Earth and Planetary Sciences (ES1101)

(Minerals: Building Blocks of Rocks)
(Autumn 2021 by Gaurav Shukla)

Book: **1) Understanding Earth by Grotzinger & Jordan (Text Book)**
2) Earth: An introduction to Physical Geology by Tarbuck & Lutgens
3) The Solid Earth: An introduction to global geophysics by Fowler

Structure of Minerals

Most abundant elements in the crust

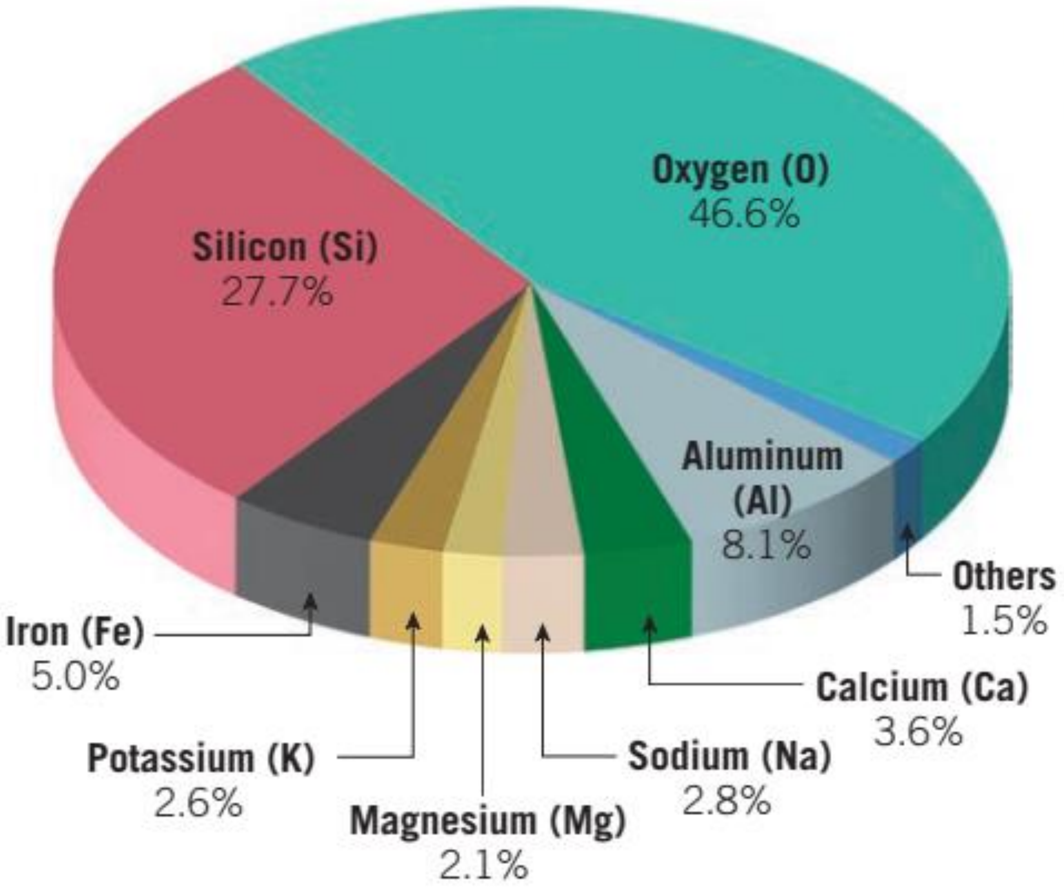


Figure 3.30
The eight most abundant elements in the continental crust

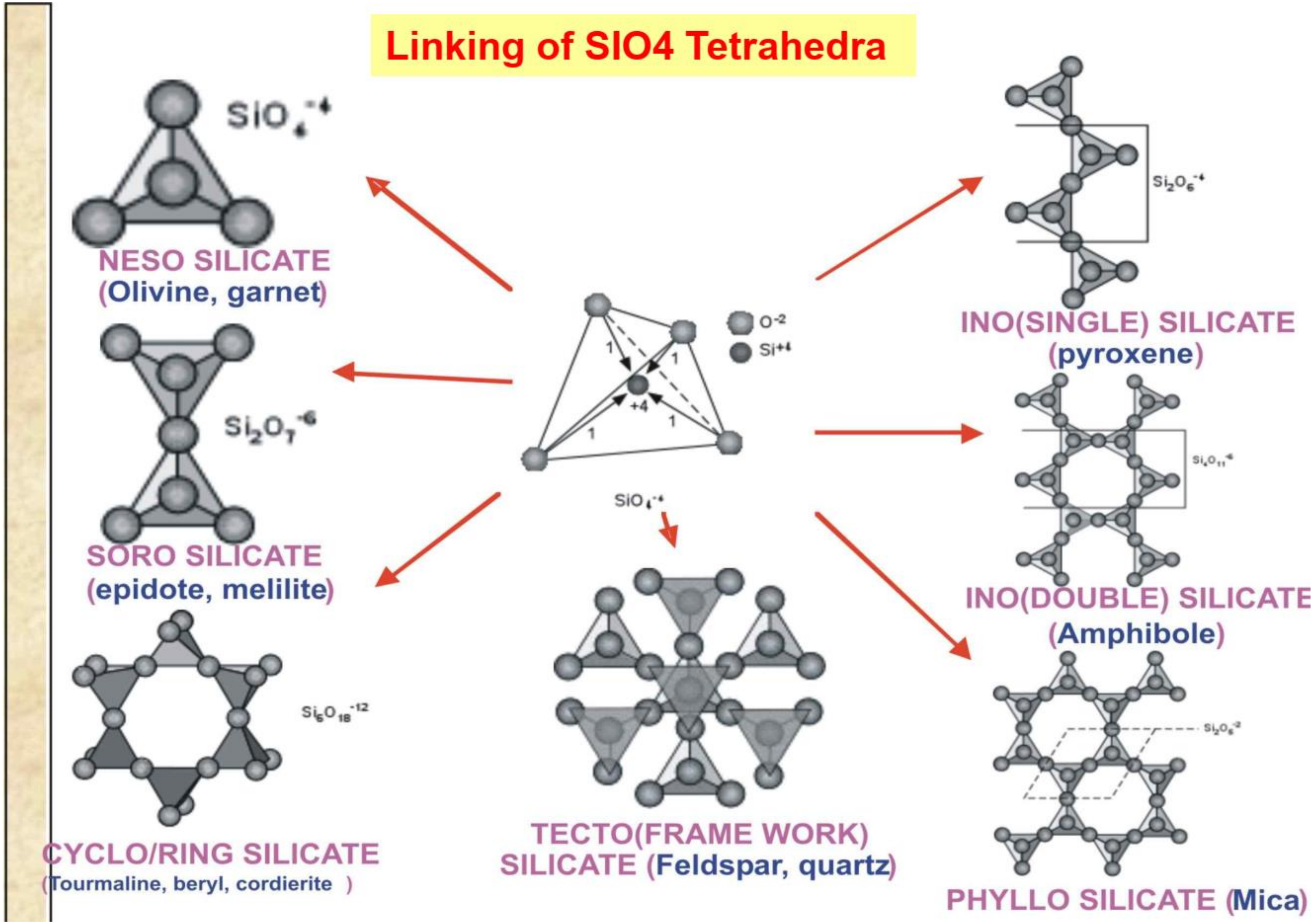
Minerals Classification

- **More than 4000 minerals have been identified, and several new ones are identified each year.**

