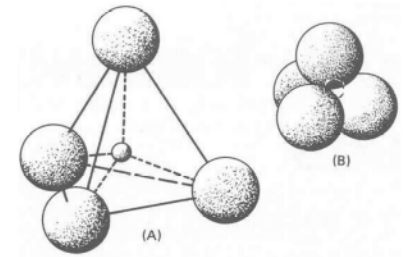


Classification of Common Minerals



The SiO_4 tetrahedron is first shown “blown up”, then with the right relative size of Si^{+4} (small) and O^{-2} (large).

– **olivine** isolated tetrahedra with 0 oxygen shared



– **pyroxene** 1-D chains with 2 oxygen shared



– **mica** 2-D sheets with 3 oxygen shared



– **quartz** 3-D framework with all 4 oxygen shared



While quartz = $\text{Si}^{+4}(\text{O}^{-2})_2$ is electrically neutral, the others are not and in those cases cations such as Fe^{+2} , Mg^{+2} , and Ca^{+2} must be added to the crystal.

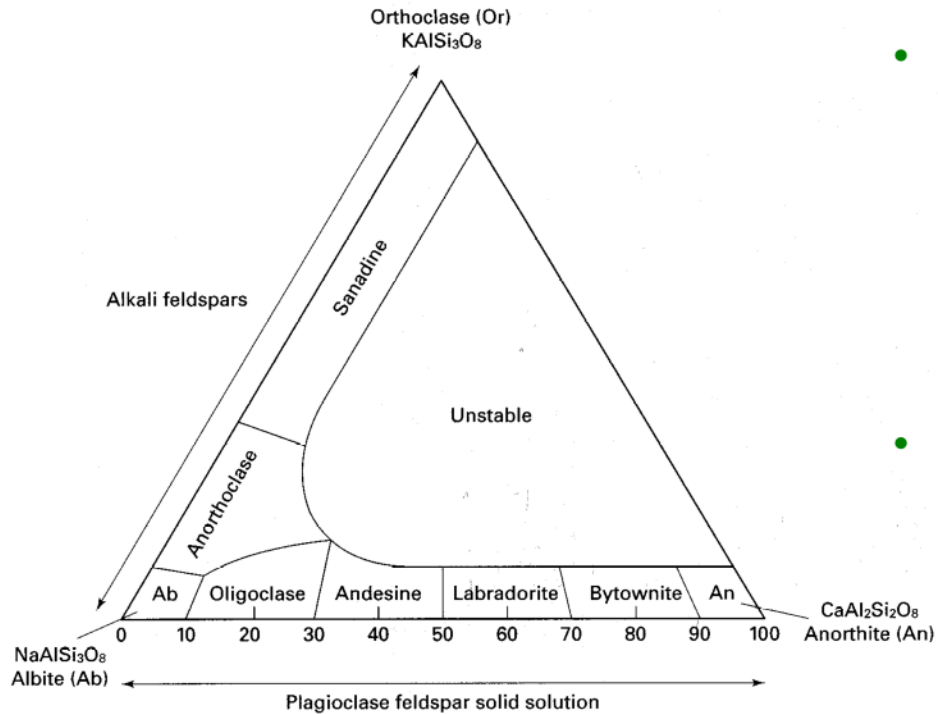
Deitrich & Skinner 1979

– **feldspar** In the quartz 3-D framework, Al^{+3} can replace Si^{+4} in the center of some of the tetrahedra, as long as appropriate cations like K^{+1} , Na^{+1} , and Ca^{+2} are also added to preserve charge neutrality. (This substitution by Al also happens to some of the Si in mica)

• Some minerals (described later) are simple oxides without silicon

• Within each type of silicates, mineral names are given based on the type of cation

