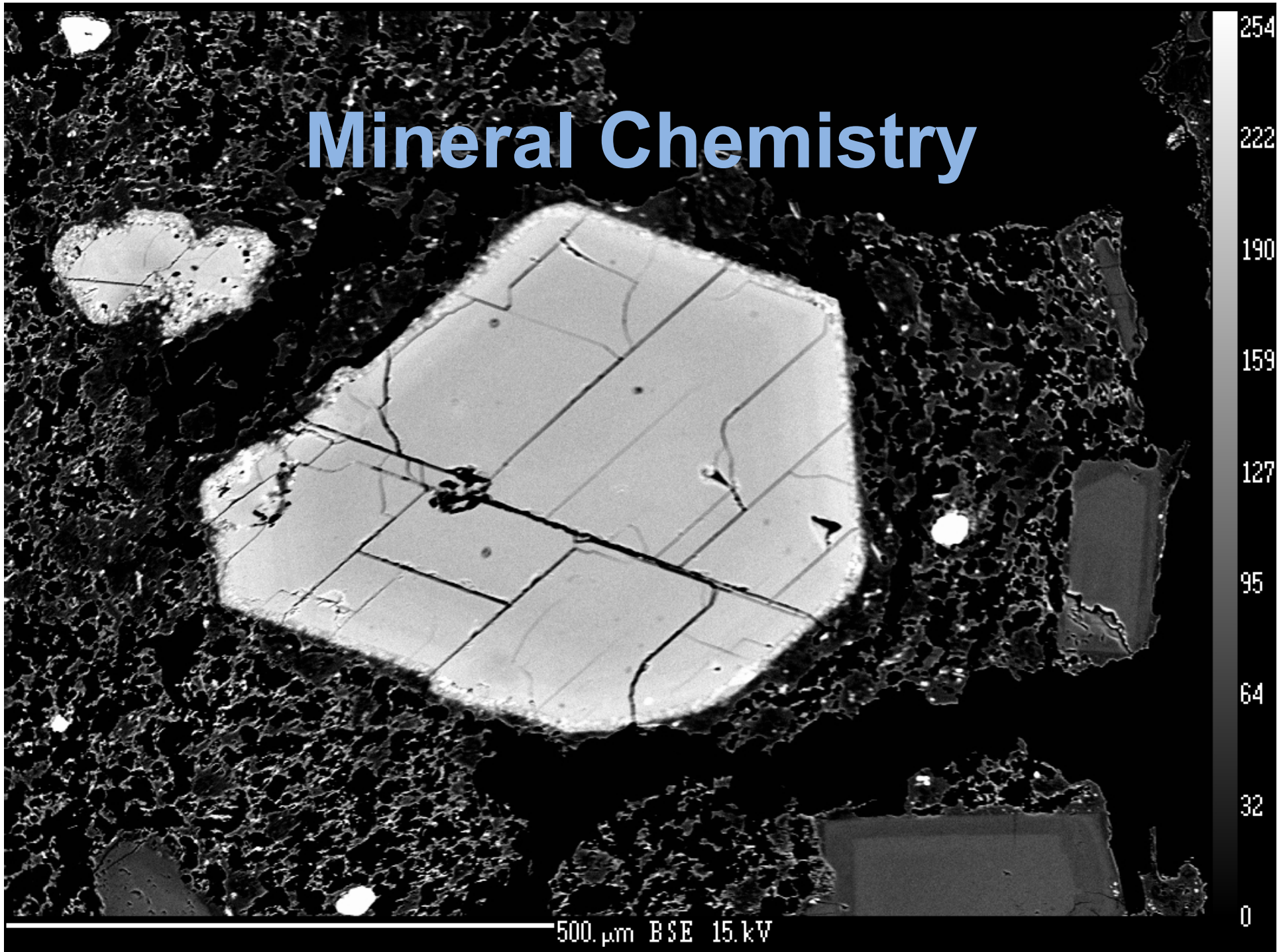
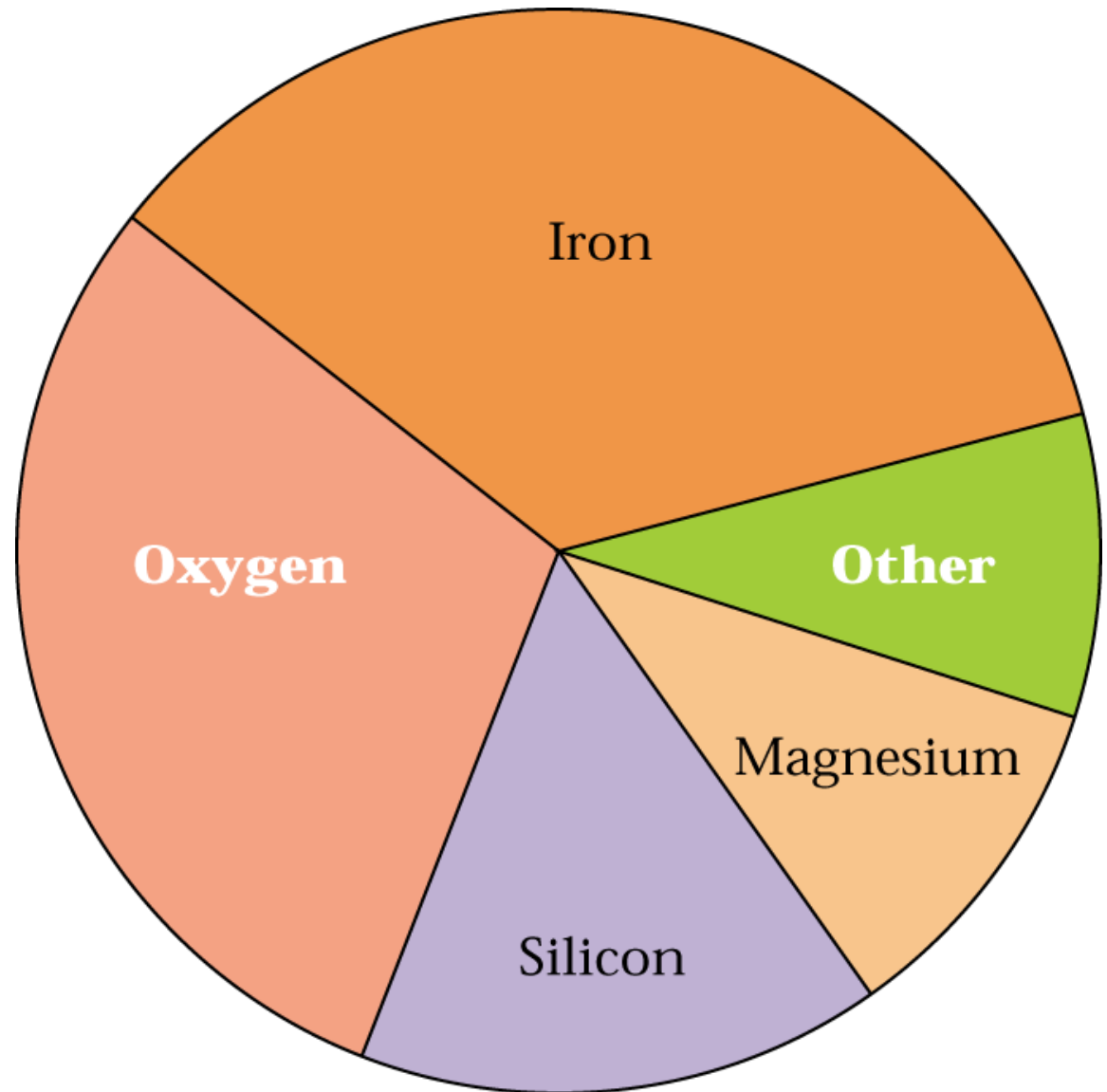


# Mineral Chemistry

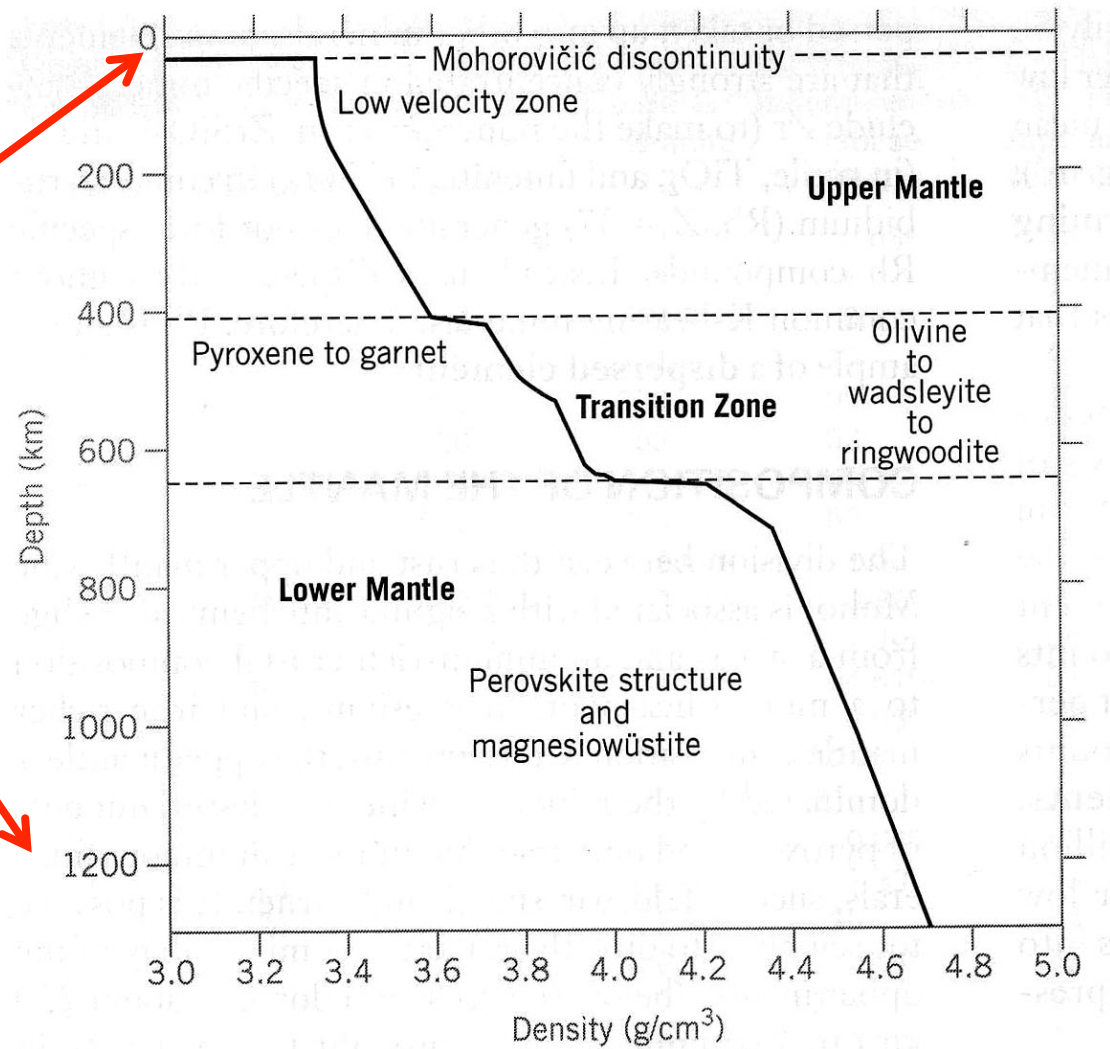
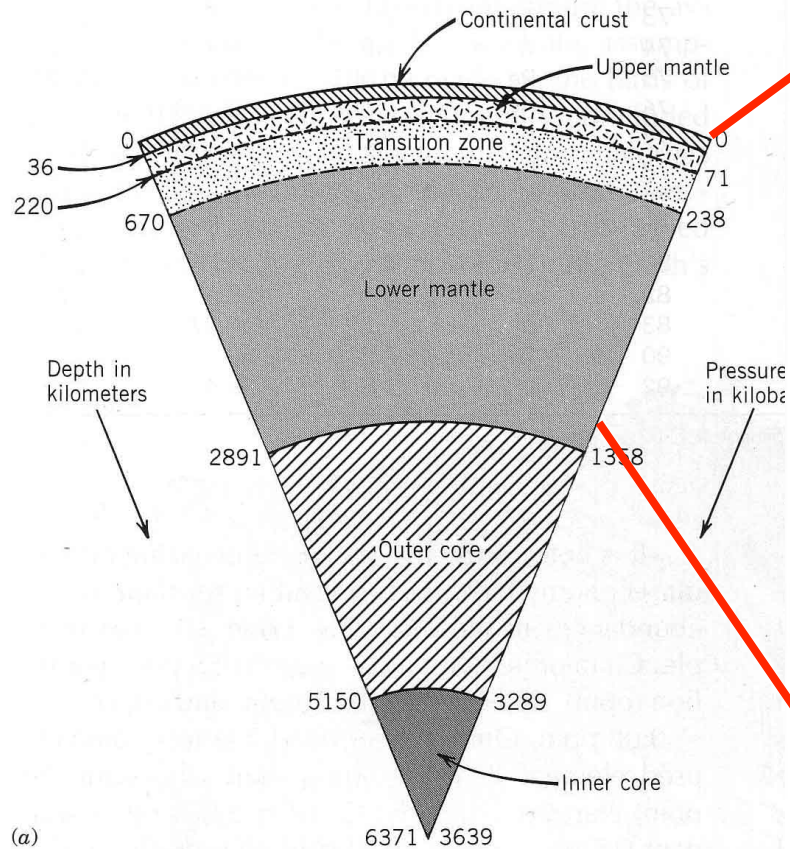


# Chemical Composition of the Earth

- **Whole Earth (wt. %)**
  - Fe 25%
  - O 30%
  - Si 15%
  - Mg 13%
  - Other 7%
- Explained by **olivine** composition and iron-rich core
- Note olivine structure changes with pressure!

