

Mineralogy

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1 Introduction

Understanding minerals is the key to understanding the Earth. They are the building blocks of our planet and are our ways of interpreting the processes happening in inaccessible locations. To begin, let's define a mineral.

- A mineral must be a **naturally occurring solid**. Although we are capable of producing crystalline substances with the same properties, they are not considered real minerals.
- A mineral must have a **crystalline structure fixed in a specific, orderly pattern**. We will discuss this more in detail later.
- A mineral must be **inorganic**. Minerals cannot be organic substances such as proteins or fats. Minerals can be formed by organisms, however, they must have defined crystalline structures. Pearls and amber, which are organically produced solids with properties similar to minerals, lack a defined structure. In contrast, aragonite-bearing components produced by marine organisms *are* considered minerals, as they have defined crystal structures.
- A mineral must have a **definite chemical composition**. Geologists must be able to describe a mineral using a chemical formula, although individual minerals can have slight variations in composition (which is the case for many mineral varieties).

Minerals each have unique properties, including chemical and physical properties which are used by geologists to classify and identify them. We will discuss many of these properties throughout this guide.

2 Crystal Properties

2.1 Basic Mineral Chemistry

Minerals are classified into 8 main groups based on chemical composition: silicates, native elements, carbonates, halides, oxides, phosphates, sulfates, and sulfides. They are composed of mono- or polyatomic cations (positively charged ion) and anions (negatively charged), making them ionic compounds. We will discuss each mineral group below, with examples of each:

- **Silicates** - The silicate family is the largest and most abundant group of minerals. All silicates are composed of silica tetrahedra, SiO_4^{4-} , organized in several configurations.
 - **Nesosilicates**, or 'island' silicates, are composed of single tetrahedra, and include the minerals olivine and kyanite.
 - **Sorosilicates**, with isolated double tetrahedra, consist of two tetrahedra linked together to form an hourglass-like shape. An example is the mineral epidote.
 - **Inosilicates**, or chain silicates, are subdivided into single- and double-chained silicates, with multiple tetrahedra linked together. Single-chained inosilicates include pyroxenes, while double-chained inosilicates include amphiboles.
 - **Phyllosilicates**, or sheet silicates, are composed of tetrahedra which form plates, and include clay minerals including the mica group.

- **Cyclosilicates**, or ring silicates, are formed by three, four, or six tetrahedra linked together to form a ring. Common cyclosilicates include tourmaline and beryl.
- **Tectosilicates**, or framework silicates, form three-dimensional shapes, and are the most complex form of silicate. These include quartz and feldspar.

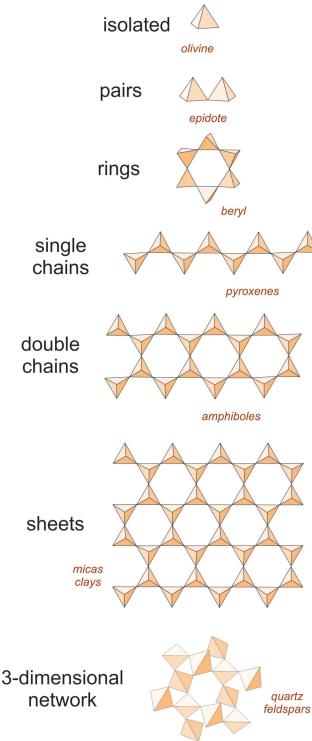


Image: Open Geology

- **Native Elements** - Native elements have chemical formulas of one single element. Many are valuable, and this group includes gold (Au), silver (Ag), copper (Cu), diamond (C), and sulfur (S).

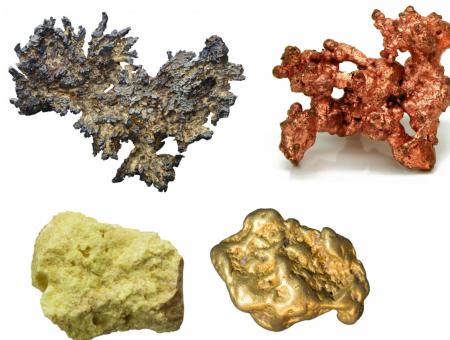


Image: Examples of native elements. From top left to bottom right: Silver, Copper, Sulfur, Gold

- **Carbonates** - Carbonate minerals include carbonate, CO_3 , in their chemical formulas. Common carbonates include the polymorphs calcite and aragonite (CaCO_3), which will be discussed later. Other carbonates include azurite and malachite.

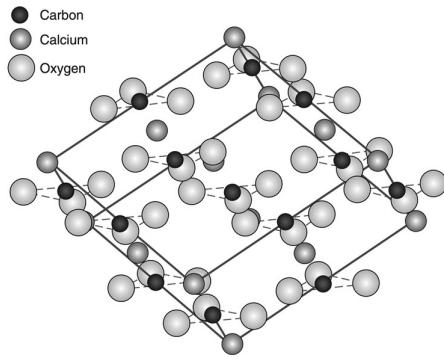
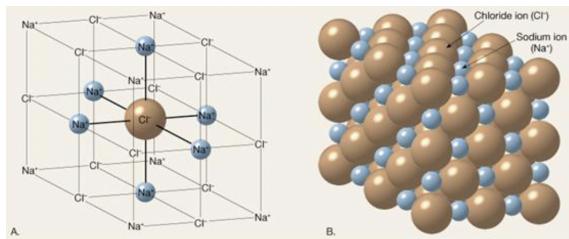


Image: Crystal structure of carbonate minerals.

- **Halides** - Halides are composed of metals bonded to halogens (F, Cl, Br, I). This group includes halite (NaCl), also known as table salt, and fluorite (CaF_2).

Image: Halides contain halogens. The structure of Halite (NaCl) is shown.

- **Oxides** - Oxides are composed of one or two metals bonded to oxygen, and this group contains many important ores. Important oxides include hematite (Fe_2O_3) and magnetite (Fe_3O_4), both iron ores.
- **Phosphates** - Phosphates are composed of phosphorus, arsenic, or vanadium bonded to oxygen. This group includes apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl},\text{OH})$), turquoise ($\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$), and vanadinite ($\text{Pb}_5(\text{VO}_4)_3\text{Cl}$). Fluorine, chlorine, and hydroxide are all able to be part of apatite's chemical formula.
- **Sulfates** - Sulfates include sulfur bonded to oxygen in their chemical compositions. One common example is gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which is formed when salt water evaporates and leaves behind a mineral. Another sulfate, anhydrite (CaSO_4), can turn into gypsum when exposed to water.
- **Sulfides** - Sulfides are composed of sulfur bonded to metals. They can be distinguished from sulfates by their lack of oxygen. Common sulfides are pyrite (FeS_2) and galena (PbS).

2.2 Crystal Structures

A crystal is a single, continuous piece of a crystalline solid, typically bound by flat surfaces called crystal faces, that grow naturally as the mineral forms. The angle between two adjacent crystal faces of one specimen is identical to the angle between the corresponding faces of another specimen.



Image: Fluorite, with an Isometric system, exhibits crystal faces that intersect at 90° angles.

The atoms, ions, or molecules that make up crystals are arranged in specific, regular, and repeating patterns. These arrangements determine the crystal structure of a mineral, which are classified in crystal systems. There are seven crystal systems, based on the lengths and axes of a crystal's unit cell. The unit cell is the smallest division of any crystal structure that depicts the whole of the crystal lattice.

- Triclinic - All three axes are unequal in length, and none are perpendicular to each other. Examples include plagioclase, microcline, rhodonite, and turquoise

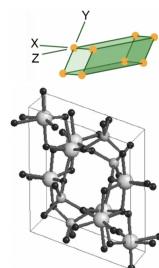
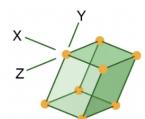


Image: The triclinic unit cell of Kyanite.

- Monoclinic - All three axes are unequal in length, and two axes are perpendicular to each other. Examples include actinolite, augite, epidote, and azurite.



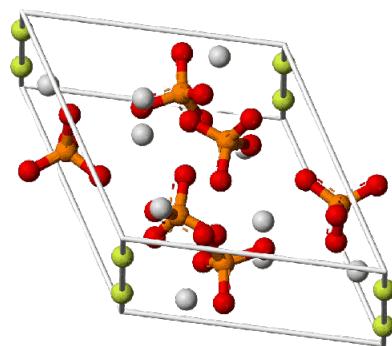


Image: The monoclinic unit cell of Azurite.

- Orthorhombic - All three axes are unequal in length, and all are perpendicular to one another. Examples include olivine, aragonite, celestite, and topaz.

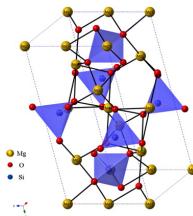
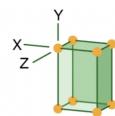


Image: The orthorhombic unit cell of Olivine.

- Tetragonal - Two of the three axes are equal in length, and all three axes are perpendicular to one another. Examples include zircon, chalcopyrite, rutile, and apophyllite.