Classification of Feldspars

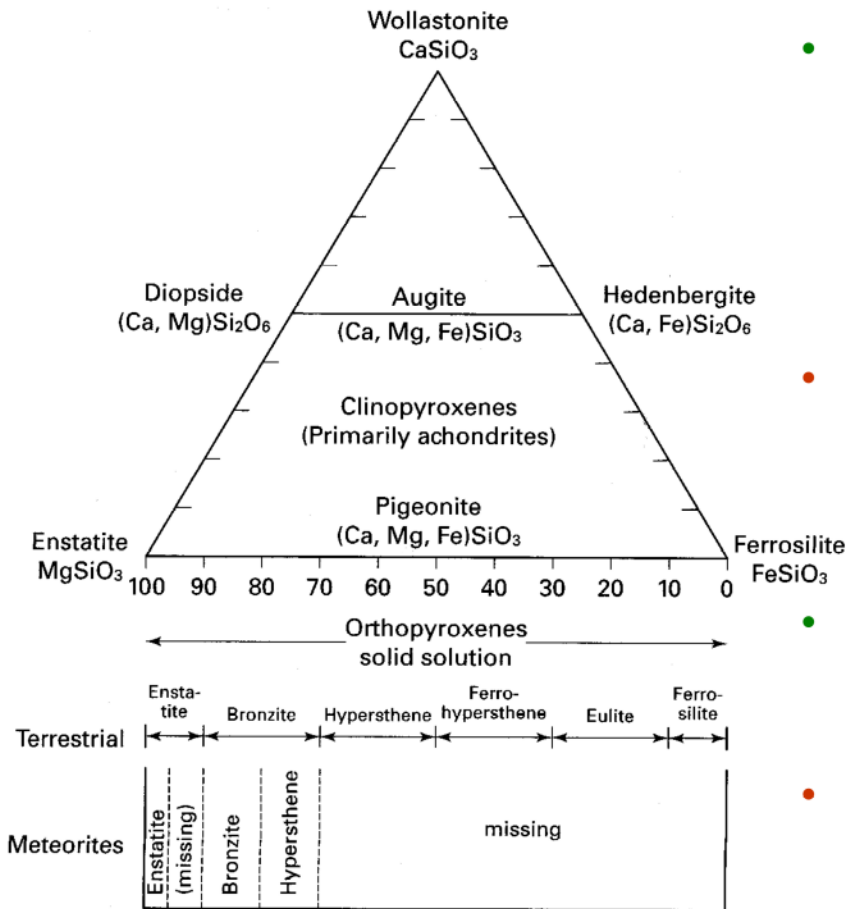


From Norton 2002. Cambridge Encyclopedia of Meteorites

- 3-D network of SiO_4 tetrahedra with O's shared, just like quartz,
 except one or two Si^{+4} replaced by Al^{+3} ,
 and a K^{+1} or Na^{+1} or Ca^{+2} cation added to compensate.
- End-members
 - $\text{K Al Si}_3\text{O}_8$ Orthoclase
 - $\text{Na Al Si}_3\text{O}_8$ Albite
 - $\text{Ca Al}_2\text{Si}_2\text{O}_8$ Anorthite

- Alkali feldspars: solid solution between K and Na end-members
- Plagioclase feldspar: solid solution between Na and Ca end-members
- No solution allowed between K and Ca. Rocks with an intermediate bulk composition separates into a mixture of alkali and plagioclase feldspar crystals.

Classification of Mafics: Pyroxene



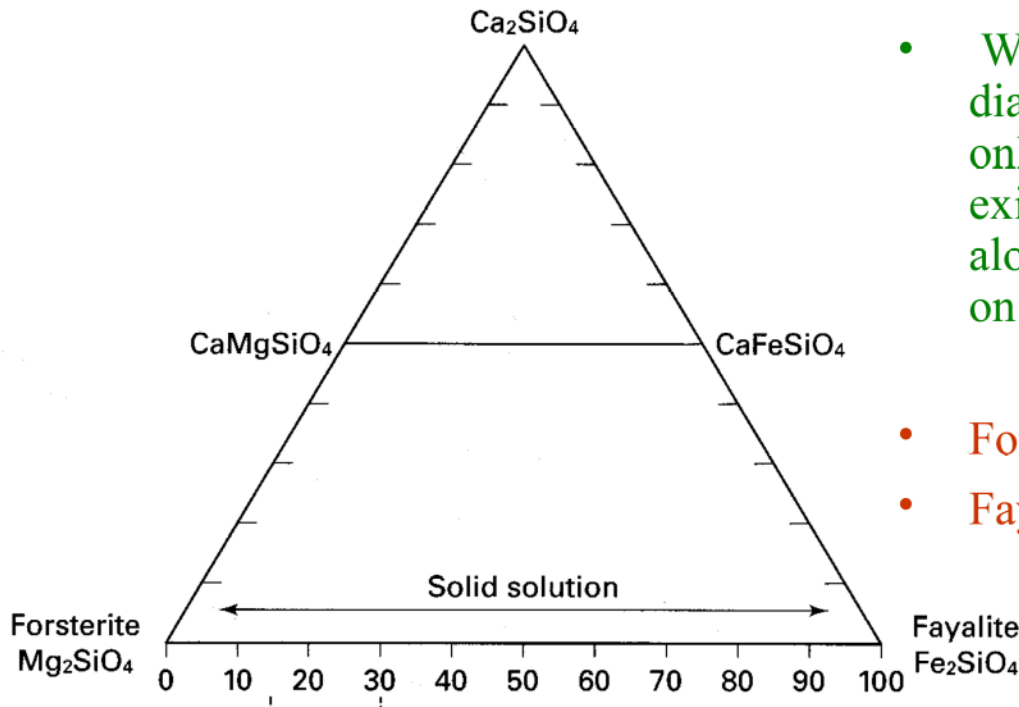
From Norton 2002 "The Cambridge Encyclopedia of Meteorites"

- In pyroxenes the SiO_4 tetrahedra are linked into chains by the sharing of two O in each tetrahedron, giving a total of $2 + 2 \cdot 1/2 = 3$ O per Si: SiO_3^{-2} which must be balanced by a +2 cation such as Fe^{+2} , Mg^{+2} , or Ca^{+2}
- Orthopyroxenes
 - Enstatite Mg Si O_3
 - Ferrosilite Fe Si O_3
- Wollastonite Ca Si O_3
 - (not a true pyroxene – different crystal structure)
- Clinopyroxenes (up to 50% Ca cations)
 - Diopside $\text{Ca Mg Si}_2 \text{O}_6$
 - Hedenbergite $\text{Ca Fe Si}_2 \text{O}_6$
 - Augite $(\text{Ca, Mg, Fe}) \text{Si O}_3$
- Other names used for intermediate compositions
 - Pigeonite = low Ca “orthopyroxene”

Classification of Mafics: Olivine

- In olivine each SiO_4^{-4} tetrahedra is isolated, with no shared oxygen. For each tetrahedra the crystal must contain two +2 cations.

