Hashemite University

Faculty of Natural Resources and Environment

Department of earth and environmental sciences

Mineralogy (1201220)

Chapter 7: Mineral Classification (1.Silicates)

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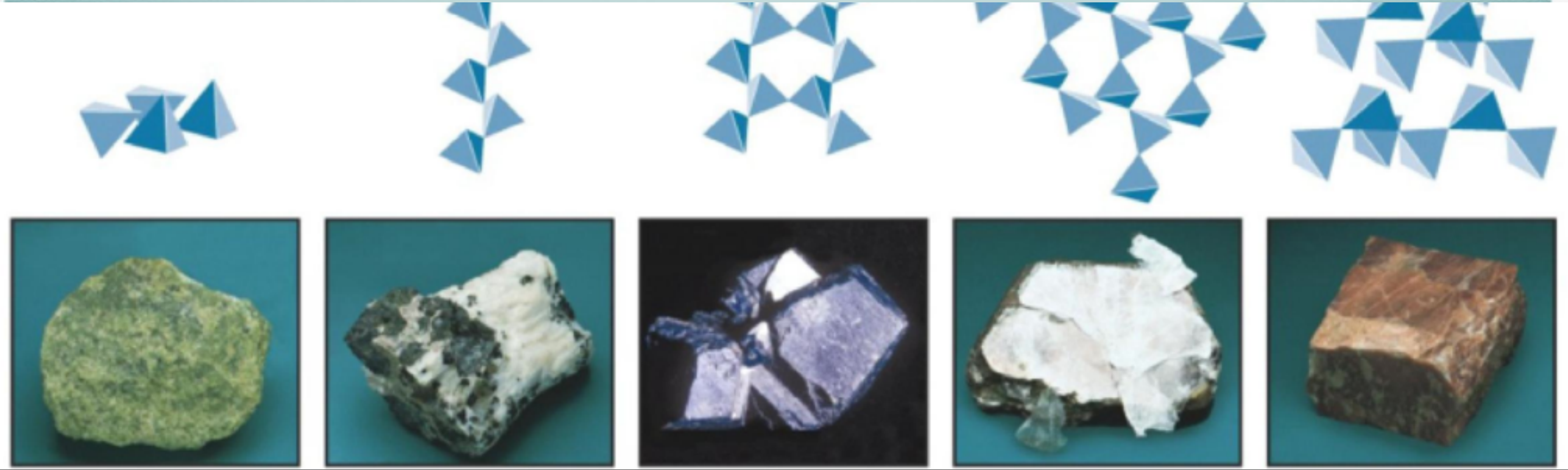
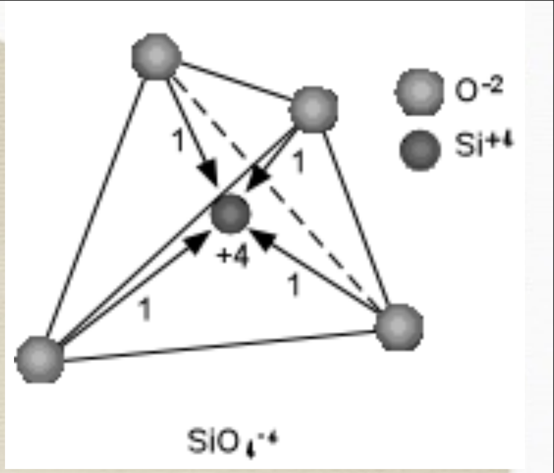




1. **Silicates**

Silicate Structures and Structural Formula

The radius ratio of Si^{+4} to O^{-2} requires that Si^{+4} be coordinated by 4 O^{-2} ions in tetrahedral coordination. In order to neutralize the +4 charge on the Si cation, one negative charge from each of the Oxygen ions will reach the Si cation.

Thus, each Oxygen will be left with a net charge of -1, resulting in a SiO_4^{-4} tetrahedral group that can be bonded to other cations. It is this SiO_4^{-4} tetrahedron that forms the basis of the silicate minerals.

1. Nesosilicates

If the corner oxygens are not shared with other SiO_4^{-4} tetrahedrons, each tetrahedron will be isolated.

The basic structural unit is then $\mathbf{SiO_4}^{-4}$.

Olivine is a good example: $(Mg,Fe)_2SiO_4$.

- **Nesosilicates**

1. Phenakite group
    - **Phenakite** - Be_2SiO_4
    - **Willemite** - Zn_2SiO_4
2. Olivine group
    - **Forsterite** - Mg_2SiO_4
    - **Fayalite** - Fe_2SiO_4
    - **Tephroite** - Mn_2SiO_4
3. Garnet group
    - **Pyrope** - $Mg_3Al_2(SiO_4)_3$
    - **Almandine** - $Fe_3Al_2(SiO_4)_3$
    - **Spessartine** - $Mn_3Al_2(SiO_4)_3$
    - **Grossular** - $Ca_3Al_2(SiO_4)_3$
    - **Andradite** - $Ca_3Fe_2(SiO_4)_3$
    - **Uvarovite** - $Ca_3Cr_2(SiO_4)_3$
    - **Hydrogrossular** - $Ca_3Al_2Si_2O_8(SiO_4)_{3-m}(OH)_{4m}$
4. Zircon group
    - **Zircon** - $ZrSiO_4$
    - **Thorite** - $(Th,U)SiO_4$

5. Al_2SiO_5 group

- Andalusite - Al_2SiO_5
- Kyanite - Al_2SiO_5
- Sillimanite - Al_2SiO_5
- Dumortierite - $Al_{6.5-7}BO_3(SiO_4)_3(O,OH)_3$
- Topaz - $Al_2SiO_4(F,OH)_2$
- Staurolite - $Fe_2Al_9(SiO_4)_4(O,OH)_2$

6. Humite group - $(Mg,Fe)_7(SiO_4)_3(F,OH)_2$

- Norbergite - $Mg_3(SiO_4)(F,OH)_2$
- Chondrodite - $Mg_5(SiO_4)_2(F,OH)_2$
- Humite - $Mg_7(SiO_4)_3(F,OH)_2$
- Clinohumite - $Mg_9(SiO_4)_4(F,OH)_2$

. Datolite - $CaBSiO_4(OH)$

. Titanite - $CaTiSiO_5$

. Chloritoid - $(Fe,Mg,Mn)_2Al_4Si_2O_{10}(OH)_4$

. Mullite (aka Porcelainite) - $Al_6Si_2O_{13}$

Garnet

$(Mg,Fe,Mn,Ca)_3(Fe^{3+},Cr,Al)_2Si_3O_{12}$

Garnets are isometric minerals and thus isotropic in thin section, metamorphic mineral

Equigranular, euhderal to subhedral habit; poor cleavage

Optics: Colorless, isotropic, high relief.

Complex solid solution with the following end–member compositions and their characteristic colors:

Pyrope $Mg_3Al_2Si_3O_{12}$ – deep red to black

Almandine $Fe_3Al_2Si_3O_{12}$ – deep brownish red

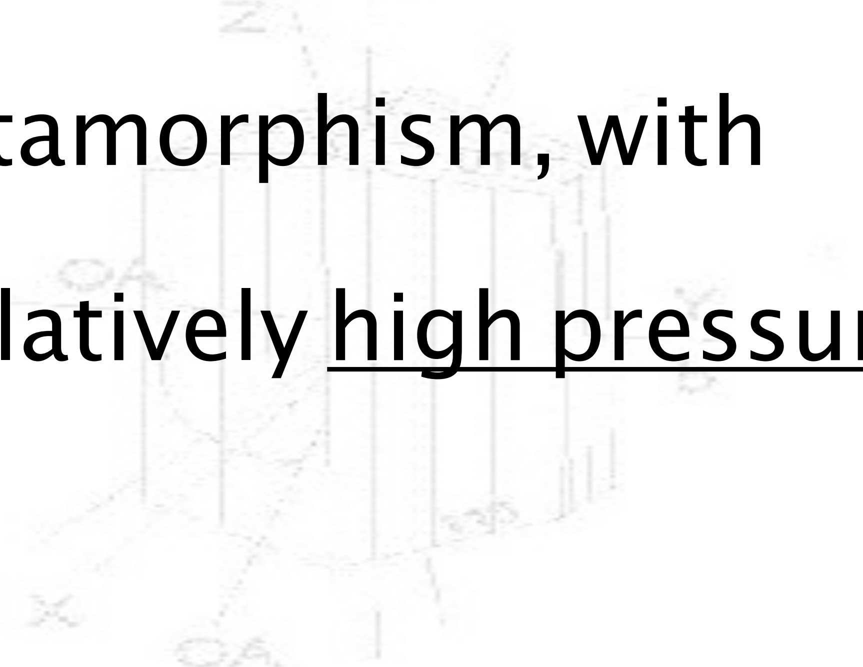
Spessartine $Mn_3Al_2Si_3O_{12}$ – brownish red to black

Grossular $Ca_3Al_2Si_3O_{12}$ – yellow–green to brown

Andradite $Ca_3Fe_2Si_3O_{12}$ – variable–yellow, green, brow

Uvarovite $Ca_3Cr_2Si_3O_{12}$ – emerald green

The Aluminosilicates Al_2SiO_5
Kyanite, Sillimanite, Andalusite



In metamorphic rocks the Al_2SiO_5 polymorphs provide rather general estimates of the pressure and temperature of metamorphism, with

Kyanite indicating relatively high pressure,

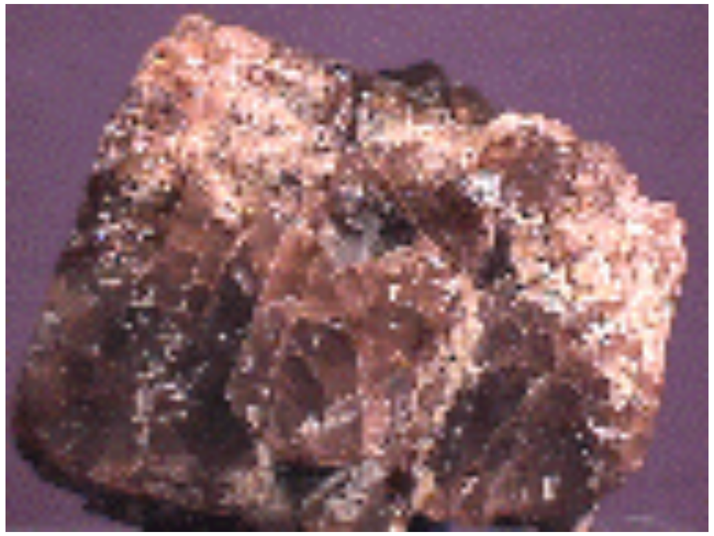
andalusite indicating low temperature and pressure, and

sillimanite indicating high temperature.

Kyanite – Vitreous bluish bladed tablets with single cleavage; H: 5–7

Sillimanite – Vitreous brown to green clustered prisms with single cleavage.

Andalusite – Vitreous flesh-red, reddish brown square prisms; H: 7.5



Staurolite

$Fe_2Al_9O_6(SiO_4)_4(O,OH)_2$

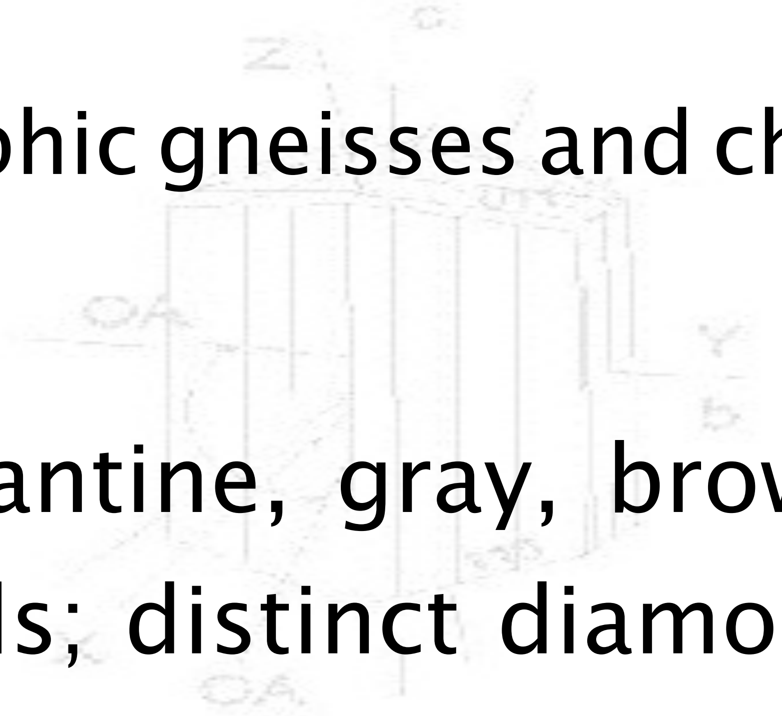
Staurolite is a common mineral in medium grade metamorphic rocks, usually metamorphosed shales.