- **Common minerals that make up most of the Earth's crust are only a few dozens and known as rock-forming minerals.**

- **As we have seen that the oxygen and silicon are the most common elements in the Earth's crust, so the silicate minerals account for more than 90% of the crust.**

Minerals Classification: Silicate Minerals



Minerals Classification: Silicate Minerals

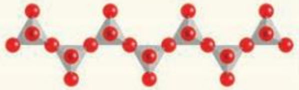
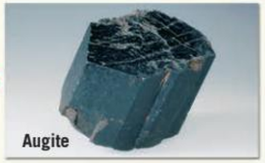
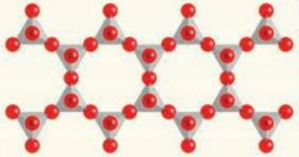
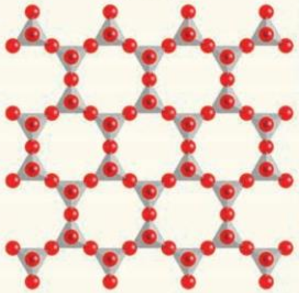
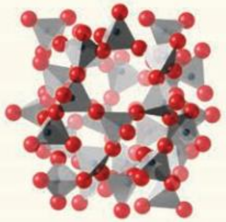
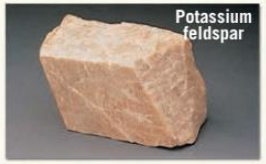
Table 11.1 Silicate Classification[a]

Silicate Class	Number of O^{2-} Shared per Tetrahedron	Z:O Ratio	Structural Configuration
Orthosilicates	0	1:4	Isolated tetrahedra
Disilicates	1	2:7	Double tetrahedra
Ring silicates	2	1:3	Rings of tetrahedra
Chain silicates			Chains of tetrahedra
Single chain	2	1:3	
Double chain	2 or 3	4:11	
Sheet silicates	3	2:5	Sheets of tetrahedra
Framework silicates	4	1:2	Framework of tetrahedra

[a] Z refers to the cation(s), usually Si^{4+}, and also Al^{3+}, that occupy the tetrahedral sites.

Minerals Classification:
Silicate Minerals

Common Silicate Minerals and Mineral Groups

	Mineral/Formula	Cleavage	Silicate Structure	Example
	Olivine group $(Mg,Fe)_2SiO_4$	**None**	**Single tetrahedra** 	
	Pyroxene group (Augite) $(Mg,Fe,Ca,Na)AlSiO_3$	**Two planes at 90°**	**Single chains** 	
	Amphibole group (Hornblende) $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$	**Two planes at 60° and 120°**	**Double chains** 	
Micas	**Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	**One plane**	**Sheets** 	
Micas	**Muscovite** $KAl_2(AlSi_3O_{10})(OH)_2$			
Feldspars	**Potassium feldspar (Orthoclase)** $KAlSi_3O_8$	**Two planes at 90°**	**Three-dimensional networks** 	
Feldspars	**Plagioclase** $(Ca,Na)AlSi_3O_8$			
	Quartz SiO_2	**None**		

Phase Transitions in Olivine

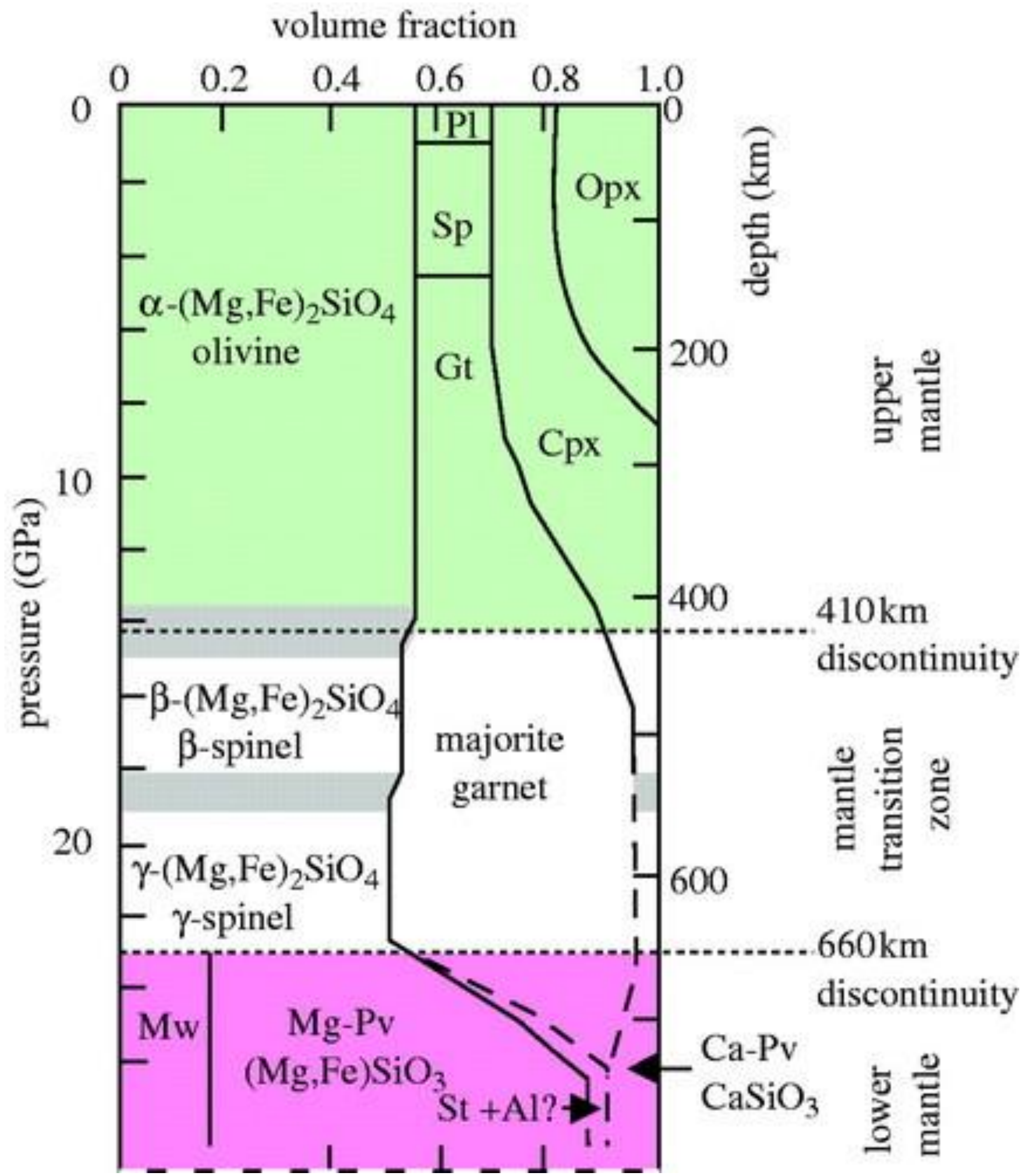
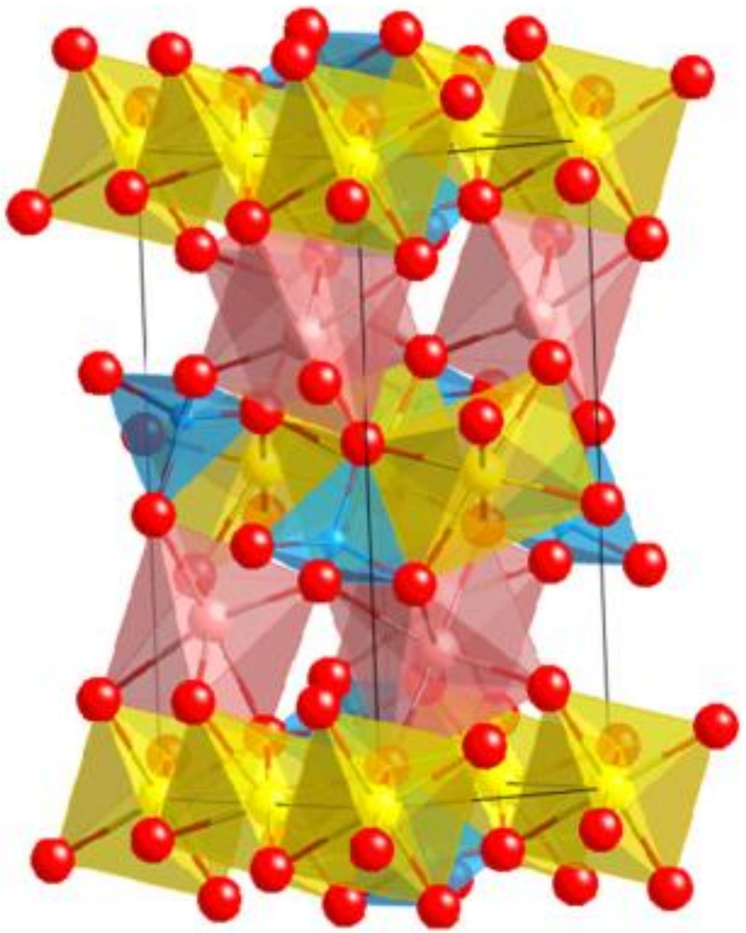