- We could use an Mg Fe Ca ternary diagram as we did for pyroxene, but the only common compositions for which there exists a solid solution are those essentially along the bottom – on the Mg Fe line.



- Forsterite $\text{Mg}_2 \text{Si O}_4$
- Fayalite $\text{Fe}_2 \text{Si O}_4$

From Norton 2002 "The Cambridge Encyclopedia of Meteorites"

Common non-silicate planetary minerals

- Many of the non-silicate minerals are simple oxides.

– Corundum	Al_2O_3	Al_2^{+3}	O_3^{-2}
– Rutile	Ti_2O_3	Ti_2^{+3}	O_3^{-2}
– Ilmenite	FeTiO_3	$\text{Fe}^{+3}\text{Ti}^{+3}$	O_3^{-2}
– Hematite	Fe_2O_3	Fe_2^{+3}	O_3^{-2}

- Families of similar form also exist, such as the spinel group, named after one of its members.

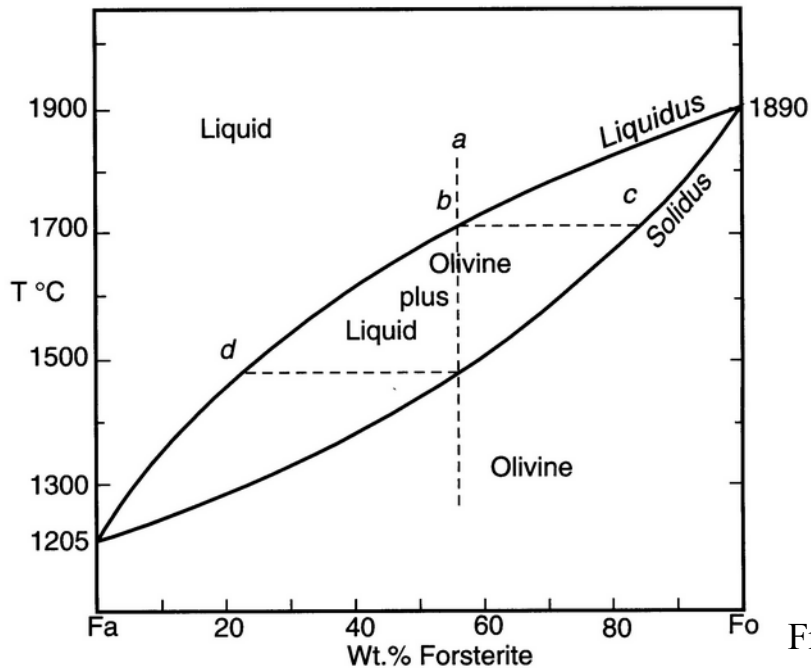
The general formula is $\text{X}^{+2}\text{O} \cdot \text{Y}_2^{+3}\text{O}_3$ where X and Y can be as follows

Name	X⁺²	Y⁺³	Formula
spinel	Mg	Al	MgAl_2O_4
magnetite	Fe	Fe	Fe_3O_4
chromite	Fe	Cr	FeCr_2O_4

- Common sulfides are

– Troilite	FeS
– Pyrite	FeS_2
– Pyrrhotite	FeS to Fe_7S_8
– Galena	PbS
– Sphalerite	ZnS

Melting and Crystallization: Solid Solutions



- Minerals where solid solutions exist like:
Olivine: $(\text{Mg, Fe})_2\text{SiO}_4$: any Mg can replace any Fe
- Pure Mg_2SiO_4 (Forsterite) melts at 1890°C
- Pure Fe_2SiO_4 (Fayalite) melts at 1205°C
- Mg crystals survive at higher temperature because Mg bonds are stronger than Fe ones.
- For given intermediate composition:

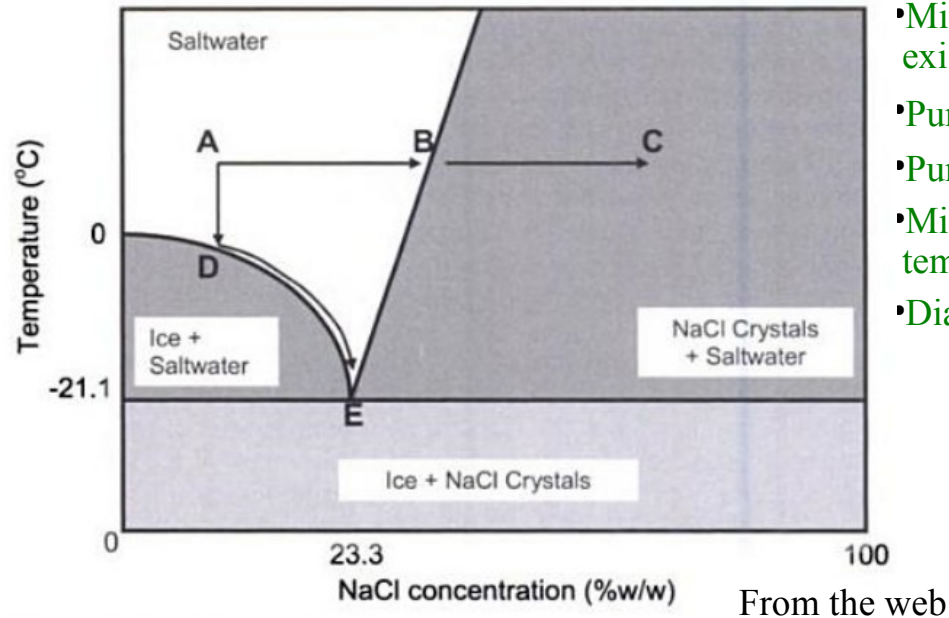
Liquidus gives temperature above which system is all liquid

