MSFC-2218

2009 MSFC Regolith Simulant TIM
Short Course

Terrestrial and Lunar Geological Terminology for non-Geoscientists

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Fundamental ways the Moon differs from the Earth

- Highly volatile elements are effectively absent in minerals on the Moon
  - <1 ppb H_2O
  - No H-bearing minerals. No hydrous (OH) or hydrated (H_2O) minerals. No clays, micas, or amphiboles.
- Volatile elements are depleted relative to Earth
  - Less Na
- The oxygen fugacity (fO_2) is much lower on the Moon
  - On Earth, most iron occurs as Fe^{3+} and Fe^{2+}.
  - On the Moon, most iron occurs as Fe^{2+}, with some Fe^0. There is no Fe^{3+}.

Minerals

A mineral is:

- naturally occurring
- inorganic

A mineral has:

- characteristic chemical composition
- regular internal order

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A mineral has:

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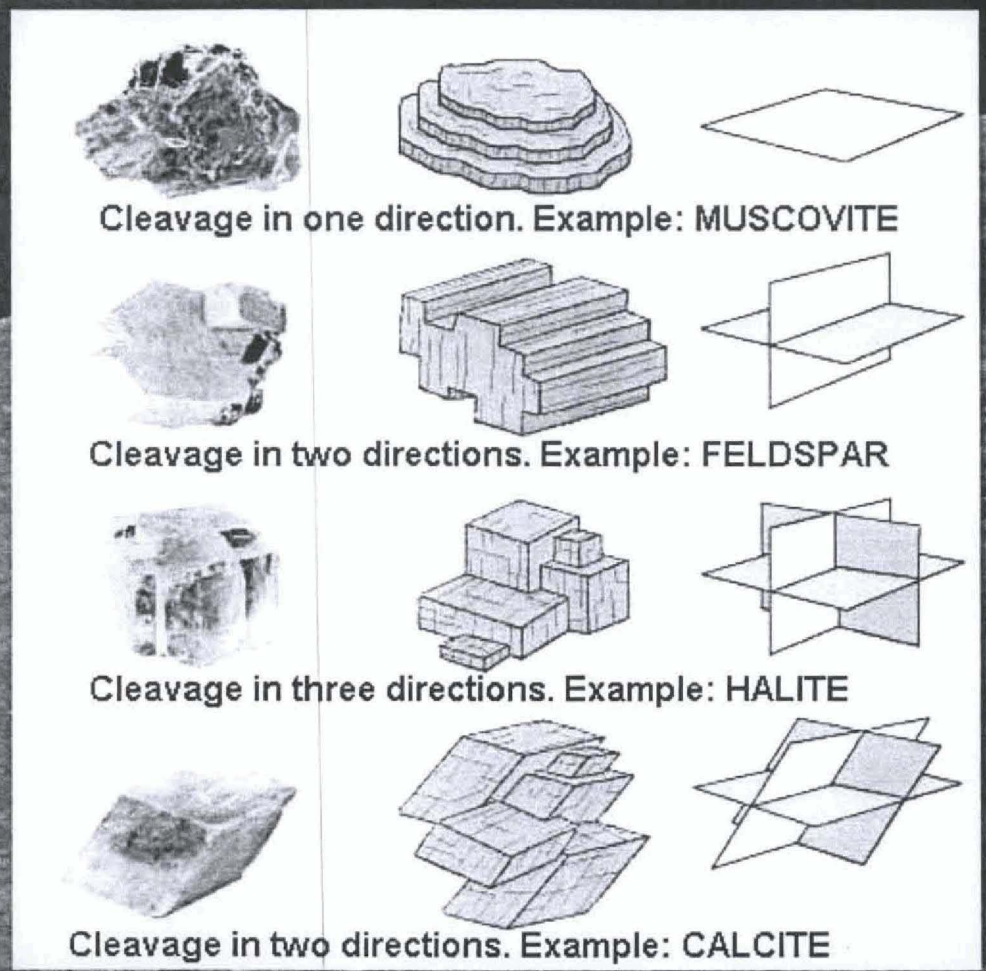
- regular internal order

➢ Diagnostic characteristics

- color
- crystal form
- hardness
- cleavage
- fracture
- specific gravity (SG)
- melting temperature (T_M)