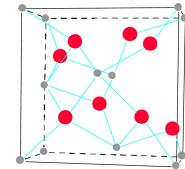
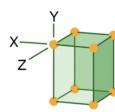


Image: The tetragonal unit cell of Zircon.

- Trigonal - All three axes are of equal length, and none of the axes is perpendicular to another, but three crystal faces all have the same size and shape. Examples include calcite, corundum, hematite, and quartz.

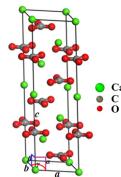
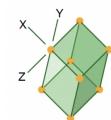


Image: The trigonal unit cell of Calcite.

- Hexagonal - Closely related to the trigonal system (in the same crystal family), of four axes, three are of equal length, and are separated by equal angles, and lie in the same plane. The fourth axis is perpendicular to the plane of the other three axes. Examples include dolomite, beryl, apatite, and graphite.

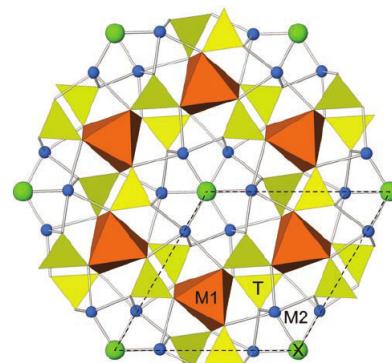
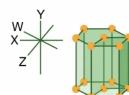


Image: The hexagonal structure of apatite. Note the unit cell (dotted outline).

- Isometric (cubic) - All three axes are equal in length, and all are perpendicular to one another. Examples include almandine, copper, magnetite, halite, and fluorite.

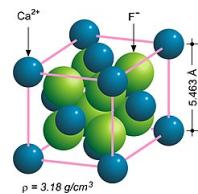
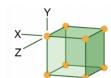


Image: The isometric unit cell of Fluorite.

Images: Encyclopedia Britannica

2.3 Solid Solutions

A solid solution series forms when there is a range of composition between two minerals (known as endmembers). An example is olivine, which has endmembers Forsterite (Mg_2SiO_4), and Fayalite (Fe_2SiO_4). Solid solutions are often represented by compositional diagrams, which are a graphical representation of solid solutions. Phase diagrams can be used to describe chemical equilibrium in such systems, and are covered in a later section.

Examples of minerals that form series are biotite, pyroxenes, olivine, garnet, and feldspars.

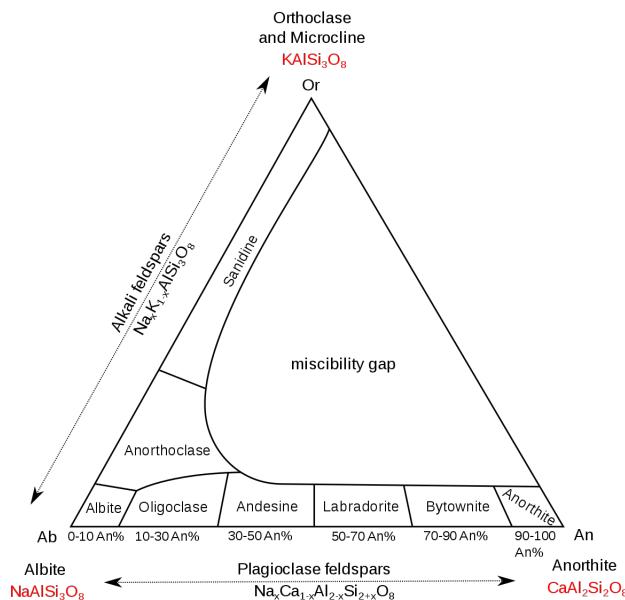


Image: The Feldspar ternary diagram, which illustrates the plagioclase solid solution (endmembers Albite and Anorthite), and the Alkali Feldspar solid solution (endmembers Orthoclase and Albite).

When a solid solution becomes unstable, *exsolution* occurs and the two phases separate into distinct lamellae. This is largely caused by differences in cation size. An example of a solution which forms exsolution lamellae is plagioclase. Notice the 'miscibility gap' in the Feldspar ternary: Solutions within this gap cannot form a complete solid solution, resulting in exsolution. Exsolution will be covered in greater depth in the phase diagrams section.

2.4 Twinning

Twinning is a form of symmetrical intergrowth between two or more adjacent crystals of the same mineral. The surface along which the lattice points are shared in twinned crystals is called the composition surface, and the reflection created by this symmetry is called the twinning plane.

Crystal twins can form in multiple ways:

- Growth twins result from an interruption in the lattice during formation or growth of a crystal due to a possible formation from a larger substitution ion. Growth twinning likely

begins early in crystal growth. It starts when an atom or ion joins a crystal face in an unideal position, forming a seed for a growth twin. The original crystal and its twin then grow together.

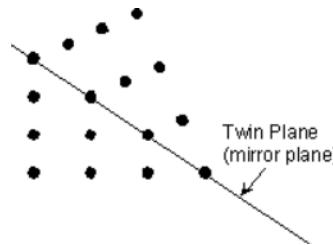


Image: Contact Growth Twinning, Tulane University

- Annealing/transformation twins result from a change in crystal system (or a displacive polymorphic transition) during cooling as one form becomes unstable, and the crystal structure must transform into another more stable form. When the phase change takes place, different parts of the crystal break their original structure along a different choice in axis resulting in new symmetries.

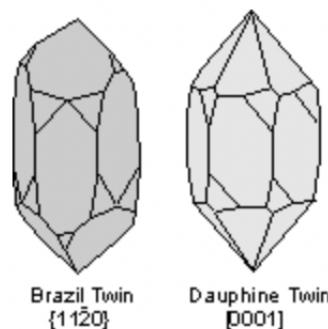


Image: Brazil and Dauphine law twinning in Quartz result from transformation. Source: Tulane University

- Deformation/gliding twins occur from shear stress on the crystal after the crystal has formed. The crystal structure is displaced along successive planes of the crystal.

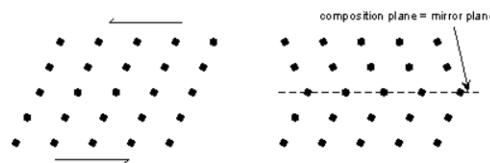


Image: Deformation Twinning, Tulane University

There are several types of twinning:

- Contact twinning occurs when the crystal faces meet on a single composition plane; it usually looks like mirror images across the boundary. Contact twins can be formed from either reflection or rotation. Plagioclase, quartz, and gypsum often exhibit contact twinning.



Image: Mindat

- Penetration twinning occurs when the individual crystals appear as if they pass through each other in a symmetrical manner. Penetration twins usually are formed from rotation. Orthoclase, staurolite, and pyrite often exhibit penetration twinning.



Image: Alex Strekeisen

- Multiple/repeated twinning occurs when several twin crystal parts are aligned by the same twin law. When these crystal parts are parallelly aligned, they are called polysynthetic twins. Closely spaced polysynthetic twins may appear as striations on a crystal face. Albite, calcite, and pyrite often exhibit polysynthetic twinning.



Image: Portland State University

- When multiple twins are not parallel, they are cyclic twins. Rutile, aragonite, and chrysoberyl often exhibit cyclic twinning, typically in a radiation pattern.



Image: Wikipedia

- Several twin crystals parts by the same twin law are parallelly aligned. (When several twin crystals aligned by the same twin laws are NOT parallel, they can simply be referred to as multiple or repeated twins.)

Twin laws define the orientation between twin crystals. They are specific to minerals and/or crystal systems. For example, staurolite crystals are very characteristically twinned with angles almost precisely 90° or 30° (Staurolite Law). Other common examples of twin laws include Japan Law (quartz), Manebach Law (Swallow Tail Twins in gypsum), and Albite Law (plagioclase).

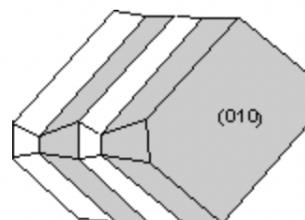


Image: Albite law



Image: Japan law

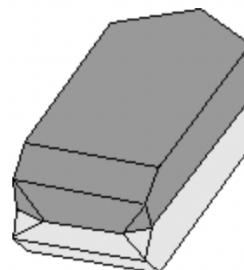


Image: Manebach law

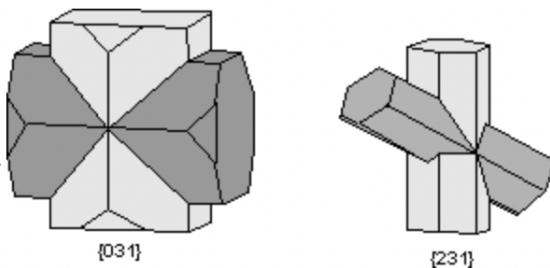


Image: Staurolite law

2.5 Pseudomorphism & Isomorphism

A pseudomorph is a mineral that replaces another and retains the latter's shape. There are three types of pseudomorphs: substitution, alteration, and incrustation.