Solidus gives temperature below which system is all solid

- If you have melt with composition “a” and cool it, first crystals form at temperature of the b-c line ($\sim 1700^\circ\text{C}$). The melt (which makes up almost all the system) will have composition “a” but the crystals will be more Mg rich, with composition “c”.
- As you continue to cool it the composition of the melt shifts to the left (towards Fe) since you are preferentially extracting Mg. As long as crystals stay in equilibrium with melt the melt composition will follow the liquidus curve while the crystal composition follows the solidus curve.
- At a temperature just below 1500° the crystals have composition “a”, the same as the original melt, and the liquid composition reaches “d”. Virtually all of the system must now be solid and “d” represents the last dregs of liquid. If you cool it any further than this the system is all solid with original composition “a”.
- You can find the relative amounts of liquid and solid using the “lever” rule: If F is fraction and C is composition

$$F_{\text{melt}} \times C_{\text{melt}} + F_{\text{crystals}} \times C_{\text{crystals}} = C_{\text{system}} \quad \text{and} \quad F_{\text{melt}} + F_{\text{crystals}} = 1$$

Melting and Crystallization: Immiscible Solids

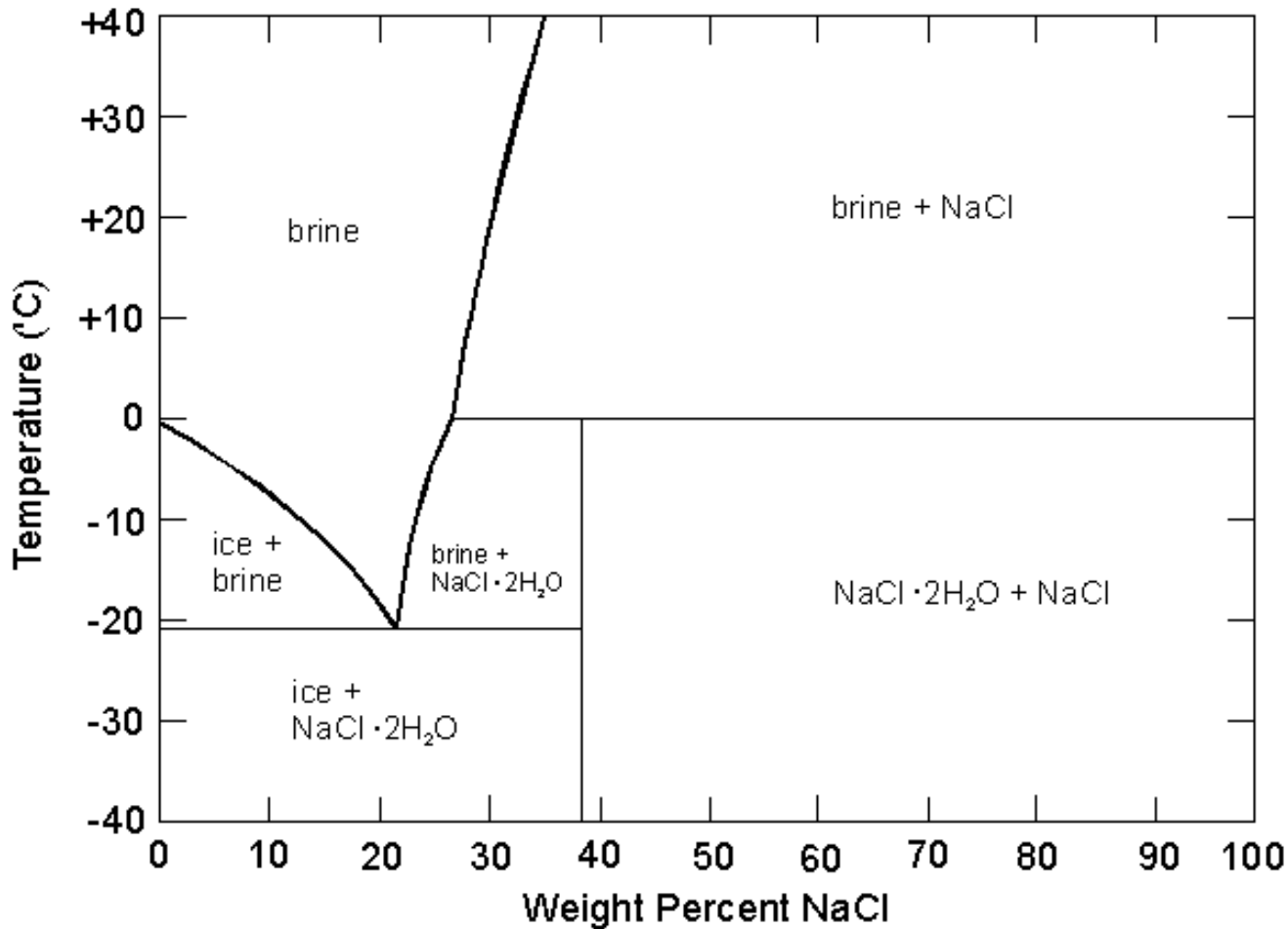


- Minerals where only pure crystals of end-member composition exist. (This is simplified salt – in reality hydrated salts exist)
- Pure H₂O melts as 0° C
- Pure NaCl melts at 801° C
- Mixtures of the right intermediate composition can melt at temperatures less than either end-member.