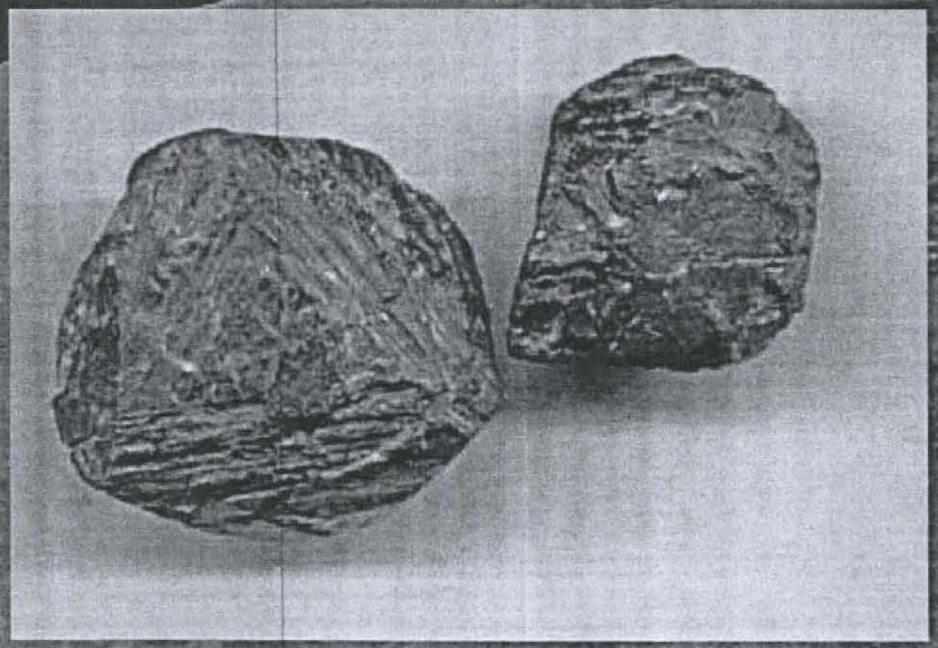
Minerals: cleavage



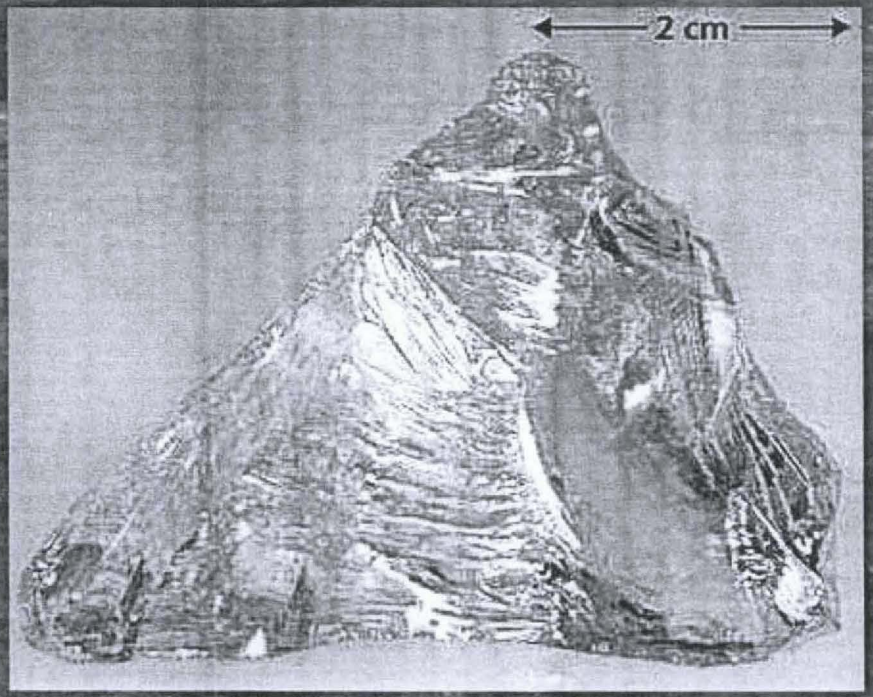
- Cleavage describes the propensity of a mineral to break along preferred orientations
- It is controlled by the internal order, or crystal structure, of a mineral.
- Described by the quality, the number of planes, and the angle between planes.