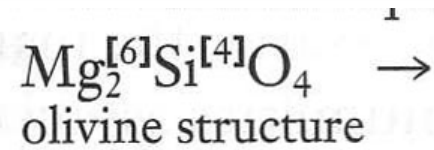
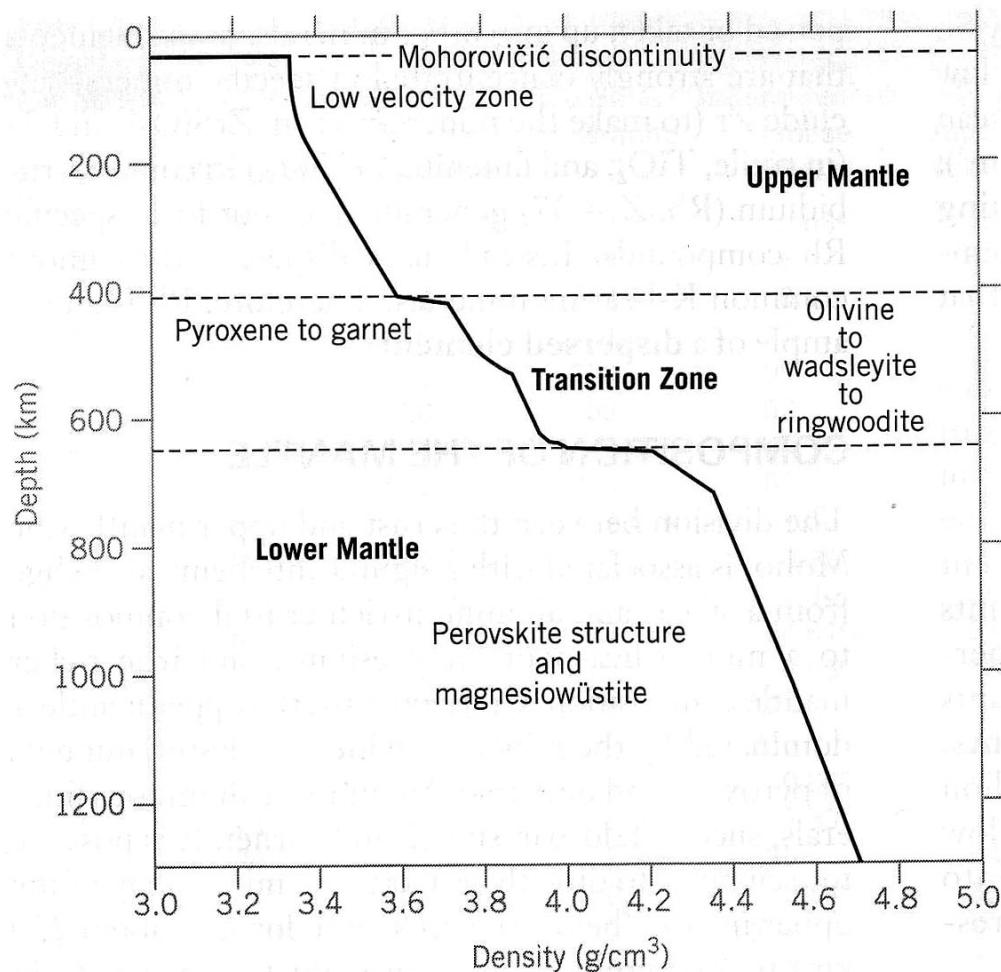


# Chemical Composition of the Earth

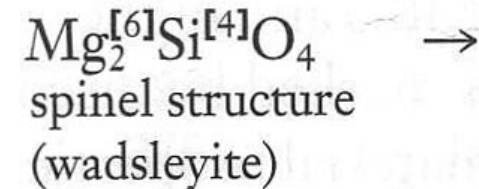




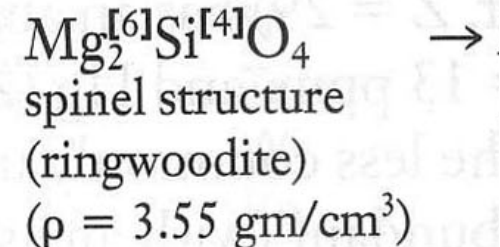
# Chemical Composition of the Earth



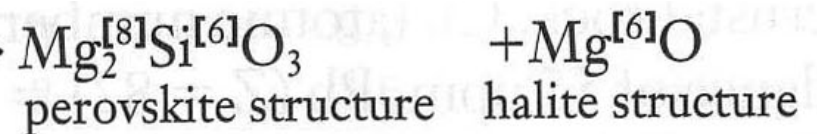
$$(\rho = 3.22 \text{ gm/cm}^3)$$



$$(\rho = 3.47 \text{ gm/cm}^3)$$



$$(\rho = 3.55 \text{ gm/cm}^3)$$

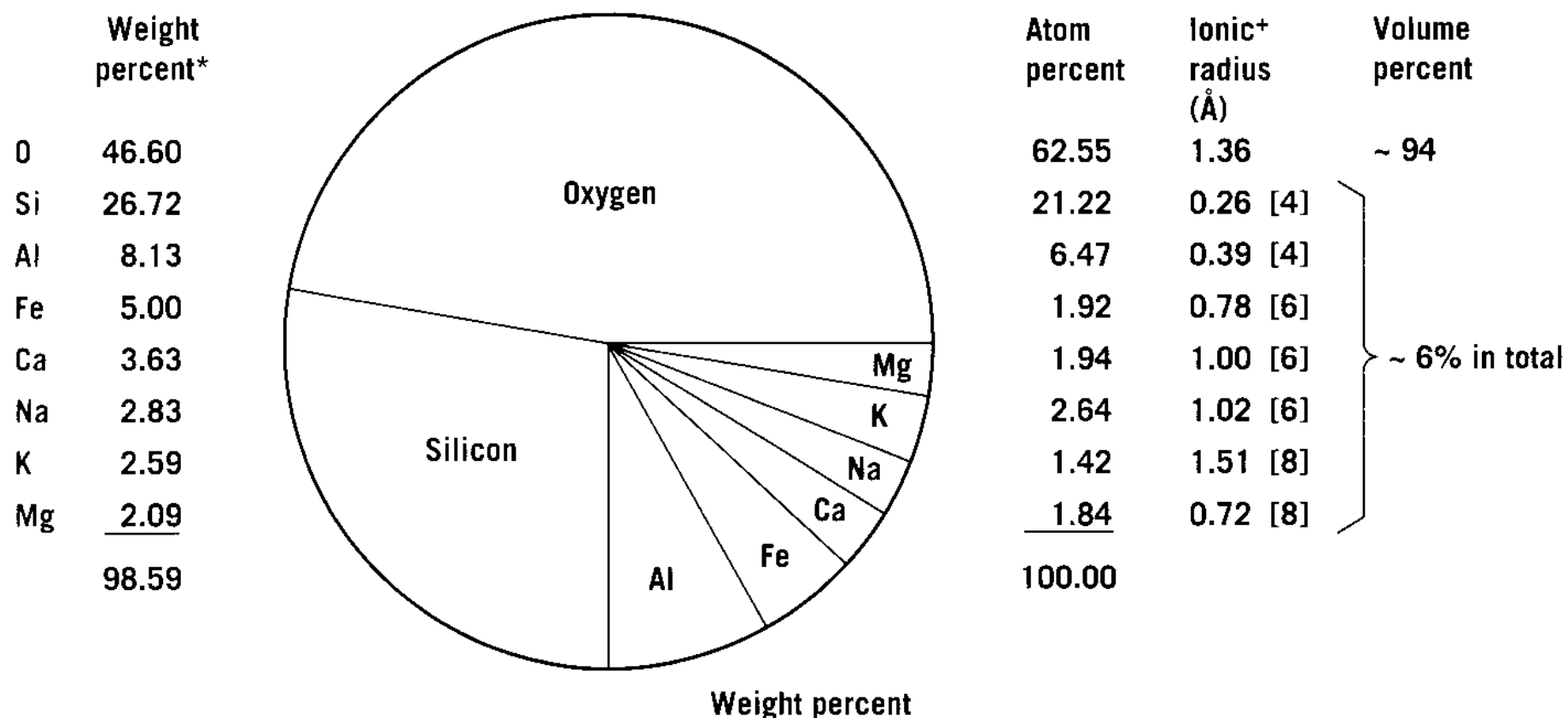


$$(\rho = 4.10 \text{ gm/cm}^3)$$



# Chemical Composition of the Earth

- Average Crust



# Chemical Composition of the Earth

## Major Elements

Major Elements																																					
hydrogen 1 H 1.0079																				helium 2 He 4.0026																	
lithium 3 Li 6.941		beryllium 4 Be 9.0122																		boron 5 B 10.811		carbon 6 C 12.011		nitrogen 7 N 14.007		oxygen 8 O 15.999		fluorine 9 F 18.998		neon 10 Ne 20.180							
sodium 11 Na 22.990		magnesium 12 Mg 24.305																		aluminum 13 Al 26.982		silicon 14 Si 28.086		phosphorus 15 P 30.974		sulfur 16 S 32.065		chlorine 17 Cl 35.453		argon 18 Ar 39.948							
potassium 19 K 39.098		calcium 20 Ca 40.078		scandium 21 Sc 44.956		titanium 22 Ti 47.867		vanadium 23 V 50.942		chromium 24 Cr 51.996		manganese 25 Mn 54.938		iron 26 Fe 55.845		cobalt 27 Co 58.933		nickel 28 Ni 58.693		copper 29 Cu 63.546		zinc 30 Zn 65.39		gallium 31 Ga 69.723		germanium 32 Ge 72.61		arsenic 33 As 74.922		selenium 34 Se 78.96		bromine 35 Br 79.904		krypton 36 Kr 83.80			
rubidium 37 Rb 85.468		strontium 38 Sr 87.62		yttrium 39 Y 88.906		zirconium 40 Zr 91.224		niobium 41 Nb 92.906		molybdenum 42 Mo 95.94		technetium 43 Tc [98]		ruthenium 44 Ru 101.07		rhodium 45 Rh 102.91		palladium 46 Pd 106.42		silver 47 Ag 107.87		cadmium 48 Cd 112.41		indium 49 In 114.82		tin 50 Sn 118.71		antimony 51 Sb 121.76		tellurium 52 Te 127.60		iodine 53 I 126.90		xenon 54 Xe 131.29			
caesium 55 Cs 132.91		barium 56 Ba 137.33		lanthanum 57-70 * 57-70		lutetium 71 Lu 174.97		hafnium 72 Hf 178.49		tantalum 73 Ta 180.95		tungsten 74 W 183.84		rhenium 75 Re 186.21		osmium 76 Os 190.23		iridium 77 Ir 192.22		platinum 78 Pt 195.08		gold 79 Au 196.97		mercury 80 Hg 200.59		thallium 81 Tl 204.38		lead 82 Pb 207.2		bismuth 83 Bi 208.98		polonium 84 Po [209]		astatine 85 At [210]		radon 86 Rn [222]	
francium 87 Fr [223]		radium 88 Ra [226]		actinium 89-102 * 89-102		lawrencium 103 Lr [262]		rutherfordium 104 Rf [261]		dubnium 105 Db [262]		seaborgium 106 Sg [266]		bohrium 107 Bh [264]		hassium 108 Hs [269]		meitnerium 109 Mt [268]		unnilium 110 Uun [271]		ununium 111 Uuu [272]		unbibium 112 Uub [277]		unbiquadium 114 Uuq [289]											

\* Lanthanide series

\*\* Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	euroium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]



Major elements >1 wt%

– O, Si, Al, Fe, Ca, Na, K, Mg

# Chemical Composition of the Earth

## Major Elements

hydrogen 1 H 1.008																		helium 2 He 4.0026																			
lithium 3 Li 6.941		beryllium 4 Be 9.0122																boron 5 B 10.811		carbon 6 C 12.011		nitrogen 7 N 14.007		oxygen 8 O 15.999		fluorine 9 F 18.998		neon 10 Ne 20.180									
sodium 11 Na 22.990		magnesium 12 Mg 24.305																aluminum 13 Al 26.982		silicon 14 Si 28.086		phosphorus 15 P 30.974		sulfur 16 S 32.065		chlorine 17 Cl 35.453		argon 18 Ar 39.948									
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rubidium 37 Rb 85.468		strontium 38 Sr 87.62		yttrium 39 Y 88.906		zirconium 40 Zr 91.224		niobium 41 Nb 92.906		molybdenum 42 Mo 95.94		technetium 43 Tc [98]		ruthenium 44 Ru 101.07		rhodium 45 Rh 102.91		palladium 46 Pd 106.42		silver 47 Ag 107.87		cadmium 48 Cd 112.41		indium 49 In 114.82		tin 50 Sn 118.71		antimony 51 Sb 121.76		tellurium 52 Te 127.60		iodine 53 I 126.90		xenon 54 Xe 131.29			
caesium 55 Cs 132.91		barium 56 Ba 137.33		lanthanum 57-70 * *		lutetium 71 Lu 174.97		hafnium 72 Hf 178.49		tantalum 73 Ta 180.95		tungsten 74 W 183.84		rhenium 75 Re 186.21		osmium 76 Os 190.23		iridium 77 Ir 192.22		platinum 78 Pt 195.08		gold 79 Au 196.97		mercury 80 Hg 200.59		thallium 81 Tl 204.38		lead 82 Pb 207.2		bismuth 83 Bi 208.98		polonium 84 Po [209]		astatine 85 At [210]		radon 86 Rn [222]	
francium 87 Fr [223]		radium 88 Ra [226]		actinium 89-102 * * * *		lawrencium 103 Lr [262]		rutherfordium 104 Rf [261]		dubnium 105 Db [262]		seaborgium 106 Sg [266]		bohrium 107 Bh [264]		hassium 108 Hs [269]		meitnerium 109 Mt [268]		darmstadtium 110 Ds [271]		roentgenium 111 Rh [272]		copernicium 112 Cn [277]		nihonium 113 Nh [284]		flerkovium 114 Fl [289]		tennessine 115 Ts [294]		oganeson 116 Og [294]					

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- Minor elements 0.1-1 wt.%: Ti, Mn, P
- typically includes volatile elements too