- Diagram shows:

- Clear portion: pure liquid brines
- Dark gray to left is: ice crystals plus saltwater
- Dark gray to right is: salt crystals plus saltwater.
- Light gray at bottom: mixture of pure salt crystals and pure ice crystals

- If you cool a “melt” with the composition of “A” then when it reaches “D” it begins to form pure ice crystals. Since you are preferentially extracting ice, the “melt” composition shifts towards Salt. As the melt cools the melt composition follows the “D” to “E” curve. At any point the amount of ice crystals and the amount of melt can be found from the lever rule.
- Point “E” is called the “Eutectic”
- The Eutectic Composition is 23.3% NaCl by weight. The Eutectic Temperature is -21.1° C.
- If you cool the system any further then both pure ice and pure salt crystals will form. When the entire system is crystallized it will be a “mechanical” mixture of pure ice and pure salt crystals whose bulk composition will match the original composition of the “melt”.
- If you heat an initially solid mechanical mixture of salt and ice the first melt will appear at the Eutectic Temperature with the Eutectic Composition. As the temperature is raised the melt will evolve along either the D-E or E-B curve until the melt composition matches the bulk composition.

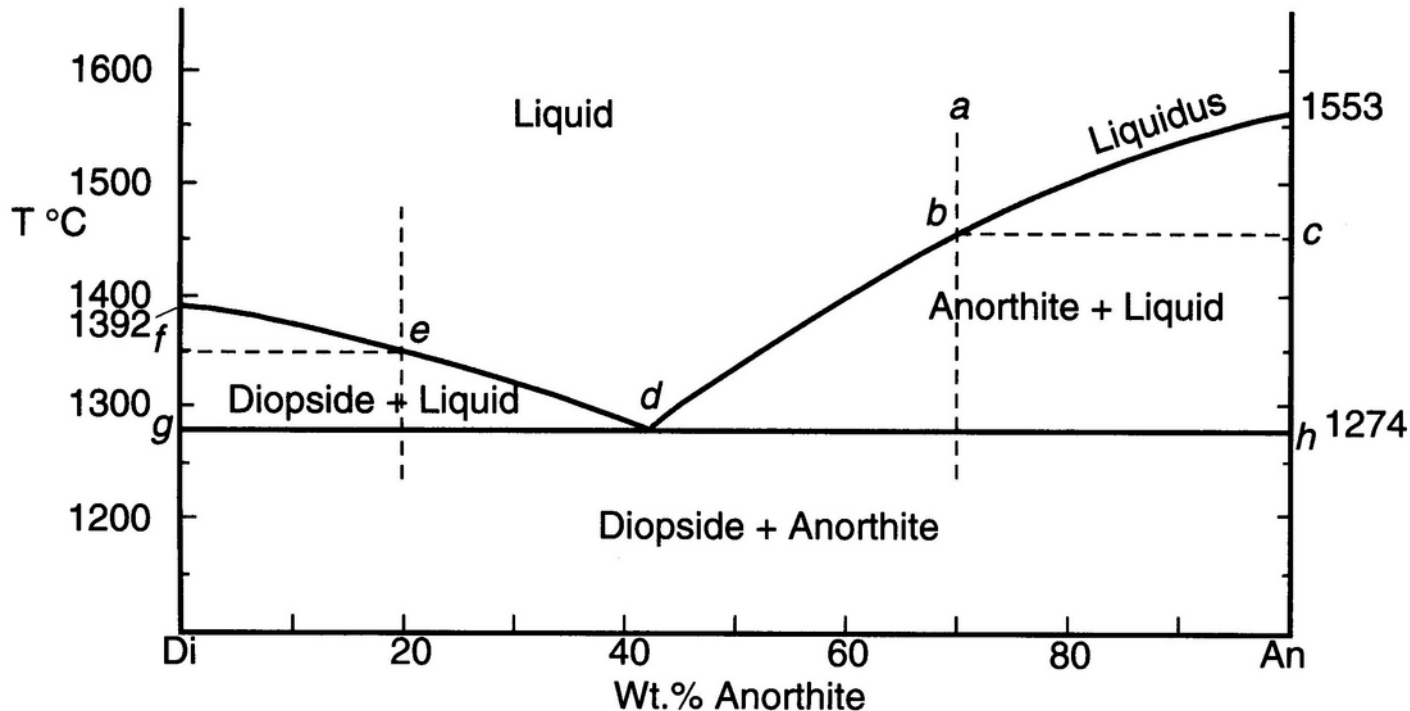
Melting and Crystallization: Real Salt



- Real salt can form not only pure H₂O ice and pure NaCl crystals but also a hydrated salt NaCl·2H₂O crystal so the actual phase diagram is more complicated.