Figure 1. Schematic of the volumetric mineral constitution of a peridotite mantle down to the lower mantle (modified after Ito & Takahashi 1987). Peridotite is a dense coarse-grained igneous rock consisting mainly of olivine and pyroxene. It is high in Fe and Mg and contains less than 45% Si. Peridotite can be found in xenoliths (rock fragments) brought to the surface by magma deriving from the upper mantle. Pl = plagioclase–$CaAl_2Si_2O_8$; Sp = spinel–$MgAl_2O_4$; Gt = garnet–$(Mg,Fe,Ca)_3Al_2Si_3O_{12}$; majorite garnet–$Mg_3(Mg,Si)_2Si_3O_{12}$; Cpx = clinopyroxene–$(Ca,Fe,Mg)SiO_3$; Opx = orthopyroxene–$(Mg,Fe)SiO_3$; Mg-Pv = Mg-perovskite–$(Mg,Fe)SiO_3$; olivine–$(Mg,Fe)_2SiO_4$; Mw = magnesiowüstite–$(Mg,Fe)O$; Ca-Pv = Ca-perovskite–$CaSiO_3$; St = stishovite–$SiO_2$.

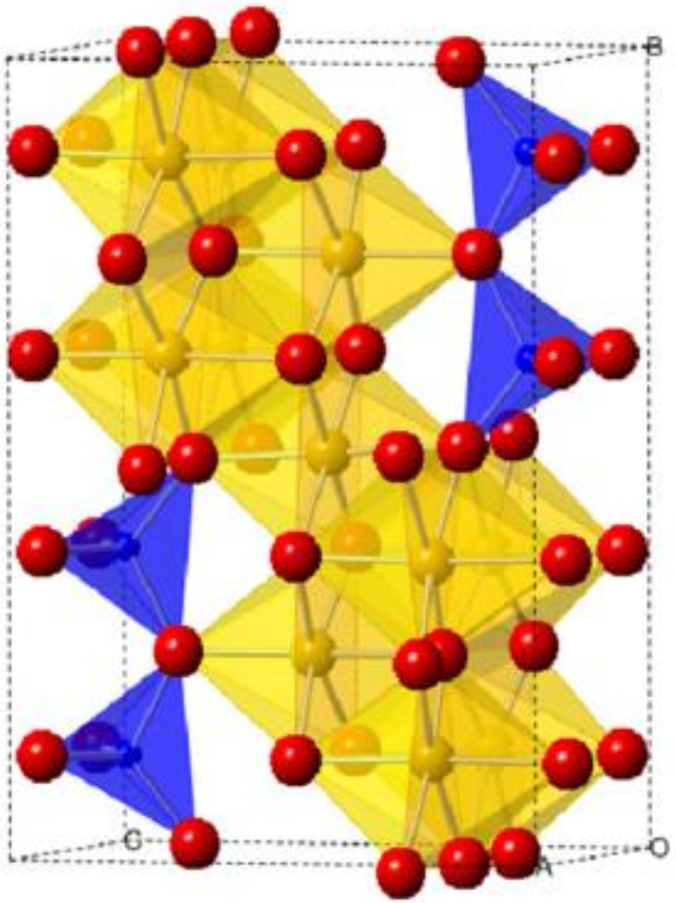
https://royalsocietypublishing.org/doi/10.1098/rsta.2005.1675