Moderate to high grade metamorphic mineral formed from Al-rich source rocks

Resinous to vitreous reddish-brown to brownish black 6-sided prisms; commonly forms penetrating twins

Titanite $CaTiO(SiO_4)$

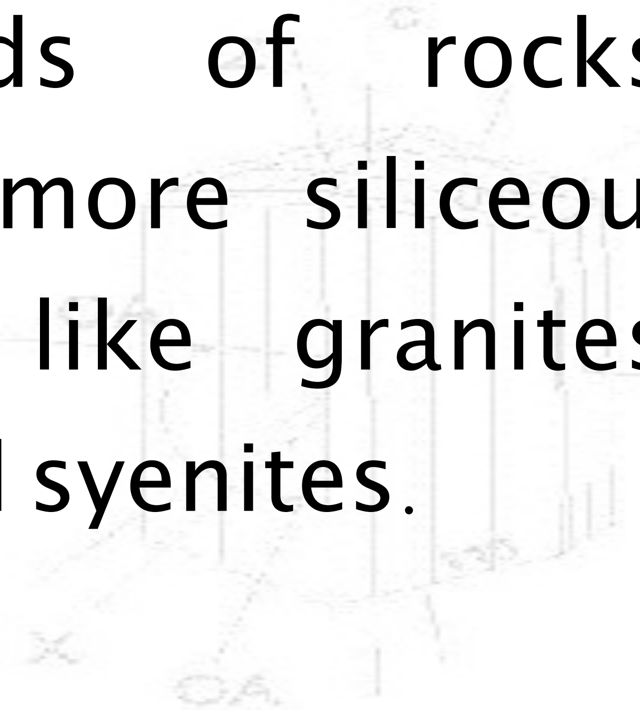
Common accessory mineral in plutonic igneous rocks like granites, granodiorites, and syenites. It is also found as larger crystals in metamorphic gneisses and chlorite bearing schists.



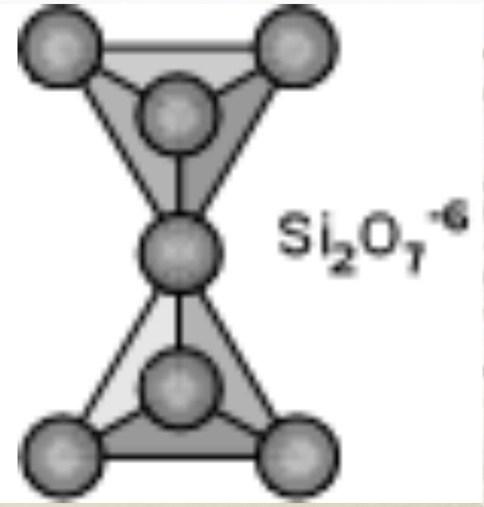
Resinous to adamantine, gray, brown, green, yellow or black lens crystals; distinct diamond-shaped cleavage; H: 5-5.5

Zircon is $ZrSiO_4$.

common accessory mineral in nearly all kinds of rocks, particularly the more siliceous igneous rocks, like granites, granodiorites, and syenites.



Zircon usually contains high amounts of radioactive elements like U and Th.



2. Sorosilicates

If one of the corner oxygens is shared with another tetrahedron.

there are two linked tetrahedrons isolated from all other tetrahedrons.

In this case,the basic structural unit is $\mathbf{Si_2O_7^{-6}}$.

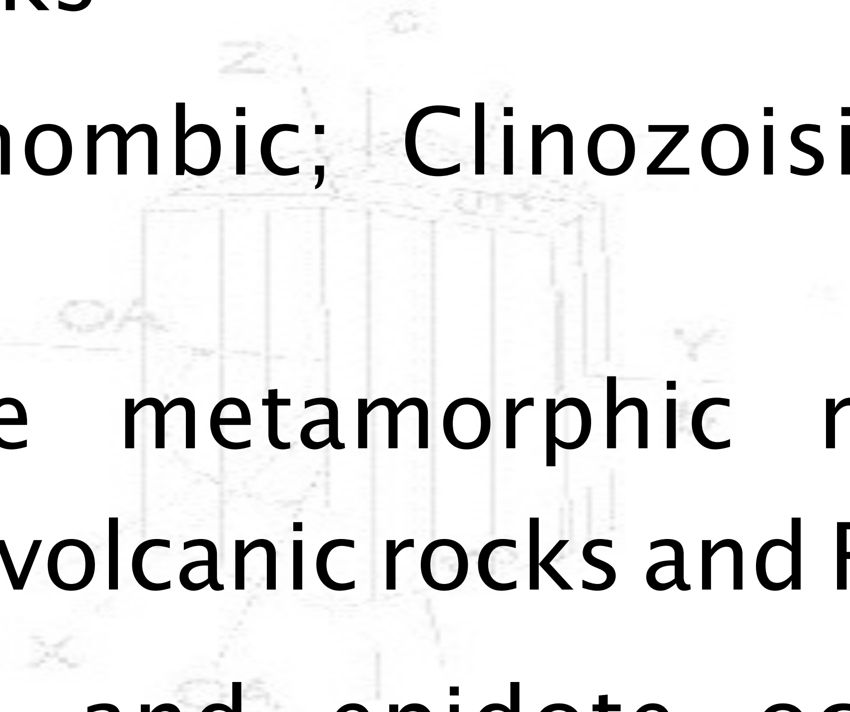
A good example of a sorosilicate is the mineral hemimorphite – $Zn_4Si_2O_7(OH)\cdot H_2O$.

Sorosilicates

- Hemimorphite (calamine) – $Zn_4(Si_2O_7)(OH)_2 \cdot H_2O$
- Lawsonite – $CaAl_2(Si_2O_7)(OH)_2 \cdot H_2O$
- Ilvaite – $CaFe^{2+}{}_2Fe^{3+}O(Si_2O_7)(OH)$
- Epidote group (has both $(SiO_4)^{4-}$ and $(Si_2O_7)^{6-}$ groups)
  - Epidote – $Ca_2(Al,Fe)_3O(SiO_4)(Si_2O_7)(OH)$
  - Zoisite – $Ca_2Al_3O(SiO_4)(Si_2O_7)(OH)$
  - Clinozoisite – $Ca_2Al_3O(SiO_4)(Si_2O_7)(OH)$
  - Tanzanite – $Ca_2Al_3O(SiO_4)(Si_2O_7)(OH)$
  - Allanite – $Ca(Ce,La,Y,Ca)Al_2(Fe^{2+},Fe^{3+})O(SiO_4)(Si_2O_7)(OH)$
  - Dollaseite–(Ce) – $CaCeMg_2AlSi_3O_{11}F(OH)$
- Vesuvianite (idocrase) – $Ca_{10}(Mg,Fe)_2Al_4(SiO_4)_5(Si_2O_7)_2(OH)_4$

Epidote Group

Common accessory and alteration mineral in igneous rocks and is a common phase in various grades of metamorphic rocks

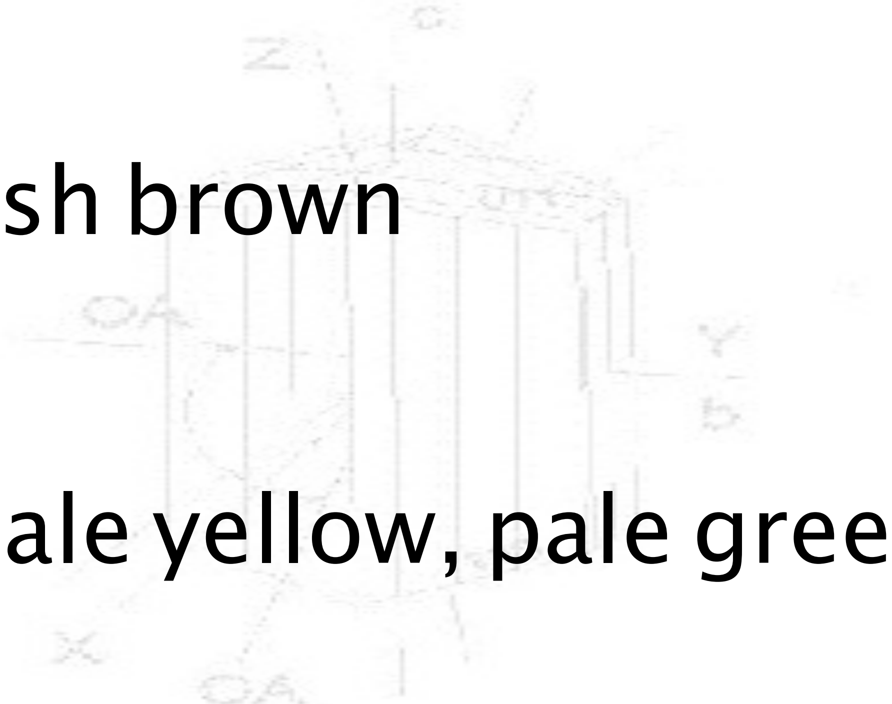


Zoisite – Orthorhombic; Clinozoisite and Epidote – Monoclinic

all in low grade metamorphic rocks, particularly metamorphosed volcanic rocks and Fe–Al rich shales.

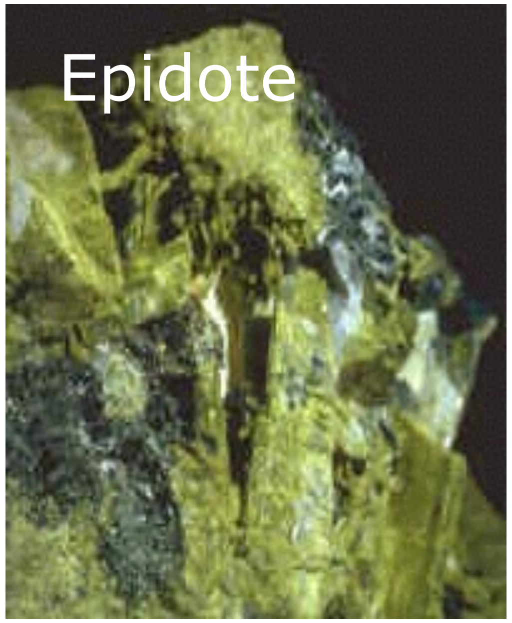
Both Clinozoisite and epidote occur as alteration products of plagioclase and as veins in granitic rocks.

Physical Properties: prismatic vitreous crystals to very fine resinous massive granules; H: 6–7



Zoisite: Gray, greenish brown

Clinozoisite: Gray, pale yellow, pale green, colorless

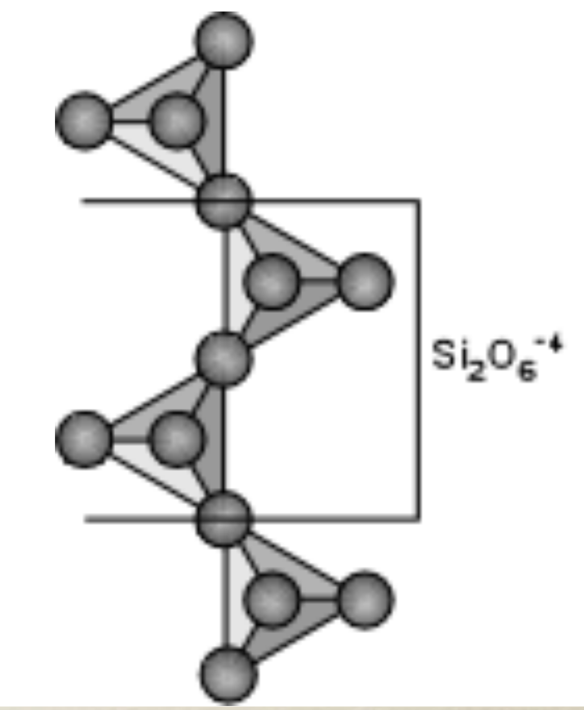


Epidote: Pistachio green to yellow green,

3. Inosilicates (Single chain)

If two of the oxygens are shared in a way to make long single chains of linked SiO_4 tetrahedra.

In this case the basic structural unit is **$Si_2O_6^{-4}$** or **SiO_3^{-2}**.



This group is the basis for the pyroxene group of minerals, like the orthopyroxenes $(Mg,Fe)SiO_3$ or the clinopyroxenes $Ca(Mg,Fe)Si_2O_6$.