# Chemical Composition of the Earth

## Trace Elements

<h1>Trace Elements</h1>																										helium 2 He 4.0026									
hydrogen 1 H 1.0079		beryllium 4 Be 9.0122																boron 5 B 10.811		carbon 6 C 12.011		nitrogen 7 N 14.007		oxygen 8 O 15.999		fluorine 9 F 18.998		neon 10 Ne 20.180							
lithium 3 Li 6.941		magnesium 12 Mg 24.305																aluminum 13 Al 26.982		silicon 14 Si 28.086		phosphorus 15 P 30.974		sulfur 16 S 32.065		chlorine 17 Cl 35.453		argon 18 Ar 39.948							
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unbinilium 110 Uub [271]		unbinilium 111 Uuu [272]		unbinilium 112 Uub [273]		unbinilium 113 Uub [274]		unbinilium 114 Uub [275]		unbinilium 115 Uub [276]		unbinilium 116 Uub [277]		unbinilium 117 Uub [278]		unbinilium 118 Uub [279]		unbinilium 119 Uub [280]		unbinilium 120 Uub [281]		unbinilium 121 Uub [282]		unbinilium 122 Uub [283]		unbinilium 123 Uub [284]		unbinilium 124 Uub [285]		unbinilium 125 Uub [286]		unbinilium 126 Uub [287]			

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The rest--- Trace elements (<0.1wt.%)  
 reported in ppm or parts per million: 0.01 to 100,000 ppm  
 ppm → wt. %      ppm\*10,000= wt. %

# Mineral Formulas

- Multi-Step Process:
  1. Write out cations, followed by anions or anionic groups
  2. Make sure the charge is balanced
  3. Group cations by structural site (coordination!)
- Ex: diopside:  $\text{CaMgSi}_2\text{O}_6$ 
  1.  $\text{Ca}^{+2}\text{Mg}^{+2}\text{Si}_2^{+4}\text{O}_6^{-2}$  ✓
  2.  $2 + 2 + (4*2) + (-2*6) = 0$  ✓
  3.  $^{\text{VIII}}\text{Ca}^{\text{VI}}(\text{Mg,Fe})^{\text{IV}}\text{Si}_2\text{O}_6$  ✓

# Converting from Analysis

- Multi-Step Process:
  - Chemical data usually reported in wt.% oxide
    - wt. % from early chemical analyses by wet chemistry titrations
    - Modern equipment measures atomic proportions, but calibrates to wt. %
  - Must covert wt. % to molecular (or “atomic”)%
  - Simplify to relate to a chemical formula, typically normalize to a set number of “oxygens”



# Converting from Analysis

- Multi-Step Process:
  1. Calculate moles of oxide = wt.% / molecular wt.
  2. " moles of oxygen = moles oxide\*oxygen stoichiometry
  3. " moles of cation = moles oxide\*cation stoichiometry
  4. Recalculate based on a set number of oxygen (or anions)
    - a. Choose a desired amount of oxygen
    - b. Divide amount of oxygen by the sum moles oxygen
    - c. Multiply this factor by each cation value
  5. Identify structural site for each cation

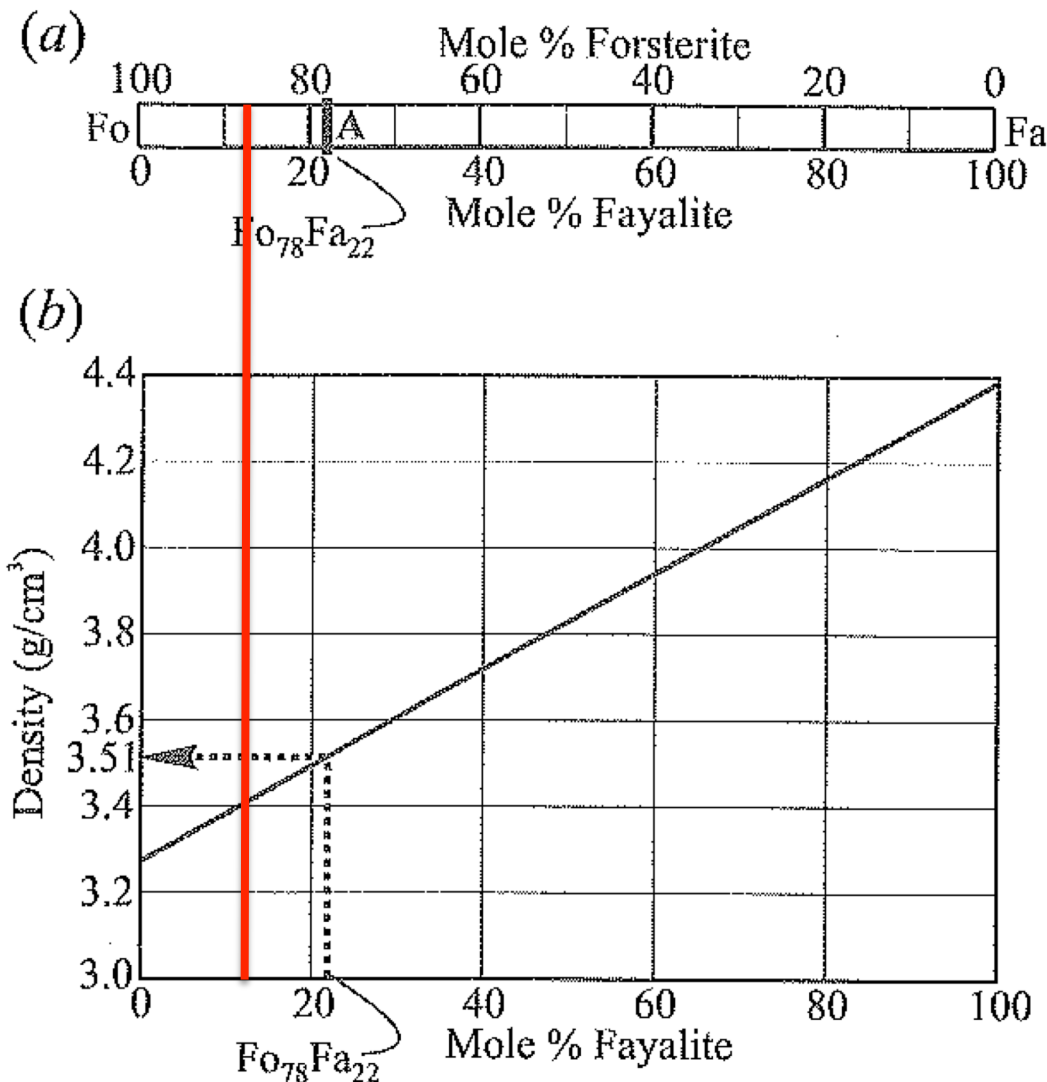
# Converting from Analysis

			1	2	3	4	5	
	wt. %	molecular wt. (x/mol)	Moles Oxide	Moles Oxygen	Cation Moles	normalized to Oxygen	Site	
SiO <sub>2</sub>	<b>39.80</b>	60.08	0.6625	1.325	0.6625	0.996	tet	
Al <sub>2</sub> O <sub>3</sub>	0.05							
K <sub>2</sub> O	-0.01							
MnO	0.20							
				0.16763				
FeO	<b>12.04</b>	71.85	0.1676	1176	0.1676	0.2521	oct	<b>Fo content</b>
NiO	0.40							<b>0.874</b>
Na <sub>2</sub> O	-0.02							
					1.1671			
MgO	<b>47.04</b>	40.30	1.167	1.167	66253	1.755	oct	
CaO	0.32							
TiO <sub>2</sub>	0.03							
Cr <sub>2</sub> O <sub>3</sub>	0.07							
Total	99.95			2.660			4 Oxygen Desired	

1.504 =cation mult. Factor

# Plotting Compositions

Our olivine was **Fo<sub>87</sub>**, so we can plot as 87% forsterite



We can use this to understand useful physical properties of the mineral, like density (right) and as we will see later, temperature!

**Fo<sub>87</sub> will have a density = 3.4 g/cm<sup>3</sup>**

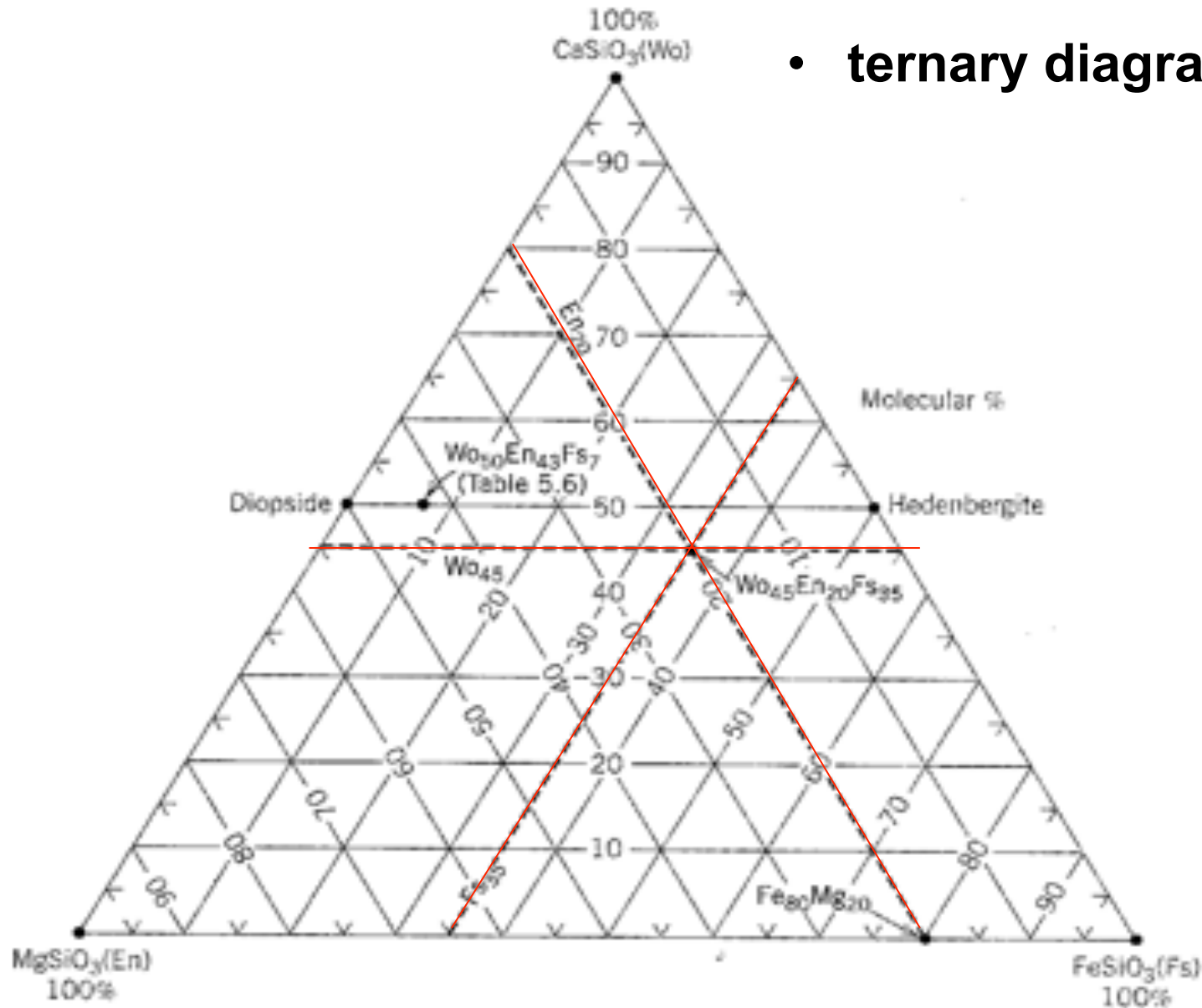


# Plotting Compositions

- If you have more than two variable elements, a **ternary diagram** can be useful!
  - *Pyroxenes*
  - Feldspars
  - Garnets (\*2!)
- What if you have more than 3 variables?
  - Can plot a 3<sup>rd</sup> dimension, ex: Spinel Prism