Phase Transitions in Olivine



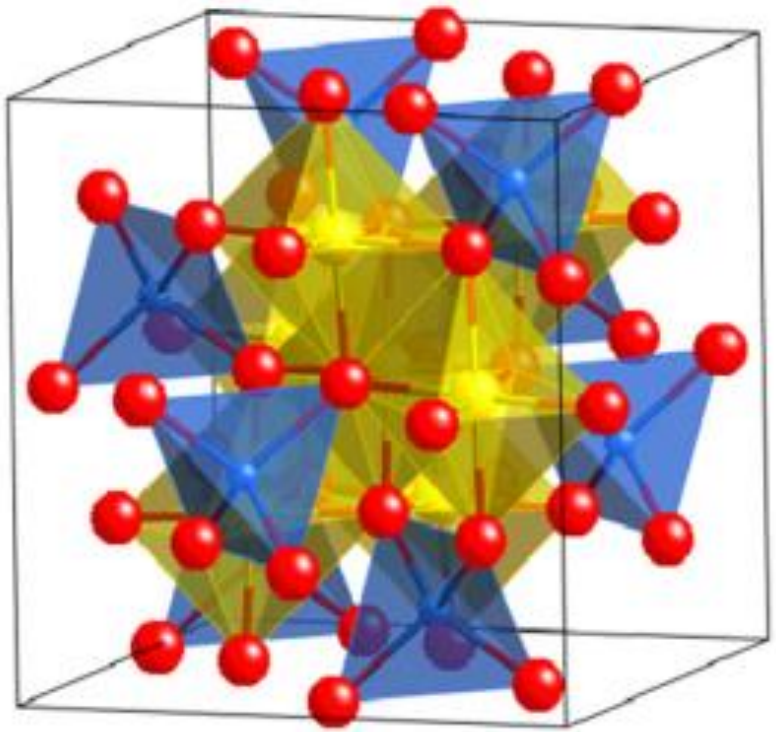
olivine

α –Olivine



wadsleyite

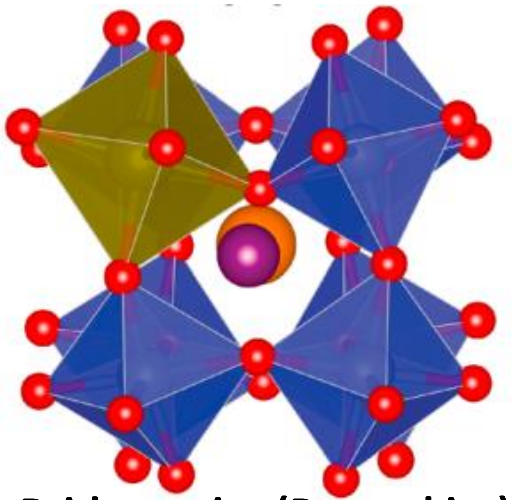
β –Olivine



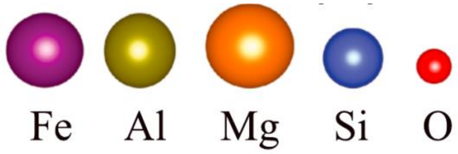
ringwoodite

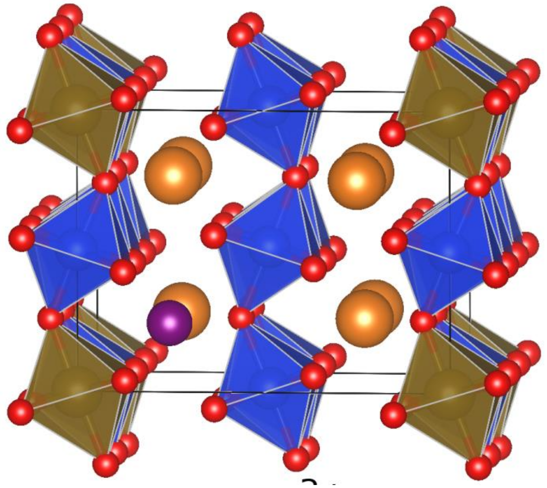
γ –Olivine

Phase Transitions in Bridgmanite



Bridgmanite (Perovskite),
Orthorhombic



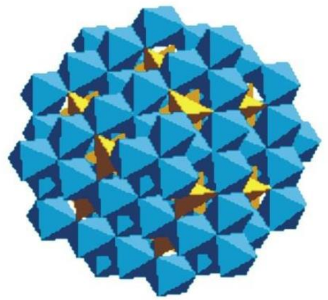


Post-perovskite, Orthorhombic
(expected to be in the D’’ region)

Some interesting details about Olivine

- **Nesosilicate: Isolated SiO_4 Tetrahedra**
- **Most common mineral in the Earth's mantle**
- **$(Mg,Fe)_2SiO_4$**
- **Mg, Fe form MO_6 Octahedra that link Tetrahedra**
- **Olivine is Orthorhombic near surface conditions called Alpha olivine**
- **At higher P-T, Alpha olivine changes to Beta olivine which contains sites that contain (OH)**
- **At still higher P-T, changes to gamma olivine which is isometric and can contain OH**
- **At still higher P-T changes to perovskite structure**

RINGWOODITE

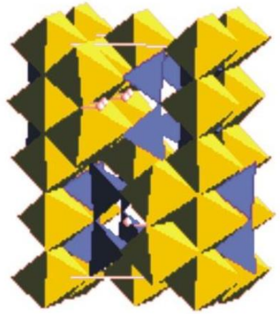


(Fe,Mg)2SiO4 in the spinel (Cubic) structure is kno
as ringwoodite (γ). Here, Si atoms occupy the tetrahedral sites (yellow) and Fe and Mg atoms occupy the *edge-sharing* octahedral sites (blue).

SPINEL (AB2O4)

SiMg2O4

WADSLEYITE



OH in the structure

Intermediate between the olivine and spinel (ringwoodite) structure is a phase known as **wadsleyite** (β (Mg,Fe)2SiO4) The wadsleyite (or beta-spinel) structure is currently of great interest because it is being invoked as a reservior of water (as chemically bound OH) in the Earth's mantle.

Alpha to Beta at 410 Km, Beta to Gamma at 520 Km, Gamma to Perovskite at 660 Km

Exploring Earth's Interior using Seismic Waves

Alpha to Beta at 410 Km, Beta to Gamma at 520 Km, Gamma to Perovskite at 660 Km

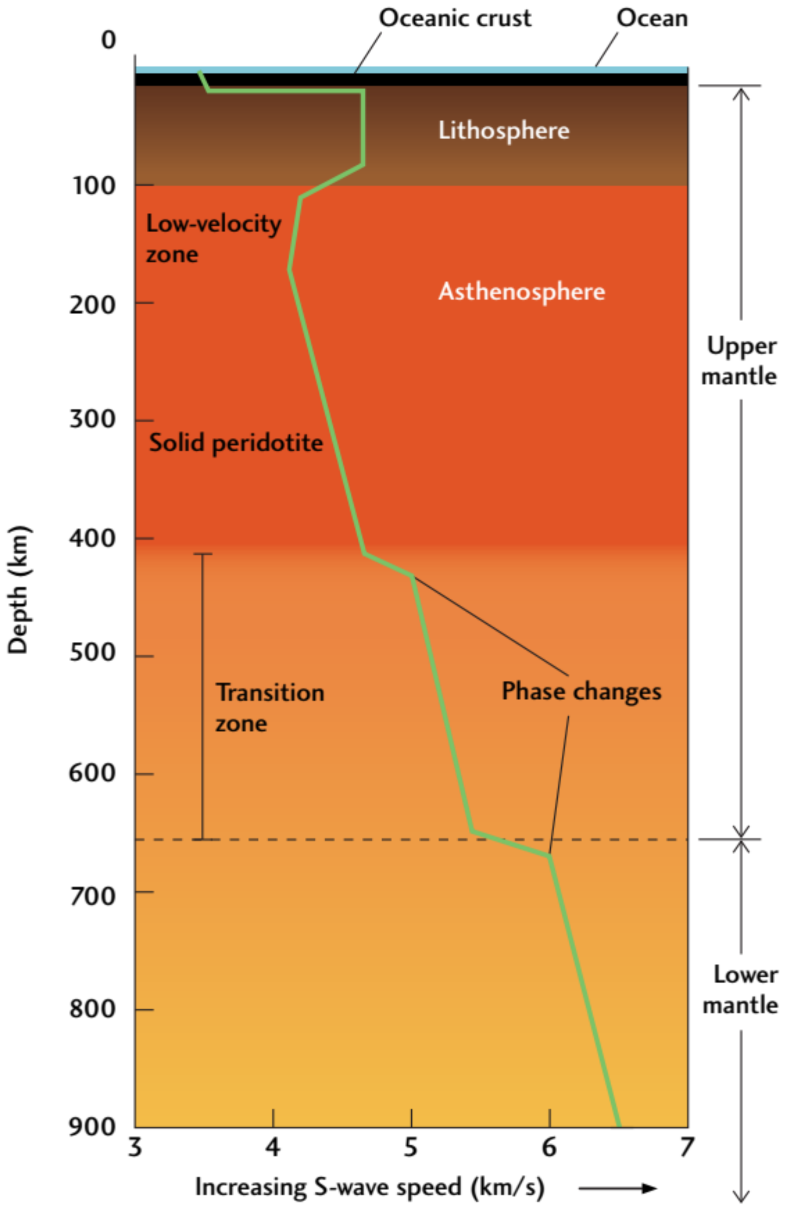


FIGURE 14.8 ■ The structure of the mantle beneath old oceanic lithosphere, showing S-wave velocities to a depth of 900 km. Changes in S-wave velocity mark the strong, brittle lithosphere, the weak, ductile asthenosphere, and a transition zone, in which increasing pressure forces rearrangements of atoms into denser and more compact crystal structures (phase changes).