- A substitution pseudomorph occurs when one mineral replaces another. Besides crystal shape, the mineral retains the properties of the replacing mineral. One example of this situation is the mineral goethite replacing pyrite. The resulting mineral has every property of goethite, but now has a cubic shape resembling pyrite.



Image: Goethite pseudomorph after pyrite.

- An alteration pseudomorph can form in several ways. There can be a change in crystal structure but no alteration in chemical composition, resulting in a paramorph, as in the case of aragonite and calcite. Additionally, losing or gaining a part of the chemical formula can result in an alteration pseudomorph, as with the minerals anhydrite and gypsum. Adding water to anhydrite results in gypsum.



Image: Calcite paramorph after aragonite.

- An incrustation pseudomorph (or epimorph) forms when one mineral covers the other and the covered mineral dissolves. The mineral covering the other keeps its shape, and occasionally another mineral fills the vacancy left behind.



Image: Quartz epimorph after fluorite. Note the quartz casts of pre-existing fluorite.

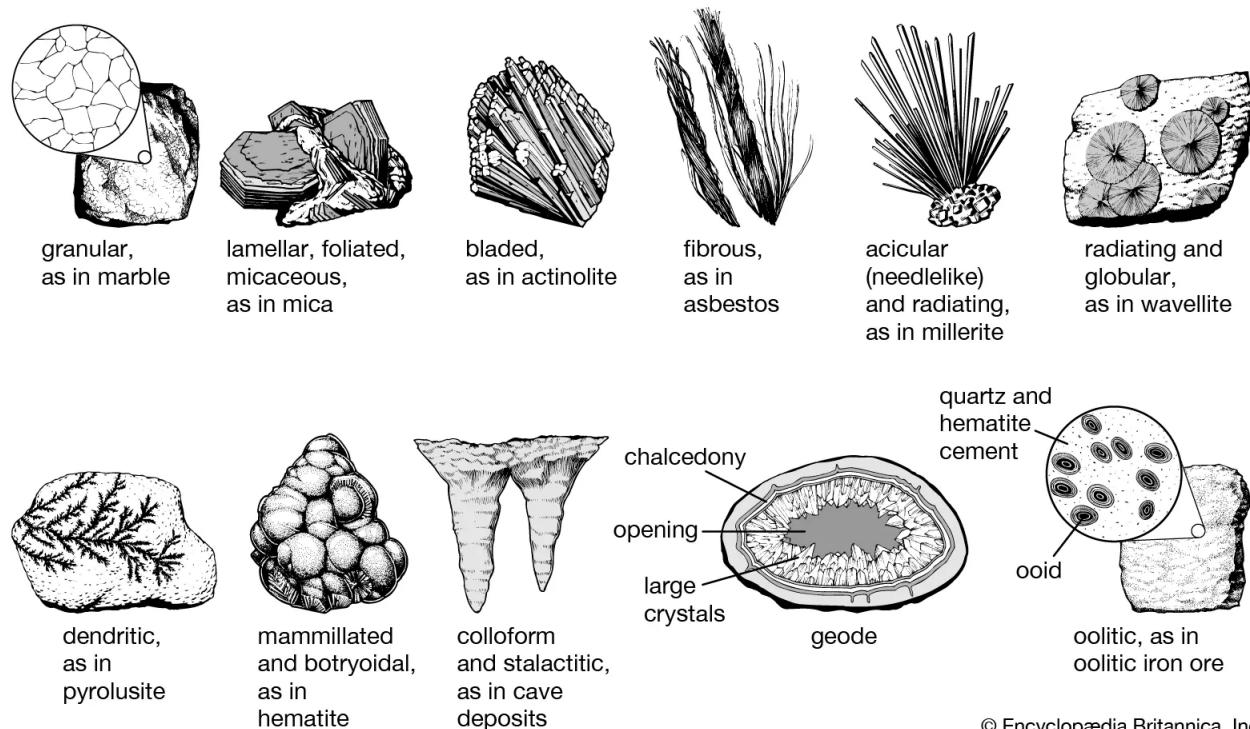
An isomorph is a mineral that has the same chemical composition as another, but it has a different metal ion. Isomorphs also have similar crystal structures and forms. Isomorphs can be seen in solid solution series, where each endmember has a slightly different formula. An example of isomorphs would be albite and orthoclase. Albite has the chemical formula $\text{NaAlSi}_3\text{O}_8$, while orthoclase has the formula KAlSi_3O_8 ; the only difference in composition is sodium versus potassium. Another example would be the olivine series endmembers forsterite (Mg-only - Mg_2SiO_4) and fayalite (Fe-only - Fe_2SiO_4).

3 Physical Properties

A combination of many physical properties can help you identify minerals. Some have very unique properties, while others have unique combinations.

3.1 Habit

Habit describes the crystal shape of a mineral. Many minerals have characteristic habit, such as the commonly seen prismatic hexagonal shape of quartz and the striated elongated crystals of tourmaline. Some common habits are prismatic, bladed, acicular (needle-like), druzy (crystals coating a surface), fibrous, tabular (wide and flat), and stalactitic (stalactites or stalagmites).

Common crystal aggregations and habits

© Encyclopædia Britannica, Inc.

Image: Encyclopedia Britannica

Find more crystal habits and examples here: https://en.wikipedia.org/wiki/Crystal_habit**3.2 Luster**

Luster describes the way light reflects off of a mineral, especially its brilliance or dullness. Luster can be described in many ways, but some common terms include vitreous (glassy), metallic, dull, resinous, adamantine, and greasy luster. Vitreous minerals include quartz, metallic include pyrite, hematite can be dull, sphalerite is resinous, diamond is adamantine, graphite is greasy. These minerals and their lusters are visible below:



Images: John Betts Fine Minerals, Mini Me Geology, Geology.com, Mindat, Le Comptoir Géologique, Nevada Outback Gems

From top left to bottom right: quartz, pyrite, hematite, sphalerite, diamond, and graphite.

3.3 Diaphaneity

Diaphaneity can also be called transparency, and it is the mineral's ability to allow light to pass through it. A mineral's diaphaneity is usually described as transparent, semitransparent, translucent, or opaque. Transparent minerals allow nearly all light to pass through, such as in rock crystal quartz. On the other hand, opaque minerals block all light, such as the mineral graphite.

Although diaphaneity is rarely a distinct property of a specific mineral, it can greatly aid the identification process.

3.4 Color

Color is the least reliable method of mineral identification. Minerals can display a variety of colors for a variety of reasons, which makes it very hard to identify a mineral simply based on color. Impurities can result in color changes, such as iron appearing in the crystal lattice of quartz to produce the brown variety known as smoky quartz.

3.5 Streak

When a mineral is scraped against a piece of porcelain known as a streak plate, it leaves a trail of color known as streak, depending, of course, on the mineral's hardness. One can also file off a small piece of the mineral and smear it onto the plate. For the sake of describing streak, however, we will ignore hardness. A mineral's streak can be very different from the mineral's color, such as the brass-colored mineral pyrite's greenish black streak, but it is much more consistent.

Streak can be very helpful in identifying certain minerals; one of the most notable examples is with the aforementioned hematite and magnetite. Both appear dark, and if one were to not know the characteristic habits of both, it would be best to perform a streak test. Hematite would leave a bright red or orange streak, while magnetite would leave a dark gray or black streak.

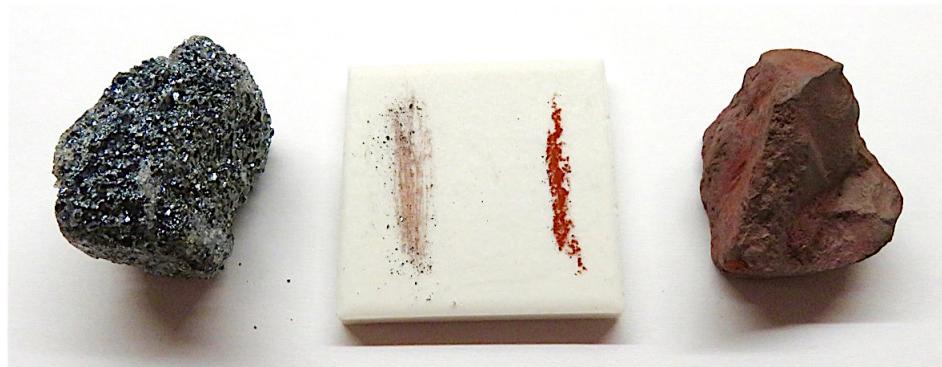


Image: BC Open Textbooks
A side-by-side comparison of magnetite and hematite's streaks.

3.6 Specific Gravity

Specific gravity is the weight of a mineral compared to the weight of water, both of the same volume. Water has a specific gravity of 1.0.

Specific gravity can be very helpful in identifying minerals when physical ones are present, especially in the case of barite, a heavy mineral with a specific gravity of 4.2 to 4.6. Lighter minerals are usually described as those with a specific gravity around 2.9 or lower, as in the case of gypsum, which has a specific gravity of 2.32.