- **Inosilicates**

Single chain inosilicates

1. Pyroxene group
    - Enstatite - orthoferrosilite series
        - Enstatite - $MgSiO_3$
        - Ferrosilite - $FeSiO_3$
    - Pigeonite - $Ca_{0.25}(Mg,Fe)_{1.75}Si_2O_6$
    - Diopside - hedenbergite series
        - Diopside - $CaMgSi_2O_6$
        - Hedenbergite - $CaFeSi_2O_6$
        - Augite - $(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$
    - Sodium pyroxene series
        - Jadeite - $NaAlSi_2O_6$
        - Aegirine (Acmite) - $NaFe^{3+}Si_2O_6$
    - Spodumene - $LiAlSi_2O_6$
2. Pyroxenoid group
    - Wollastonite - $CaSiO_3$
    - Rhodonite - $MnSiO_3$
    - Pectolite - $NaCa_2(Si_3O_8)(OH)$

Pyroxene group

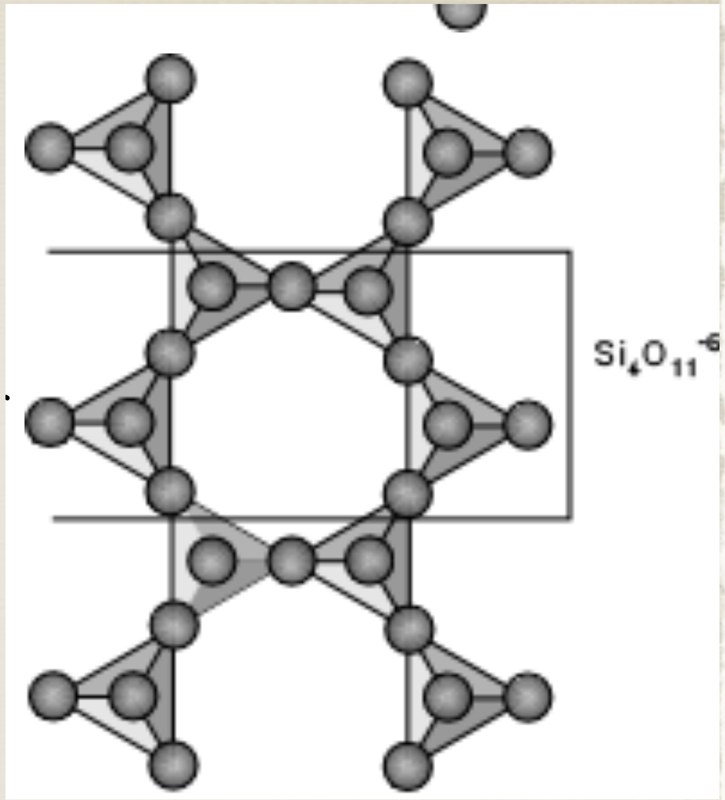
The pyroxenes can be divided into several groups based on chemistry and crystallography:

1. **Orthorhombic Pyroxenes (Orthopyroxenes – Opx):** these consist of a range of compositions between **enstatite – $MgSiO_3$ and ferrosilite – $FeSiO_3$**

2. **Monoclinic Pyroxenes (Clinopyroxenes – Cpx):** the **Diopside– Hedenbergite series – Diopside ($CaMgSi_2O_6$) – Ferrohedenbergite ($CaFeSi_2O_6$)**

The Sodic Pyroxenes – **Jadeite** ($NaAlSi_2O_6$) and **Aegerine** ($NaFe^{+3}Si_2O_6$)

3. Inosilicates (Double chain)



If two chains are linked together so that each tetrahedral group shares 3 of its oxygens, we can from double chains, with the basic structural group being **$Si_4O_{11}^{-6}$**.

The amphibole group of minerals are double chain silicates, for example the tremolite – ferroactinolite series– $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$.

Double chain inosilicates

1. Amphibole group

- Anthophyllite – $(Mg,Fe)_7Si_8O_{22}(OH)_2$
- Cumingtonite series
  - Cummingtonite – $Fe_2Mg_5Si_8O_{22}(OH)_2$
  - Grunerite – $Fe_7Si_8O_{22}(OH)_2$
- Tremolite series
  - Tremolite – $Ca_2Mg_5Si_8O_{22}(OH)_2$
  - Actinolite – $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
- Hornblende – $(Ca,Na)_{2-3}(Mg,Fe,Al)_5Si_6(Al,Si)_2O_{22}(OH)_2$
- Sodium amphibole group
  - Glaucophane – $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
  - Riebeckite (asbestos) – $Na_2Fe^{2+}{}_3Fe^{3+}{}_2Si_8O_{22}(OH)_2$
  - Arfvedsonite – $Na_3(Fe,Mg)_4FeSi_8O_{22}(OH)_2$

Amphiboles

Hornblende is the most common amphibole and has more in common with the **Tremolite** – Ferroactinolite series.

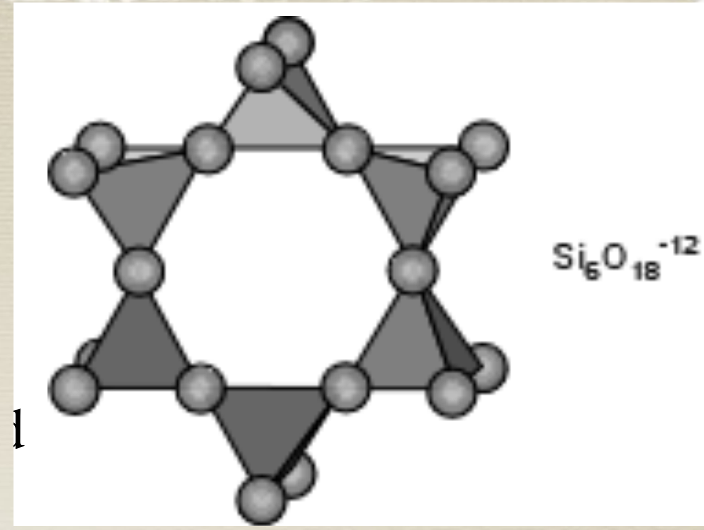
The sodic amphiboles have the following formulae:

Glaucophane – $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$

Riebeckite – $Na_2Fe_3^{+2}Fe_2^{+3}Si_8O_{22}(OH)_2$

Arfvedsonite – $NaNa_2Fe_4^{+2}Fe^{+3}Si_8O_{22}(OH)_2$

All of the amphiboles except Anthophyllite are monoclinic



4. Cyclosilicates (Ring Silicates)

If two of the oxygens are shared and the structure is arranged in a ring.

Six membered ring forming the structural group $\mathbf{Si_6O_{18}^{-12}}$. Three membered rings, $\mathbf{Si_3O_9^{-6}}$, four membered rings, $\mathbf{Si_4O_{12}^{-8}}$**,** and five membered rings $\mathbf{Si_5O_{15}^{-10}}$ are also possible.

A good example of a cyclosilicate is the mineral Beryl – $Be_3Al_2Si_6O_{18}$.

- **Cyclosilicates**

- 3-member ring
  - Benitoite - $BaTi(Si_3O_9)$
- 6-member ring
  - Axinite - $(Ca,Fe,Mn)_3Al_2(BO_3)(Si_4O_{12})(OH)$
  - Beryl/Emerald - $Be_3Al_2(Si_6O_{18})$
  - Cordierite - $(Mg,Fe)_2Al_3(Si_5AlO_{18})$
  - Tourmaline - $(Na,Ca)(Al,Li,Mg)_{3-}(Al,Fe,Mn)_6(Si_6O_{18}(BO_3)_3(OH)_4$

Cyclosilicates

The most common minerals based on this structure are **Beryl, Cordierite, and Tourmaline**.

Beryl forms different <u>gemstones</u> depending on color

Tourmaline is a common mineral in pegmatites (SiO_2 – rich igneous rocks with large grain size), where it is associated with quartz and alkali feldspar.

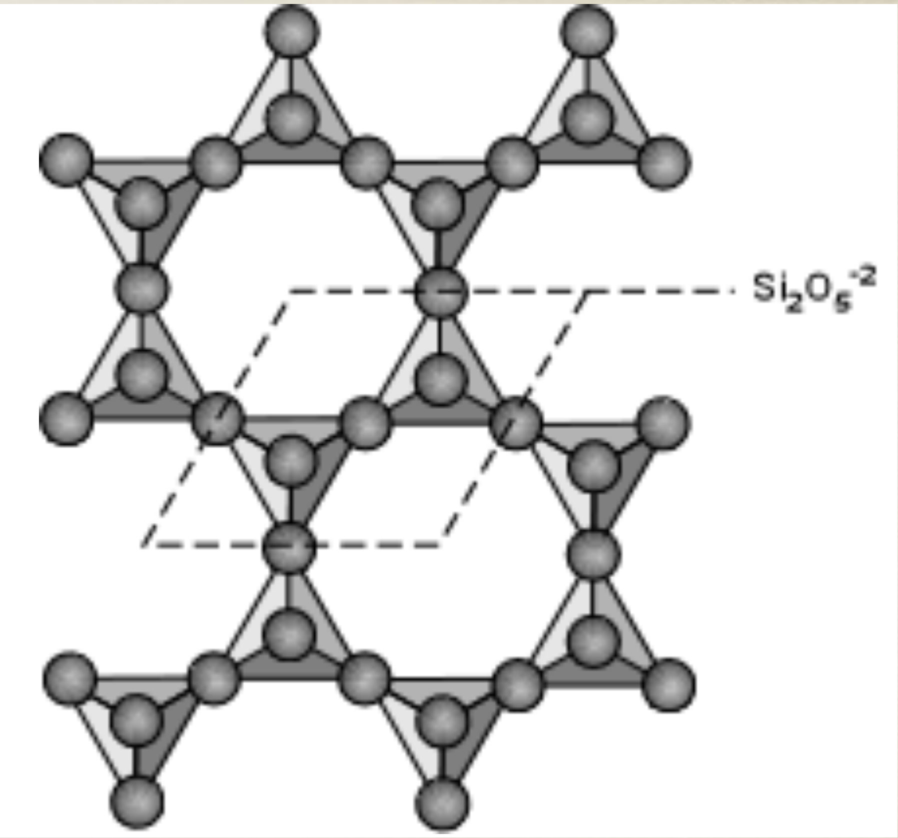
5. Phyllosilicates (Sheet Silicates)

If 3 of the oxygens from each tetrahedral group are shared such that an infinite sheet of SiO_4 tetrahedra are shared.

In this case the basic structural group is $Si_2O_5^{-2}$.

The micas, clay minerals, chlorite, talc, and serpentine minerals are all based on this structure.

A good example is biotite – $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$.



- # Phylosilicates

1. Serpentine group
    - Antigorite - $Mg_3Si_2O_5(OH)_4$
    - Chrysotile - $Mg_3Si_2O_5(OH)_4$
    - Lizardite - $Mg_3Si_2O_5(OH)_4$
2. Clay mineral group
    - Halloysite - $Al_2Si_2O_5(OH)_4$
    - Kaolinite - $Al_2Si_2O_5(OH)_4$
    - Illite - $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$
    - Montmorillonite - $(Na,Ca)_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$
    - Vermiculite - $(MgFe,Al)_3(Al,Si)_4O_{10}(OH)_2 \cdot 4H_2O$
    - Talc - $Mg_3Si_4O_{10}(OH)_2$
    - Palygorskite - $(Mg,Al)_2Si_4O_{10}(OH) \cdot 4(H_2O)$
3. Mica group
    - Biotite - $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$
    - Muscovite - $KAl_2(AlSi_3)O_{10}(OH)_2$
    - Phlogopite - $KMg_3(AlSi_3)O_{10}(OH)_2$
    - Lepidolite - $K(Li,Al)_{2\text{-}3}(AlSi_3)O_{10}(OH)_2$
    - Margarite - $CaAl_2(Al_2Si_2)O_{10}(OH)_2$
    - Glauconite - $(K,Na)(Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2$
4. Chlorite group
    - Chlorite - $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \bullet (Mg,Fe)_3(OH)_6$

Serpentine group of minerals has the formula – $Mg_3Si_2O_5(OH)_4$. Three varieties of serpentine are known. Antigorite and Lizardite are usually massive and fine grained, while Chrisotile is fibrous.

Mica Group

Muscovite, Paragonite, and Margarite are the white micas, and

Biotite and Clintonite (Xanthophyllite) the black mica.