Melting: Immiscible Solids (Diopside + Anorthite)

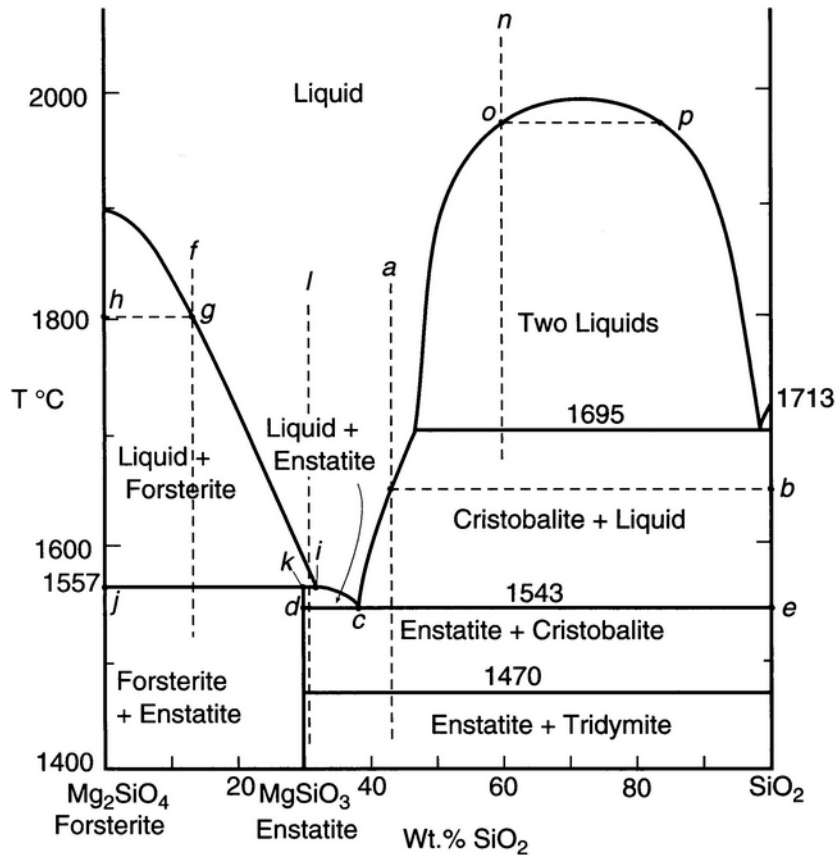
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From Winter 2001

- Crystals of the pyroxene Diopside ($\text{MgCaSi}_2\text{O}_6$) and the feldspar Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) are immiscible and so have a phase diagram similar to that of the simplified salt.

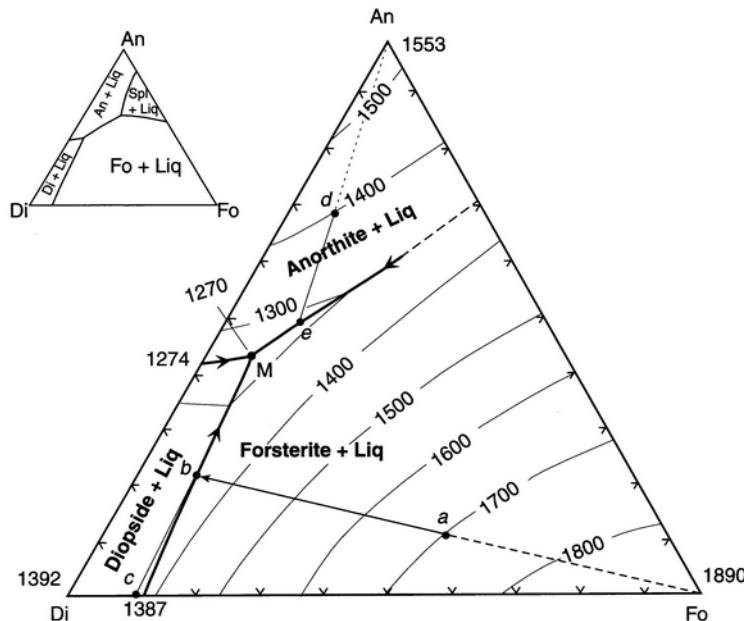
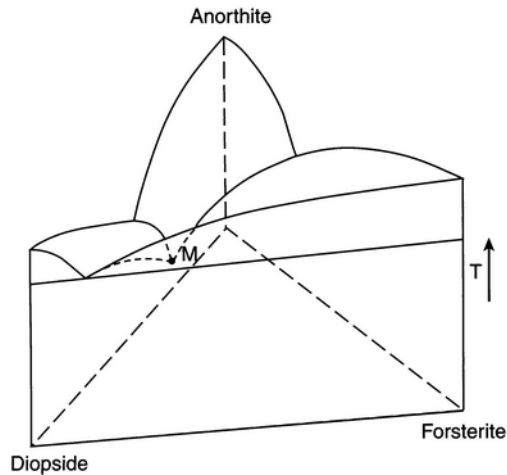
Melting: Immiscible Solids and Immiscible Liquids



