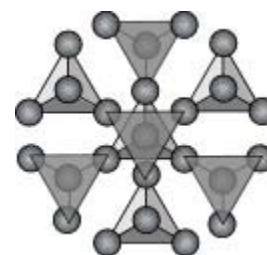


EENS 2110	Mineralogy
Tulane University	Prof. Stephen A. Nelson
Tectosilicates, Carbonates, Oxides, & Accessory Minerals	

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Tectosilicates (Framework Silicates)

The tectosilicates or framework silicates have a structure wherein all of the 4 oxygens of SiO_4^{-4} tetrahedra are shared with other tetrahedra. The ratios of Si to O is thus 1:2.



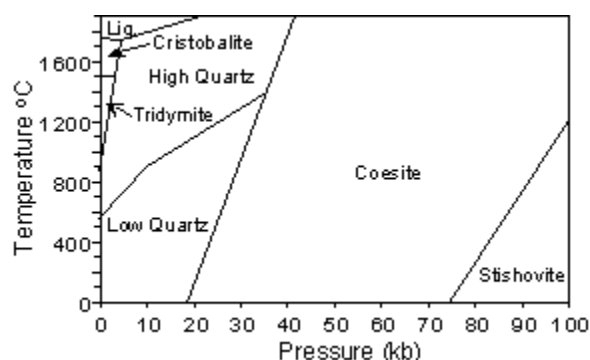
Since the Si - O bonds are strong covalent bonds and since the structure is interlocking, the tectosilicate minerals tend to have a high hardness.

SiO_2 Minerals

There are nine known polymorphs of SiO_2 , one of which does not occur naturally. These are:

Name	Crystal System	Density (g/cm^3)	Refractive Index (mean)
Stishovite	Tetragonal	4.35	1.81
Coesite	Monoclinic	3.01	1.59
Low (α) Quartz	Hexagonal	2.65	1.55
High (β) Quartz	Hexagonal	2.53	1.54
Kaetite (synthetic)	Tetragonal	2.50	1.52
Low (α) Tridymite	Monoclinic or Orthorhombic	2.26	1.47
High (β) Tridymite	Hexagonal	2.22	1.47
Low (α) Cristobalite	Tetragonal	2.32	1.48
High (β) Cristobalite	Isometric	2.20	1.48

Stishovite and Coesite are high pressure forms of SiO_2 , and thus have much higher densities and refractive indices than the other polymorphs. Stishovite is the only polymorph where the Si occurs in 6 fold (octahedral) coordination with Oxygen, and this occurs due to the high pressure under which the mineral forms. Both Stishovite and Coesite have been found associated with meteorite impact structures.



At low pressure with decreasing temperature, SiO₂ polymorphs change from high Cristobalite - Low Cristobalite - High Tridymite - Low Tridymite - High Quartz - Low Quartz. The high to low transformations are all displacive transformations. Since displacive transformations require little rearrangement of the crystal structure and no change in energy, the high (α) polymorphs do not exist at the surface of the earth, as they will invert to the low (β) polymorphs as temperature is lowered.

Transformations between α Cristobalite, α Tridymite, and α Quartz, however, as well as between the high pressure polymorphs and Quartz, are reconstructive transformations. Since reconstructive transformations require significant structural rearrangement and significant changes in energy, they occur slowly, and the high temperature and high pressure polymorphs can occur as metastable minerals at the Earth's surface.

Quartz

Quartz is hexagonal and commonly occurs as crystals ranging in size from microscopic to crystals weighing several tons. Where it crystallizes unhindered by other crystals, such as in cavities in rock or in a liquid containing few other crystals, it shows well-developed hexagonal prisms and sometimes showing apparent hexagonal pyramids or dipyramid. When it crystallizes in an environment where growth is inhibited by the surroundings, it rarely shows crystal faces. It is also found as microcrystalline masses, such as in the rock chert, and as fibrous masses, such as in chalcedony.

As visible crystals, Quartz is one of the more common rock forming minerals. It occurs in siliceous igneous rocks such as volcanic rhyolite and plutonic granitic rocks. It is common in metamorphic rocks at all grades of metamorphism, and is the chief constituent of sand. Because it is highly resistant to chemical weathering, it is found in a wide variety of sedimentary rocks.

Several varieties of Quartz can be found, but these are usually only distinguishable in hand specimen.

Rock Crystal - clear Quartz in distinct crystals - usually found growing in open cavities in rock.

Amethyst - violet colored Quartz, with the color resulting from trace amounts of Fe in the crystal.

Rose Quartz - a pink colored variety, that usually does not show crystal faces, the color resulting from trace amounts of Ti⁺⁴.

Smokey Quartz - a dark colored variety that may be almost black, usually forming well-formed crystals. The color appears to result from trace amounts of Al⁺³ in the structure.

Citrine - a yellow colored variety.

Milky Quartz - a white colored variety with the color being due to fluid inclusions. Milky Quartz is common in hydrothermal veins and pegmatites.

A fibrous variety of Quartz is called Chalcedony. It is usually brown to gray to translucent with a waxy luster. It is found lining or filling cavities in rock where it was apparently precipitated from an aqueous solution. When it shows bands of color, it is commonly called by the following names:

Carnelian - red colored Chalcedony

Chrysoprase - apple-green colored as a result of coloration from NiO.