Chlorite group has a structure that consists of phlogopite T–O–T layers. common mineral in low grade metamorphic rocks

Clay minerals: most common products of chemical weathering, and thus are the main constituents of the fine–grained sedimentary rocks called mudrocks (including mudstones, claystones, and shales).

the clay minerals can be divided in to three main classes:

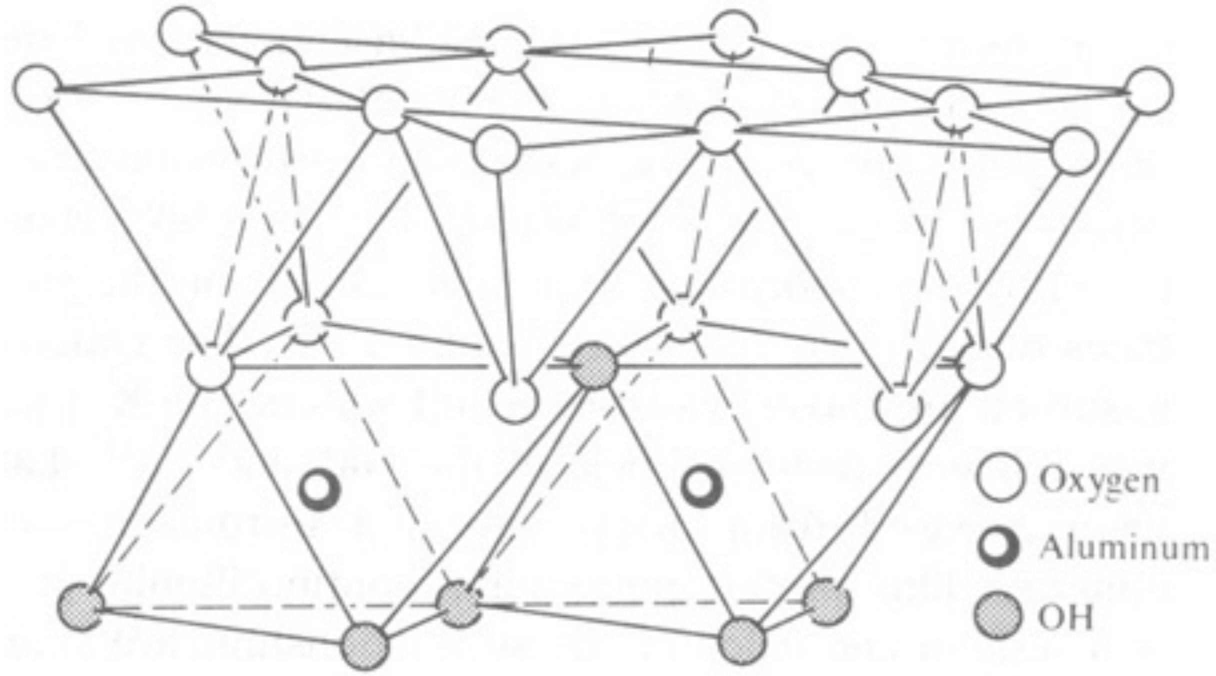
1. The kandites based on a structure similar to Kaolinite

2. The smectites based on a structure similar to Pyrophyllite

3. The illites based on a structure similar to Muscovite

Structure of Phyllosilicates

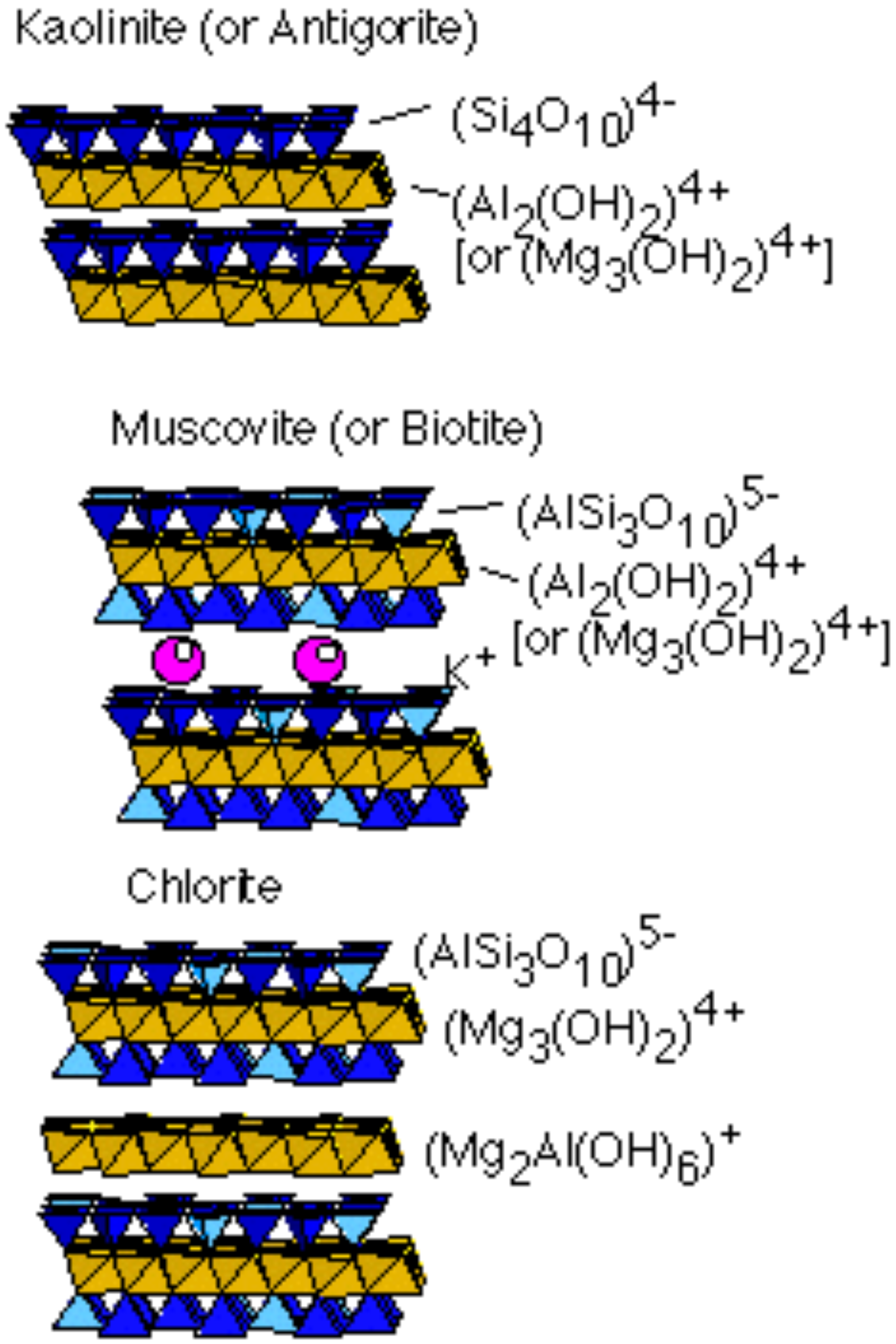
- Octahedral layer
  - Layer of octahedral coordinated
    - magnesium (brucite layer) or
    - Aluminum (gibbsite layer)
  - Makes up the other basic structural unit

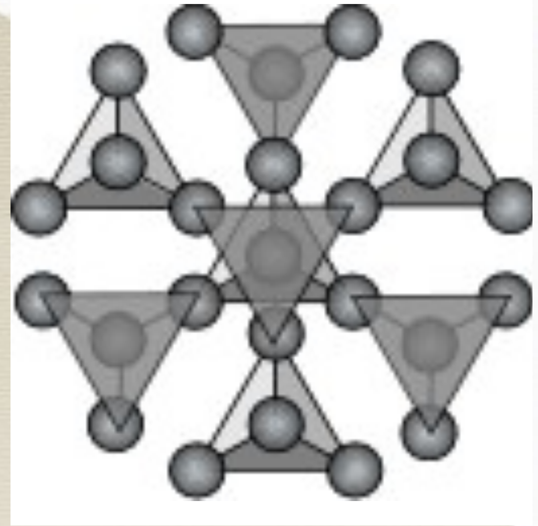


Kaolinite: $Al_2Si_2O_5(OH)_4$
1:1 tetrahedral – octahedral sheets

The Major Clay Mineral Groups

- Kaolinite group:
  - 1:1 TO clay minerals
- Mica (illite) group:
  - 2:1 TOT clay minerals
  - Expandible clays:
    - Smectite–montmorillonite complex 2:1 clay minerals
- Chlorite
  - Fe– and Mg–rich TOT clays





6. Tectosilicates (Framework Silicates)

If all of the corner oxygens are shared with another SiO_4 tetrahedron, then a framework structure develops.

The basic structural group then becomes **SiO_2**. The minerals quartz, cristobalite, and tridymite all are based on this structure.

If some of the Si^{+4} ions are replaced by Al^{+3} then, the feldspar and feldspathoid minerals are formed.

Tectosilicates

1. Quartz group
   - Quartz - SiO_2
   - Tridymite - SiO_2
   - Cristobalite - SiO_2
   - Coesite - SiO_2
2. Feldspar family
   - a. Alkali-feldspars (potassium-feldspars)
     - Microcline - $KAlSi_3O_8$
     - Orthoclase - $KAlSi_3O_8$
     - Anorthoclase - $(Na,K)AlSi_3O_8$
     - Sanidine - $KAlSi_3O_8$
     - Albite - $NaAlSi_3O_8$
   - b. Plagioclase feldspars
     - Albite - $NaAlSi_3O_8$
     - Oligoclase - $(Na,Ca)(Si,Al)_4O_8$ (Na:Ca 4:1)
     - Andesine - $(Na,Ca)(Si,Al)_4O_8$ (Na:Ca 3:2)
     - Labradorite - $(Na,Ca)(Si,Al)_4O_8$ (Na:Ca 2:3)
     - Bytownite - $(Na,Ca)(Si,Al)_4O_8$ (Na:Ca 1:4)
     - Anorthite - $CaAl_2Si_2O_8$

- **Tectosilicates**

3. Feldspathoid family
    - Nosean - $Na_8Al_6Si_6O_{24}(SO_4)$
    - Cancrinite - $Na_6Ca_2(CO_3,Al_6Si_6O_{24}).2H_2O$
    - Leucite - $KAlSi_2O_6$
    - Nepheline - $(Na,K)AlSiO_4$
    - Sodalite - $Na_8(AlSiO_4)_6Cl_2$
        - Hauyne - $(Na,Ca)_{4\text{-}8}Al_6Si_6(O,S)24(SO_4,Cl)_{1\text{-}2}$
    - Lazurite - $(Na,Ca)_8(AlSiO_4)_6(SO_4,S,Cl)_2$
- Petalite - $LiAlSi_4O_{10}$
- Scapolite group
    - Marialite - $Na_4(AlSi_3O_8)_3(Cl_2,CO_3,SO_4)$
    - Meionite - $Ca_4(Al_2Si_2O_8)_3(Cl_2CO_3,SO_4)$
- Analcime - $NaAlSi_2O_6 \cdot H_2O$

4. Zeolite family
    - Natrolite - $Na_2Al_2Si_3O_{10} \cdot 2H_2O$
    - Chabazite - $CaAl_2Si_4O_{12} \cdot 6H_2O$
    - Heulandite - $CaAl_2Si_7O_{18} \cdot 6H_2O$
    - Stilbite - $NaCa_2Al_5Si_{13}O_{36} \cdot 17H_2O$
    - Scolecite - $CaAl_2Si_3O_{10}.3H_2O$
    - Mordenite - $(Ca,Na_2,K_2)Al_2Si_{10}O_{24} \cdot 7H_2O$

SiO_2 Minerals

Stishovite and Coesite are high pressure forms of SiO_2

At low pressure with decreasing temperature, SiO_2 polymorphs change from high Cristobalite – Low Cristobalite – High Tridymite – Low Tridymite – High Quartz – Low Quartz.

Opal is amorphous, and thus a mineraloid.

Feldspars

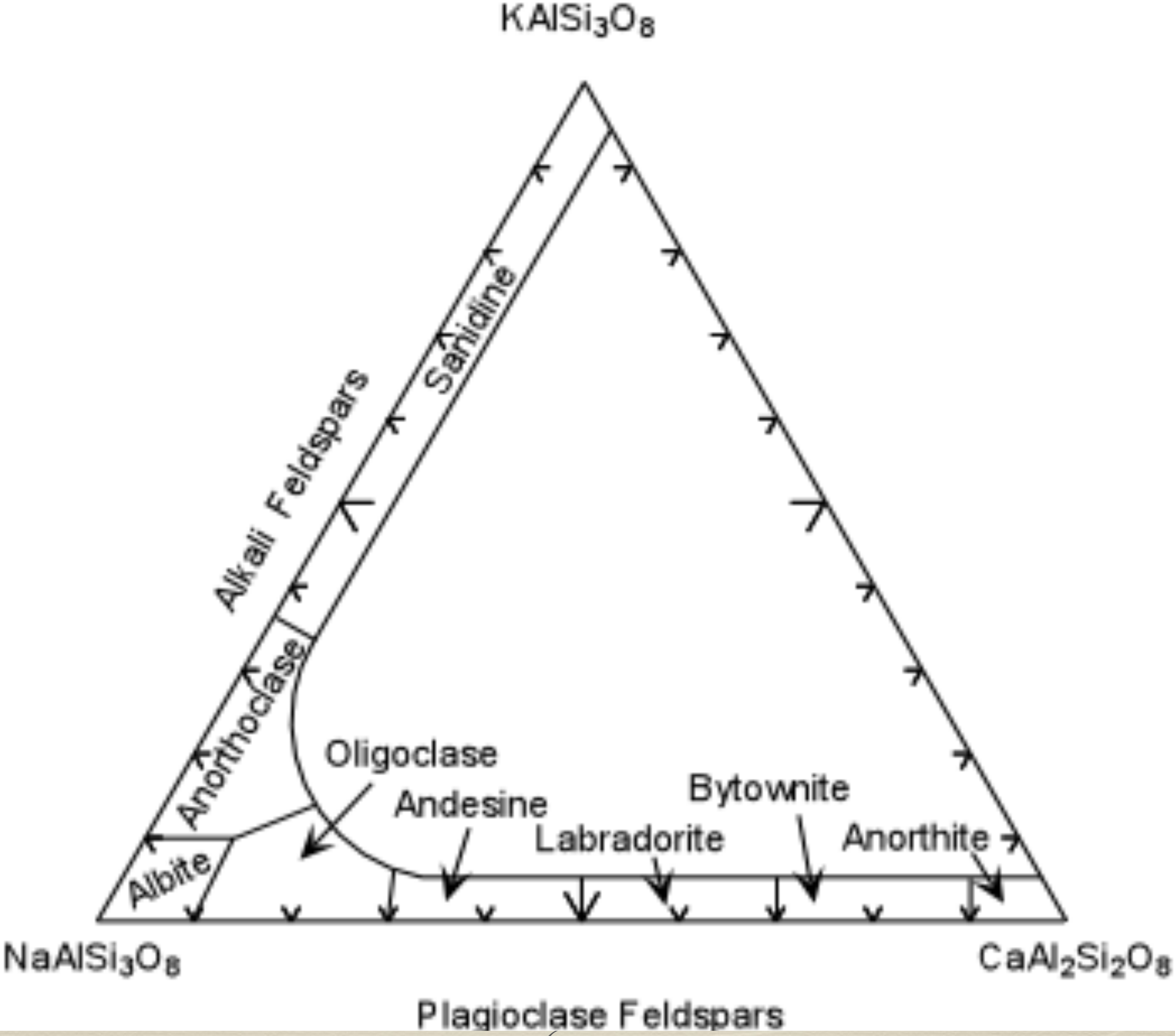
The feldspars are the most common minerals in the Earths crust.

