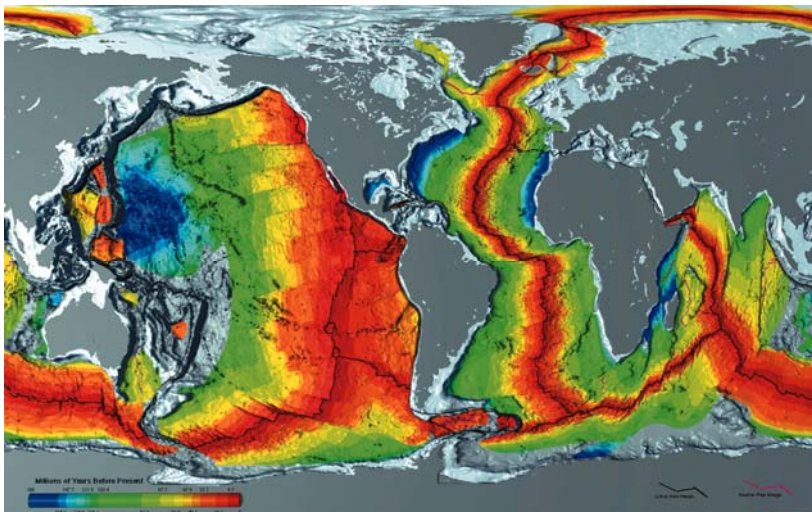
Peridotite is made of olivine + clinopyroxene + orthopyroxene

On the rising part of a convection cell, decompression melting occurs



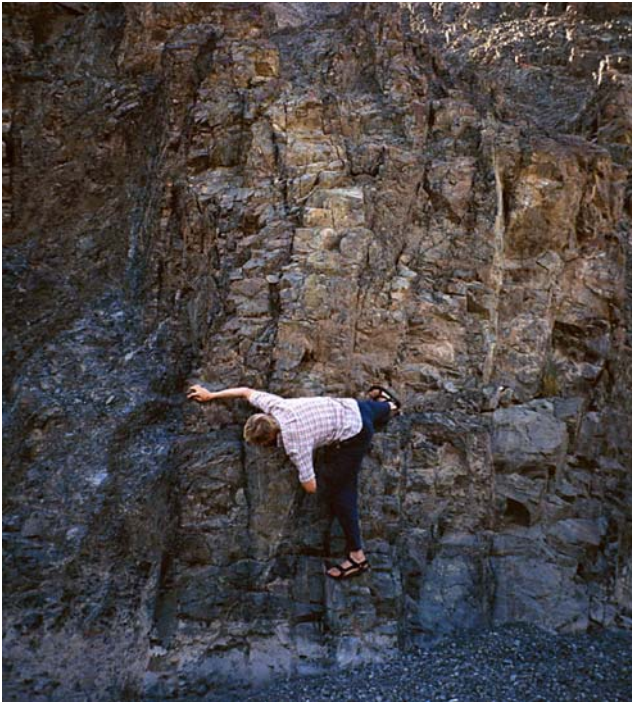
http://gore.ocean.washington.edu/classpages/ocean410_2001/notes/unit05.htm

This melting is incongruent and depletes the clinopyroxene component in peridotite, producing basalt (MORB) that erupts at the seafloor at mid-ocean ridges and diabase dikes and gabbro that crystallize beneath the seafloor.