Agate - alternating curving layers of Chalcedony with different colors or different porosities.

Onyx - alternating layers of Chalcedony of different colors or porosities arranged in parallel planes.

Bloodstone - green Chalcedony containing red spots of jasper (see below)

Very fine grained aggregates of cryptocrystalline quartz makes up rock like Flint and Chert. Flint occurs as nodules in limestone, whereas chert is a layered rock deposited on the ocean floor. The red variety of flint is called Jasper, where the color results from inclusions of hematite.

Optical Properties

Quartz is uniaxial positive with a low relief and low birefringence, thus exhibited only 1^o gray to 1^o white interference colors. In thin section it is almost always colorless when viewed without the analyzer inserted. One of its most distinguishing properties in thin section is that it usually has a smooth, almost polished-like surface texture. Quartz is easily distinguished from the Feldspars by the biaxial nature of feldspars, and from Nepheline which is uniaxial negative. Apatite, has similar birefringence to quartz, but is uniaxial negative and has a very high relief.

In Chalcedony, the fibers are usually elongated perpendicular to the c-crystallographic axis and thus are length fast. Normal quartz, when it show an elongated habit, is elongated parallel to the c axis, and is thus length slow.

Tridymite

Tridymite is the high temperature polymorph of SiO₂. Thus, it is only commonly found in igneous rocks that have been cooled rapidly to surface temperatures, preventing the slow transformation to quartz, the stable form of SiO₂ at surface temperatures. Because of this, we only expect to find Tridymite in siliceous volcanic rocks like rhyolites, where it commonly occurs as wedge shaped crystals in cavities in the rock. In volcanic rocks, Tridymite is commonly associated with Cristobalite and Sanidine.

Optical Properties

Tridymite usually occurs as orthorhombic or monoclinic wedge shaped crystals with a positive

2V between 40 and 90°. The wedge shape of the crystals is the result of twinning on {110}, and usually as 2 to 3 twinned individuals. Although it has similar birefringence to quartz and feldspar, it has lower refractive indices, and thus shows negative relief compared to quartz and feldspars.

Cristobalite

Cristobalite is also a high temperature SiO₂ polymorph, and thus has a similar occurrence to Tridymite. It also occurs in thermally metamorphosed sandstones. In volcanic rocks it can occur both as a lining in open cavities, and as fine grained crystals in the groundmass of the rock.

Optical Properties

Cristobalite is tetragonal and thus uniaxial. It has a negative optic sign and shows lower relief than quartz, but has similar birefringence.

Opal

Opal is amorphous, and thus a mineraloid, with a formula - SiO₂·nH₂O.

Feldspars

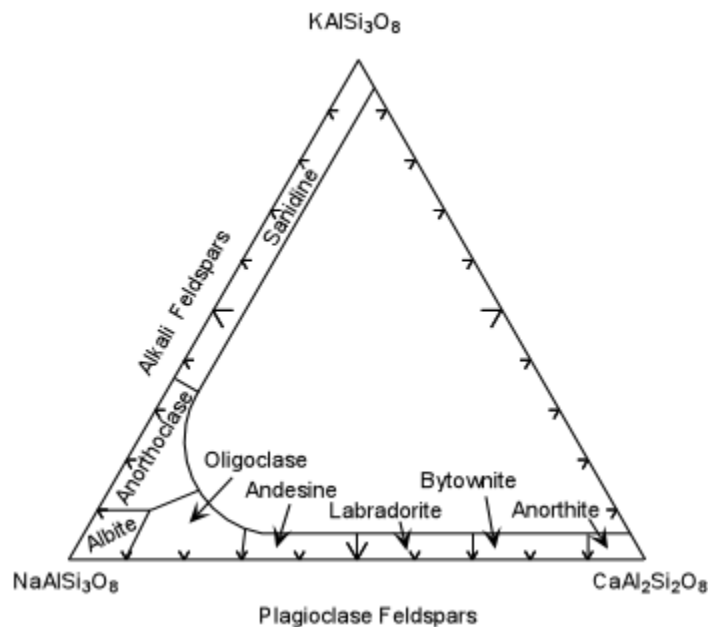
The feldspars are the most common minerals in the Earth's crust. They consist of three end-members:

KAlSi₃O₈ - Orthoclase (or), NaAlSi₃O₈ - Albite (ab), and CaAl₂Si₂O₈ -Anorthite (an)

KAlSi₃O₈ and NaAlSi₃O₈ form a complete solid solution series, known as the alkali feldspars and NaAlSi₃O₈ and CaAl₂Si₂O₈ form a complete solid solution series known as the plagioclase feldspars.

The feldspars have a framework structure, consisting of SiO₄ tetrahedra sharing all of the corner oxygens. However, in the alkali feldspars 1/4 of the Si⁺⁴ ions are replaced by Al⁺³ and in the plagioclase feldspars 1/4 to 1/2 of the Si⁺⁴ ions are replaced by Al⁺³. This allows for the cations K⁺, Na⁺, and Ca⁺² to be substituted into void spaces to maintain charge balance.