They consist of three end–members:

$KAlSi_3O_8$ – Orthoclase (or), $NaAlSi_3O_8$ – Albite (ab), and $CaAl_2Si_2O_8$ –Anorthite (an)

Feldspathoids

The feldspathoid group of minerals are SiO_2 poor, alkali rich minerals that occur in low SiO_2, high Na_2O – K_2O igneous rocks. The main feldspathoids are Nepheline $(Na,K)AlSiO_4$, Kalsilite $KAlSi_2O_6$, and Leucite $KAlSi_2O_6$.


$KAlSi_3O_8$
Alkali Feldspars
Sanidine
Anorthoclase
Albite
Oligoclase
Andesine
Labradorite
Bytownite
Anorthite
$NaAlSi_3O_8$
$CaAl_2Si_2O_8$
Plagioclase Feldspars

General Formula for Silicates

$$X_mY_n(Z_pO_q)W_r$$

where **X** represents an 8 to 12 fold coordination site for large cations like K^+, Rb^+, Ba^{+2}, Na^+, and Ca^{+2}.

Y represents a 6–fold (octahedral) site for intermediate sized cations like Al^{+3}, Mg^{+2}, Fe^{+2}, Fe^{+3}, Mn^{+2}, and Ti^{+4}.

Z represents the tetrahedral site containing Si^{+4}, and Al^{+3}.

O is oxygen,and **W** is a hyrdoxyl (OH^{-1}) site into which can substitute large anions like F^{-1} or Cl^{-1}.

The subscripts m, n, r, p, and q and are chosen to maintain charge balance.

This is summarized in the table shown here. In this table note that there is very little substitution that takes place between ions that enter the X, Y, and Z sites.

The exceptions are mainly

substitution of Al^{+3} for Si^{+4}, which is noted in the Table, and whether the X site is large enough to accept the largest cations

like K^{+1}, Ba^{+2}, or Rb^{+1}.

Site	C.N.	Ion
Z	4	Si^{+4}
		Al^{+3}
Y	6	Al^{+3}
		Fe^{+3}
		Fe^{+2}
		Mg^{+2}
		Mn^{+2}
		Ti^{+4}
X	8	Na^{+1}
		Ca^{+2}
	8 - 12	K^{+1}
		Ba^{+2}
		Rb^{+1}

2. Non-Silicate Minerals

- **Oxides**
- **Sulfides**
- **Sulfates**
- **Native Elements**
- **Carbonates**
- **Halides**
- **Phosphates**

- Many nonsilicate minerals have economic value and deposited as ore.
- Examples
  - Hematite (oxide mined for iron ore)
  - Halite (halide mined for salt)
  - Sphalerite (sulfide mined for zinc ore)
  - Native Copper (native element mined for copper)

- **Oxide Minerals**: have oxygen (O) as anion. They include magnetite, hematite, spinel, chromite, chrysoberyl, cuprite, corundum, ilmenite, rutile, uranitite and others.

- **Hydroxides**: have OH as anions. They make a relatively small group, which includes three groups of minerals: limonites (goethite, lepidocrocite), bauxites (gibbsite, diaspore) and (manganese oxide and some hydroxide minerals).

- **Sulfate Minerals**: have SO4 as anion. They include gypsum, anhydrite, barite, and others.

- **Sulfides**: have S as anion, and the group includes sphalerite, galena, pyrite, chalcopyrite, arsenopyrite, pyrrhotite, cinnabar, marcasite, molybdenite, bornite, chalcosite, covellite and others.

- **Native elements**: include gold, silver, copper, nickel, zinc, lead, sulfur, diamond, mercury, iron, platinum, arsenic, bismuth, antimony and others

- **Carbonates**: have CO3 as anion. They are easy to identify because they react to hydrochloric acid include calcite, magnesite, siderite, rhodocrosite, dolomite, aragonite, azurite and malachite.

- **Halide Minerals** : have one of the halogens (fluorine, chlorine, bromine, iodine and astatine) as anions. The group includes halite (rock salt), fluorite, sylvite, atacamite, …
- **Phosphate Minerals**: have PO4 as aniones. The group includes apatite, monazite, arsenite, turquoise, vanadite and others.
- **Mineraloids Group (Non-Crystalline Minerals)**

Opal

Pearl contain the mineral "calcium carbonate" but the structure is bonded together by organic materials.

Obsidian is not a "crystal" but is instead amorphous-glass.

Amber is a heterogeneous composite with a "gem-like" appearance, but consists of resinous bodies that are soluble in alcohol.

Accessory minerals: a constituent mineral present in small quantity and not taken into account in identifying a rock.

The oxide minerals are very common and usually occur as accessory minerals in all kinds of rocks, include:

Corundum – Al_2O_3

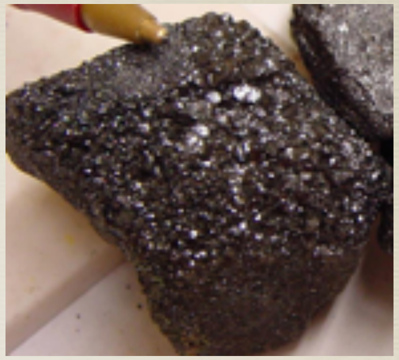
Corundum is hexagonal and occurs in Al–rich igneous and metamorphic rocks.

Spinel – $MgAl_2O_4$

isometric mineral that occurs ultrabasic rocks like peridotite, and in many low silica ignoeous rocks like basalts. It is also found in Al–rich contact metamorphic rocks.

Chromite – $Fe^{+2}Cr_2O_4$

Chromite is isometric, and usually opaque in thin section. It is found in low silica, Mg–rich igneous rocks, usually associated with Olivine as small inclusions.

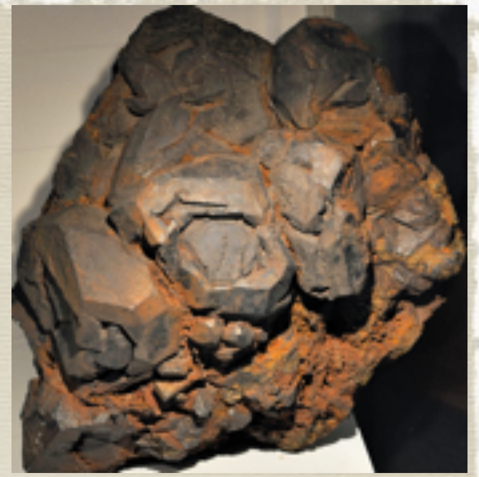


Magnetite – Fe_3O_4

found as an accessory mineral in all rock types. It is isometric and commonly crystallizes with an octahedral habit.

Hematite – Fe_2O_3

Hematite is one of the most important ores of Fe. It is more oxidized than Magnetite, and thus forms as an alteration product of magnetite. Hematite is hexagonal as massive habit.



Ilmenite – $FeTiO_3$

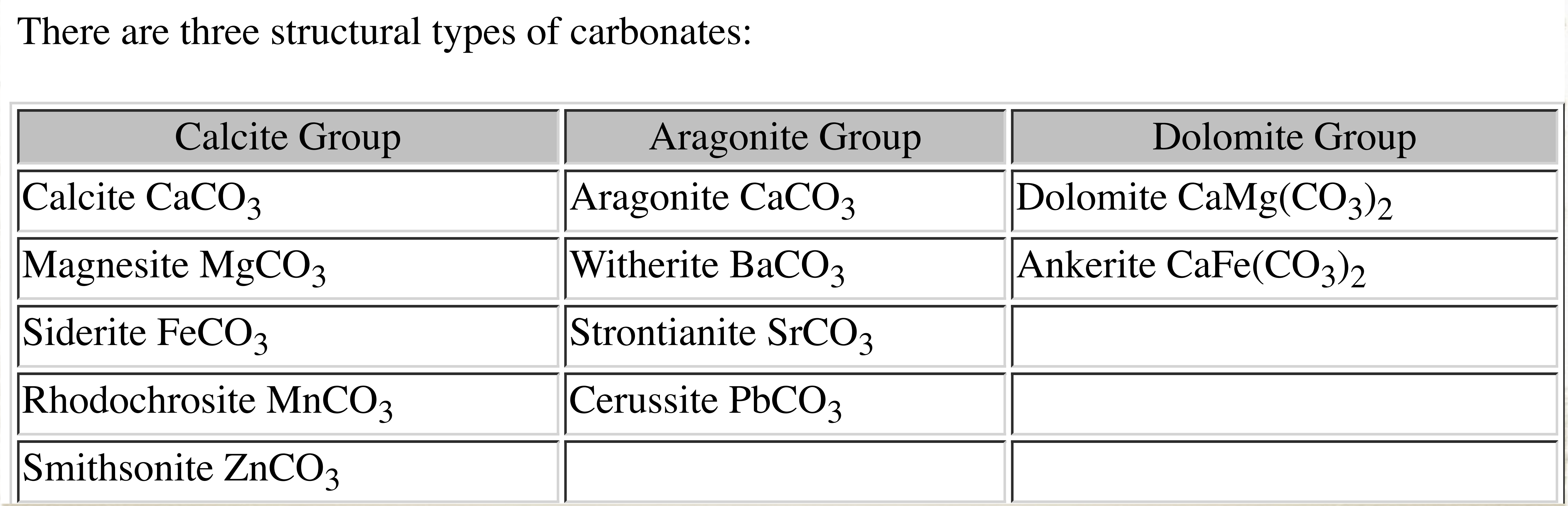
found as a common accessory mineral in a wide range of igneous volcanic and plutonic rocks, as well as metamorphic and clastic sedimentary rocks.

Apatite Ca5(PO4)3(OH,F)

Apatite is another very common accessory mineral in igneous rocks and many metamorphic rocks.

Carbonates

an important group of minerals near the Earths surface. Carbonate minerals make up the bulk of limestones and dolostones in clastic sedimentary rocks.



There are three structural types of carbonates:

Calcite Group	Aragonite Group	Dolomite Group
Calcite $CaCO_3$	Aragonite $CaCO_3$	Dolomite $CaMg(CO_3)_2$
Magnesite $MgCO_3$	Witherite $BaCO_3$	Ankerite $CaFe(CO_3)_2$
Siderite $FeCO_3$	Strontianite $SrCO_3$	
Rhodochrosite $MnCO_3$	Cerussite $PbCO_3$	
Smithsonite $ZnCO_3$		

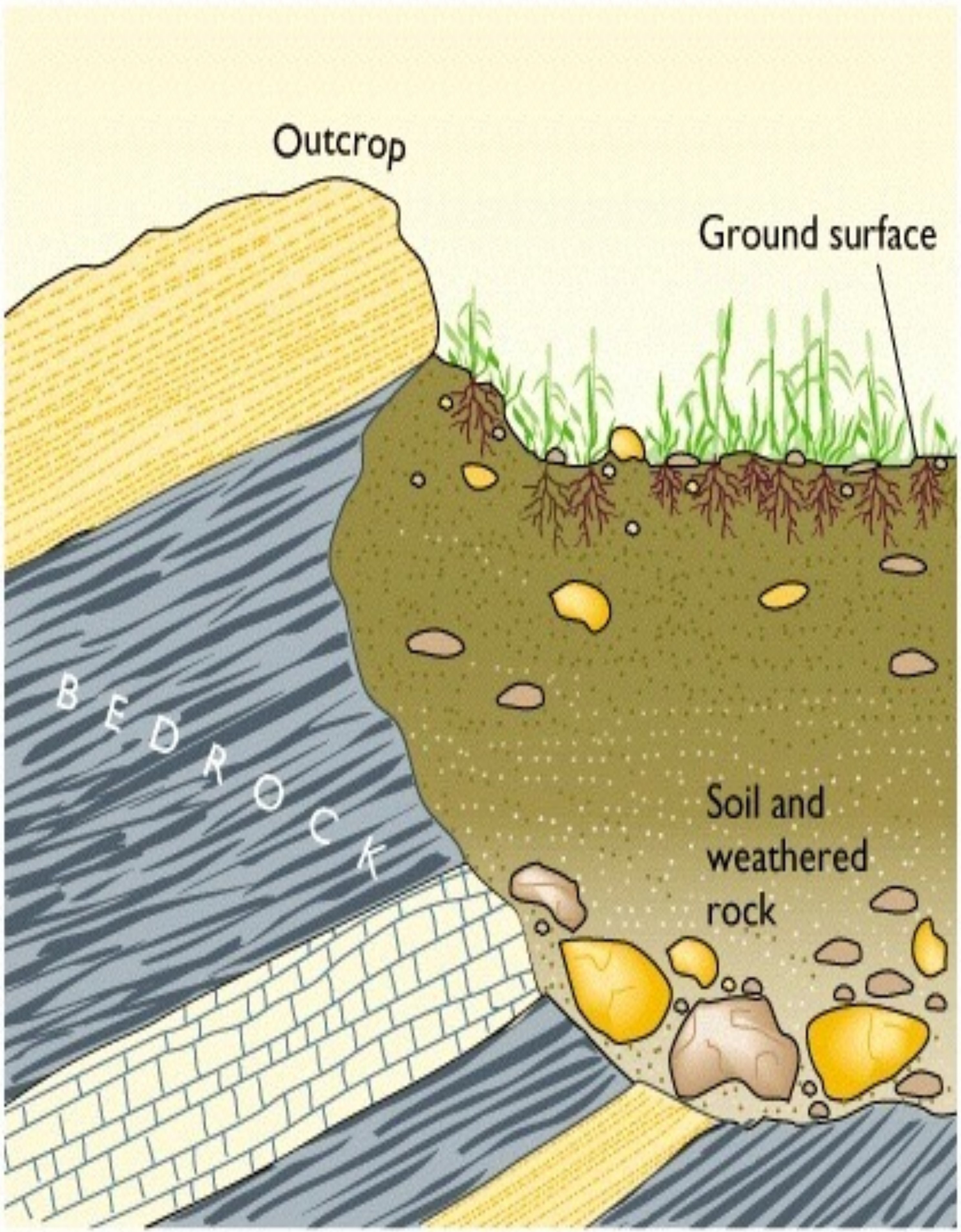
In addition, there are the hydroxyl Cu carbonates – Malachite, $Cu_2CO_3(OH)_2$ and Azurite $Cu_3(CO_3)_2(OH)_2$.