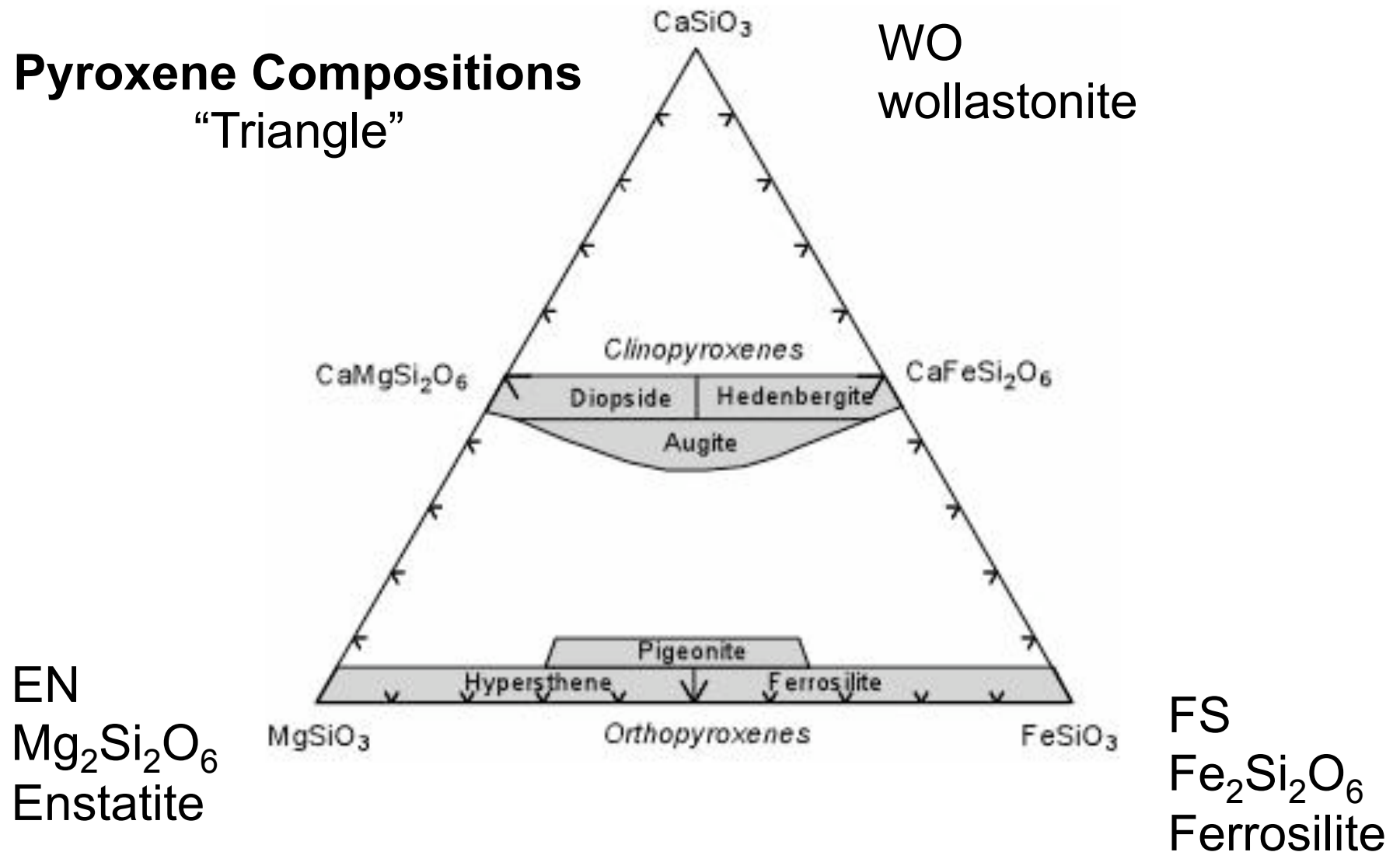
# Plotting Compositions

- ternary diagram *Pyroxenes*



# Classification Diagrams

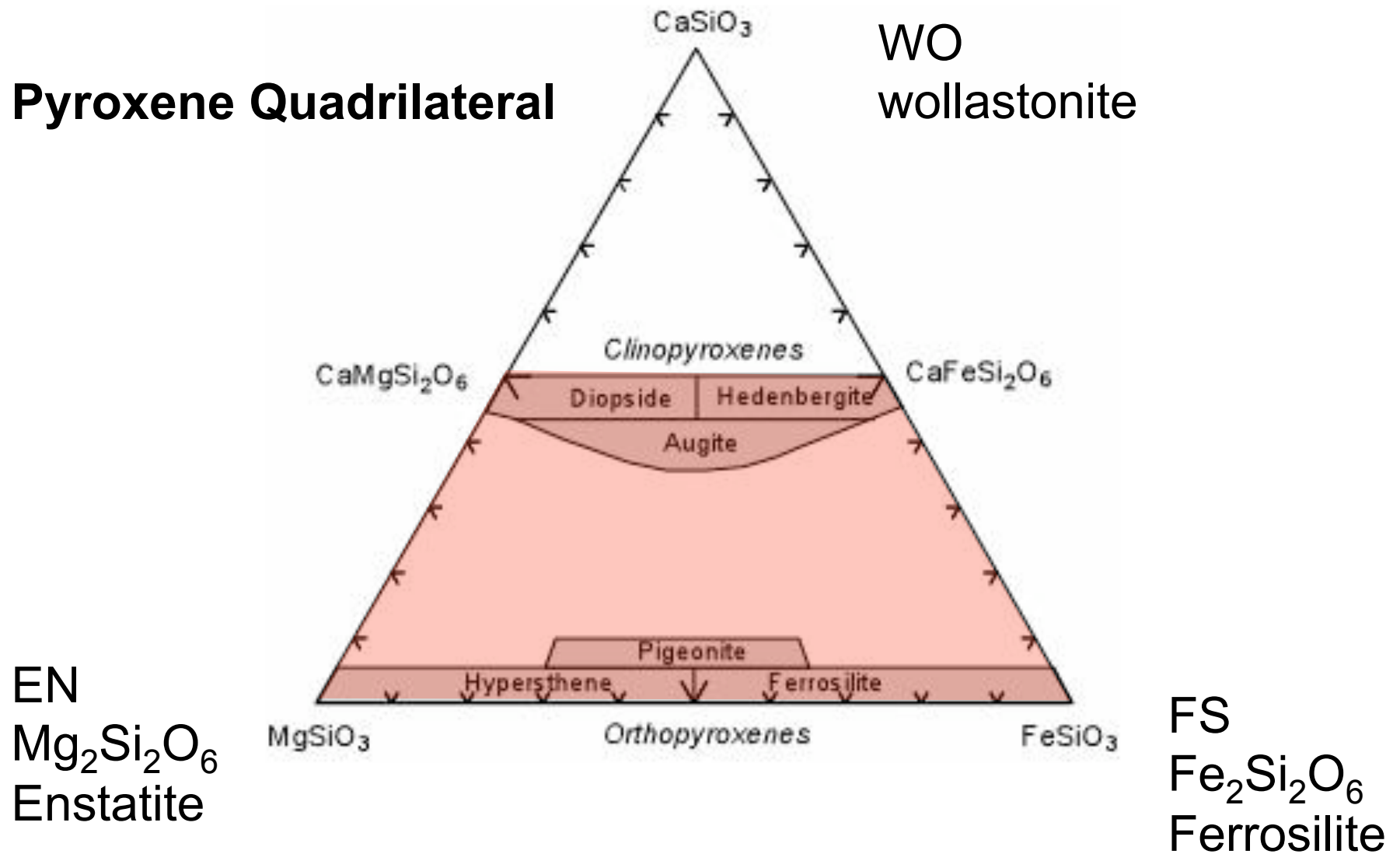
## Pyroxene Compositions “Triangle”





# Classification Diagrams

## Pyroxene Quadrilateral



# Plotting Compositions

- If you have more than two variable elements, a **ternary diagram** can be useful!
  - *Pyroxenes*
  - Feldspars
  - Garnets (\*2!)
- What if you have more than 3 variables?
  - Can plot a 3<sup>rd</sup> dimension, ex: Spinel Prism

***Before we examine these, let's think about solid solution more!***

# Solid Solution

- 3 Basic Types Solid Solution:
  1. **Substitution (Simple or Coupled)**
  2. **Omission**
  3. **Interstitial**
- Continuous (all proportions of elements can substitute)
- Discontinuous/Partial (restricted range of compositions)

# Solid Solution

## 1. Substitution Solid Solution

- Similar elements can substitute into a structural vacancy following **Goldschmidt's Rules**:
  - Similar size (+/- 15%)
  - Electric neutrality is maintained (net charge of substitution equal)
  - Similar electronegativity (bond type)
- Other Factors include:
  - Availability of Ions
  - **Temperature and pressure** effects on mineral structure

# Solid Solution

## 1a. Simple Substitution

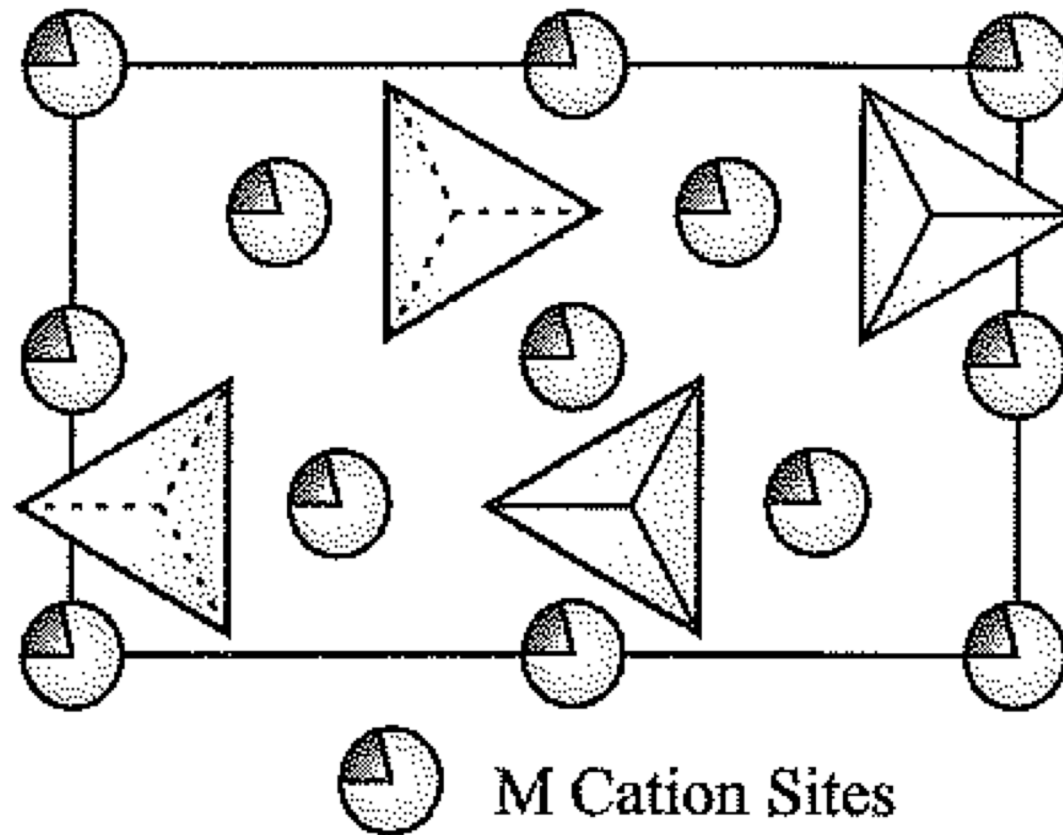
- Remember Pauling's First rule: coordination of structural sites dependent on Radius Ratio
- If **size difference <15%**, generally can accommodate substitution!
- Must be same charge!
- Increases in Temperature loosen structure, allowing larger size difference!\*\*

\*\*decrease in temperature may cause *exsolution*

- Ex: **olivine** Fe-Mg; **pyroxenes** Fe-Mg, (Mg,Fe)-Ca;  
**alkali feldspar** Na-K