Compositions of natural feldspars are shown in the diagram below based on the 3 components - NaAlSi₃O₈ - Albite (ab), KAlSi₃O₈ - Orthoclase (or) and CaAl₂Si₂O₈. The Alkali Feldspars form a complete solid solution between ab and or, with up to 5% of the an component. The high temperature more K-rich variety is called Sanidine and the more Na-rich variety is called anorthoclase.

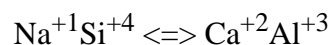


The plagioclase feldspars are a complete solid solution series between ab and an, and can contain small amounts of the or component. Names are given to the various ranges of composition, as shown here in the diagram are:

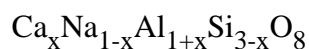
- Albite - ab_{90} to ab_{100}
- Oligoclase - ab_{70} to ab_{90}
- Andesine - ab_{50} to ab_{70}
- Labradorite - ab_{30} to ab_{50}
- Bytownite - ab_{10} - ab_{30}
- Anorthite - ab_0 to an_{10}

Plagioclase Feldspars

Plagioclase is the most common feldspar. It forms initially by crystallization from magma. The plagioclase solid solution series is coupled solid solution where the substitution is:

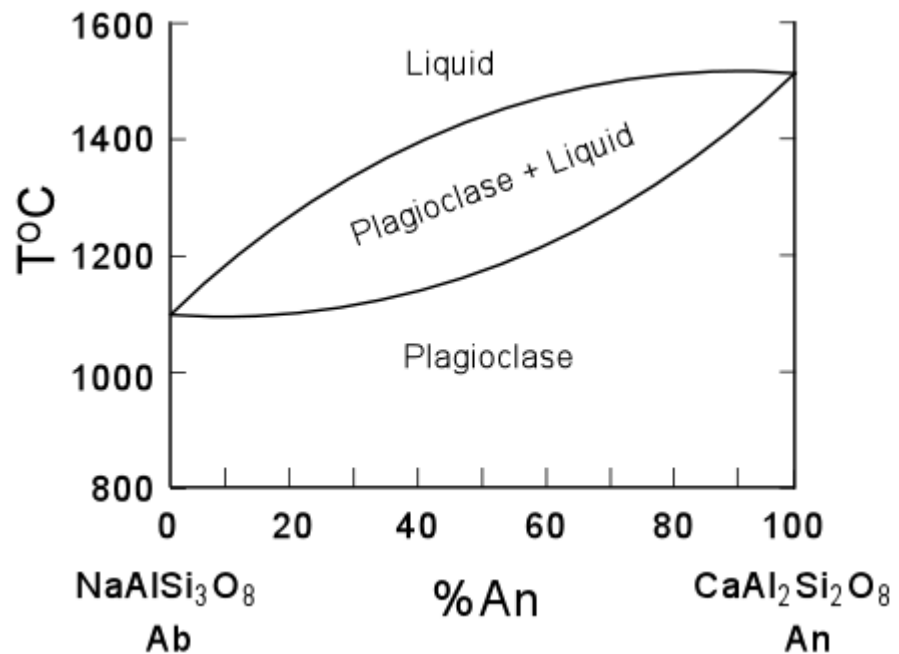


Thus, the general chemical formula for plagioclase can be written as:



where x is between 0 and 1.

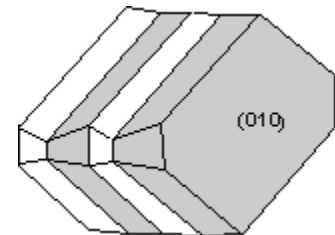
The phase diagram for the plagioclase series is shown here, and shows that the Anorthite component has a higher melting temperature than the Albite component. Thus, on crystallization, higher temperatures will favor more An-rich plagioclase which will react with the liquid to produce more Ab-rich plagioclase on cooling.



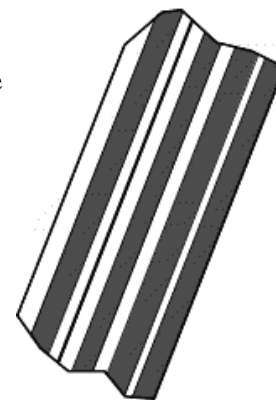
Plagioclase occurs in basalts, andesites, dacites, rhyolites, gabbros, diorites, granodiorites, and granites. In most of these igneous rocks, it always shows the characteristic albite twinning. Plagioclase also occurs in a wide variety of metamorphic rocks, where it is usually not twinned. In such rocks where the plagioclase is not twinned, it is difficult to distinguish from the alkali feldspars. Plagioclase can be a component of clastic sedimentary rocks, although it is less stable near the Earth's surface than alkali feldspar and quartz, and usually breaks down to clay minerals during weathering.

Properties

In hand specimen, plagioclase is most commonly white colored and shows perfect {100} and good {010} cleavage. It is most easily identified and distinguished from quartz, sanidine, orthoclase, and microcline, by its common polysynthetic twinning on {010}. If this twinning is not present, plagioclase can still be distinguished from quartz by its cleavage, but cannot easily be distinguished from the alkali feldspars. If both plagioclase and alkali feldspar occur in the same rock, the two can usually be distinguished by differences in color or differences in the extent of weathering.