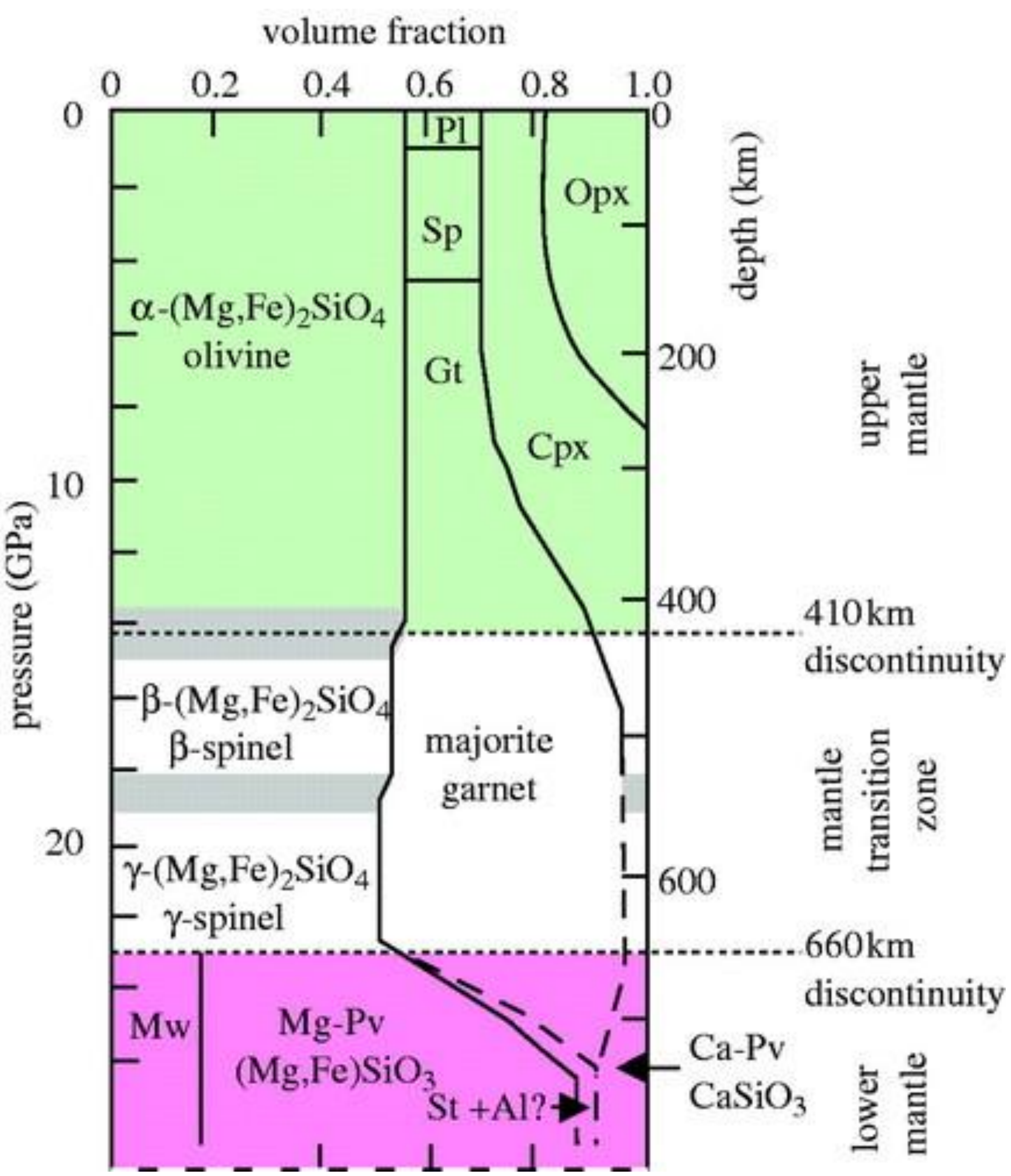


TABLE 4.2 Summary of Mantle Mineral Assemblages for Average Garnet Lherzolite from High-Pressure Studies

Depth (km)	Mineral assemblage (minerals in vol%)		Density contrast (%)	Slope of reaction (MPa/°C)
<410	Olivine	58		
	Opx	11		
	Cpx	18		
	Garnet	13		
350-450	Opx-Cpx → Majorite		6	+1.5
410-km discontinuity				
410	Olivine (α phase) → Wadsleyite (β phase)		6	+5.5
410-550	Wadsleyite	58		
	Majorite	30		
	Cpx	9		
	Opx	3		
520-km discontinuity				
520	Wadsleyite → Ringwoodite (γ phase) Ca-garnet → Ca-perovskite		1	+3.0
550-660	Ringwoodite	58		
	Majorite	37		
	Ca-Perovskite	5		
660-km discontinuity				
660	Ringwoodite → Bridgmanite + Magnesiowustite		7-9	−0.5 to −3.5 (dry); ≤−2 (wet)
650-680	Majorite → Perovskite			+1.5 to +2.5
650–680	Ilmenite → Perovskite			
650–680	Pyroxene → Akimotoite			
680–2900	Bridgmanite	77		
	Magnesiowustite	15		
	Ca-Perovskite	8		
	Silica (?)			
D″ discontinuity				
2600-2750	Bridgmanite → post-perovskite		1	7-10

Opx, orthopyroxene; Cpx, clinopyroxene.
Data from Ita and Stixrude (1992), Christensen (1995), Mambole and Fleitout (2002), Hirose (2002), Katsura et al. (2003), Fei et al. (2004), Litsov et al. (2005), Wolstencroft and Davies (2011).

Compositional Variation in Minerals

- During chemical analysis of different samples of *a mineral*, it is routinely found that these samples do not have same chemical composition (Definite but not a fixed chemical composition).

- Composition variation is possible because different cations can interchangeably occupy the various sites. The term applied to this compositional variation is **solid solution**.

- Practically all naturally occurring minerals containing Fe-Mg-Mn-Ca or Na-K etc. are solid solutions.

- Quartz (SiO_2) is not a solid solution.

Compositional Variation in Minerals

Substitution Solid Solution: Substitution of one cation for another.