Mineral Weathering

Geologists recognize two categories of weathering processes

1. **Physical Weathering** – disintegration of rocks and minerals by a physical or **mechanical** process.
2. **Chemical Weathering** – chemical alteration or decomposition of rocks and minerals.

Although we separate these processes, both work together to break down rocks and minerals to smaller fragments or to minerals more stable near the Earths surface.



Weathering: decomposition and disintegration of rock

Product of weathering is <u>regolith or soil</u>

Regolith or soil that is transported is called <u>sediment</u>

Movement of sediment is called <u>erosion</u>

Physical Weathering

Physical weathering takes place by a variety of processes. Among them are:

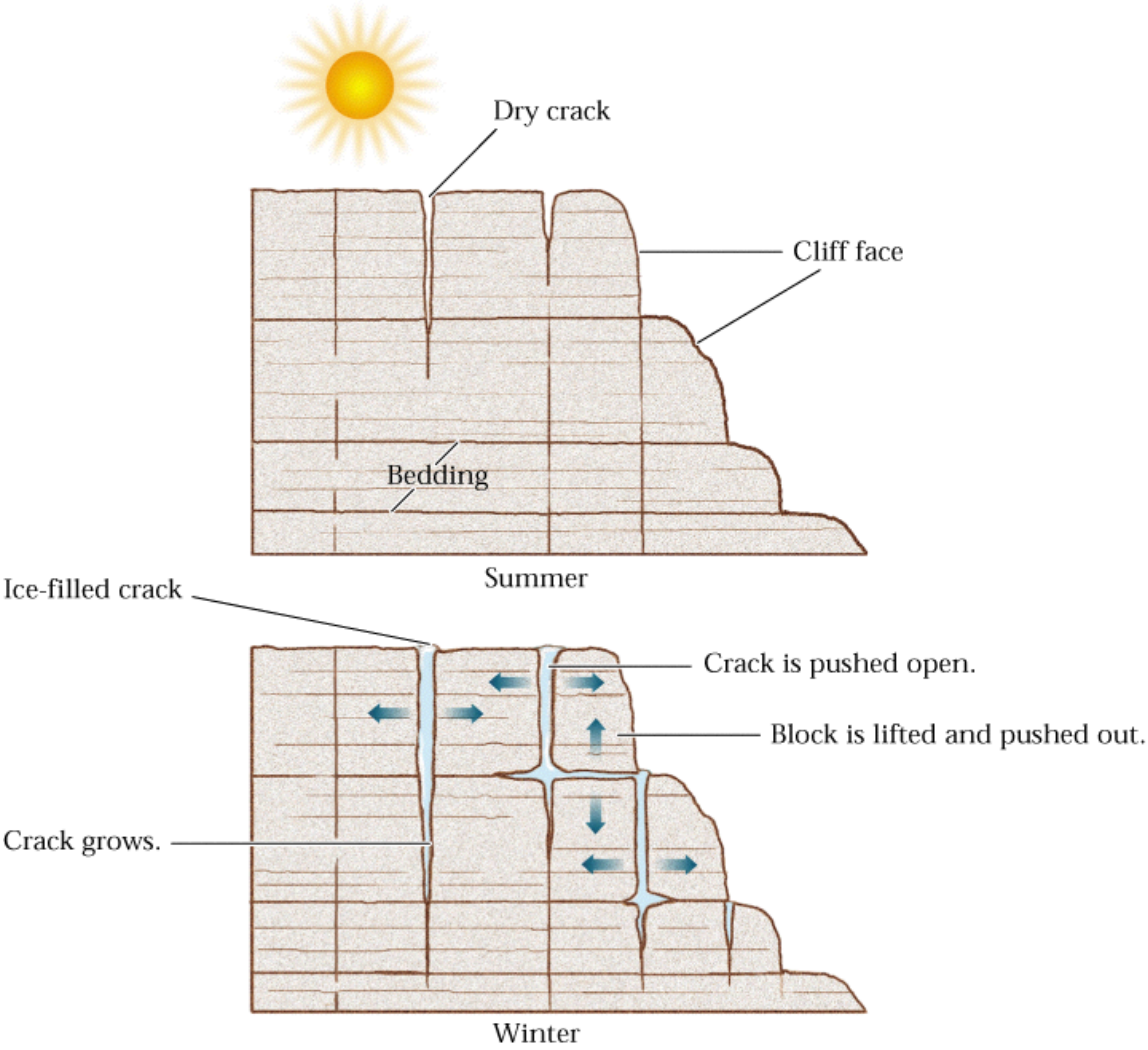
- **Development of Joints** – Joints are regularly spaced fractures or cracks in rocks that show no offset across the fracture (fractures that show an offset are called faults).

– Joints form as a result of **expansion** due to cooling or relief of pressure as overlying rocks are removed by erosion.

- **Crystal Growth** – As water percolates through fractures and pore spaces it may contain ions that precipitate to form crystals. As these crystals grow they may exert an outward force that can expand or weaken rocks.
- **Heat** – daily heating and cooling of rocks
- **Plant and Animal Activities** –

  – Plant roots can extend into fractures and grow, causing expansion of the fracture.

– Animals burrowing or moving through cracks can break rock.

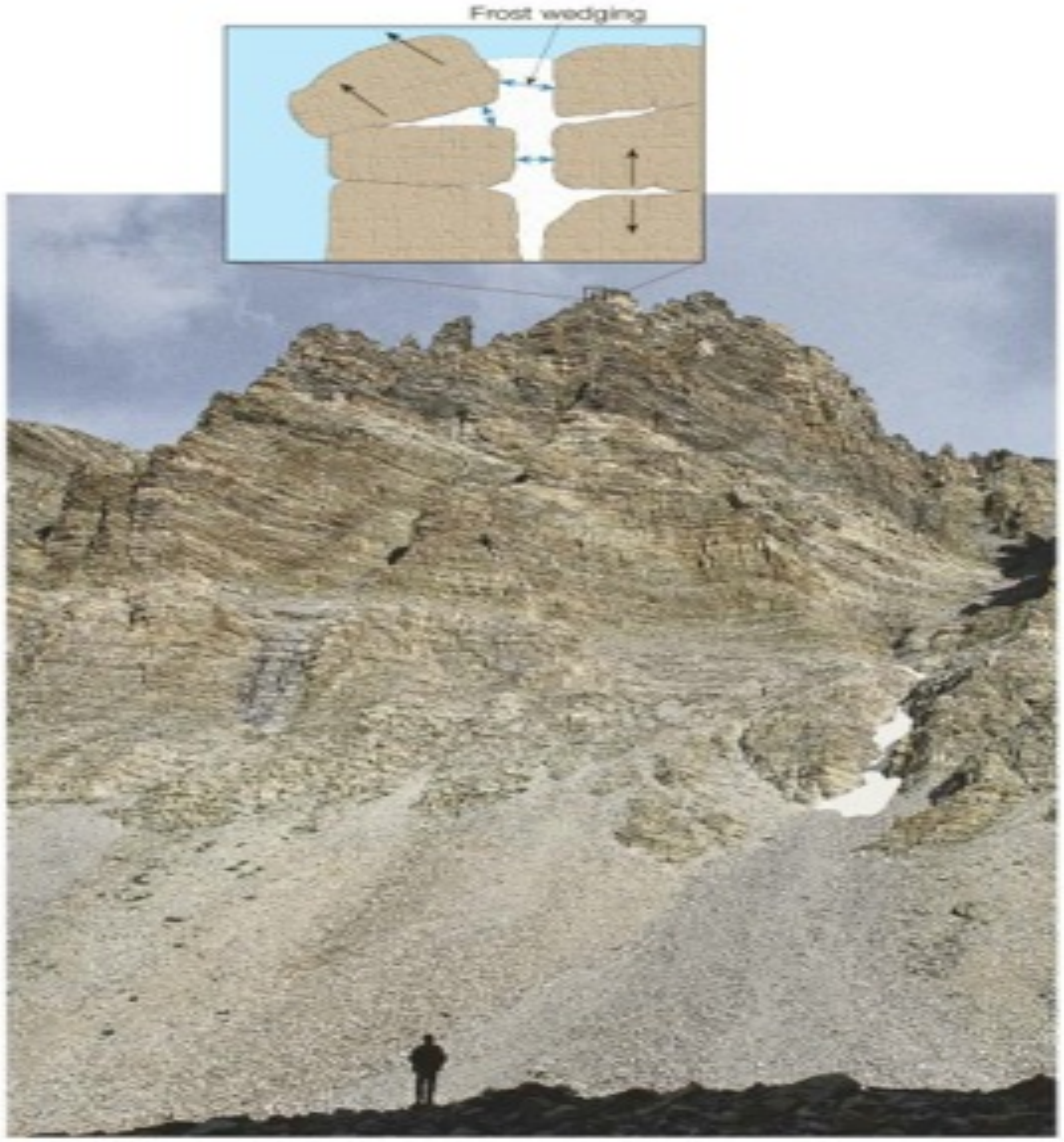

Dry crack
Cliff face
Bedding
Summer
Ice-filled crack
Crack is pushed open.
Block is lifted and pushed out.
Crack grows.
Winter

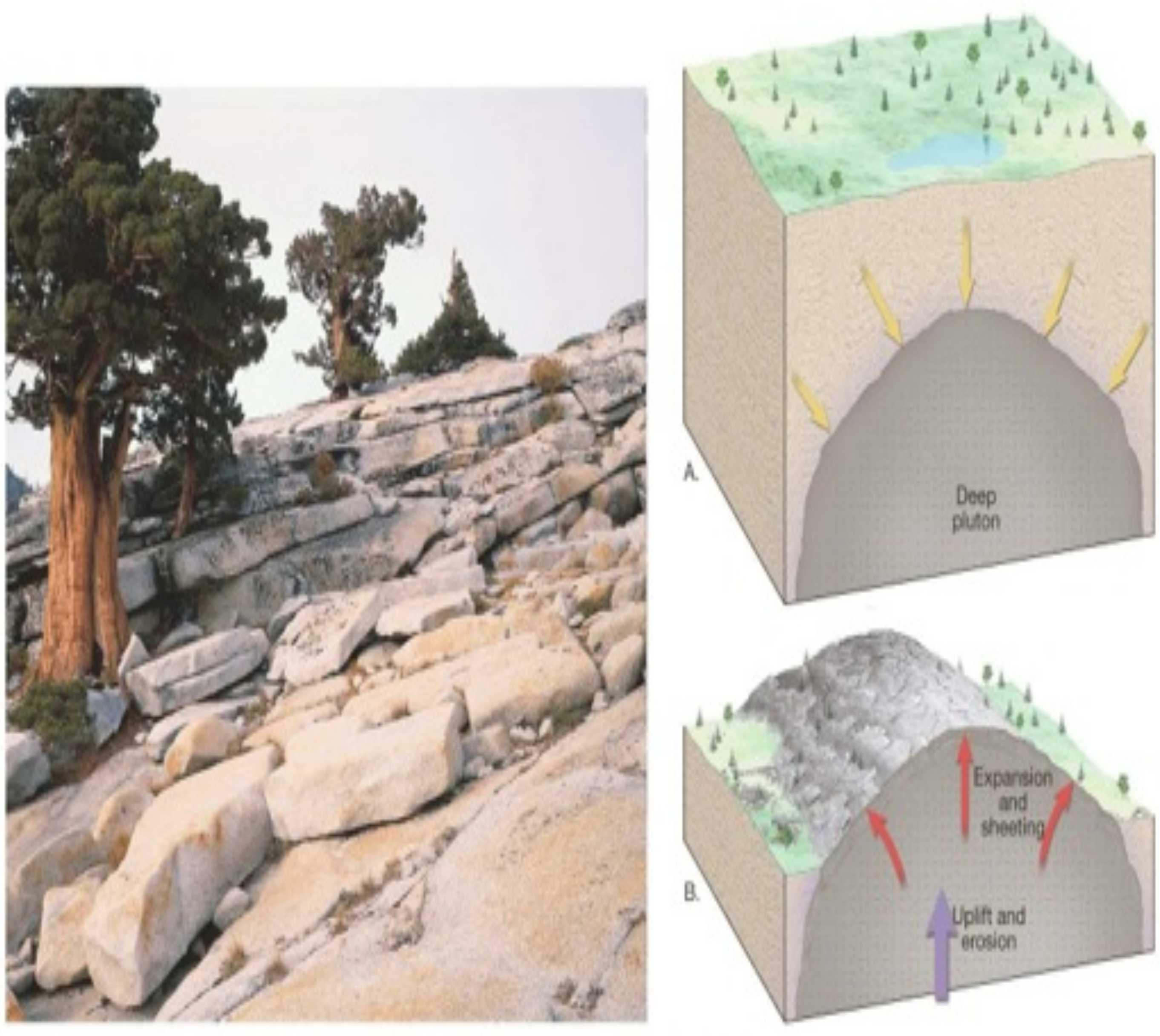
- **Frost Wedging** – Upon freezing, there is an increase in the volume of the water.