In thin section, plagioclase commonly shows the characteristic albite polysynthetic twinning. This twinning is the most characteristic identifying feature of plagioclase, and makes its identification easy when present. Although some cross-hatched twinning may also occur in plagioclase, it is always very simple with only one or two cross twins per grain. Thus, be careful not to identify plagioclase as microcline. The cross-hatched twinning in microcline is always much more complex.



Plagioclase often shows zoning. This is exhibited by the extinction position changing from the

rim to the core of the crystal. Remember that zoning is caused by incomplete reaction of crystals with liquid during cooling of a solid solution. Often the zoning is very complex, and is sometimes oscillatory. Normal zoning would show Ca - rich cores and Na - rich rims, but reverse zoning is possible under certain conditions.

In metamorphic rocks plagioclase may not show twinning making it difficult to distinguish from orthoclase. The two can be distinguished by staining the thin section with stains that make the K-feldspars one color and the more Ca-rich feldspars another color. In this class, we will not have time to look at these staining techniques. You should, however, be aware, that such staining techniques exist, so that if you need them in the future, you can use them.

The optical properties of the plagioclase series vary widely as a function of composition of the plagioclase. In general, all plagioclases show low order interference colors, and thus, low birefringence. Optic sign and $2V$ vary widely, and are thus, not very distinguishing features of plagioclase. Although, as you have seen in lab, it is possible to estimate the composition of plagioclase from a combination of extinction angle and twinning.

Alkali Feldspars (K,Na)AlSi₃O₈

As an alkali feldspar cools from high temperature to lower temperature, the crystal structure changes from that of sanidine, which is monoclinic, through orthoclase, also monoclinic, but with a different crystal structure than sanidine, to microcline, which is triclinic. These transformations are order-disorder transformations, and thus require large amounts of time. Furthermore, if the feldspar is allowed to cool very slowly, then exsolution will occur, and the solid solution will separate into a Na-rich phase and a K-rich phase. Thus, one expects to find sanidine in rocks that were cooled very rapidly from high temperature, i.e. volcanic rocks. Orthoclase and microcline will be found in plutonic igneous rocks (cooled slowly at depth in the earth) and in metamorphic rocks. In addition, in the plutonic rock types if the cooling takes place slowly enough, then perthitic exsolution lamellae may also form.

All of the alkali feldspars have low relief and low birefringence. Thus the interference colors may range up to 1° white. Since this is the same interference color we expect for quartz, care must be taken to avoid confusing feldspars and quartz.

Sanidine

Sanidine generally occurs with an equant habit (almost square) and shows perfect {001} and {010} cleavages, which readily distinguish it from quartz. Rarely does sanidine show twinning, but when it does, it is usually simple twinning. Optic axis figures will only be found on sections showing both cleavages. Sanidine is optically negative with a $2V$ of $20 - 50^{\circ}$. This distinguishes it from quartz, which is uniaxial positive, and from the other alkali feldspars which show larger values of $2V$.

Orthoclase

Orthoclase is a common alkali feldspar in granitic rocks and K - Al rich metamorphic rocks. It often shows perfect {001} and {010} cleavages which will distinguish it from quartz. Also, quartz usually shows a smooth surface texture, while orthoclase appears much rougher. Orthoclase is also biaxial, which further distinguishes it from quartz. The $2V$ of orthoclase

varies from 60 to 105°, and thus it may be either positive or negative. The 2V angle distinguishes orthoclase from sanidine, but is otherwise not very useful because of its wide range.

Microcline

Microcline is the lowest temperature form of alkali feldspar. Upon cooling, orthoclase must rearrange its structure from monoclinic to triclinic. When this happens, twinning usually results. The twinning characteristic of microcline is a combination of albite twinning and pericline twinning. This results in a cross-hatched pattern (often called tartan twinning) that is the most distinguishing characteristic of microcline.

Anorthoclase

Anorthoclase is a Na - rich feldspar with approximately equal amounts of the Anorthite (Ca) and orthoclase (K) components. Generally anorthoclase occurs in Na - rich volcanic rocks. Like the other alkali feldspars, it has perfect {001} and {010} cleavages. Sections showing both of the cleavages are best for determining the optic sign and 2V. Anorthoclase sometimes shows twinning, but generally not the multiple twinning seen in the plagioclase feldspars, but a cross-hatched twinning similar to that seen in microcline, but on a very fine scale. Anorthoclase, like sanidine shows a low 2V of 5 to 20°, and is optically negative. Anorthoclase can sometimes be distinguished from sanidine by the fact that anorthoclase usually forms crystals with a tabular, elongated habit, while sanidine forms crystals with a more equant habit.

Feldspathoids

The feldspathoid group of minerals are SiO₂ poor, alkali rich minerals that occur in low SiO₂, high Na₂O - K₂O igneous rocks. In general, these minerals are not compatible with quartz, and therefore, are rarely, if ever, seen in rocks that contain quartz. They do, however, often occur with feldspars. Because of the alkalic nature of the rocks that contain feldspathoids, associated pyroxenes and amphiboles are of the sodic variety, i.e. aegerine or riebeckite.