pillowed flows in Oman

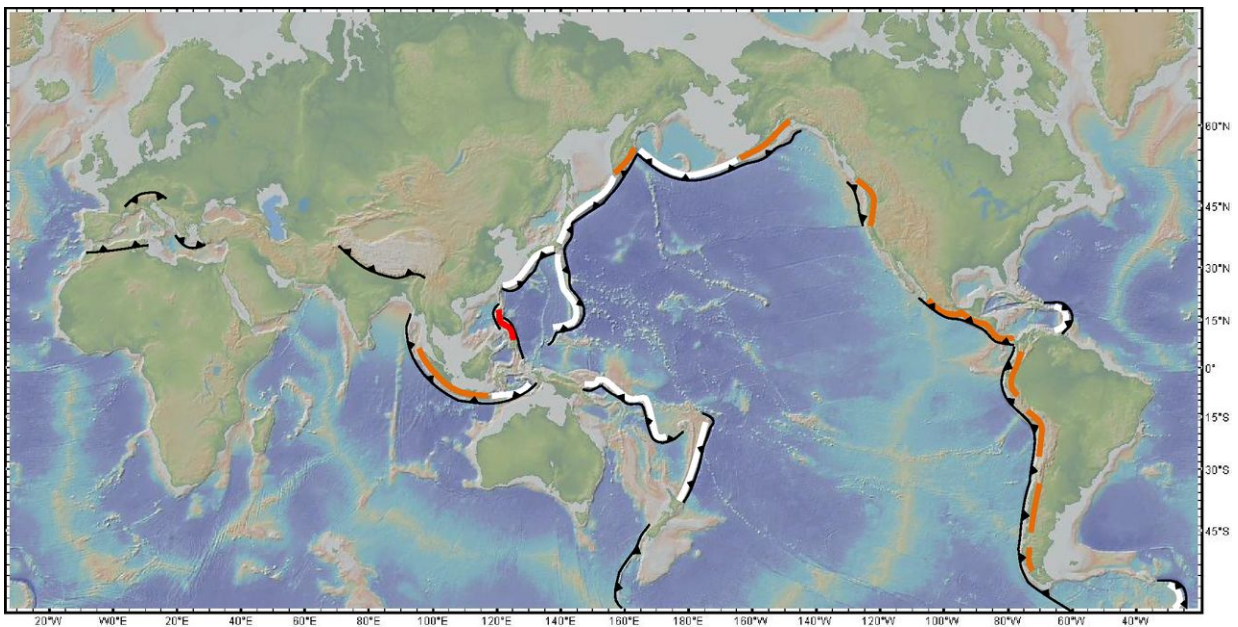


sheeted dikes in Oman



gabbro in Oman

Subduction Zone Magmatism



<http://geosphere.geoscienceworld.org/content/9/1/21/F4.expansion.html>

Oceanic lithosphere undergoes hydration during and after formation.
Oceanic lithosphere cools, eventually becoming gravitationally unstable and subducting
During subduction, the downgoing plate heats and devolatilizes.

The volatiles migrate upward and trigger melting of the convecting mantle wedge at $\sim 1000^{\circ}\text{C}$.