From Winter 2001

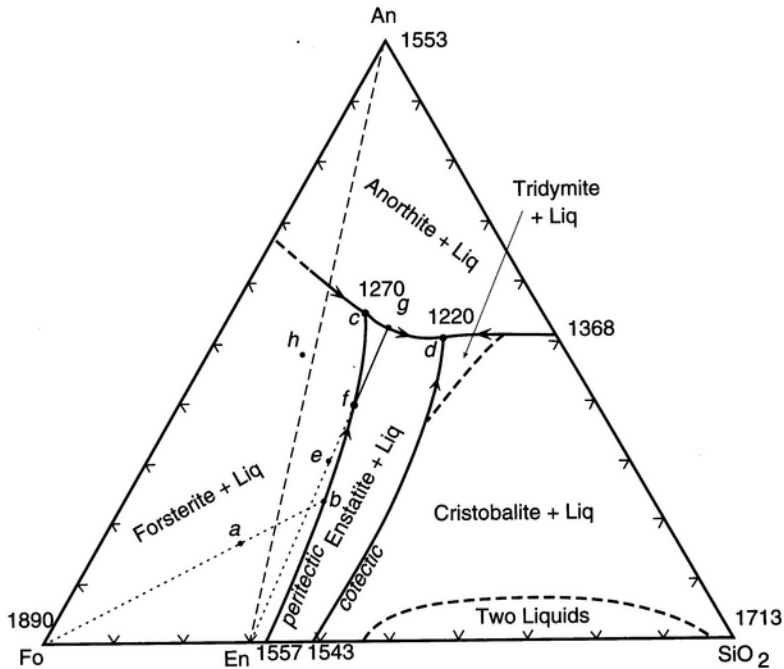
- Since both mathematically and physically:
- $\text{Mg}_2\text{SiO}_4 + \text{SiO}_2 \leftrightarrow 2 \text{MgSiO}_3$
- Forsterite + Quartz \leftrightarrow Enstatite
- Enstatite can be plotted on an axis stretching between Fo and Qtz
- We can have crystals of Fo, En, or Qtz
- The quartz crystals can have two forms:
 - Cristobalite at higher temperature
 - Tridymite at lower temperature
- The quartz rich liquid actually separates into two immiscible liquids
- Point “i” is “peritectic” point. At this point in a cooling liquid + Forsterite system, all the Forsterite reacts with the melt to form Enstatite plus some residual melt

Melting: 3 Component Phase Diagrams



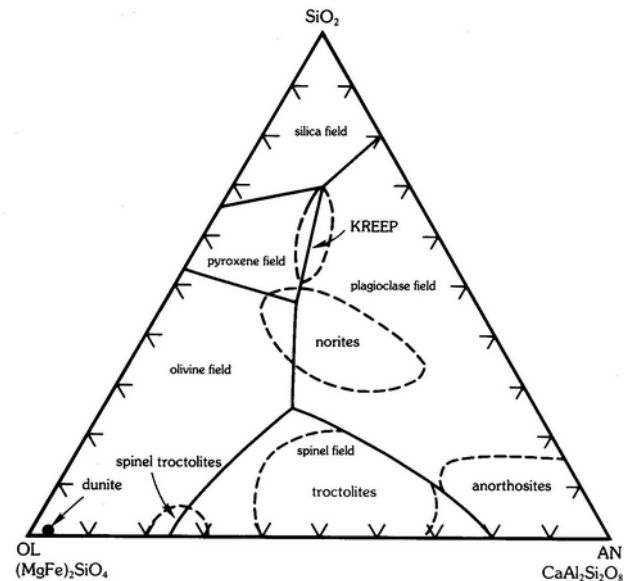
- For 3 component systems could plot composition in x-y plane using a triangle plot, and temperature in Z.
- Along any outside edge it looks like the two component plots we have studied:
 - The two curved liquid + crystal curves meet at a eutectic
- In 3-D those curved lines become curved surfaces – meeting at a line called a cotectic.
 - The melt will evolve along the curved surface – away from what ever corner represents the crystal being formed
 - Once the system reaches the cotectic the melt will evolve downhill along that cotectic till it reaches the eutectic point “M”
- Because 3-D plots are hard to read, we usually just plot a projection, looking vertically down on the composition plane and drawing in the various phase boundaries and cotectics. The melt will follow those lines as it crystallizes