The main feldspathoids are Nepheline (Na,K)AlSiO₄, Kalsilite KAlSi₂O₆, and Leucite KAlSi₂O₆. At high temperature there is complete solid solution between Nepheline and Kalsilite, but at low temperature Nepheline can contain only about 12 wt% K₂O.

Other similar members of the feldspathoid group are:

Sodalite 3NaAlSiO₄·NaCl
 Nosean 3NaAlSiO₄·NaSO₄
 Häüyne 3NaAlSiO₄·Ca(Cl,SO₄)

Nepheline

Nepheline occurs in both volcanic and plutonic alkaline igneous rocks. In hand specimen, Nepheline is difficult to distinguish from the feldspars, and thus must usually be identified by its association with other alkalic minerals. Nepheline has a yellowish colored alteration product, called cancrinite. Nepheline is hexagonal, and thus uniaxial, making it easy to

distinguish from the feldspars. Furthermore, it is optically negative, making it distinguishable from quartz. It usually shows no cleavage, has low birefringence, and low relief (refractive indices are smaller than the feldspars). The only other common mineral with which nepheline could be confused is apatite, which is also uniaxial negative. Apatite, however, shows much higher relief than does nepheline.

Sodalite

Sodalite occurs predominantly in alkali-rich plutonic igneous rocks, like syenites, but can also be found in volcanic rocks. It is essentially 3 nepheline molecules with an added NaCl molecule. It is a clear colored isometric mineral with low relief. Thus, the only thing sodalite might be confused with is a hole in the thin section. The blue color of sodalite in hand specimen and its association with other alkali-rich minerals is usually necessary to detect its presence in a rock.

Leucite

Leucite is found in alkalic volcanic rocks, and is rarely found in plutonic rocks. It is a tetragonal mineral, however, its refractive indices ϵ and ω are so close together that it almost always appears isometric. It usually occurs as small, slightly rounded, low relief grains that go extinct upon insertion of the analyzer. Commonly, leucite contains tiny inclusions within the mineral, and sometimes shows a slight twinning, barely visible with the analyzer inserted.

Oxides

The oxide minerals are very common and usually occur as accessory minerals in all kinds of rocks. The most common oxide minerals are the following:

Corundum - Al_2O_3

Corundum is hexagonal and optically negative. It occurs in Al-rich igneous and metamorphic rocks. If transparent blue, it is the gemstone sapphire, if transparent red, it is the gemstone ruby. When it occurs as an accessory mineral it usually shows its hexagon shaped outline when looking down the c-axis. It has high refractive indices, thus shows very high relief in thin section. But it has low birefringence and commonly shows lamellar twinning.

Spinel - MgAl_2O_4

Spinel is an isometric mineral that occurs ultrabasic rocks like peridotite, and in many low silica igneous rocks like basalts, where it contains high concentrations of Cr. It is also found in Al-rich contact metamorphic rocks. It shows a wide variety of colors depending on trace amounts of other ions substituting for both Mg and Al. Because of the isometric nature, Spinel is difficult to distinguish from garnet, although spinel tends to occur as much smaller crystals.

Chromite - $\text{Fe}^{+2}\text{Cr}_2\text{O}_4$

Chromite is a major ore of Cr. It is found in low silica, Mg-rich igneous rocks, usually associated with Olivine. Often it is seen as small inclusions in Olivine, indicating that it is an early crystallizing phase in basaltic and gabbroic magmas. Chromite is isometric, and usually opaque in thin section. Electron Microprobe analysis is usually necessary to distinguish it from other opaque oxide minerals.

Magnetite - Fe_3O_4

Magnetite is one of the most common oxide minerals. It is a major ore of Fe, and is found as

an accessory mineral in all rock types. It is isometric and commonly crystallizes with an octahedral habit. In hand specimen it is most easily identified by its strongly magnetic nature, black color, and hardness of 6. In thin section it is opaque and thus difficult to distinguish from the other opaque oxide minerals. As discussed below, it forms a solid solution with Ulvospinel - Fe_2TiO_4 .

Ilmenite - FeTiO_3

Ilmenite is a major ore of Ti. It is found as a common accessory mineral in a wide range of igneous volcanic and plutonic rocks, as well as metamorphic and clastic sedimentary rocks. It forms a solid solution series with Hematite, as will be discussed below, and commonly occurs along with Magnetite. Ilmenite is hexagonal, but is usually opaque which makes its distinction from other oxide minerals difficult. Ilmenite, however, often shows an elongated or acicular habit, whereas Magnetite usually crystallizes as more equant crystals with an octahedral habit.