# Solid Solution

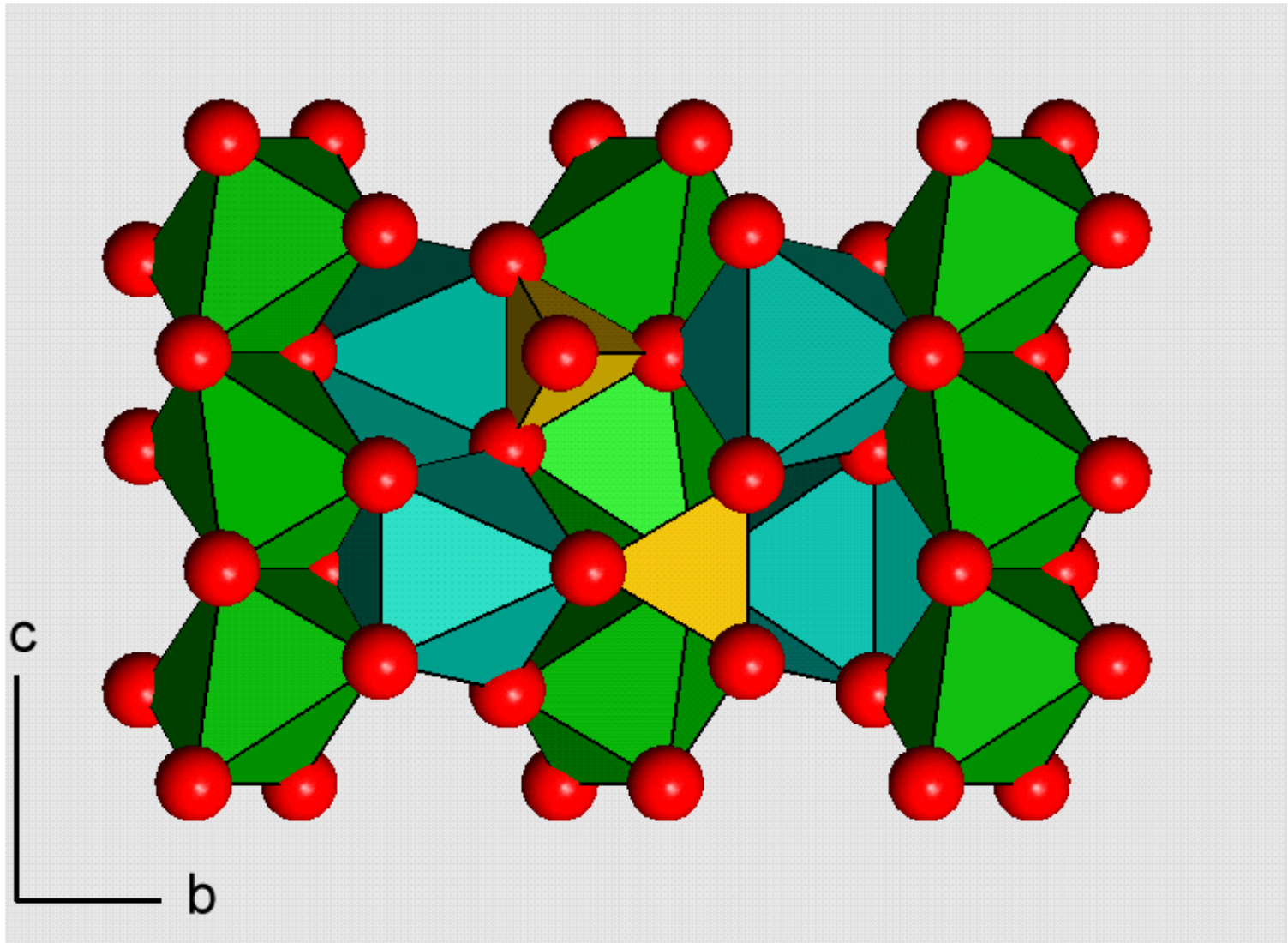
## Olivine solid soln\*





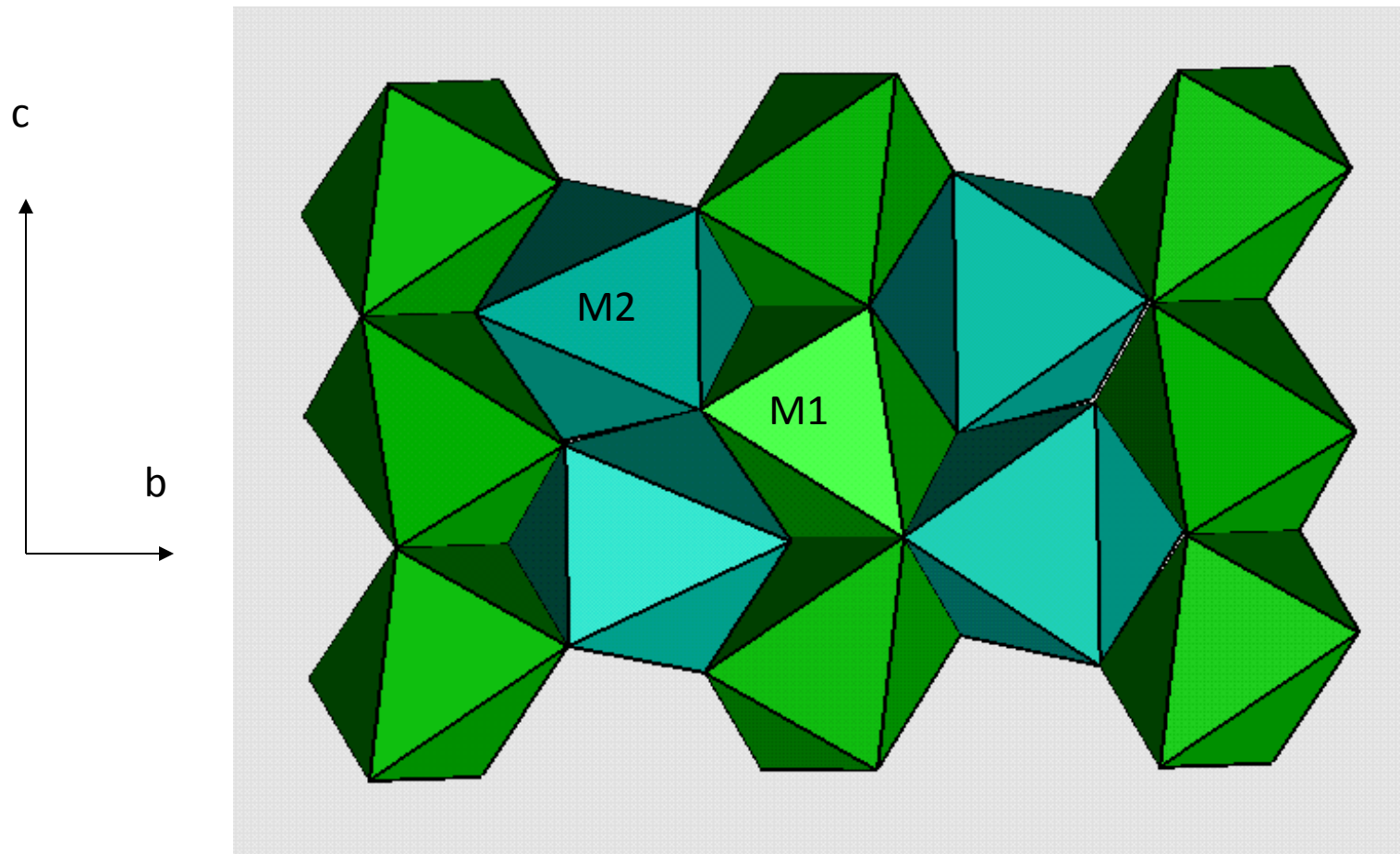
# Solid Solution

## Olivine solid soln



# Solid Solution

*note deformed octahedra= edge sharing!*



Two  
octahedral  
cation ( $\text{Mg}^{2+}$ ,  
 $\text{Fe}^{2+}$ ) sites:

M1  
M2

# Solid Solution

***Compare cation sites, where does Mg and Fe go?***

M1

Distorted 6-coordination

$\langle \text{M-O} \rangle = 2.16 \text{ \AA}$

Smaller site

M2

More Distorted 6-coordination

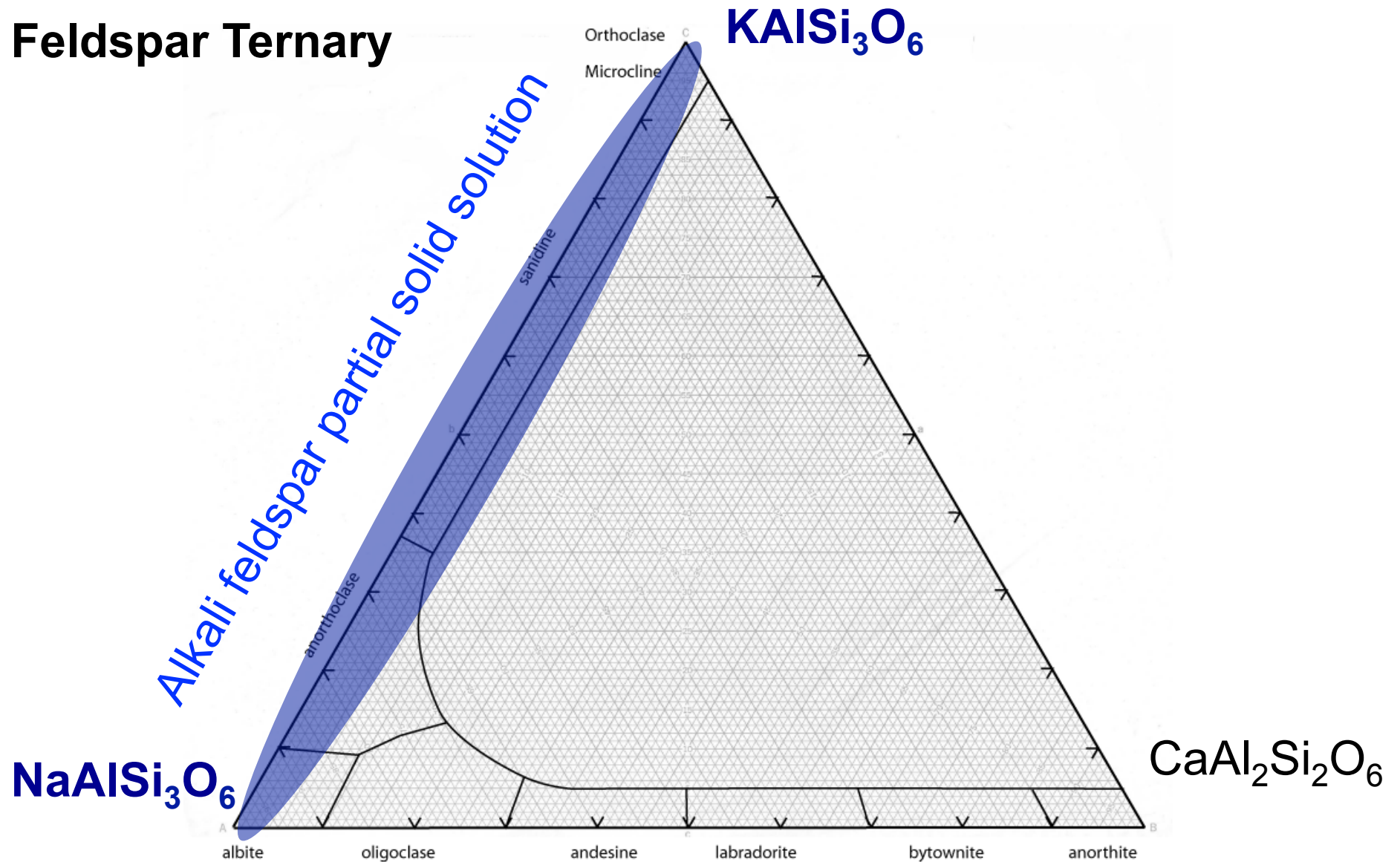
$\langle \text{M-O} \rangle = 2.19 \text{ \AA}$

Larger site

(recall:  $\text{Mg}^{2+}$  is smaller than  $\text{Fe}^{2+}$ )

# Solid Solution

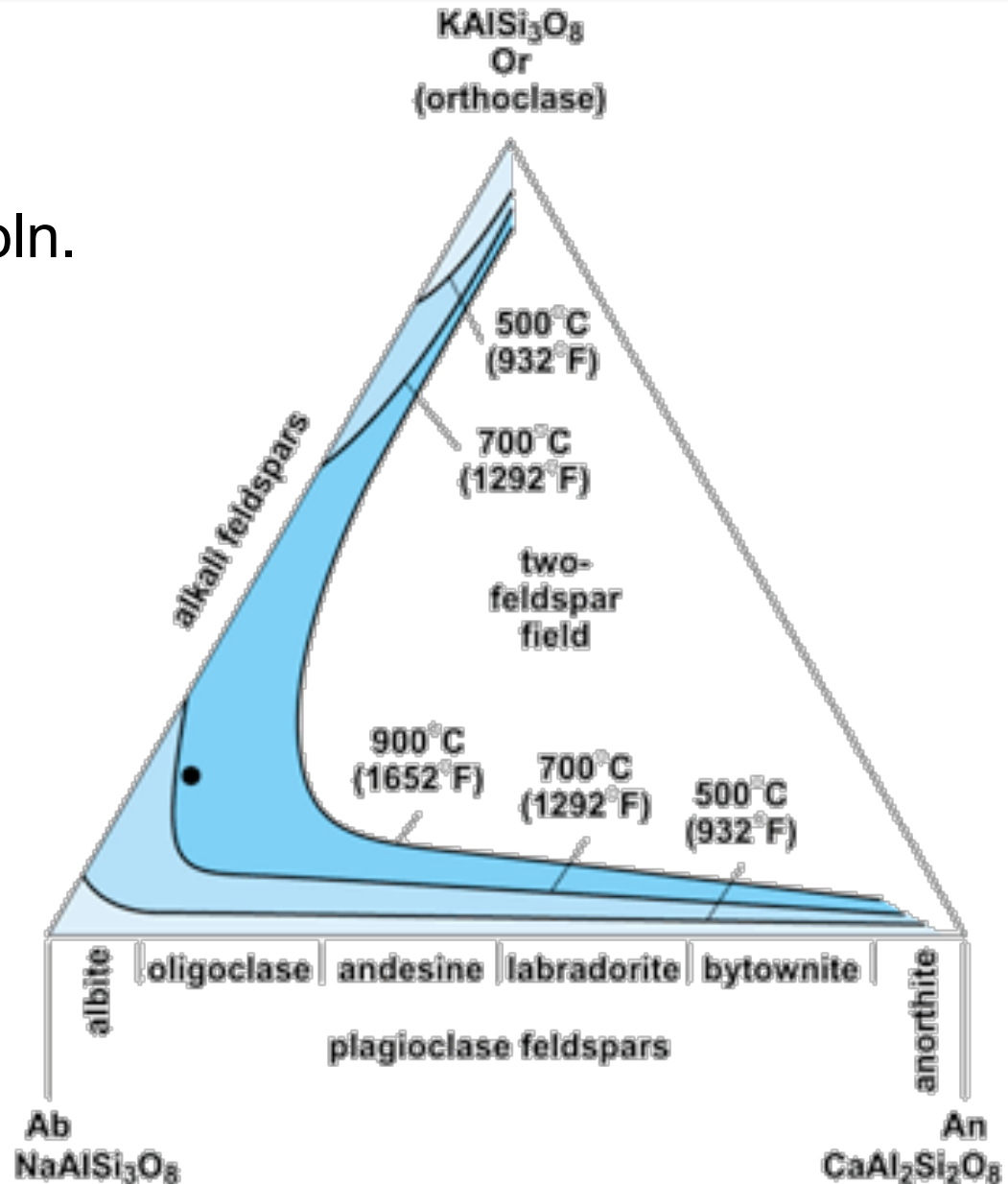
## Feldspar Ternary



# Solid Solution

## Feldspar Ternary

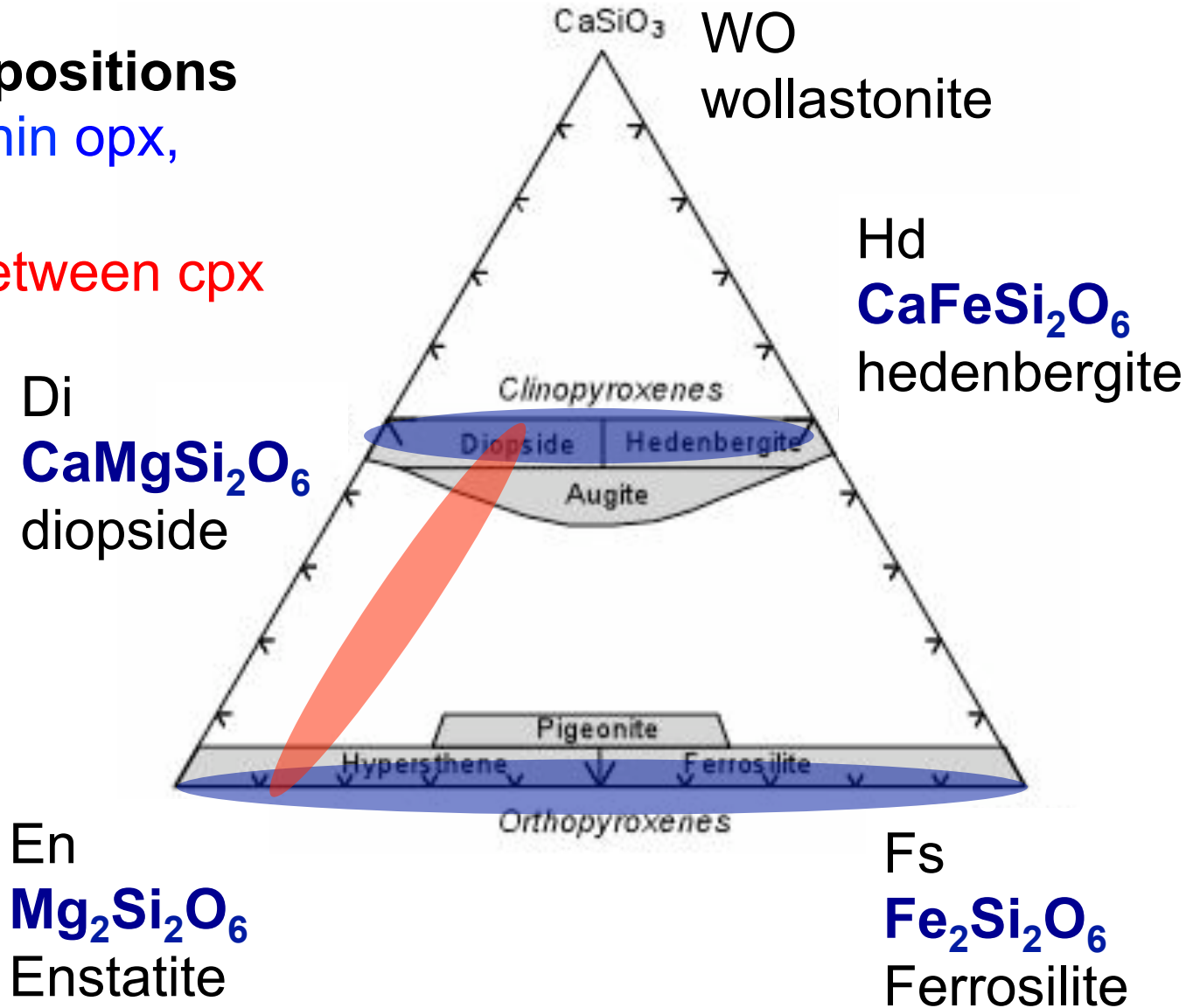
High T expands solid soln. of alkali fspars!