Melting: The An, Fo, SiO₂ diagram



From Winter 2001

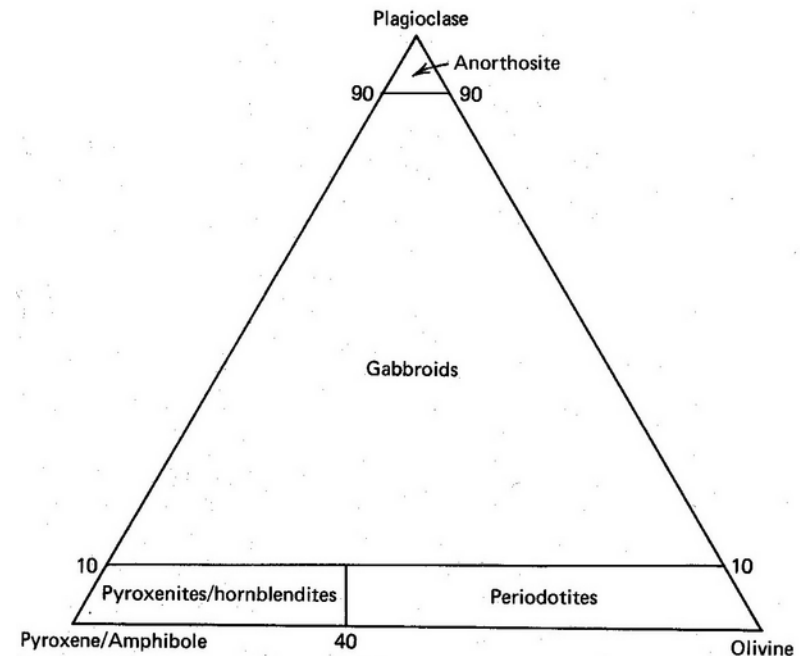
- We can plot a wider range of compositions if we remember that Diopside can be thought of as lying partway between Quartz and Forsterite
- Like the Fo SiO₂ diagram this one will have not only eutectic (or cotectic) lines, but also peritectic lines where the forsterite crystals react with the melt to form enstatite.
- Diagram below is often used for plotting lunar rock evolution. Rotated and flipped version of one from Winter. Also, axes scaled differently (by weight vs. #)



5.16 Compositions of apparently pristine lunar highland samples plotted on the olivine-anorthite-silica pseudoternary diagram. (Adapted from [42].)

Classification used for Highland Rocks: “Gabbroids”

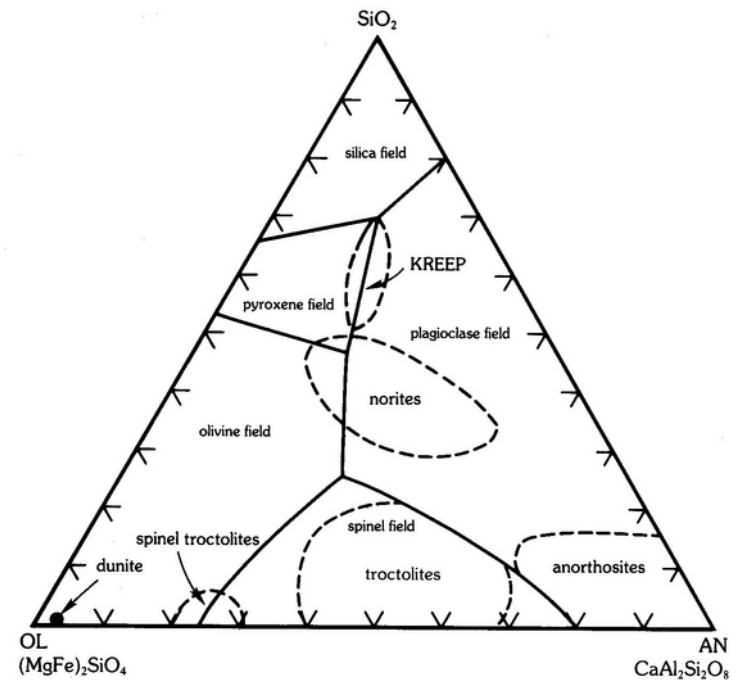
- Gabbro: Dominated by Feldspar and Mafic minerals, with little Quartz
- Note: Gabbro can be used as a specific name for rock containing plagioclase plus clinopyroxene, with perhaps olivine and orthopyroxene, or it can be used in a general sense (gabbroid) for rock containing plagioclase plus mafic materials. In much of the lunar literature it is used in the general sense.
 - Quartz: < 5% of total
 - Mafics: 35 – 65% of total (augite ± hyperthese ± olivine)
 - Plag: 90 – 100% of feldspar
- Anorthosite: Dominated by Ca Feldspar (anorthite)
 - Quartz: < 5% of total
 - Mafics: 0 – 10% (augite) typically augite
 - Plagioclase 90 – 100 % of feldspars
- Pyroxenite: Dominated by Pyroxene
 - Plagioclase: < 10% of total
 - Mafics: > 40% pyroxene
- Peridotite: Dominated by Olivine
 - Plagioclase: < 10% of total
 - Mafics: > 60% of total
 - (Dunite is name for rock with >90% olivine)



Deitrich & Skinner Figure 4.8b

Classification used for Highland Rocks: More refined names for Gabbroids

- You can plot Anorthite, Olivine, and Pyroxene in a ternary diagram for Anorthite, Olivine, Quartz since Pyroxene is “intermediate” between olivine and quartz. This has the advantage that you can plot rocks that are even closer to quartz.
- So this diagram is like previous one, but rotated so An is at the lower right, and expanded to cover a region more toward SiO_2
- Troctolites
 - Plagioclase (anorthosite) with olivine
 - Name (German) from resemblance to “speckled trout”
 - from olivine phenocrysts on light background
- Norite
 - Plagioclase (anorthosite) with orthopyroxene



5.16 Compositions of apparently pristine lunar highland samples plotted on the olivine-anorthite-silica pseudoternary diagram. (Adapted from [42].)

Taylor 1982