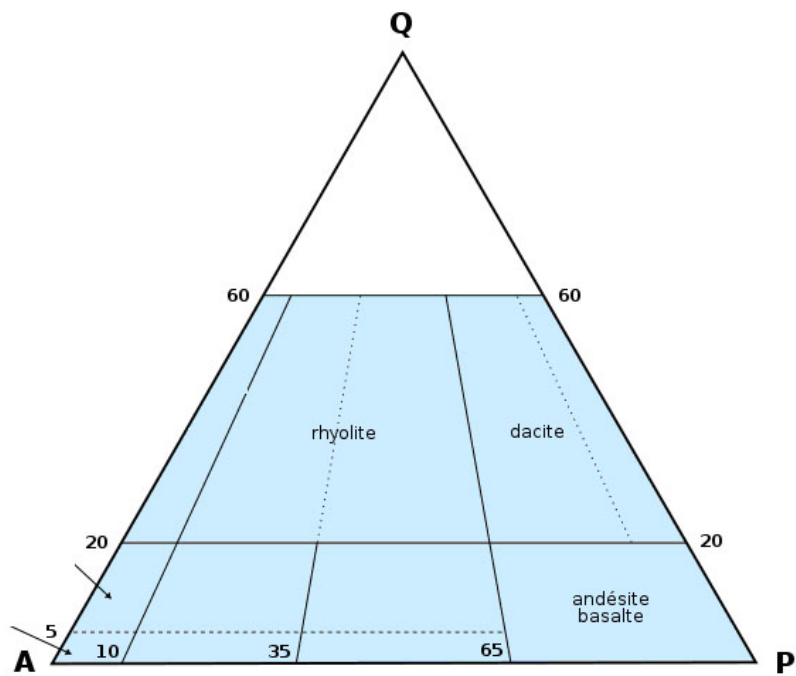
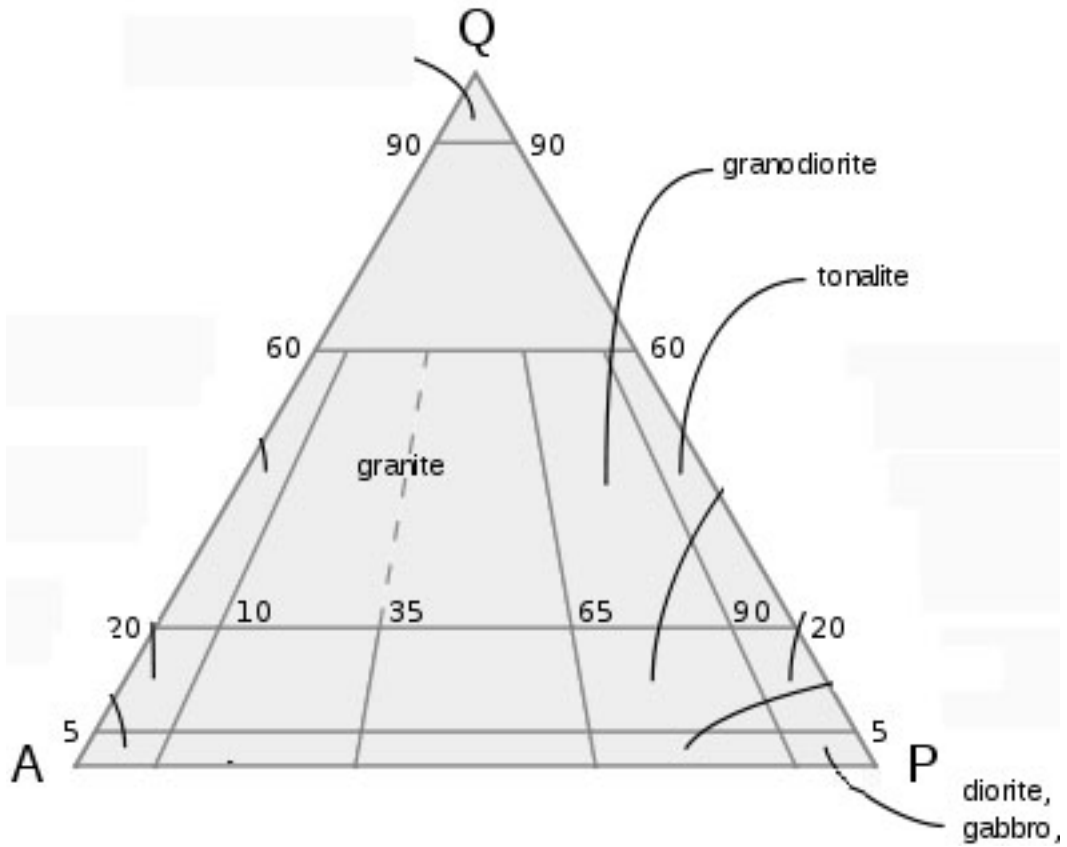
The main magma is basalt. This basalt undergoes differentiation/fractionation and assimilation/contamination to produce more-felsic rocks; more-felsic rocks can also be produced by re-melting of crustal rocks.

Plutonic rocks form batholiths.

In intra-oceanic arcs, these processes produce basalt = andesite >> dacite, rhyolite.

In continental arcs, processing is more severe, leading to andesite > dacite > basalt > rhyolite.

More-felsic rocks have higher SiO_2 , H_2O and viscosity (and are therefore more explosive).



Metamorphic Petrology

Read Chapters 8 & 9 of Klein & Philpotts

The main metamorphic facies are greenschist (albite + actinolite + epidote + chlorite), amphibolite (plagioclase + hornblende), granulite (plagioclase + clinopyroxene + orthopyroxene), blueschist (Na-amphibole + epidote or lawsonite), and eclogite (Na-clinopyroxene + garnet).

Oceanic crust undergoes low-P/high-T metamorphism at mid-ocean ridges.

Subducting oceanic crust transforms to blueschist and eclogite during high-P/low-T metamorphism; the volatiles produced migrate into the mantle wedge and cause melting. Eclogite is substantially denser than peridotite, and produces about half of the negative buoyancy of subducting plates.

Barrovian metamorphic rocks are produced during continental collision.

The sequence of minerals that appear during Barrovian metamorphism is chlorite, biotite, garnet, staurolite, kyanite, sillimanite, sillimanite + orthoclase.