3.7 Hardness

Minerals can also be identified by their ability to either scratch or be scratched by other materials. Hardness is measured by the Mohs Hardness Scale, on a scale from 1 to 10, with talc having a hardness of 1 and diamond with a hardness of 10.

It is important to remember that Mohs Hardness Scale is not linear; diamond is more than 10 times harder than talc. Other defining minerals on the scale include gypsum (2), calcite (3), fluorite (4), apatite (5), orthoclase (6), quartz (7), topaz (8), and corundum (9).

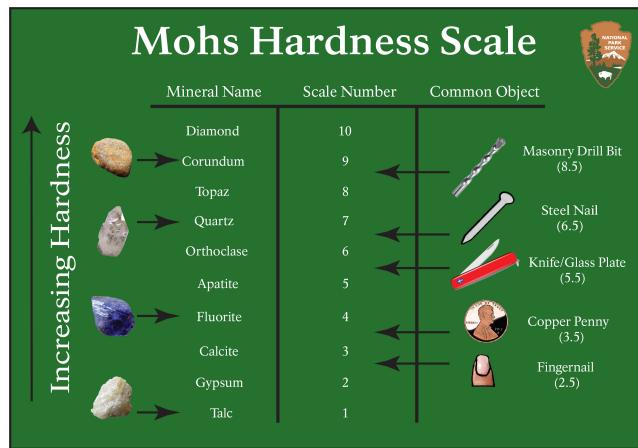


Image: National Park Service

Hardness may also be measured relative to other minerals or materials. Copper pennies (3.5), glass (5.5), and steel nails (6.5) are all used to scratch minerals to test their hardness, and a streak plate has a hardness of 7. Comparing hardness can also help in identification; if mineral A is harder than mineral B, then A can scratch B, but B cannot scratch A. Additionally, a fingernail has a hardness of 2.5, making it able to scratch softer minerals such as gypsum and talc.

Additionally, hardness can change depending on the direction in which you measure the mineral, a result of bonds, such as with kyanite, which has a hardness of 5.5 in one direction and 7 in another.

3.8 Cleavage

Cleavage describes the breakage of a mineral along smooth surfaces known as cleavage planes. If you hit a mineral with a hammer, the mineral will break naturally, following planes of weakness in its ionic structure. The structure of a crystal creates smooth planes, which are relatively weak. Cleavage can be described in five qualities: perfect, good, poor, indistinct, or none, depending on the smoothness of the plane. Types of cleavage include:

- Basal cleavage - This type of cleavage happens when only one plane exists. It is prominent in mica, which has perfect basal cleavage.
- Cubic cleavage - Cubic cleavage happens when there are three cleavage planes, each perpendicular to each other. It can be seen in cubic minerals such as galena or halite.
- Octahedral cleavage - Four cleavage planes must exist. This type of cleavage occurs in minerals like diamond and fluorite.
- Rhombohedral cleavage - Three cleavage planes exist, but they are not 90 degrees away from each other. Calcite exhibits this type of cleavage.
- Prismatic cleavage - Two cleavage planes exist, exhibited by minerals such as the amphibole group.
- Dodecahedral cleavage - This type of cleavage can be seen in minerals with six cleavage planes, such as in sphalerite.

3.9 Fracture

Similar to cleavage, fracture is the way a mineral breaks, but it doesn't follow cleavage planes.

- One type of fracture is conchoidal fracture, which describes a mineral breaking into concave shapes and is observed in flint and the rocks chert and obsidian.
- Earthy fracture is crumbly; it is common in minerals such as kaolinite and limonite.
- Hackly fracture is common in metals such as gold, copper, and silver and can be jagged and sharp.
- Splintery fracture is often seen in fibrous minerals such as tremolite, and it looks like wood splinters.
- Uneven fracture results in an uneven surface, occurring in many minerals such as pyrite, hematite, and magnetite.



Image: Radford University

Conchoidal (obsidian) and fibrous (asbestos) fracture.

4 Mineral Stability

4.1 Polymorphism

Polymorphs are multiple minerals that have the same composition but different crystal structures. Examples of polymorphs include diamond and graphite (C), kyanite and sillimanite (Al_2SiO_5), calcite and aragonite (CaCO_3), orthoclase, microcline, and sanidine (KAlSi_3O_8); and the six varieties of SiO_2 including quartz, tridymite, and cristobalite.

There are three ways by which polymorphs can form. One way is a subtle crystal structure change; bonds are shifted but not broken. These are known as displacive transformations. Another way, known as reconstructive transformation, consists of bond breaking atom rearrangement. The rate of reconstructive transformation is slow, so unstable polymorphs may be present for a long period. Order-disorder transformations occur when temperature increases and crystal structure is more disordered than at lower temperatures.

4.2 Binary Phase Diagrams

Phase diagrams are essentially graphical representations of chemical equilibrium in a system. Phase diagrams are used to visualize the stability of various phases in systems of any composition under specific temperature and pressure conditions.

Generally, two forms of binary phase diagrams can be recognized:

- **Pressure-Temperature Phase Diagrams:** These plot the stability of different phases across different temperatures and pressures. P-T phase diagrams describe solutions of fixed composition.
- **Isobaric (Constant Pressure) Phase Diagrams:** Isobaric phase diagrams plot stable phases at varying temperatures and compositions. These assume a constant pressure during the melting/crystallization process.

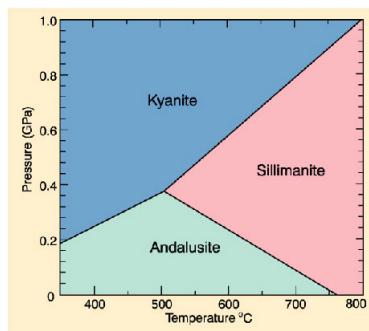


Image: Wikimedia

Pressure-Temperature Phase diagram for Al_2SiO_5 , commonly known as kyanite, andalusite, or sillimanite (all polymorphs of each other)

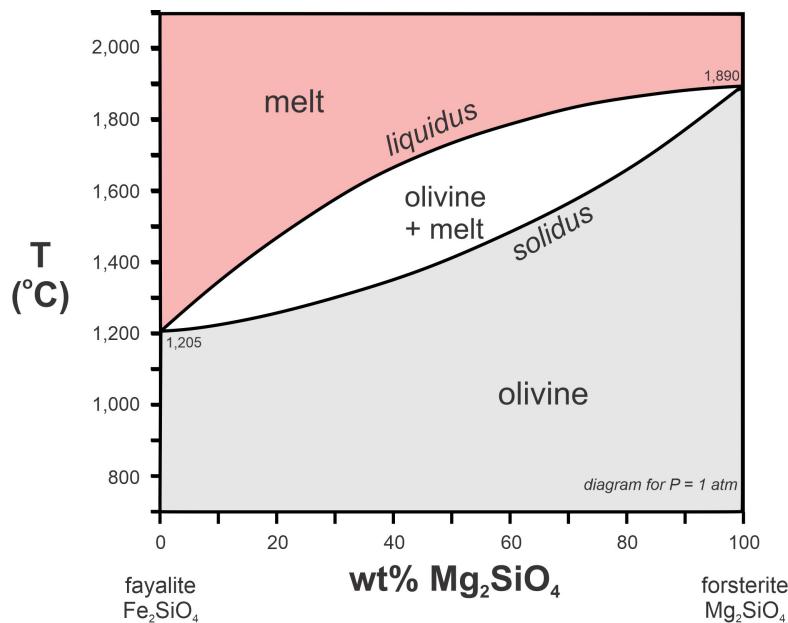


Image: OpenGeology

Isobaric phase diagram illustrating the solid-solution between Forsterite and Fayalite.

Many find isobaric phase diagrams - especially complex diagrams - difficult to interpret (3 dimensional phase diagrams can get quite complicated!). However, a great amount of useful information can be elucidated from them given the right tools.

4.2.1 Anatomy of an Isobaric Phase Diagram

There are several useful concepts to understand before learning to interpret diagrams. First, isobaric phase diagrams plot composition- usually weight percent of one component- on the horizontal axis, against temperature on the vertical axis (we call chemical constituents of a system components; for more detail on this look at Gibb's phase rule). They are used to illustrate the stability of phases during melting and crystallization processes. For brevity, this handout will only cover one crystallization process.

Additionally, phase diagrams are constructed with a few simplifications from nature. First, pressure is assumed constant, and most diagrams are plotted for pressures of 1 atm. Secondly, phase diagrams assume solutions are *ideal*, meaning volume changes with the mixing of components (and thus crystallization) are negligible, and all intermolecular forces between components are identical. Of course, these simplifications are not true for natural systems, however they serve as a useful analogue.