As the water freezes it expands and exerts a force on its surroundings.

Frost wedging is more prevalent at high altitudes where there may be many freeze–thaw cycles.

Mechanical Weathering





- **Frost wedging**
- **Alternate heating and cooling**

- **Decompression causes jointing**

Chemical Weathering

when rocks arrive near the surface as a result of uplift and erosion, they encounter conditions very different from those under which they originally formed:

- Lower Temperature (Near the surface T = –20 to 50^{O}C)

  Lower Pressure (Near the surface P = 1 to several hundred atmospheres)

- Higher free water (there is a lot of liquid water near the surface, compared with deep in the Earth)

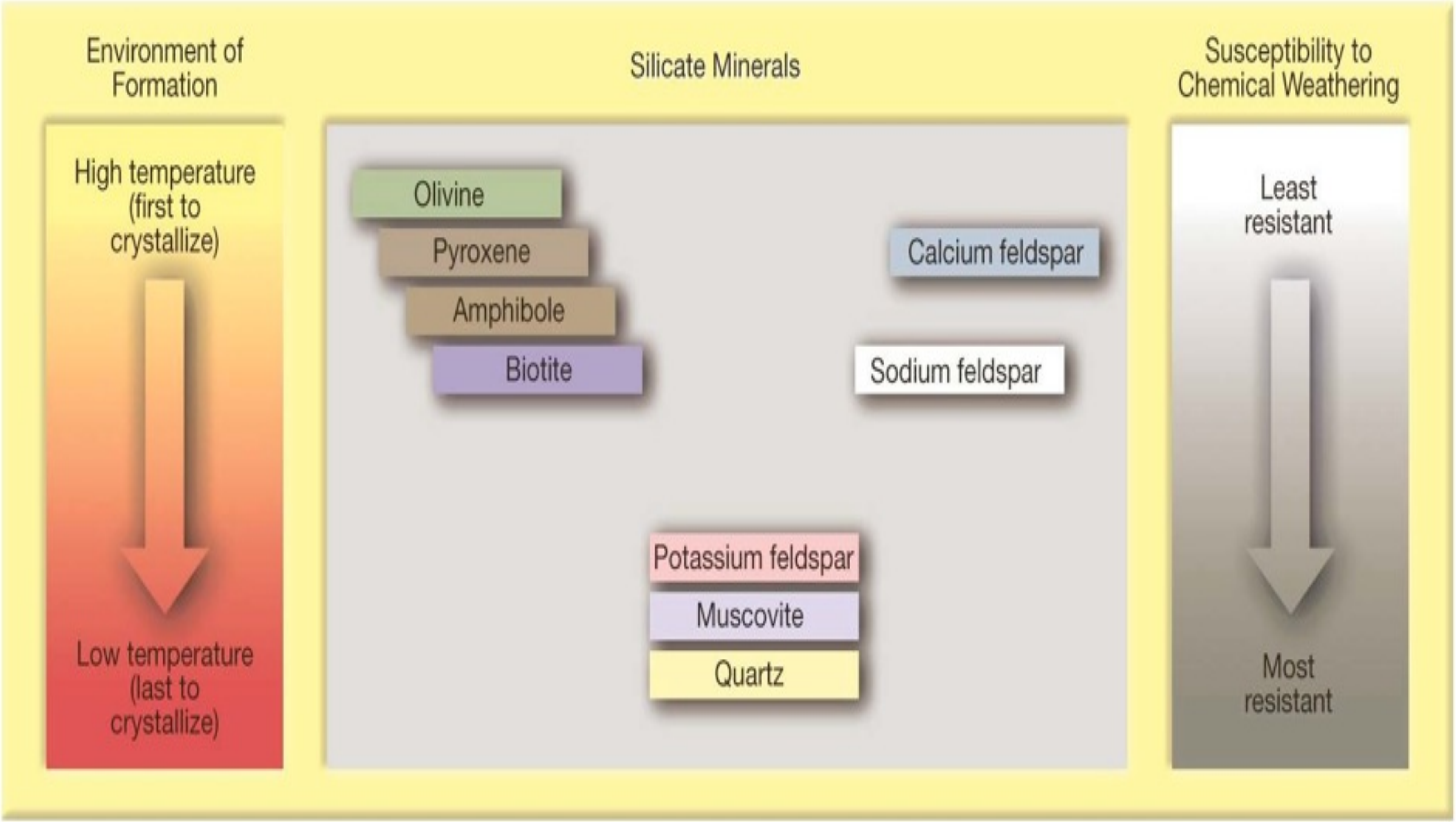
- Higher free oxygen (although O_2 is the most abundant element in the crust, most of it is tied up in silicate and oxide minerals – at the surface there is much more free oxygen, particularly in the atmosphere).

Because of these differing conditions, minerals in rocks react with their new environment to produce new minerals that are stable under conditions near the surface.

Minerals that are stable under P, T, H_2O, and O_2 conditions near the surface are, in order of most stable to:

- Iron oxides, Aluminum oxides – such as hematite Fe_2O_3, an gibbsite $Al(OH)_3$.
- Quartz*
- Clay Minerals
- Muscovite*
- Alkali Feldspar*
- Biotite*
- Amphiboles*
- Pyroxenes*
- Ca–rich plagioclase*
- Olivine*

Controls on rates of weathering

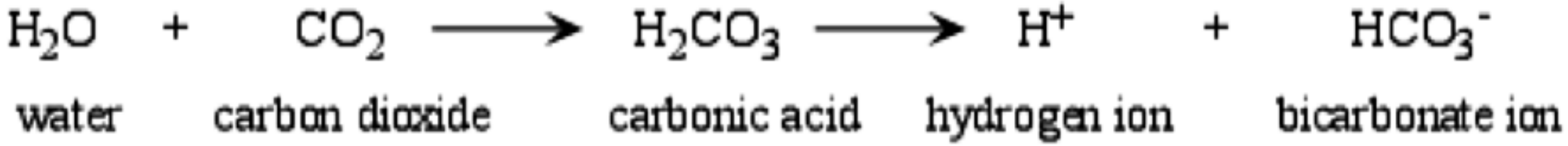


The main agent responsible for chemical weathering reactions is water and weak acids formed in water.

An acid is solution that has abundant free H^+ ions.

The most common weak acid that occurs in surface waters is **carbonic acid**.

Carbonic acid is produced in rainwater by reaction of the water with carbon dioxide (CO_2) gas in the atmosphere.



$$H_2O + CO_2 \longrightarrow H_2CO_3 \longrightarrow H^+ + HCO_3^-$$

Types of Chemical Weathering Reactions

- **Oxidation** – Since free oxygen (O_2) is more common near the Earths surface, it may react with minerals to change the oxidation state of an ion.

This is more common in Fe (iron) bearing minerals, since Fe can have several oxidation states, Fe, Fe^{+2}, Fe^{+3}.

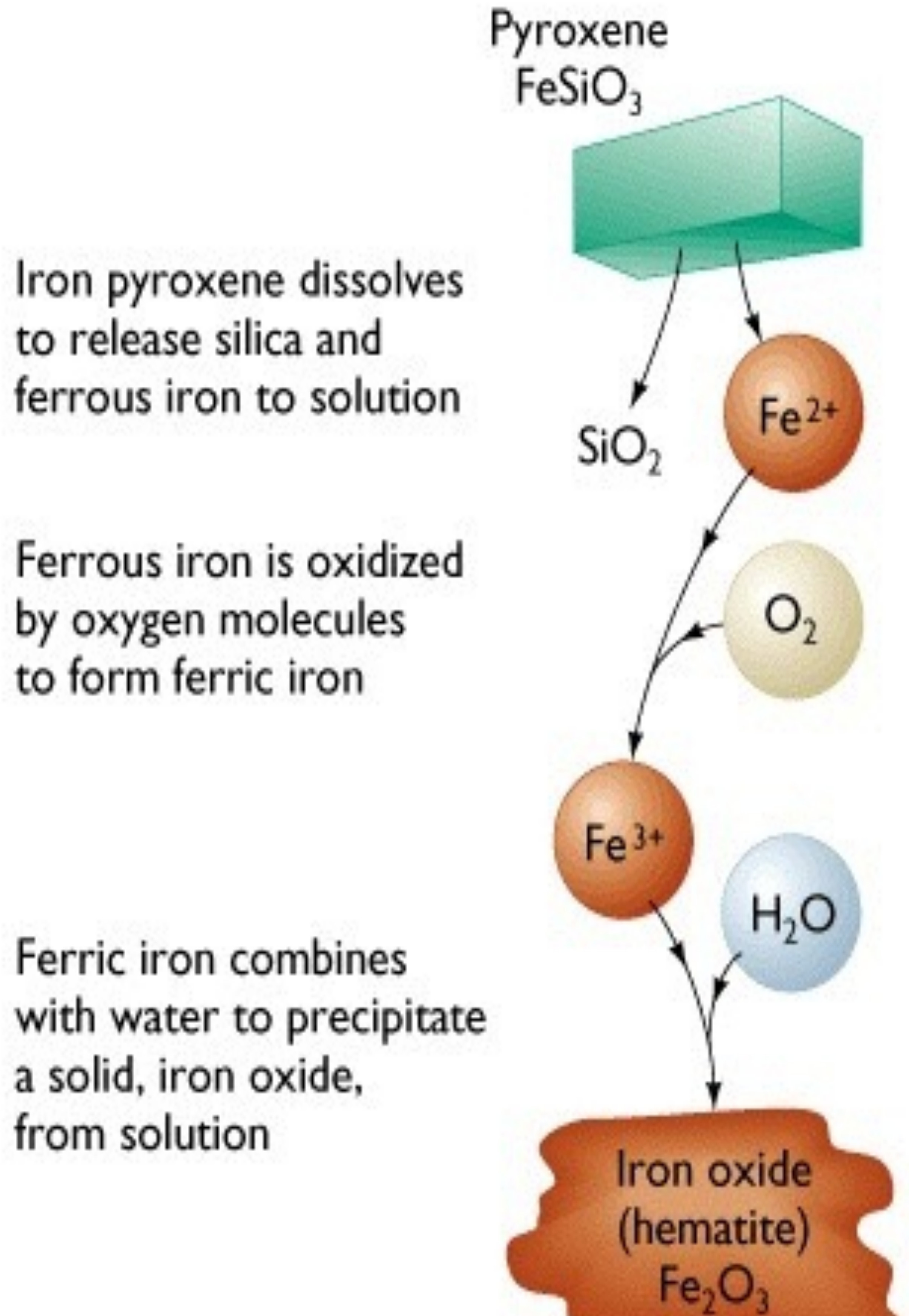
$$\underset{\text{Pyroxene}}{3Fe^{+2}SiO_3} + \underset{\text{Oxygen}}{1/2O_2} \longrightarrow \underset{\text{Magnetite}}{Fe_3O_4} + \underset{\text{Quartz}}{3SiO_2}$$

Dissolution – all of the mineral is completely dissolved by the water.

$$\underset{\text{Calcite}}{CaCO_3} + \underset{\text{Carbonic Acid}}{H_2CO_3} \longrightarrow \underset{\text{Calcium ion}}{Ca^{2+}} + \underset{\text{Bicarbonate ion}}{2(HCO_3)^-}$$

Oxidation

Oxidation can affect any iron bearing mineral, for example, ferromagnesian silicates which react to form hematite and limonite



Iron pyroxene dissolves to release silica and ferrous iron to solution

Ferrous iron is oxidized by oxygen molecules to form ferric iron

Ferric iron combines with water to precipitate a solid, iron oxide, from solution

Oxidation of pyrite and other sulfide minerals forms sulfuric acid which acidifies surface water and rain