# Solid Solution

## Pyroxene Compositions

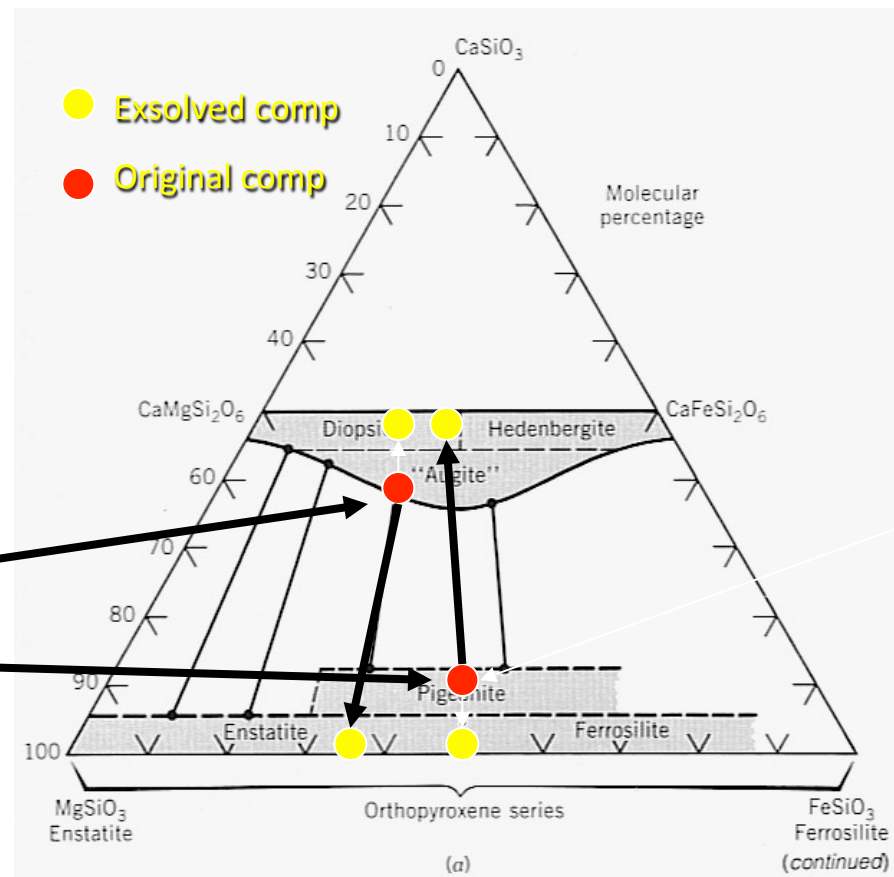
- Complete within opx, some cpx
- Incomplete between cpx and opx





# Solid Solution

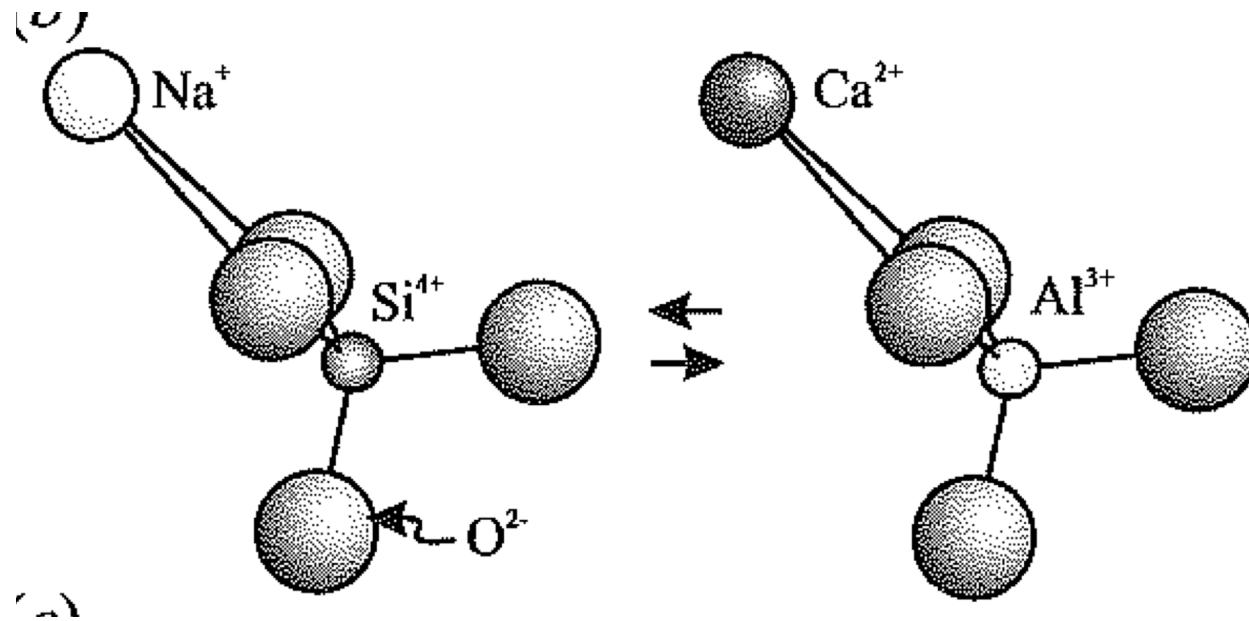
## Pyroxene exsolution (opx and cpx)



# Solid Solution

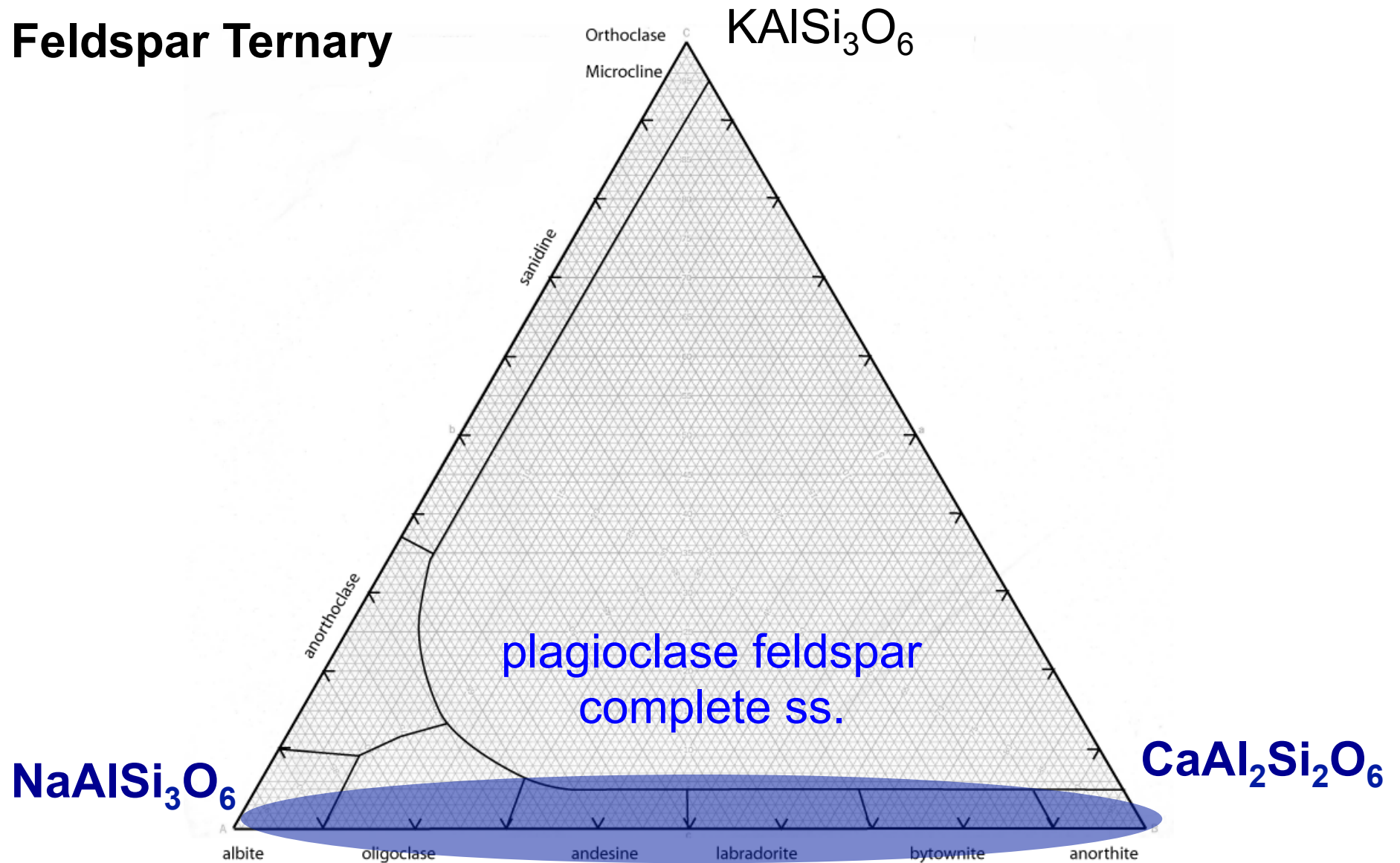
## 1b. Coupled Substitution

- Similar size, but *different charge*
- Elements pair up in exchange to maintain neutral charge
- Example: Albite-Anorthite



# Solid Solution

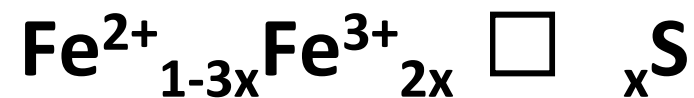
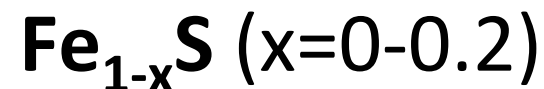
## Feldspar Ternary



# Solid Solution

## 2. Omission Solid Solution

- Charge balance maintained by leaving a structural site unfilled
- Ex: pyrrhotite

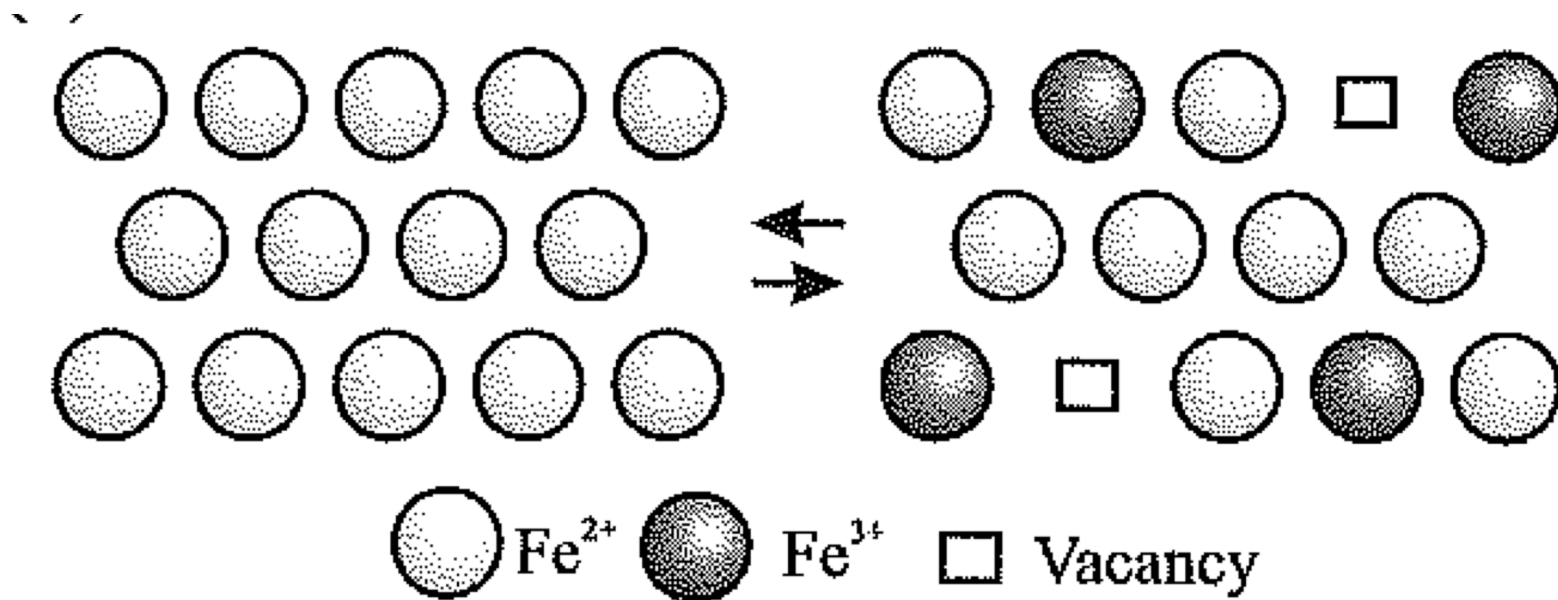
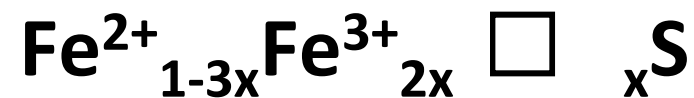
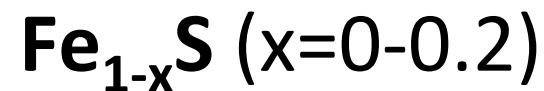