- Requirement for substitution solid solution:
  - Ion sizes must be similar
  - Charge neutrality must be maintained
  - Similar electronegativity

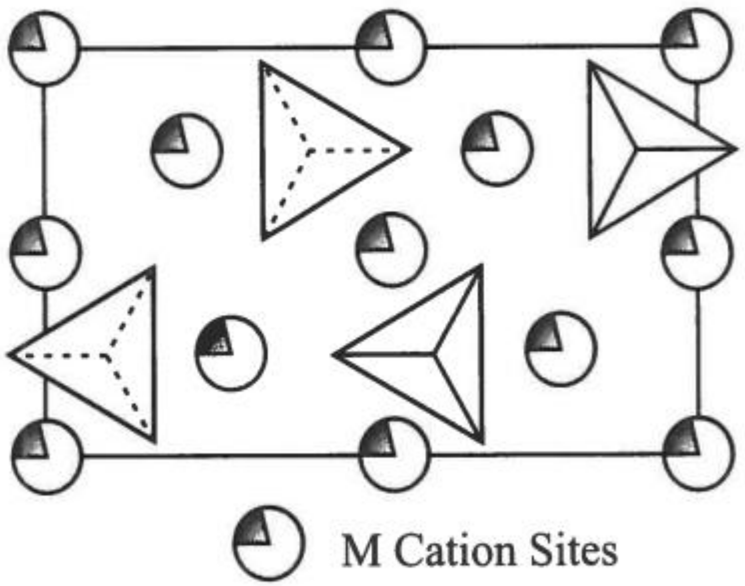
- ✓ If the difference in ion size is less than 15%, extensive substitution is possible.
- ✓ If the size difference is ~15-30%, limited substitution possible.
- ✓ If the size difference is greater than 30%, substitution is very unlikely.

- ***Temperature*** has a substantial influence on the degree to which ions of different sizes may substitute for each other.

Compositional Variation in Minerals

Substitution Solid Solution: Substitution of one cation for another.

- **Simple substitution:**
  Olivine, Forsterite (Mg_2SiO_4)-Fayalite (Fe_2SiO_4) end members



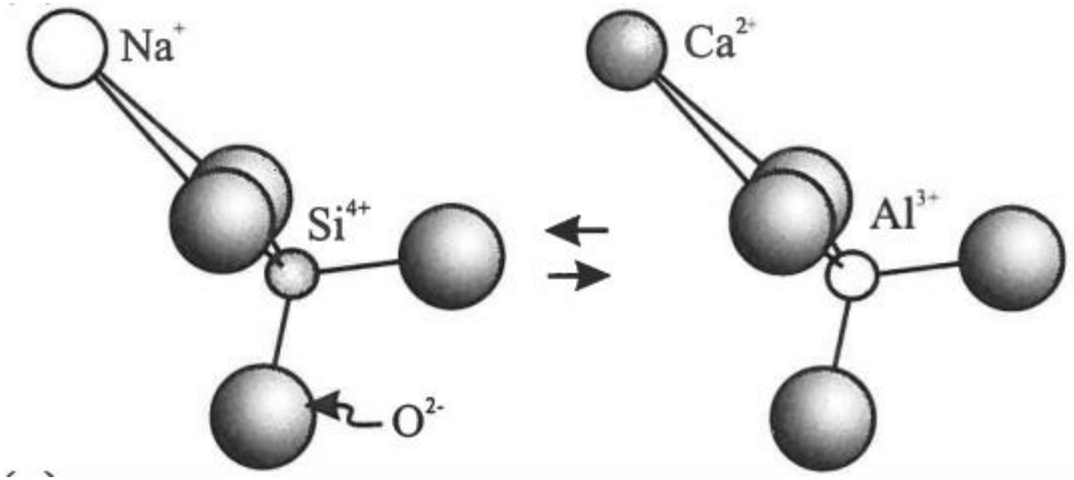
- The structure is viewed down the a-axis
- Octahedral M-sites or occupied by Mg^{2+} or Fe^{2+}
- The shaded wedge shown on M-sites represents the occupation of Fe^{2+}. In this case 22%.

Compositional Variation in Minerals

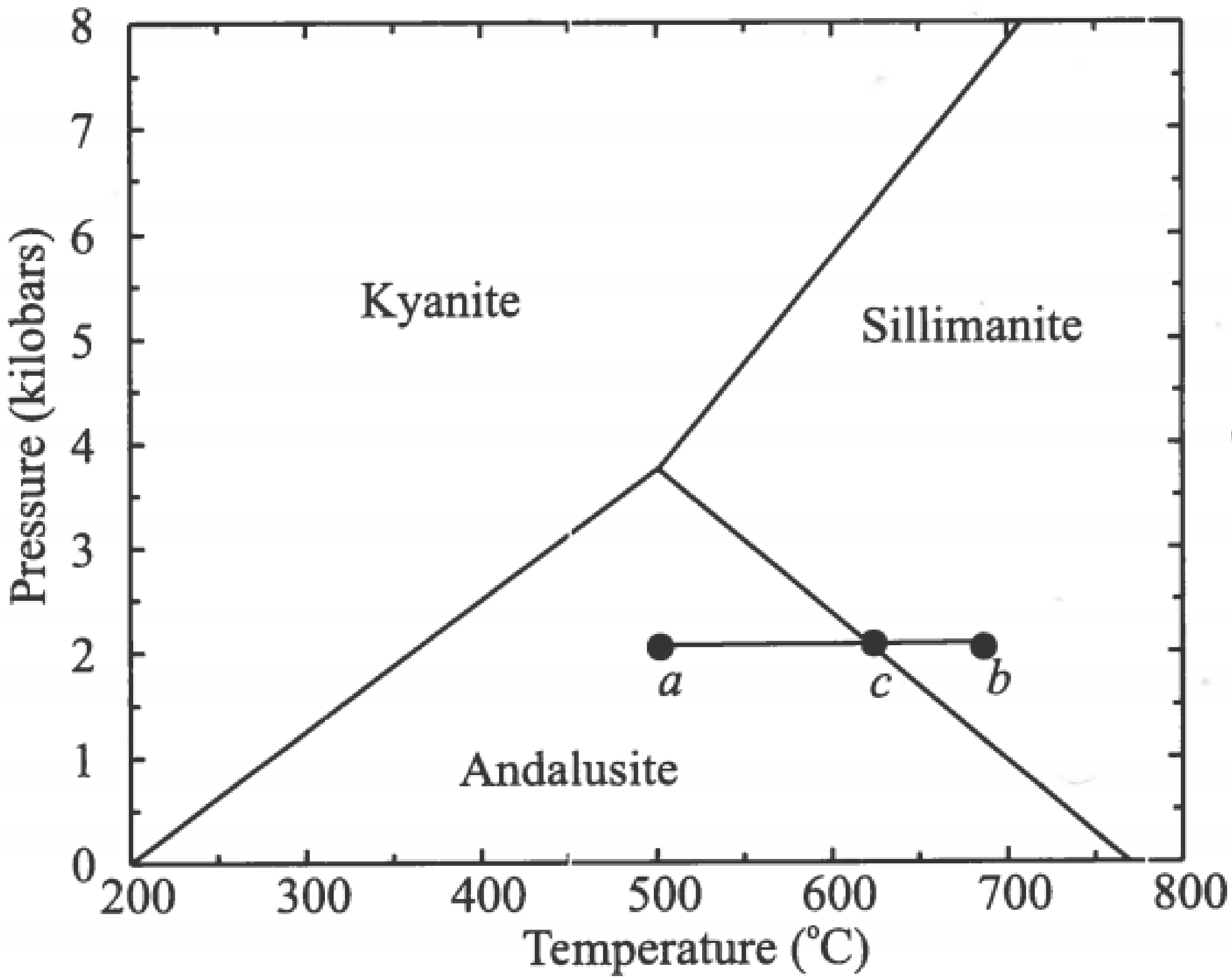
- **Coupled substitution:** Coupled substitution maintains a charge balance by coupling one substitution that increases the charge with another that reduces the charge.
  Example: Plagioclase: Albite (NaAlSi3O8)-Anorthite (CaAl2Si2O8) end members

- Ca^{2+} and Na^{+} both occupy distorted 8-fold coordination sites.
- Si^{4+} and Al^{3+} both occupy tetrahedral coordination sites.