Pyrite + oxygen + water = sulfuric acid + goethite
(iron sulfide) (iron oxide)

Hydrolysis – H^+ or OH^- replaces an ion in the mineral:

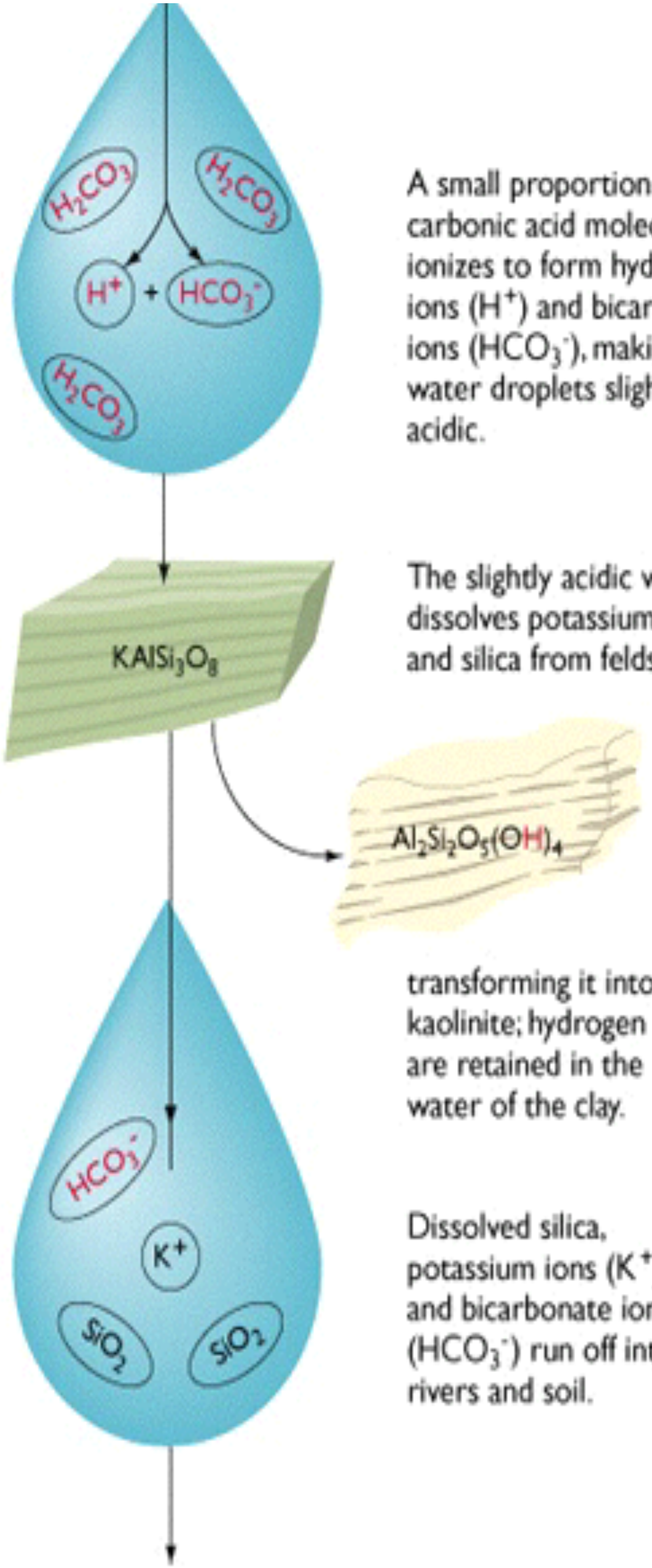
$$\underset{\text{Orthoclase}}{4KAlSi_3O_8} + \underset{\text{Hydrogen ion}}{4H^+} + \underset{\text{water}}{2H_2O} \longrightarrow \underset{\text{Potassium ion}}{4K^+} + \underset{\text{Kaolinite (clay mineral)}}{Al_4Si_4O_{10}(OH)_8} + \underset{\text{quartz}}{8\,SiO_2}$$

- **Leaching** – ions are removed by dissolution into water. In the example above we say that the K^+ ion was leached.

$$\underset{\text{Goethite}}{2FeO{\cdot}OH} \longrightarrow \underset{\text{Hematite}}{Fe_2O_3} + \underset{\text{water}}{H_2O}$$

- **Dehydration** – removal of H_2O or OH^- ion from a mineral.

Hydrolysis



A small proportion of carbonic acid molecules ionizes to form hydrogen ions (H^+) and bicarbonate ions (HCO_3^-), making the water droplets slightly acidic.

The slightly acidic water dissolves potassium ions and silica from feldspar,

transforming it into kaolinite; hydrogen ions are retained in the water of the clay.

Dissolved silica, potassium ions (K^+), and bicarbonate ions (HCO_3^-) run off into rivers and soil.

Products of weathering

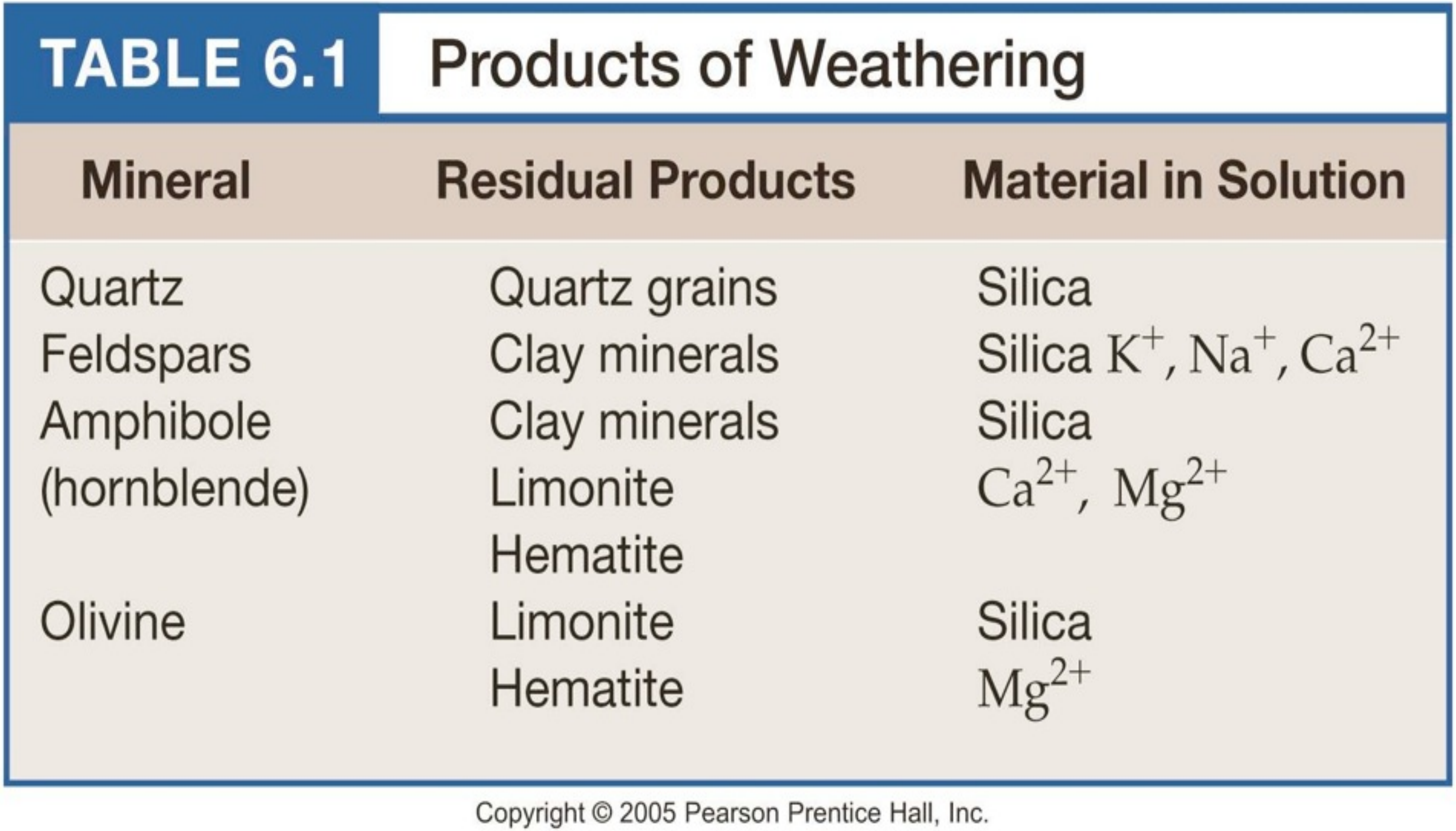
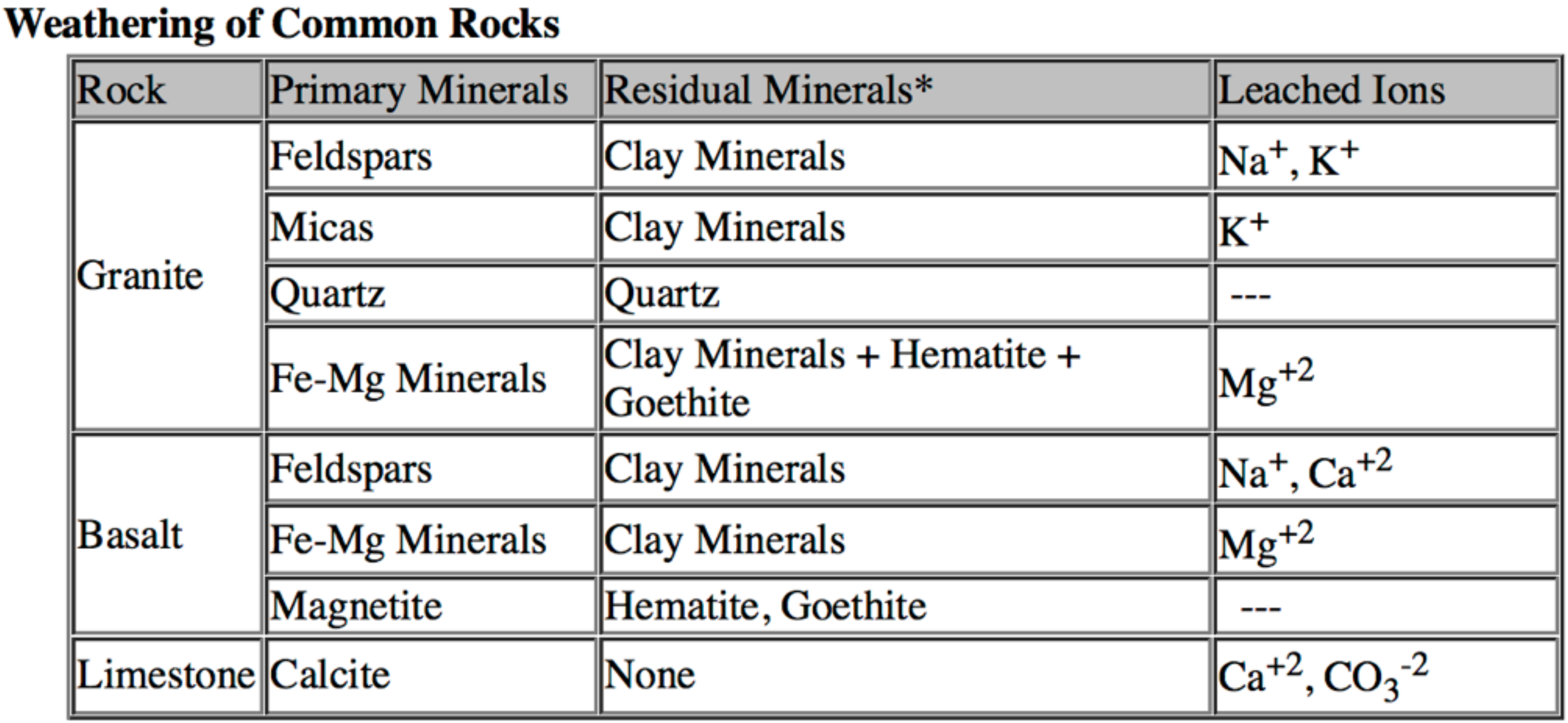


TABLE 6.1 Products of Weathering

Mineral	Residual Products	Material in Solution
Quartz	Quartz grains	Silica
Feldspars	Clay minerals	Silica K^+, Na^+, Ca^{2+}
Amphibole (hornblende)	Clay minerals Limonite Hematite	Silica Ca^{2+}, Mg^{2+}
Olivine	Limonite Hematite	Silica Mg^{2+}



Weathering of Common Rocks

Rock	Primary Minerals	Residual Minerals*	Leached Ions
Granite	Feldspars	Clay Minerals	Na^+, K^+
	Micas	Clay Minerals	K^+
	Quartz	Quartz	---
	Fe-Mg Minerals	Clay Minerals + Hematite + Goethite	Mg^{+2}
Basalt	Feldspars	Clay Minerals	Na^+, Ca^{+2}
	Fe-Mg Minerals	Clay Minerals	Mg^{+2}
	Magnetite	Hematite, Goethite	---
Limestone	Calcite	None	Ca^{+2}, CO_3^{-2}