- Vacant sites ( $\square$ ) are occasionally filled with  $\text{Fe}^{3+}$  to balance charge

# Solid Solution

## 2. Omission Solid Solution

- Ex: pyrrhotite



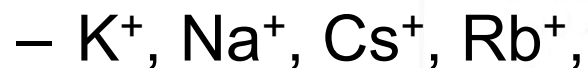


# Solid Solution

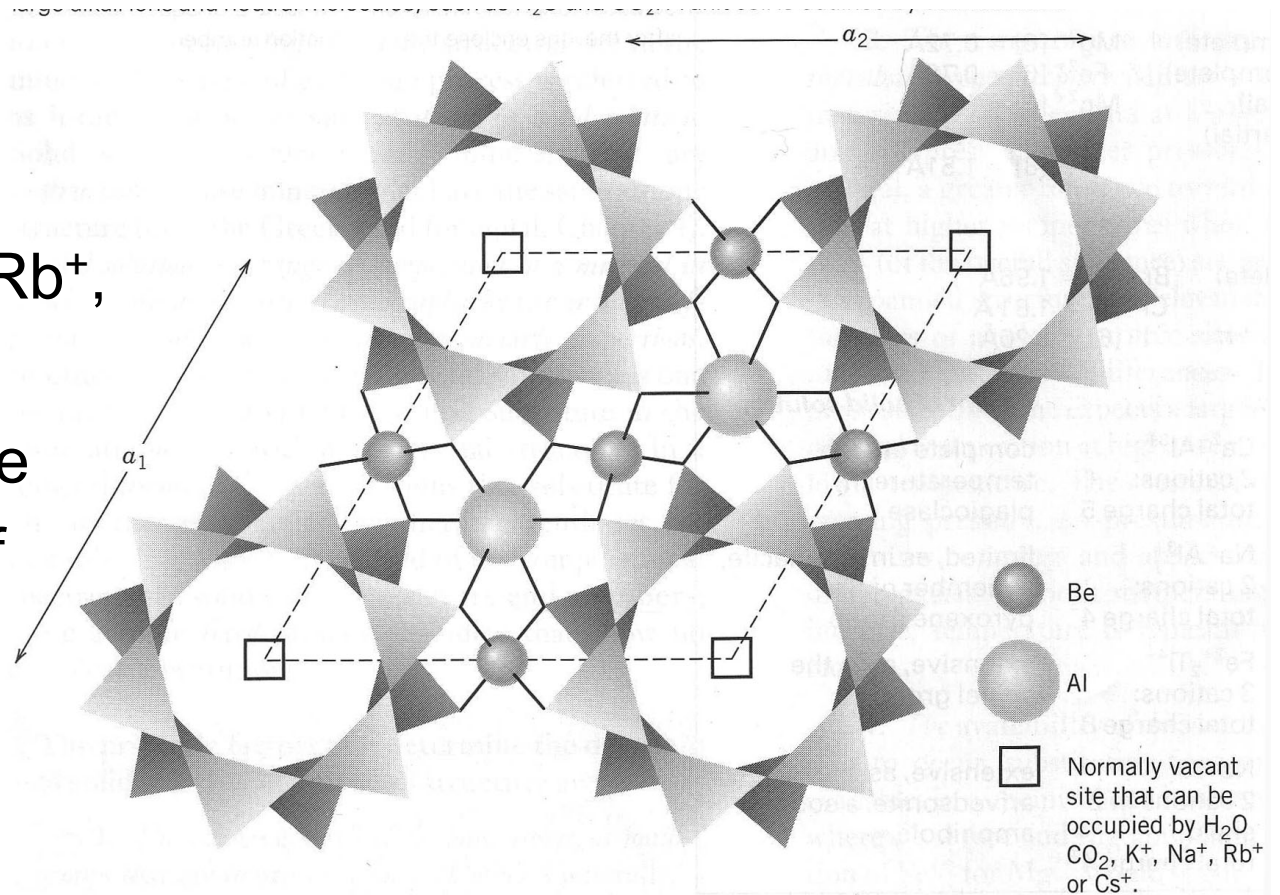
## 3. Interstitial Solid Solution

- Charge balance maintained by filling a normally unfilled structural site

- Ex: beryl



can substitute  
into center of  
sorosilicate  
ring

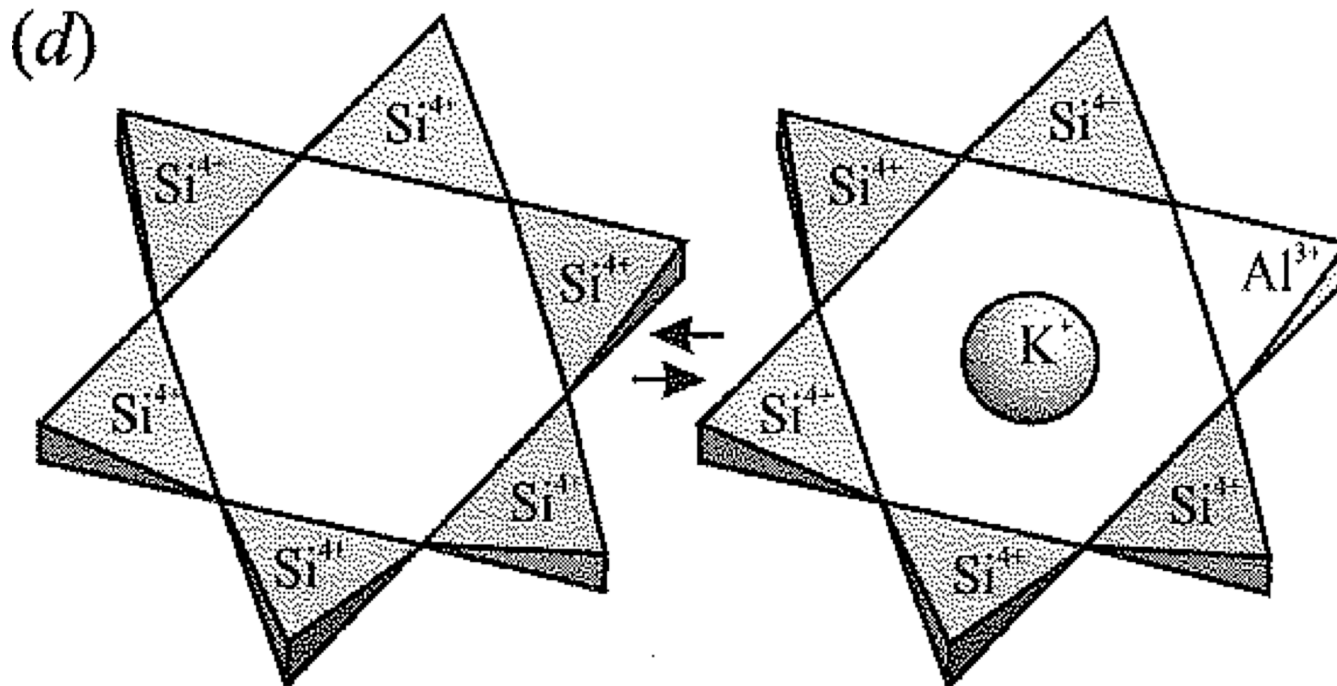




# Solid Solution

## 3. Interstitial Solid Solution

- Ex: beryl
  - $\text{Al}_2\text{Be}_3\text{Si}_6\text{O}_{18}$
  - $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Cs}^+$ ,  $\text{Rb}^+$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}_2$

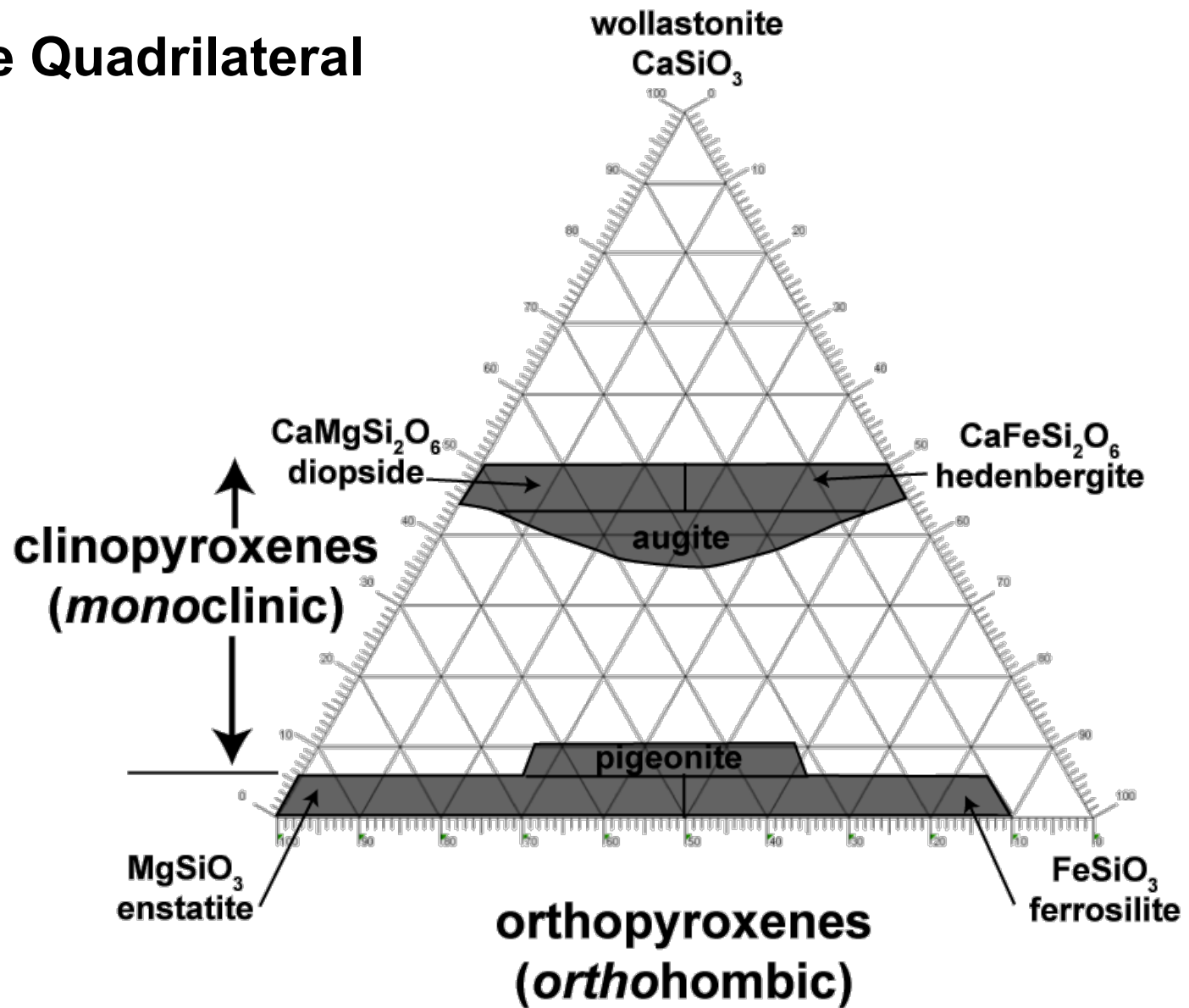


# Classification Diagrams

- If you have more than two variable elements, a **ternary diagram** can be useful!
  - Pyroxenes
  - Feldspars
  - Garnets (\*2!)
- What if you have more than 3 variables?
  - Can plot a 3<sup>rd</sup> dimension, ex: Spinel Prism