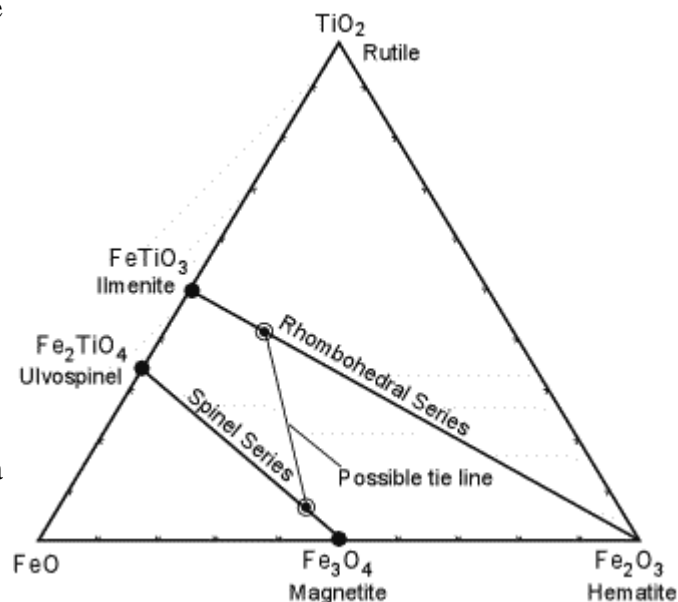
Hematite - Fe_2O_3

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 as well as other Fe bearing minerals. In most unaltered igneous rocks, hematite occurs as a component of Ilmenite in solid solution. Hematite is hexagonal, but rarely occurs in crystals where its symmetry can be determined. It is found in a variety of forms, ranging from oolitic spherules, to massive fine grained aggregates, to botryoidal masses. It is most easily distinguished by its black to dark red color and reddish brown streak. In thin section it is not easily distinguished from other opaque oxide minerals.

Iron-Titanium Oxide Geothermometer

Under magmatic conditions, Ilmenite and Hematite form a complete solid solution series, often called the rhombohedral series since both minerals crystallize in the hexagonal system. Similarly Magnetite and Ulvospinel form a complete solid solution series, called the spinel series.

The possible ranges of solid solution are shown in the diagram to the right. Coexisting compositions (as illustrated by the tie line) depend on temperature and the fugacity (similar to partial pressure) of Oxygen. If magma is rapidly cooled so as to preserve the compositions of the high temperature solid solutions, it is possible to calculate the temperature and fugacity of Oxygen that were present just before eruption of the magma. Minerals that allow for determination of the temperature of formation of minerals are referred to as a geothermometer. The example illustrated here is an important one, called the Iron-Titanium Oxide Geothermometer.



Carbonates

The carbonates are an important group of minerals near the Earth's surface. Carbonate minerals make up the bulk of limestones and dolostones. Are found as cementing agents in clastic sedimentary rocks, and make up the shells of many organisms. The carbonates are based on the CO_3^{-2} structural unit, which has carbon surrounded by 3 oxygens in triangular coordination.

Thus each Oxygen has a residual charge of $-2/3$. In the carbonate structure, no two triangles share the corner oxygens and the C-O bonds are highly covalent.

There are three structural types of carbonates:

Calcite Group	Aragonite Group	Dolomite Group
Calcite CaCO_3	Aragonite CaCO_3	Dolomite $\text{CaMg}(\text{CO}_3)_2$
Magnesite MgCO_3	Witherite BaCO_3	Ankerite $\text{CaFe}(\text{CO}_3)_2$
Siderite FeCO_3	Strontianite SrCO_3	
Rhodochrosite MnCO_3	Cerussite PbCO_3	
Smithsonite ZnCO_3		

In addition, there are the hydroxyl Cu carbonates - Malachite, $\text{Cu}_2\text{CO}_3(\text{OH})_2$ and Azurite $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$.

The Calcite Group

The calcite group minerals are all hexagonal. They have Ca, Mg, Fe, Mn, or Zn divalent cations in 6-fold coordination with the CO_3^{-2} groups, in a structure that is similar to that of NaCl. All members of this group show rhombohedral cleavage $\{01\bar{1}2\}$, thus breaking into rhomb-shaped cleavage blocks.

Calcite CaCO_3 - The most common carbonate mineral is calcite. It is the principal constituent of limestone and its metamorphic equivalent - marble. Deposits of fine grained calcite in powder form are referred to as chalk. It forms the cementing agent in many sandstones, and is one of the more common minerals precipitated by living organisms to form their skeletal structures.

Calcite is also precipitated from groundwater where it form veins, or in open cavities like caves and caverns can form the cave decorations - like stalactites and stalagmites, and encrustations. It is also precipitated from hot springs where it is called travertine.

Calcite does occur in rare igneous rocks called carbonatites. These form from carbonate magmas. Calcite is also precipitated from hydrothermal fluids to form veins associated with sulfide bearing ores.

Properties

In hand specimen, calcite is distinguished by its rhombohedral cleavage, its hardness of 3, and by its effervescence in dilute HCl. It can range in color from white, to slightly pink, to clear, but dark colored crystals can also occur. In thin section it is most readily distinguished by its

high birefringence, showing high order white interference colors, by its rhombohedral cleavage and its uniaxial negative character. Because of its high birefringence, it shows a large change in relief on rotation of the stage. Furthermore, its ϵ refractive index direction (low RI direction) when parallel to the polarizer shows a negative relief when compared to the mounting medium of the thin section. Calcite can be distinguished from Aragonite by the lack of rhombohedral cleavage and biaxial nature of Aragonite.

***Magnesite* $MgCO_3$**

Magnesite is a common alteration product of Mg-rich minerals on altered igneous and metamorphic rocks. Like calcite, it shows perfect rhombohedral cleavage, but unlike calcite, it does not readily effervesce in dilute HCl. It does, however, effervesce in hot HCl. These properties and its association with Mg-rich minerals and rocks make it distinguishable from Calcite.