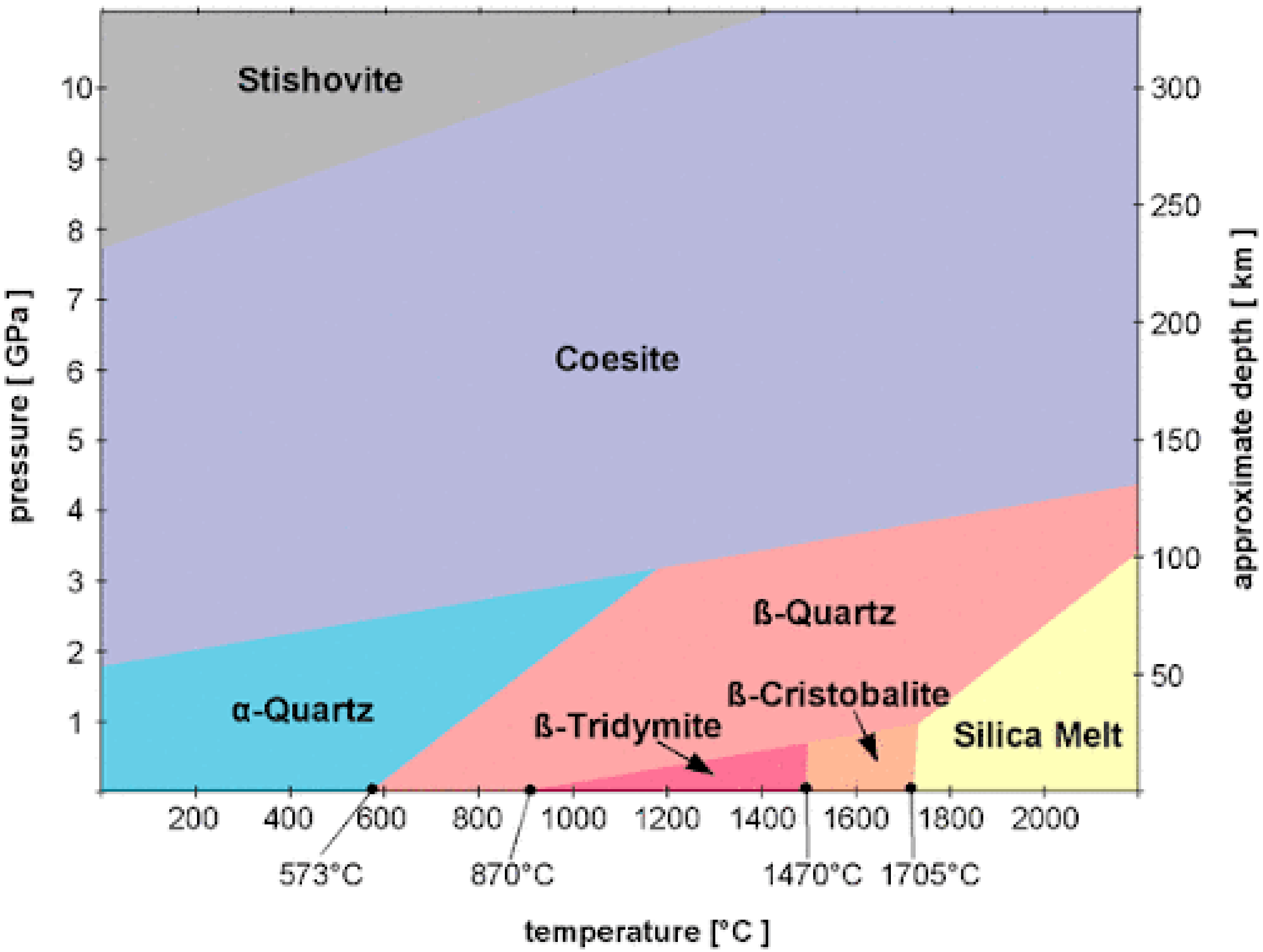
  $Ca^{2+} + Al^{3+} = Na^{+} + Si^{4+}$



Polymorphism: Al_2SiO_5



Polymorphism: SiO_2



Polymorphism: SiO_2

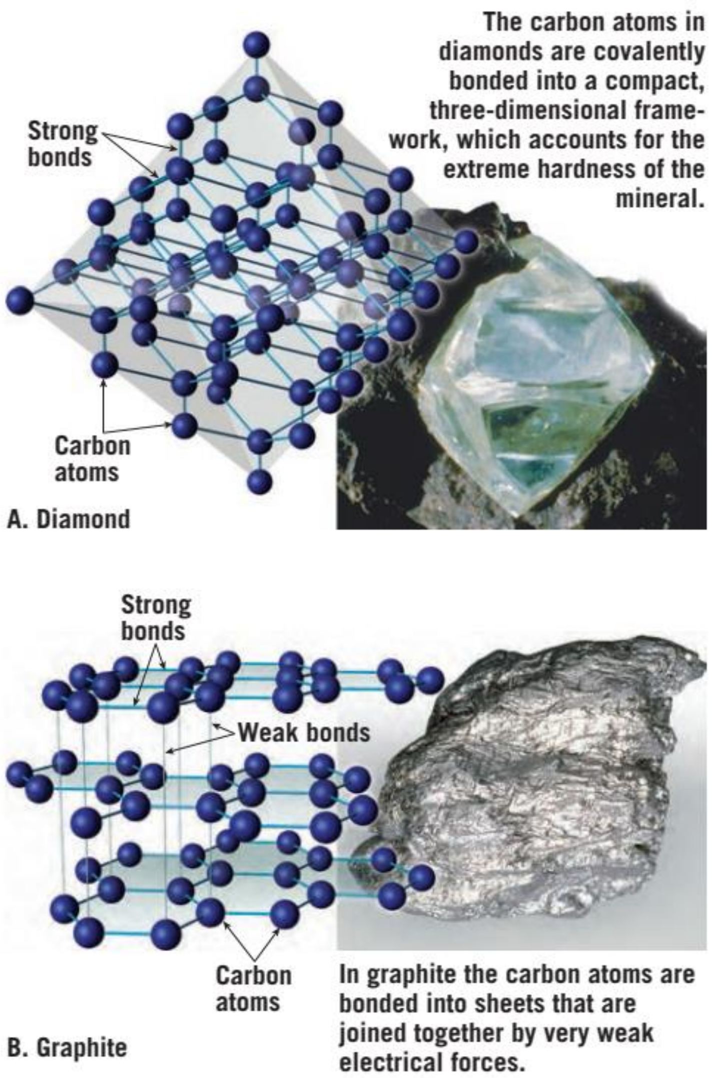
Meteor Crater, also known as Barringer Crater (Arizona, USA)