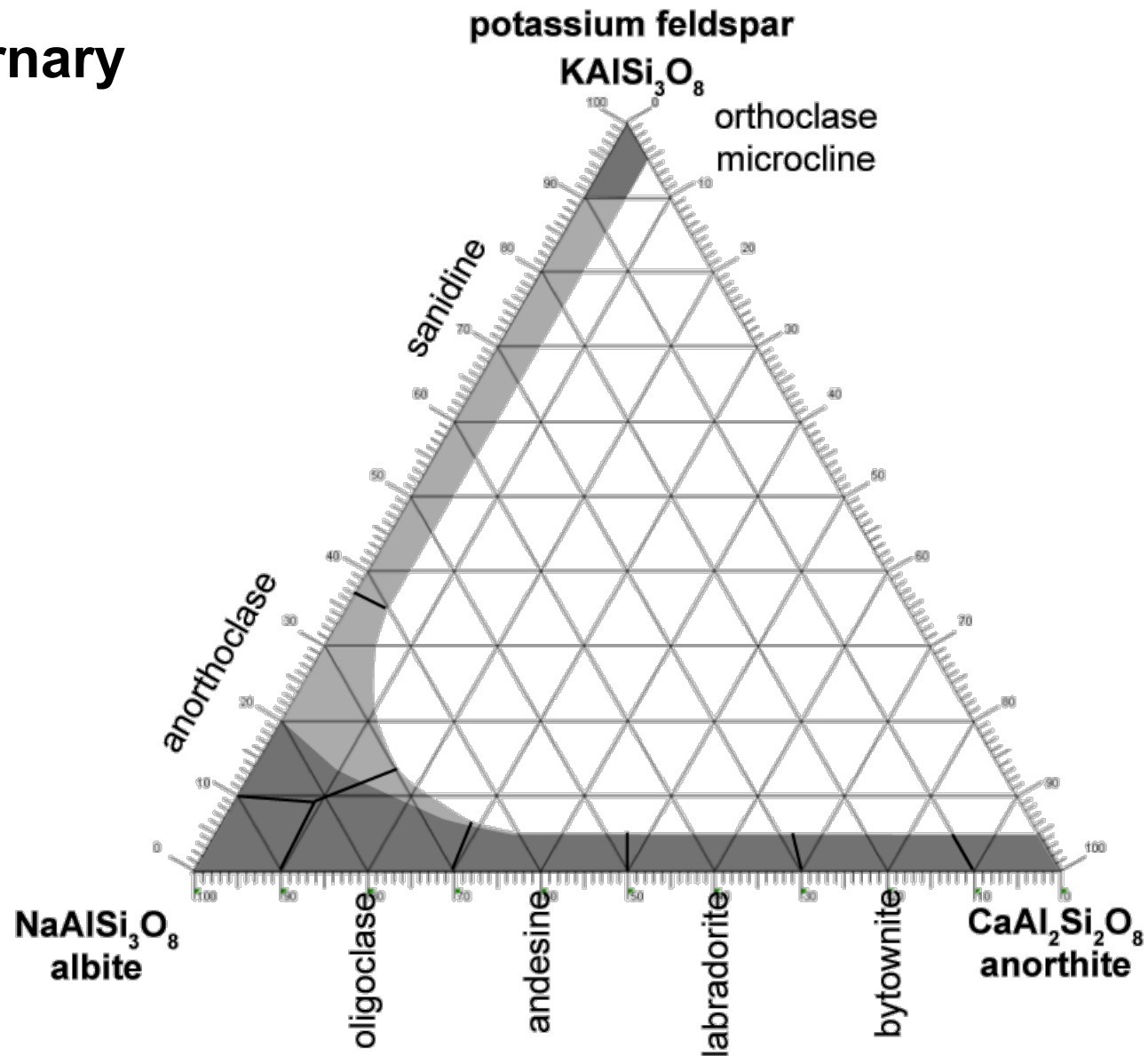
# Classification Diagrams

## Pyroxene Quadrilateral



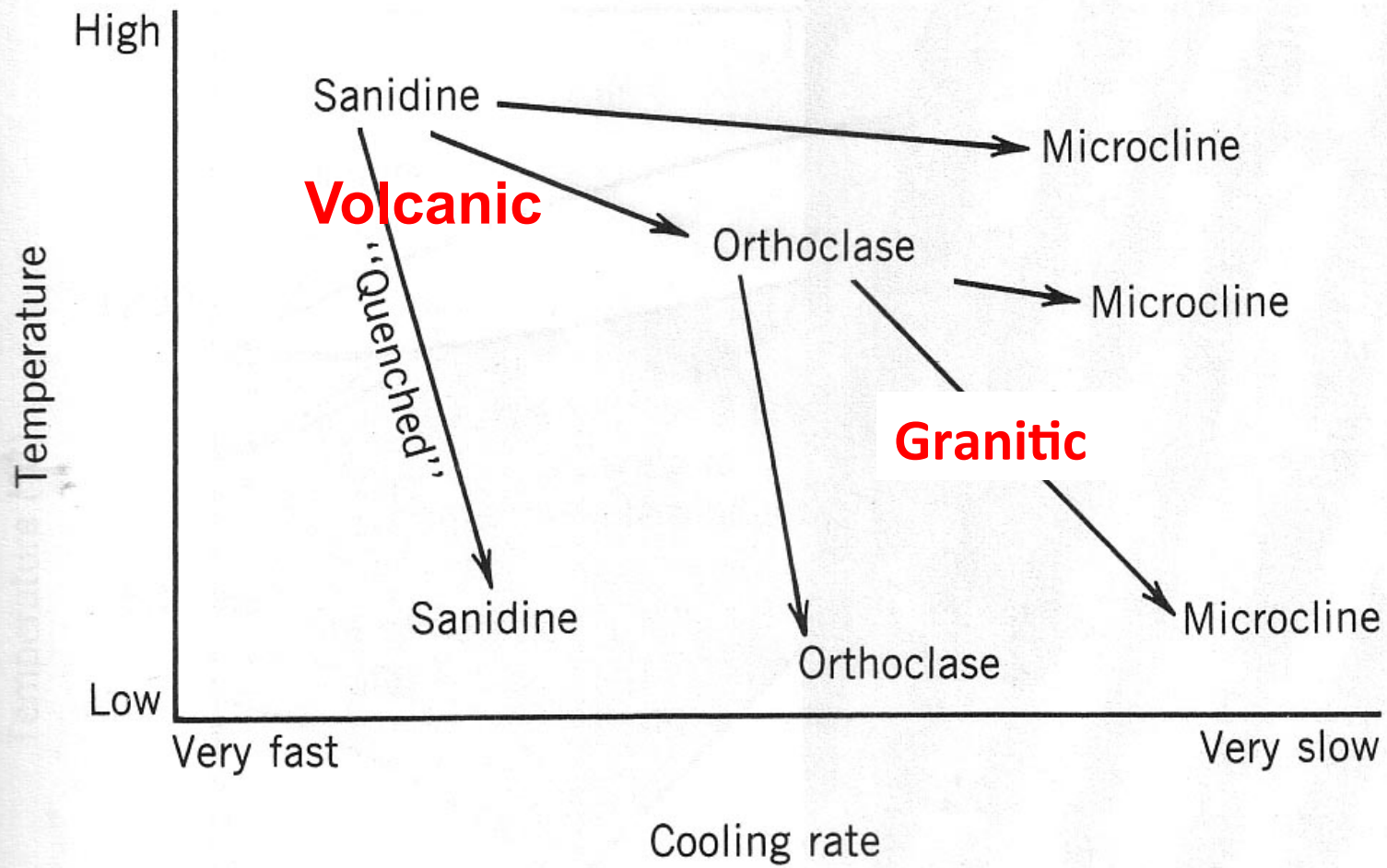
# Classification Diagrams

## Feldspar Ternary



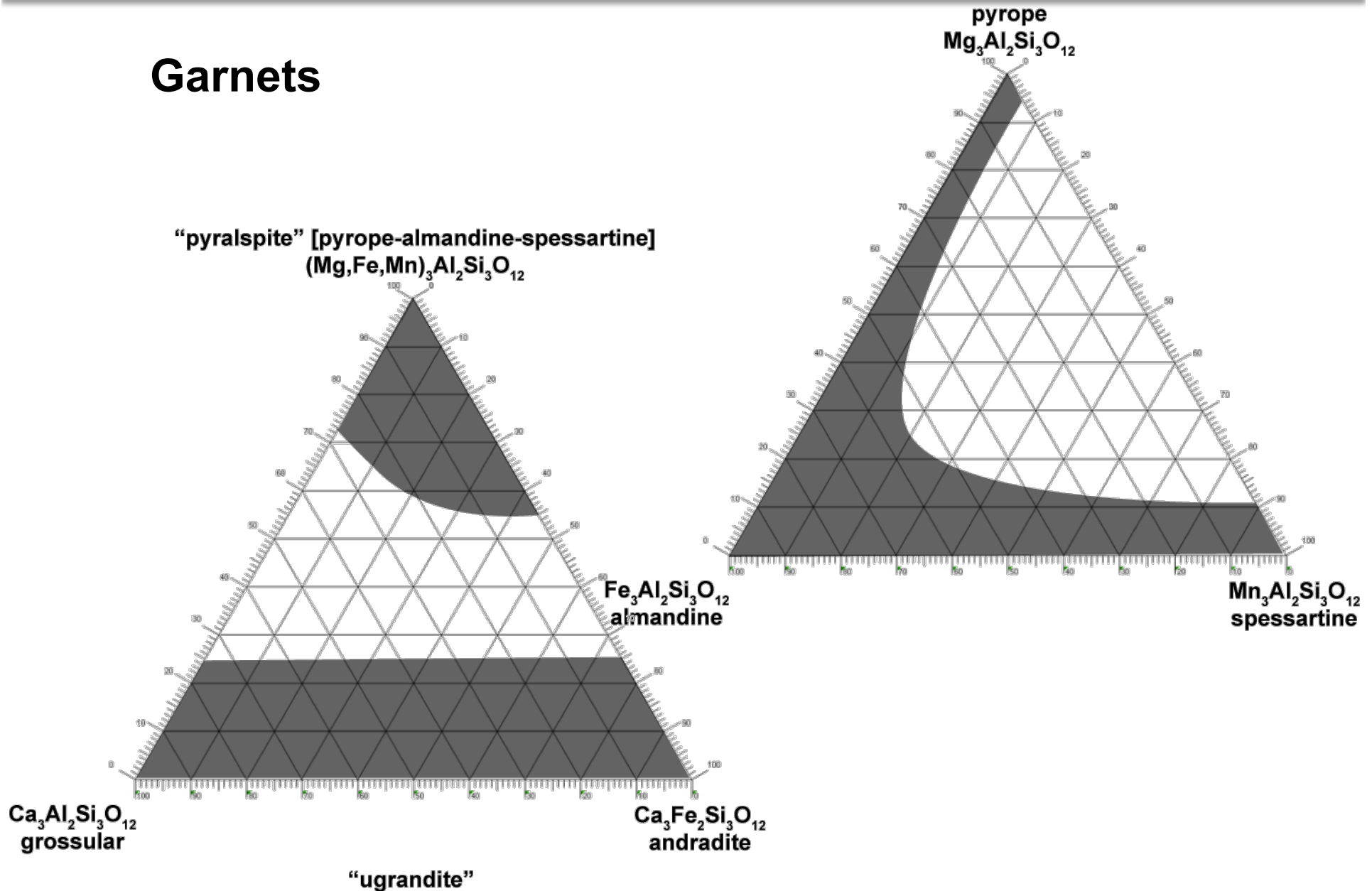
# Classification Diagrams

## Potassium Feldspars



# Classification Diagrams

## Garnets

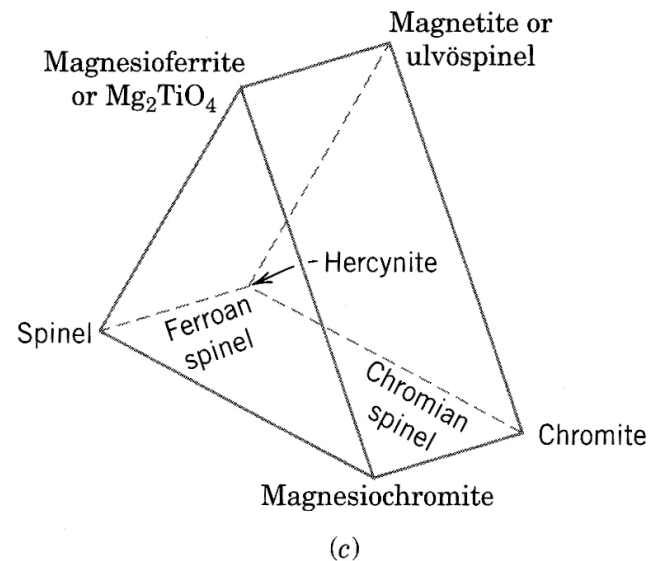
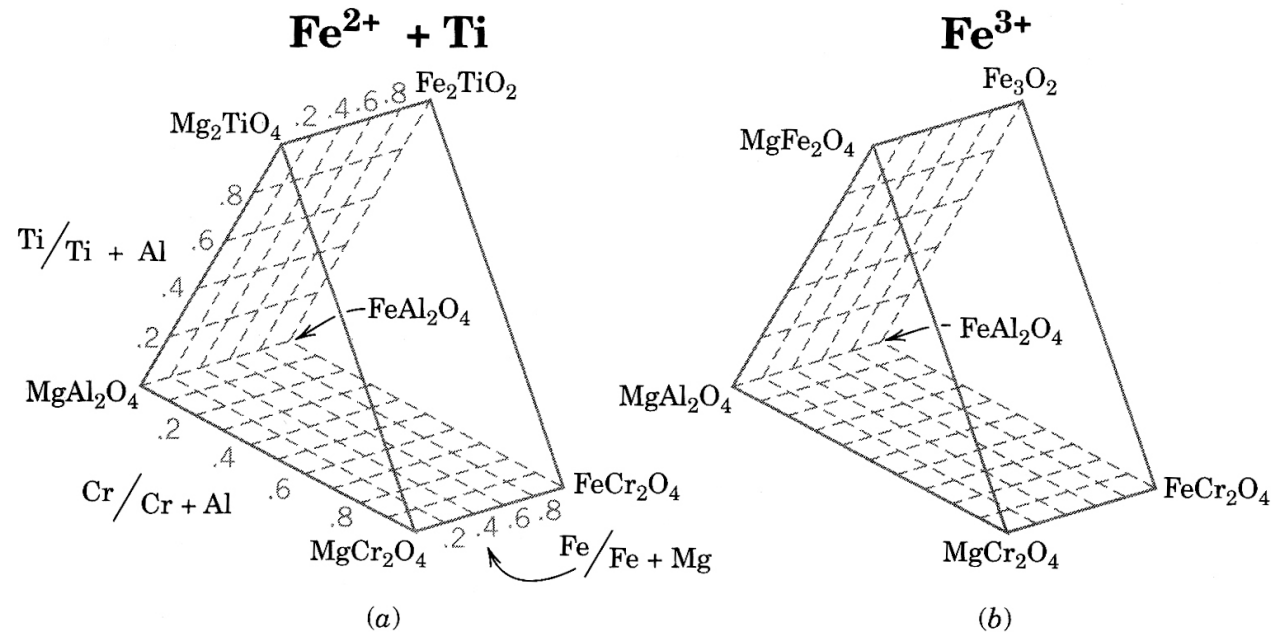




# Classification Diagrams

Spinel  
Prism

YIKES!



# Plotting Compositions

- **Classification Diagrams:**
  - Know pyroxene quadrilateral (p. 259)
  - Know feldspar ternary diagram (p. 471) and differences between Kspar types (p. 474)
  - Know the two garnet ternary diagrams (p. 490)
  - Know spinel prism (p. 384)
- Phase Diagrams (next week)
  - Know calcite-aragonite stability diagram (p. 402)
  - Know SiO<sub>2</sub> phase diagram (p. 470)
  - Know the olivine (Fo-Fa) phase diagram (p. 485)
  - Know plagioclase (Ab-An) phase diagram (p. 253)
  - Know kyanite-andalusite-sillimanite phase diagram (p. 491)