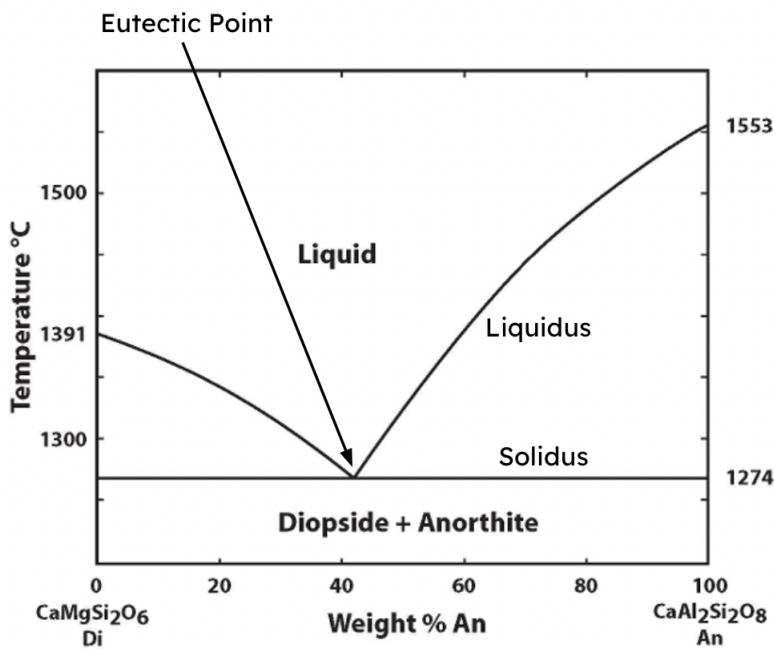


Image: Anorthite-Diopside system, with boundaries labelled.

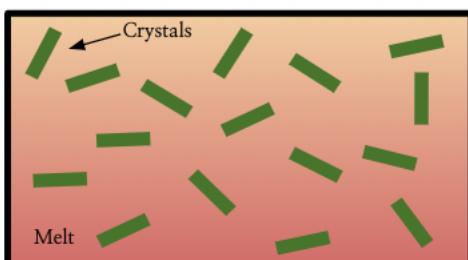
In this handout, we will consider the simple Anorthite-Diopside eutectic system. First, we will define the parts of the diagram. The field labeled 'Liquid' above, only melt is present. Across any composition of Anorthite and Diopside, this field lies above the melting point of the liquid (this is called a eutectic solution, where the melting point of the mixture is lower than that of its

components).

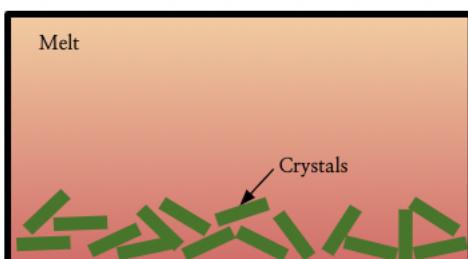
The **liquidus** is the boundary between the fields of purely liquid and liquid + solid. When a melt begins to crystallize, the composition of the remaining melt evolves along the liquidus (a point illustrated later). The **solidus** is the boundary between the field containing solid and liquid, and a purely solid field. Above, the field labelled “Diopside + Anorthite” lies below the solidus. Finally, the **eutectic point**, as labelled above, is the junction between the liquidus and the solidus for phase diagrams of eutectic solutions. This point marks the lowest temperature and composition where crystallization occurs.

4.2.2 Crystallization & Melting Processes

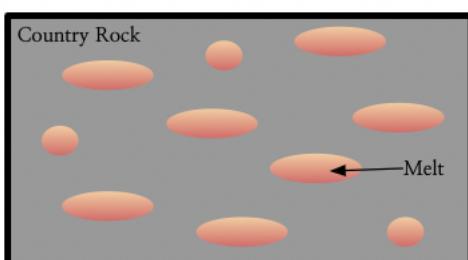
Phase diagrams are useful for dealing with various crystallization and melting processes present in geologic settings.



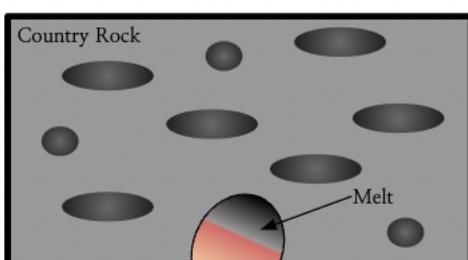
Equilibrium Crystallization: Melt and crystallized minerals remain in contact throughout the melting process. The initial composition of the melt is thus *the same* as the final composition of the crystallized solid.



Fractional Crystallization: Crystallized minerals are removed from the melt, and do not further react with the melt. Often this occurs with mafic minerals such as Olivine and Pyroxene, which can sink as they crystallize (this forms *cumulate* rock). Other mechanisms exist, but will not be discussed here.



Equilibrium Melting: Melt remains in contact with the unmelted country rock throughout the melting process. It is analogous to equilibrium crystallization.

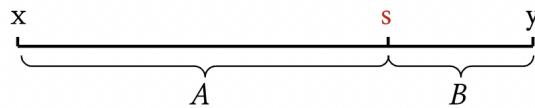


Fractional Melting: Melt is removed from the surrounding country rock upon formation. The melt is thus unable to react with the country rock, and thus the composition of the melt produced does not match that of the original country rock.

4.2.3 The Lever Rule

Phase diagrams can be used to determine the composition of different phases during melting and crystallization processes. The **lever rule** is paramount to this determination.

On isobaric phase diagrams, the fraction of solid and liquid at a specified temperature is determined using the lever rule.

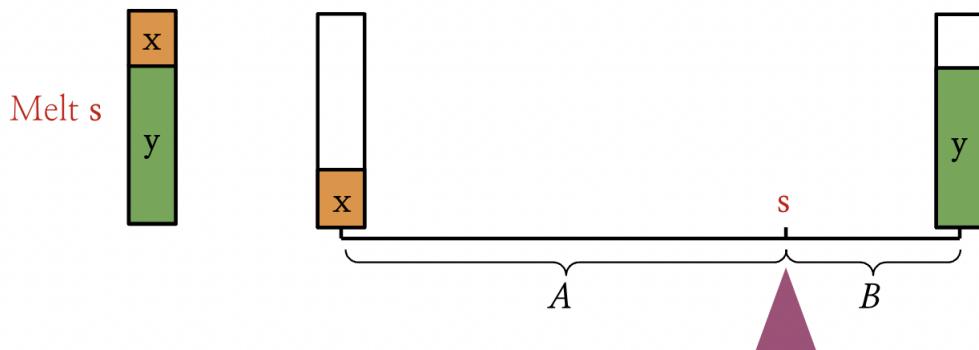


Let's consider the solution above- a one dimensional diagram for a mixture of components **x** and **y**, with a solution of **x** and **y** at **s**. To determine the composition of **s** using the lever rule, we use the lengths **A** and **B**.

$$\begin{aligned}\% \text{ } \mathbf{x} &= \frac{B}{A+B} \\ \% \text{ } \mathbf{y} &= \frac{A}{A+B}\end{aligned}$$

The concentration of component **x** can be determined with the fraction of the whole occupied by length **B**. We can think of this as: “**s** is **B** distance from **y** moving towards **x**, and **A** distance from **x** starting at **x** and moving towards **y**.”

It seems counterintuitive, but we can think about this like a balanced scale/lever:

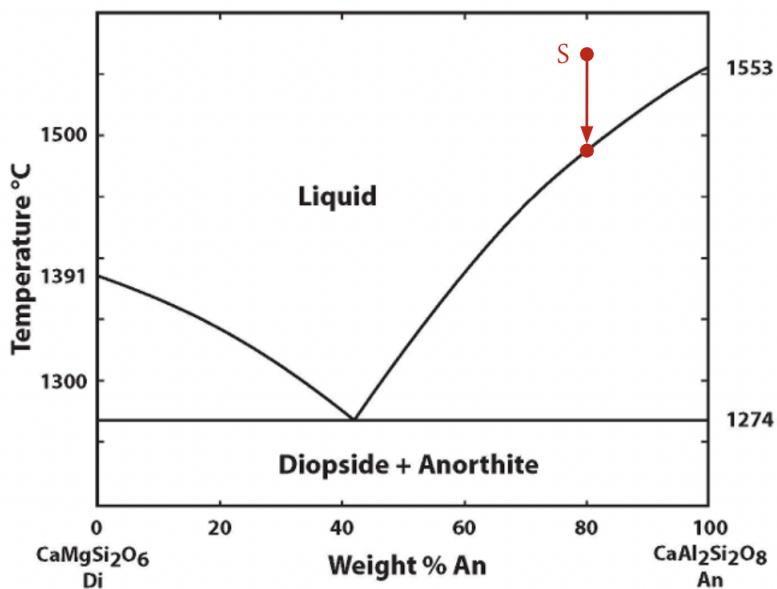


In order for the differing masses of components **x** and **y** to balance, the “arms” of the lever are different lengths, with **s** being located at the fulcrum. The length **A** is correlated to the mass of component **y**, and the length **B** is correlated to the mass of component **x**.