https://en.wikipedia.org/wiki/Meteor_Crater

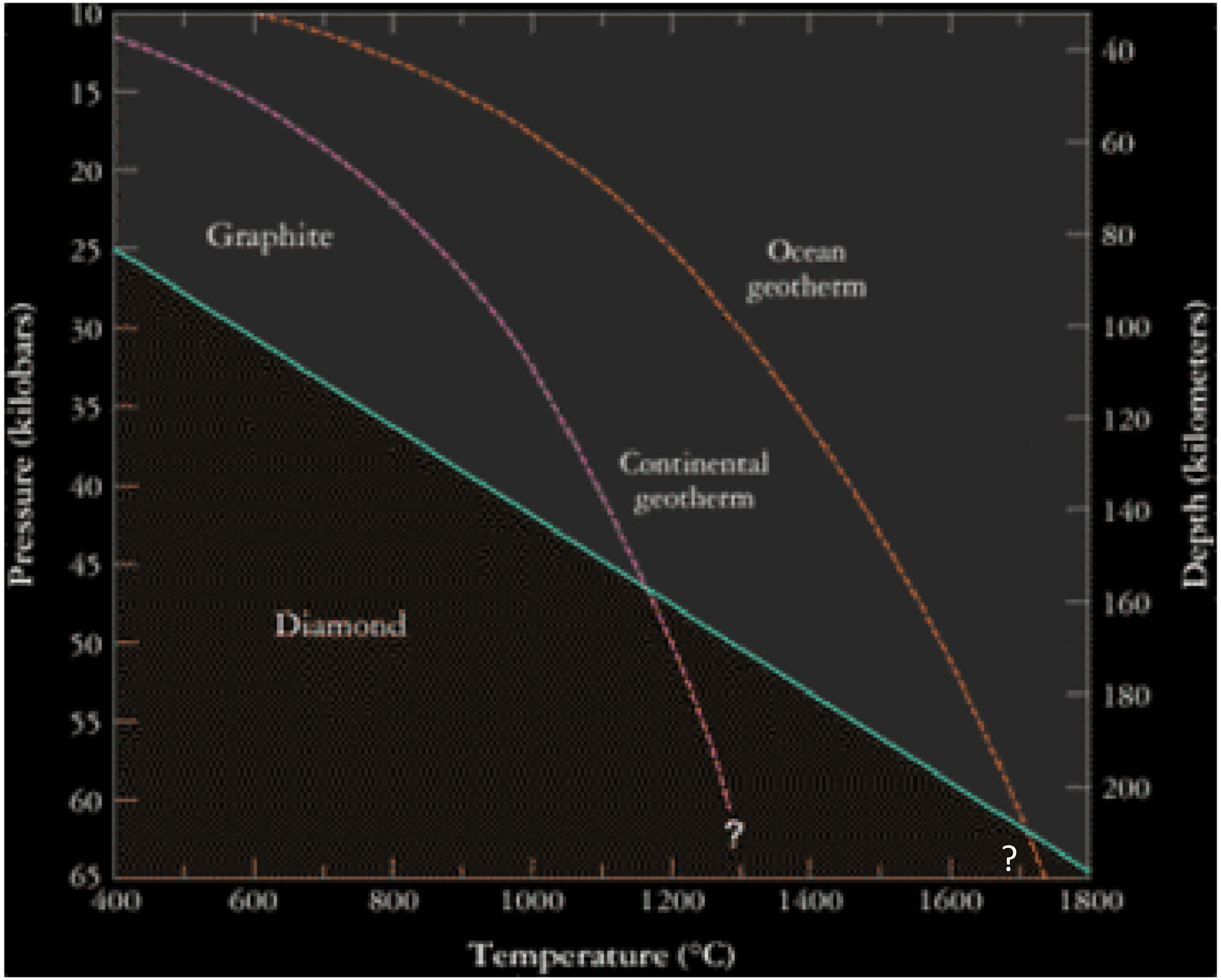
Impact crater/structure	
Confidence	Confirmed[1]
Diameter	0.737 miles (1.186 km)
Depth	560 feet (170 m)
Rise	148 feet (45 m)
Impactor diameter	160 feet (50 m)
Age	50,000 years

Polymorphism: Carbon

Figure 3.29
Diamond versus graphite
Both diamond and graphite are natural substances with the same chemical composition: carbon atoms. Nevertheless, their internal structures and physical properties reflect the fact that each formed in a very different environment. (Photo A Marcel Clemens/Shutterstock; photo B by E. J. Tarbuck)



Polymorphism: Carbon

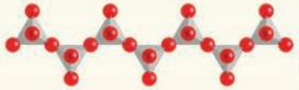
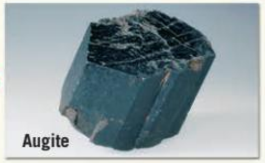
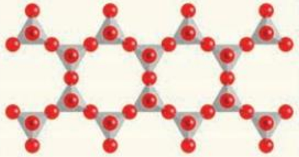
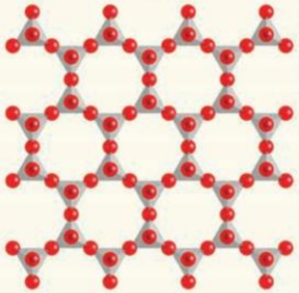
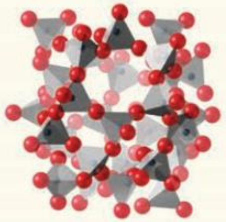
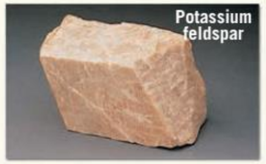


Polymorphism

Table 4.4 Common Polymorphic Mineral Groups

Chemical Composition	Mineral Name
SiO_2	α-Quartz
	β-Quartz
	α-Tridymite
	β-Tridymite
	Cristobalite
	Coesite
	Stishovite
FeS_2	Pyrite
	Marcasite
C	Graphite
	Diamond
$AlAlOSiO_4$	Andalusite
	Sillimanite
	Kyanite
$KAlSi_3O_8$	Sanidine
	Orthoclase
	Microcline

Minerals Classification:
Silicate Minerals

Common Silicate Minerals and Mineral Groups				
	Mineral/Formula	**Cleavage**	**Silicate Structure**	**Example**
	Olivine group $(Mg,Fe)_2SiO_4$	**None**	**Single tetrahedra** 	
	Pyroxene group (Augite) $(Mg,Fe,Ca,Na)AlSiO_3$	**Two planes at 90°**	**Single chains** 	
	Amphibole group (Hornblende) $Ca_2\,(Fe,Mg)_5Si_8O_{22}(OH)_2$	**Two planes at 60° and 120°**	**Double chains** 	
Micas	**Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	**One plane**	**Sheets** 	
Micas	**Muscovite** $KAl_2(AlSi_3O_{10})(OH)_2$			
Feldspars	**Potassium feldspar (Orthoclase)** $KAlSi_3O_8$	**Two planes at 90°**	**Three-dimensional networks** 	
Feldspars	**Plagioclase** $(Ca,Na)AlSi_3O_8$			
	Quartz SiO_2	**None**