***Siderite* $FeCO_3$**

Siderite forms complete solid solution series with Magnesite, although the environment in which the two minerals occur usually determines that either Mg-rich Magnesite or Fe-rich Siderite will form, and one rarely sees intermediate end members. In hand specimen, siderite is usually brown colored and effervesces only in hot HCl. In thin section it resembles Calcite, but has a much higher ϵ refractive index than Calcite and is commonly pale yellow to yellow brown in color without the analyzer inserted.

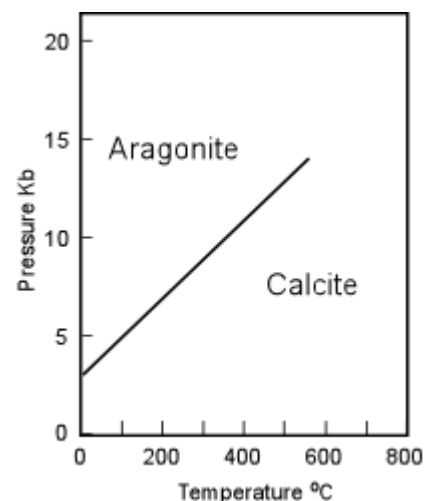
***Rhodochrosite* $MnCO_3$**

Rhodochrosite is the Mn bearing carbonate, and is thus found only in environments where there is an abundance of Manganese. It is relatively rare and occurs as hydrothermal veins and as an alteration product of Mn rich deposits. In hand specimen it shows a distinctive pink color along with the rhombohedral cleavage common to the Calcite group minerals. Hot HCl is required to make the mineral effervesce.

The Aragonite Group

The Aragonite group of minerals are all orthorhombic, and can thus be distinguished from minerals of the calcite group by their lack of rhombohedral cleavage. Aragonite ($CaCO_3$) is the most common mineral in this group.

Aragonite is the higher pressure form of $CaCO_3$ but, nevertheless occurs and forms at surface temperatures and pressures. When found in metamorphic rocks it is a good indicator of the low temperature, high pressure conditions of metamorphism, and is thus commonly found in Blueschist Facies metamorphic rocks along with Glaucophane. Water containing high concentrations of Ca and carbonate can precipitate Aragonite. Warm water favors Aragonite, while cold water favors calcite, thus Aragonite is commonly found as a deposit of hot springs. Aragonite can also form by biological precipitation, and the pearly shells of many organisms are composed of Aragonite. Fine needle-like crystals of Aragonite are produced by carbonate secreting algae.



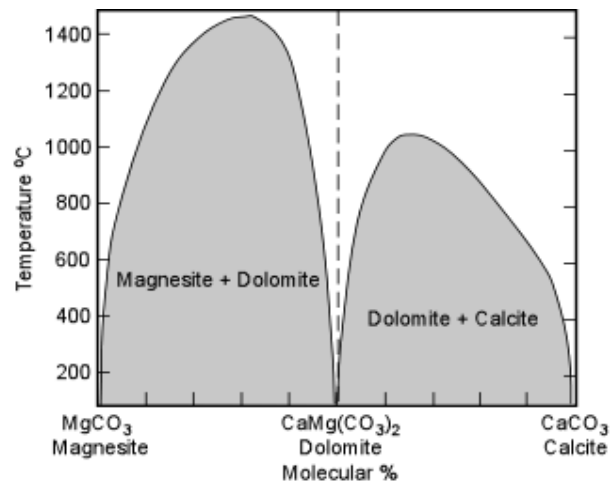
Properties

In hand specimen, Aragonite, like calcite effervesces in cold HCl. But, unlike Calcite, Aragonite does not show a rhombohedral cleavage. Instead it has single good {010} cleavage. It is usually transparent to white in color and forms in long bladed crystals. Twinning is common on {110}, and this can produce both cyclical twins, which, when present, make it look pseudo-hexagonal, and single twins. In thin section Aragonite is distinguished by its high birefringence, showing high order white interference colors, its biaxial character with a 2V of about 18°, and extinction parallel to the {010} cleavage.

The Dolomite Group

Dolomite - $\text{CaMg}(\text{CO}_3)_2$ and Ankerite - $\text{CaFe}(\text{CO}_3)_2$ form a complete solid solution series, although because Mg-rich environments are much more common than Fe-rich environments, Mg-rich dolomites are much more common than Ankerites. Ankerite is common mineral in Pre-Cambrian iron formations. Dolomite is a common constituent of older limestones, probably the result of secondary replacement of original calcite. It is also found as dolomitic marbles, and in hydrothermal veins..

Dolomite is a unique chemical composition, as can be seen in the Magnesite - Calcite phase diagram shown here. Two solvi exist at low temperatures. Thus, any high Mg-calcite - dolomite solid solutions that might exist at high temperatures would form nearly pure calcite and pure dolomite at surface temperatures, and similarly, any Magnesite - Dolomite solid solutions that might exist at high temperatures would form nearly pure Magnesite and pure Dolomite at low temperatures. Thus, Magnesite and Dolomite commonly occur together, as do Calcite and Dolomite.