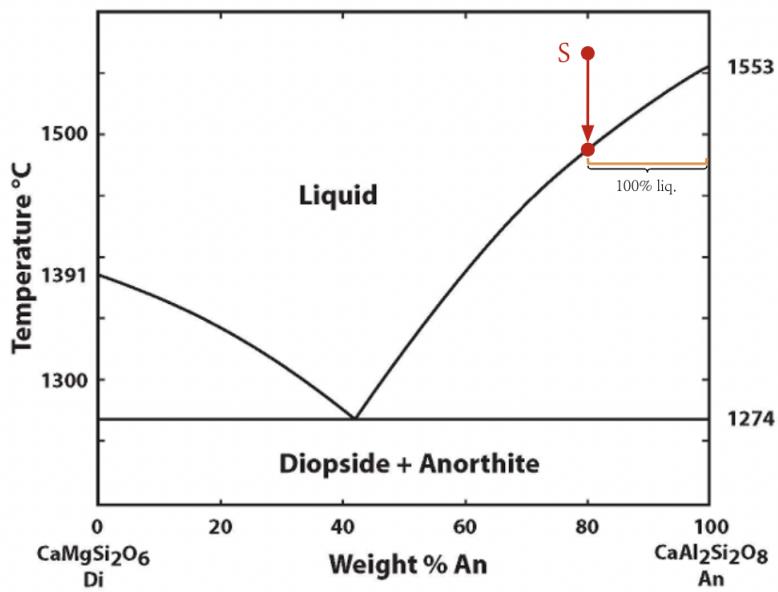
With this understanding of the lever rule, we can now apply it in more complex scenarios!

4.2.4 Worked Example: Equilibrium Crystallization

To see the lever rule in practice, and begin to understand how phase diagrams can be used to model geologic processes, let's work through the equilibrium crystallization of melt **S**, containing 80% Anorthite and 20% Diopside.



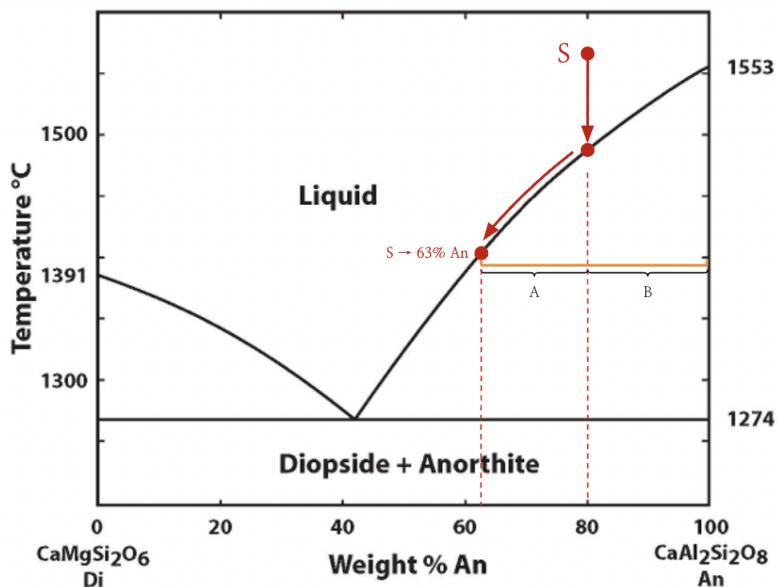
Beginning at a temperature of 1600°C, melt **S** cools. We can plot a line vertically downwards, until the line intersects the liquidus. Note that crystallization for melt **S** begins only when its path of cooling intersects the liquidus, and not at 1553°C, which is the melting point of 100% Anorthite (think back to eutectic solutions).



At this point, we can apply the lever rule. At the intersection between the cooling path of **S** and the liquidus, we can draw a horizontal line between this point and the 100% Anorthite side of the diagram. Here, we see that the “fulcrum” is at the intersection point- the mixture is still 0% Anorthite, and 100% liquid. This aligns conceptually: this intersection point/temperature is the highest temperature at which any crystallization occurs; at the instant it intersects, there are no

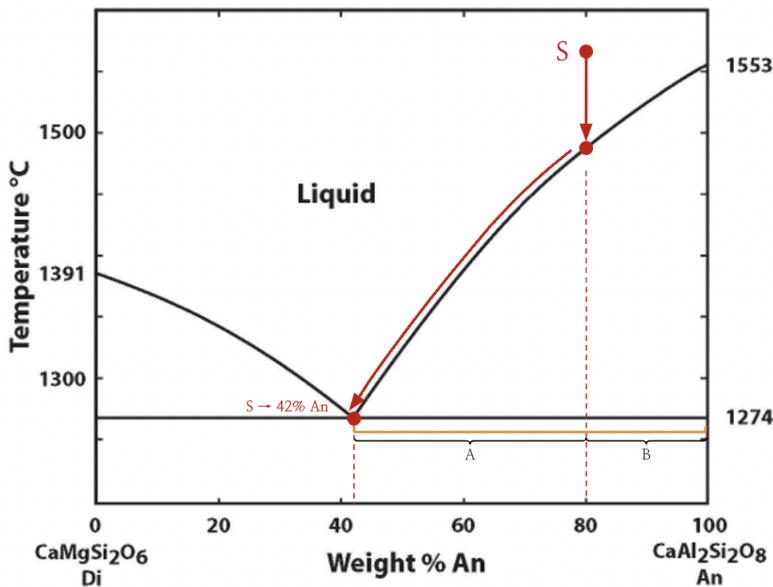
crystals.

As we cool the melt further, Anorthite will begin to crystallize. As this occurs, the melt will become richer in Diopside as Anorthite is crystallized out.



Now, as Melt **S** has cooled to 1400°C, the composition of **S** evolves along the liquidus. Thus, the liquid component of melt **S** now has a composition of 63% Anorthite. We can use the lever rule here to determine the fraction of the mixture that has crystallized as Anorthite, and the fraction that remains as the liquid:

$$\begin{aligned}\% \text{ An} &= \frac{A}{A+B} = 50\% \\ \% \text{ Liq.} &= \frac{B}{A+B} = 50\%\end{aligned}$$



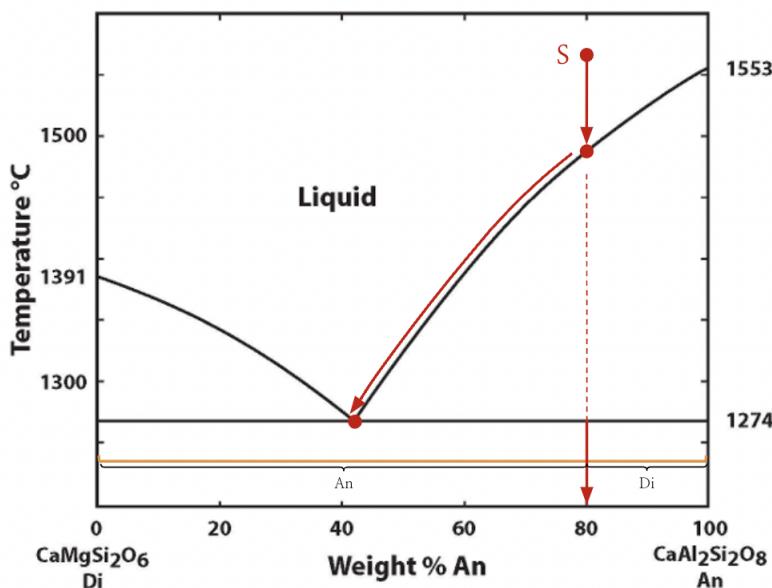
When the melt cools to 1274°C, the path of cooling intersects the solidus. Remember, after the solution cools past the solidus, the melt is entirely crystallized. The melt composition, as seen

above, intersects the *eutectic point*. This is the final liquid that can crystallize, and in this case, has a composition of 42% Anorthite. We can again use the lever rule to determine how much of the melt remains liquid:

$$\% \text{ An} = \frac{A}{A+B} = 67\%$$

$$\% \text{ Liq.} = \frac{B}{A+B} = 33\%$$

With further cooling, the liquid, now at a concentration equal to that at the eutectic point, will crystallize to form a solid solution of 42% Anorthite, making up 33% of the final solid. The remaining 67% of the solid is composed of the 100% Anorthite crystallized throughout cooling.



Finally, as this is equilibrium crystallization, the final concentrations of Anorthite and Diopside in the crystallized solid are the same as the initial concentrations in the melt. We can verify this using the lever rule once again, which confirms this to be true.

$$\% \text{ Anorthite} = \frac{Di}{An+Di} = 80\%$$

$$\% \text{ Diopside} = \frac{An}{An+Di} = 20\%$$

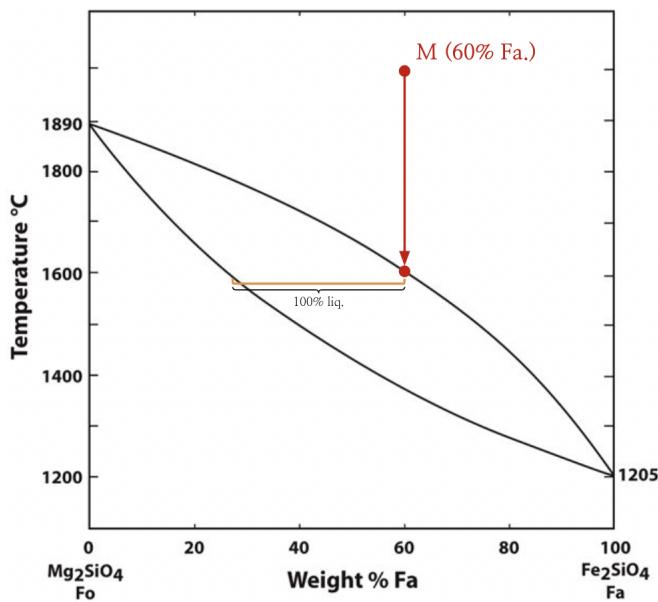
If this same melt were to crystallize by fractional crystallization, the final composition of the solid would be different. This however, is beyond the scope of this handout.

4.2.5 Worked Example: Equilibrium Crystallization of A Solid Solution

Now, we will briefly examine binary phase diagrams of solid solutions. As you may recall, solid solutions involve two or more minerals with compatible crystal structures such that cations from either component are able to occupy other sites.

Phase diagrams with solid solutions are used differently than conventional solid solutions. Looking at the Forsterite-Fayalite phase diagram above (section 4.2), notice that the solidus is curved, rather than a horizontal line. This is the case because the melting point of the final solid phase - as a solution of two components - varies depending on composition (as opposed to the eutectic

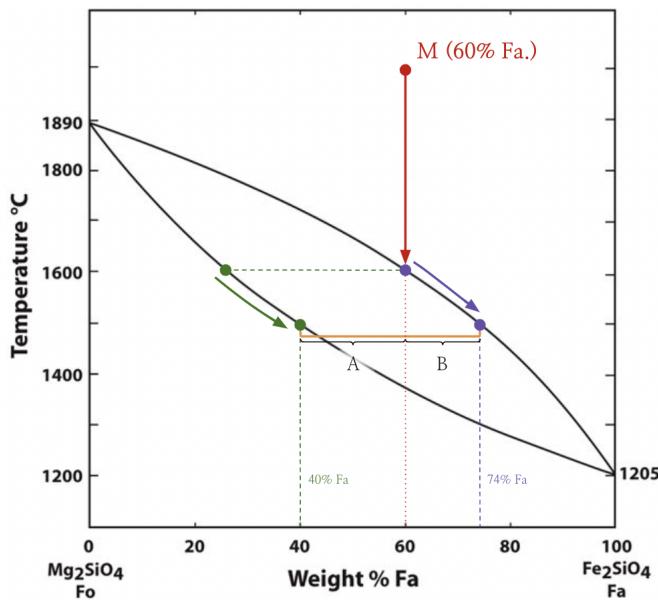
composition for eutectic solutions). To illustrate this, let's walk through the equilibrium crystallization of a simple Forsterite-Fayalite melt.



The initial melt **M** begins cooling at 2,000°C, before intersecting the liquidus. Similar to the previous phase diagram with an eutectic, we can apply the lever rule to find that the mixture remains at 100% melt. Cooling past this point however, there are two *new* facts to keep in mind:

- During equilibrium crystallization of a solid solution, the crystallized solid *continuously* reacts with the melt. The composition of the crystallized solid thus changes as it cools.
- The composition of the **solid** *evolves along the solidus*. The composition of the melt again evolves along the liquidus. The lever rule can again be applied to determine the percentage of the mixture in each phase, but is plotted *between the liquidus and the solidus*.

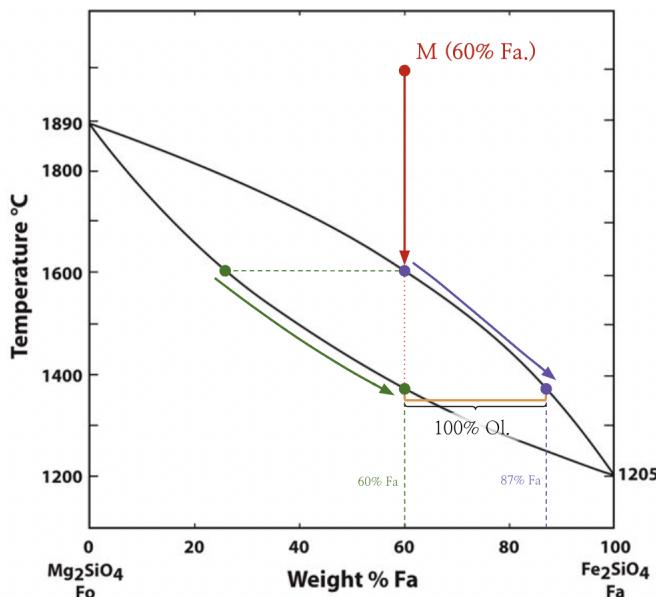
Let's see how this works:



As the melt cools to 1500°C, olivine begins to crystallize. Above, the path in green traces the composition of the solid Olivine, while the path in purple traces the melt. The composition of this olivine evolves along the solidus, continuously reacting with the melt. At 1500°C, the crystallized olivine contains 40% Fayalite. During this process, the melt evolves along the liquidus. At 1500°C, the melt has a composition of 74% Fayalite. As the melt progressively becomes more Fe-rich as Mg-rich olivine crystallizes, the crystallizing solid also becomes more Fe-rich, as shown by the green and purple arrows. We can apply the lever rule here by drawing a line between the liquidus and solidus:

$$\% \text{ liq.} = \frac{A}{A+B} = 60\%$$

$$\% \text{ Olivine} = \frac{B}{A+B} = 40\%$$

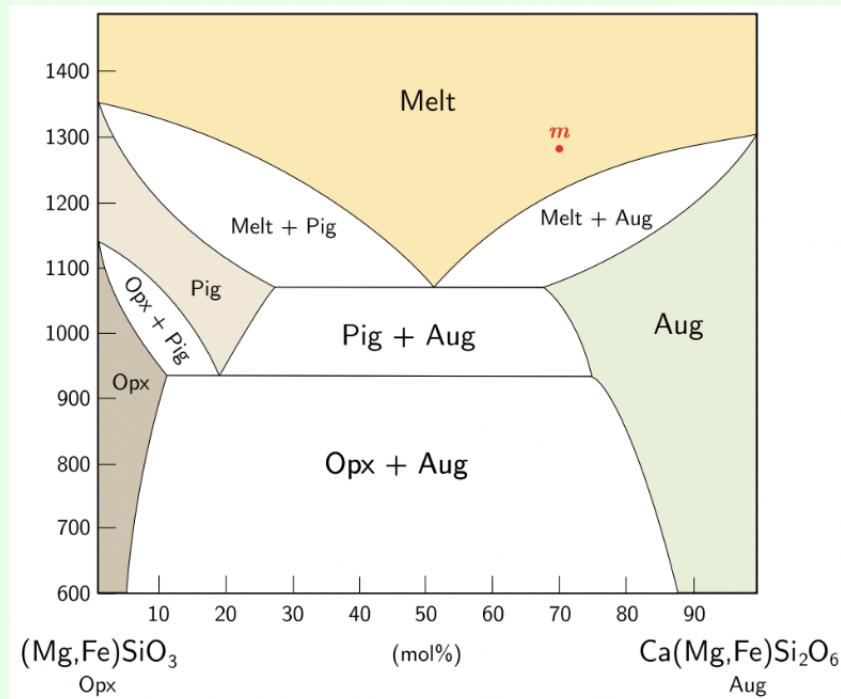


After cooling to 1380°C, the green arrow, or the composition of the Olivine solid, intersects the original composition of the melt. Recall that in all cases of equilibrium crystallization, the final solid composition and the initial melt composition are the same. Thus, at this temperature, the melt has fully crystallized to form a solid solution of 60% Fayalite. We can confirm that this is the case by applying the lever rule one final time, which reveals that the mixture is now 100% Olivine solid. The final melt composition to exist has a composition of 87% Fayalite.

This concludes our brief dive into phase diagrams. Due to the scope of this handout, only binary eutectic and solid solution phase diagrams have been covered. However, there are many more configurations that exist, as well as different paths that can be modeled. Fractional crystallization, as well as equilibrium and fractional melting can also be mapped on these diagrams, and other diagrams with more complex components also exist (peritectics, thermal barriers, diagrams with a solvus, ternary diagrams etc.).

Example (2022 USES0 Rocks & Minerals Exam #1)

A pyroxene melt of a bulk composition of 70% Aug, 30% Opx (marked m) cools slowly (assume chemical equilibrium is maintained throughout crystallization) until all the melt is crystallized. At the moment immediately after the melt completely solidifies, which of the following best approximates the composition of the augite phase?



- (A) 27% Aug
- (B) 52% Aug
- (C) 60% Aug
- (D) 70% Aug
- (E) 87% Aug

Solution: Tracing the path of the solid solution along the solidus of the “Melt + Aug” field, the final composition of the solid solution as the mixture is fully solidified is approximately 70%. This is the starting composition; this question can be easily solved by understanding that the initial and final compositions of **m** will be equal under equilibrium crystallization. Finally, as the question asks for “immediately after the melt completely solidifies”, we can ignore changes past the solvus, as exsolution occurs after the melt has fully solidified. Thus, (C) is the correct answer.