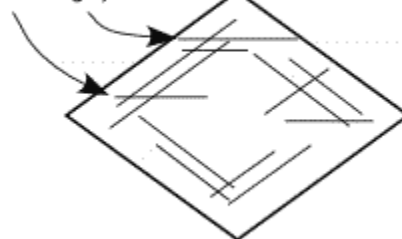


Properties Dolomite, and therefore rocks containing large amounts of dolomite, like dolostones, is easily distinguished by the fact that dolomite only fizzes in cold dilute HCl if broken down to a fine powder. Also, dolostones tend to weather to a brownish color rock, whereas limestones tend to weather to a white or gray colored rock. The brown color of dolostones is due to the fact that Fe occurs in small amounts replacing some of the Mg in dolomite.

In thin section it is more difficult to distinguish from calcite, unless it is twinned. In order to facilitate its identification in thin section, the sections are often stained with alizarin red S. This turns calcite pink, but leaves the dolomite unstained.

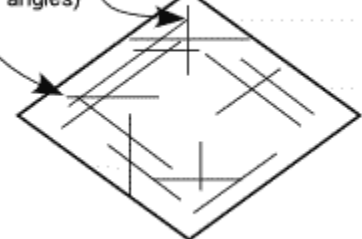
If calcite and dolomite are twinned, they are easily distinguishable from one another. Calcite shows twin lamellae that are parallel to the rhombohedral cleavage traces and parallel to the long direction of the cleavage rhombs.

Twin planes parallel to the long dimension of the rhomb (bisect the acute angle)



Calcite

Twin planes parallel both the long and short dimension of the rhomb (bisect both the acute and obtuse angles)



Dolomite

Thus, the lamellae bisect the acute angle between the cleavages. Dolomite also has twins parallel to the cleavage faces and parallel to the long direction of the rhombs, but also has twin lamellae that are parallel to the short dimension of the rhomb. Thus, dolomite would also show twin lamellae that would bisect the obtuse angle between the cleavage traces.

Accessory Minerals

Zircon ZrSiO_4

Zircon is a common accessory mineral in nearly all kinds of rocks, particularly the more siliceous igneous rocks, like granites, granodiorites, and syenites. Still, it is not often found in thin section because it is so hard that it gets plucked out during the grinding of the section. Zircon usually contains high amounts of radioactive elements like U and Th. Thus, when it is found as inclusions in minerals like biotite, it produces pleochroic haloes in the biotite as seen in thin section. Because it contains high concentrations of U and Th, it is very useful in obtaining U-Pb and Th-Pb radiometric dates on old rocks. It is very resistant to weathering and may also survive during metamorphism, allowing for dates to be obtained on the original rock prior to metamorphism (often called the protolith).

In hand specimen Zircon usually occurs as tiny reddish colored crystals. In thin section, it shows extremely high relief, with $\omega = 1.923$ to 1.960 and $\varepsilon = 1.968$ to 2.015 . and is uniaxial positive. Zircon has high birefringence, with interference colors in the higher orders (lots of reds, pinks and light greens). It is commonly colorless to pale brown or pinkish brown in polarized light without the analyzer. Generally it occurs as small crystals with relief higher than almost anything else in the thin section. This latter property should tip you off to its presence.

Sphene (Titanite) $\text{CaTiSiO}_4(\text{OH})$

Sphene is another 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.

In hand specimen as an accessory mineral, it is usually seen as small wedge-shaped crystals with a resinous to adamantine luster and brown to yellow brown color. In thin section, Sphene, has a relief similar to that of zircon, and is usually found in small crystals with an elongated diamond shape. It is generally brownish in color, shows a well developed $\{110\}$ cleavage, and high order interference colors.

Apatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F})$

Apatite is another very common and almost ubiquitous (always present) accessory mineral in igneous rocks and many metamorphic rocks. If the rock contains any phosphorous it is usually found in apatite. Apatite is hexagonal, hence uniaxial with a negative optic sign. Its refractive indices $\omega = 1.624$ to 1.666 and $\varepsilon = 1.629$ to 1.667 are higher than both quartz and nepheline, giving apatite a higher relief than these minerals. Its birefringence, expressed as 10 gray interference colors is similar to that of quartz and nepheline. Quartz, however, is optically positive. Nepheline, while optically negative, shows much lower relief than does apatite. The crystal form of apatite is usually distinctive. If cut parallel to $\{0001\}$, it usually has a hexagonal outline. If cut parallel to the C axis, it appears as doubly terminated prisms.

Examples of questions on this material that could be asked on an exam

1. What are the eight polymorphs of SiO? Briefly describe where each of these polymorphs are stable and which, if any do not have unstable polymorphs at the earth's surface conditions.
 2. For the SiO₂ polymorphs, is there a correlation between density and temperature or pressure of stability? If so, can you explain why this is?
 3. State whether each of the following minerals would be most commonly found in igneous rocks, metamorphic rocks, or both igneous and metamorphic rocks: (a) quartz, (b) plagioclase, (c) sanidine, (d) microcline, (e) nepheline, (f) sodalite, (g) leucite, (h) apatite, (i) staurolite.
 4. Which minerals would be good ores for Cr, Al, Fe, Ti, or Mn?
 5. What is the major difference between the calcite group and the aragonite group of carbonate minerals?
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