5 Common Rock-forming Minerals

Now, let's discuss common rock-forming minerals, all silicates.

5.1 Bowen's Reaction Series

Some of the most common rock-forming minerals develop through a series known as Bowen's Reaction Series, created by Canadian petrologist Norman L. Bowen. Lava or magma undergoes a process known as fractional crystallization, in which certain minerals form from molten rock at certain temperatures, and, as more minerals settle and leave the molten rock, its composition changes. The minerals which crystallize the latest, at the coolest temperatures, contain more silica (SiO_2) than those which crystallize at warmer temperatures. Their silicate structures, as discussed above, also get more complex as the molten rock cools.

Bowen's Reaction Series also describes three other relationships, that of temperature and rock composition, that of temperature and viscosity, and that of temperature and resistance to weathering (mineral stability). Rocks composed of minerals with higher silica content are known as felsic, while those composed of minerals with lower are mafic. Minerals in Bowen's Reaction Series can also be described as mafic or felsic. Higher silica content also relates to the viscosity of the magma, or the resistance to flow. Lower silica content makes the magma flow more easily. At higher temperatures, the minerals that crystallize are less resistant to weathering and form rocks which are described as mafic, often dark-colored, while minerals formed at lower temperatures are more stable and felsic, often light-colored. The relationship between temperature and stability is also known as Goldich's Dissolution Series, developed by S. S. Goldich.

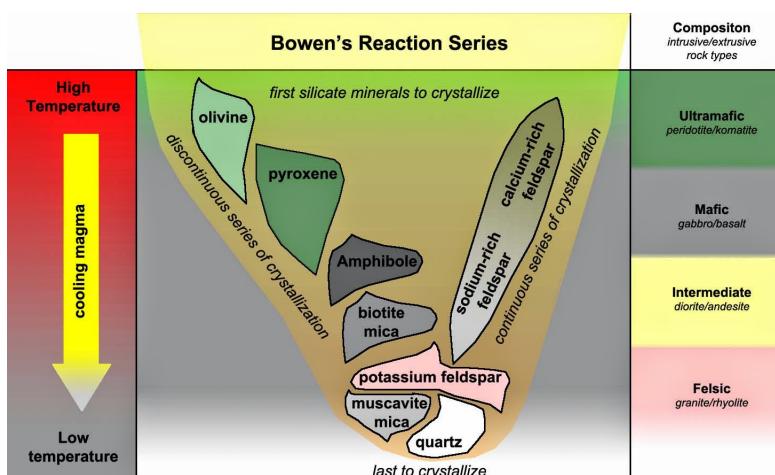


Image: Geology In

Example (2022 USESO Open Exam Section 1 #13)

The complexity of silicate structures (e.g., complex network silicates to simple isolated tetrahedra) can influence the bulk properties of rock made from those silicate minerals. Which of the following trends is associated with increasing silicate complexity?

- I) Increasing melting point
 - II) Increasing viscosity of magma
-
- (A) I only
 - (B) II only
 - (C) I and II
 - (D) None

Solution: We know that as temperature decreases, silicate structures become more complex. This means that melting points of minerals formed become lower because they form at lower temperatures. Viscosity increases as silicate structures become more complex, so (B) is correct.

5.2 Olivine

Olivine is the first to crystallize from molten rock at the highest temperatures, around 1,400°C. Olivine is most often a vitreous, green mineral, with the chemical formula $(\text{Mg},\text{Fe})_2\text{SiO}_4$, and it comes in many varieties, including the gemstone peridot and series endmembers forsterite and fayalite. It also has a hardness between 6.5 and 7.0 and an orthorhombic crystal system, forming ultramafic rocks such as peridotite and dunite, a variety of peridotite with more olivine, in the depths of the earth.



5.3 Pyroxenes

Next to form is the pyroxene group, consisting of, most commonly, dark-colored minerals, with the general formula being $\text{XY}(\text{Si},\text{Al})_2\text{O}_6$. Pyroxenes compose ultramafic, mafic, and intermediate rocks, particularly peridotite, basalt, gabbro, and andesite. One important pyroxene mineral is augite, a dark-colored, resinous to dull, monoclinic mineral with a hardness of 5.5 to 6.



Image: The Pyroxene mineral Augite.

5.4 Amphiboles

Amphiboles, similar to pyroxenes, form both igneous and metamorphic rocks, and they are especially prominent in the metamorphic rock amphibolite. Amphiboles have both orthorhombic and monoclinic crystal systems, hardnesses between 5 and 6, vitreous to dull lusters, and follow the general chemical formula RSi_4O_{11} . One important amphibole is hornblende, a dark-colored mineral with 120-degree cleavage planes.



Image: The Pyroxene mineral Augite.

5.5 Micas

Micas, most commonly muscovite and biotite, are sheetlike minerals made of thin plates, so thin that they can appear transparent when viewed through a light source. Biotite is earlier in the reaction series than muscovite, which also means that it is present in intermediate rocks. These minerals are easily split into plates, a property known as perfect basal cleavage, and are found in both igneous rocks and metamorphic rocks, notably mica schist. The general mica group formula is $AB_{2-3}(X, Si)_4O_{10}(O, F, OH)_2$, with hardness from 2 to 4, a pearly or vitreous luster, and all are monoclinic.



Image: The Mica group mineral Muscovite.

5.6 Feldspars

Feldspars are the most common minerals in the Earth's crust. There are two types of feldspars, plagioclase and alkali feldspars. Plagioclase feldspars occur in felsic, intermediate, and mafic rocks, including granite, diorite, basalt, andesite, and rhyolite. Plagioclase feldspars include labradorite, andesine, and albite. Alkali feldspars, also known as potassium or K feldspars, are found in felsic igneous rocks, notably granite. This group includes orthoclase/microcline, which commonly twins, and sanidine.

The composition of feldspars can be described by a triangle known as the Feldspar Ternary Diagram, with each point representing an endmember with a different composition: orthoclase/microcline with potassium, albite with sodium, and anorthite with calcium. Potassium feldspars have the chemical formula $KAlSi_3O_8$, sodium have the formula $NaAlSi_3O_8$, and calcium have the formula $CaAl_2Si_2O_8$. Refer to binary phase diagrams to see the Feldspar Ternary Diagram.

Feldspars also have their own branch on Bowen's Reaction Series, known as the continuous branch, on which calcium-rich minerals crystallize at higher temperatures than sodium-rich minerals.

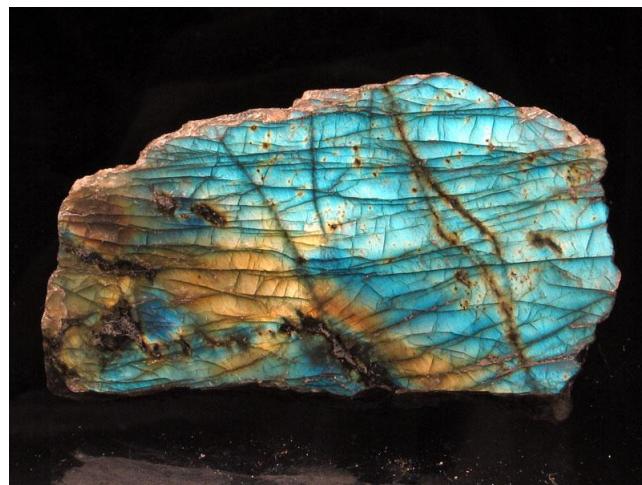


Image: The plagioclase feldspar Labradorite.

5.7 Quartz

Following potassium feldspar and muscovite, quartz forms last in Bowen's Reaction Series. It is the second most abundant mineral in the Earth's crust, and it is composed entirely of silica (SiO_2).

Quartz forms felsic igneous rocks such as granite, sedimentary rocks like sandstone, and metamorphic rocks like schist, gneiss, and quartzite. It is also often found as large crystals in pegmatites. Because it forms at the coolest temperatures, quartz is very resistant to weathering, which explains why it commonly occurs as sediment, especially sand. Quartz also has many well-known varieties: amethyst (a purple variety), citrine (yellow-orange), smoky quartz (brown-black), and rock crystal (clear). It has a hardness of 7, a trigonal or hexagonal crystal system, and vitreous luster.

Quartz also is split into two groups, alpha and beta quartz. Alpha quartz, also known as low quartz, is stable at cooler temperatures up to 573°C, while beta, or high, quartz, is stable at temperatures above 573°C.

Another classification system of quartz separates the mineral into crypto- and macrocrystalline quartz. Cryptocrystalline varieties have very small crystals, and this group includes the minerals chalcedony, agate, and jasper.

On the other hand, the crystals of macrocrystalline quartz are much more visible, and this group includes the aforementioned citrine, smoky quartz, amethyst, and rock crystal. For macrocrystalline quartz, color can be somewhat reliable, as long as one is able to first determine that a mineral is quartz.



Image: Macrocrystalline Quartz.