Minerals: fracture

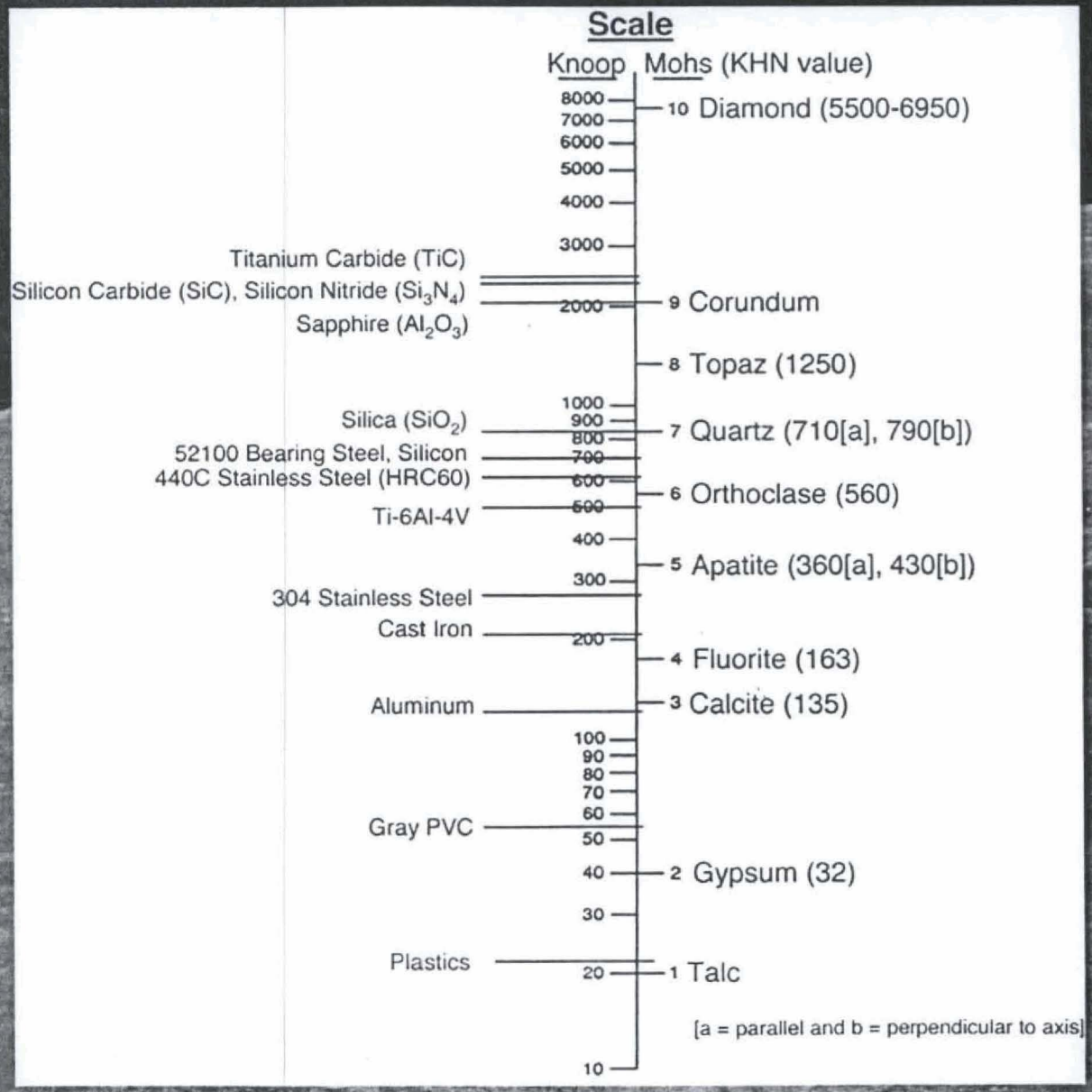
Uneven fracture



Conchoidal fracture



Minerals: hardness

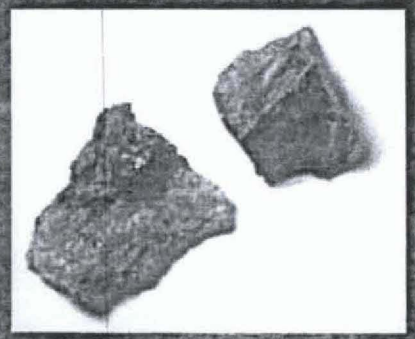


- Mohs is a relative scale of hardness measured by scratching
- Knoop (and others) are absolute scales of indentation.

Minerals: hardness

Olivine

Na-plagioclase



Ca-plagioclase

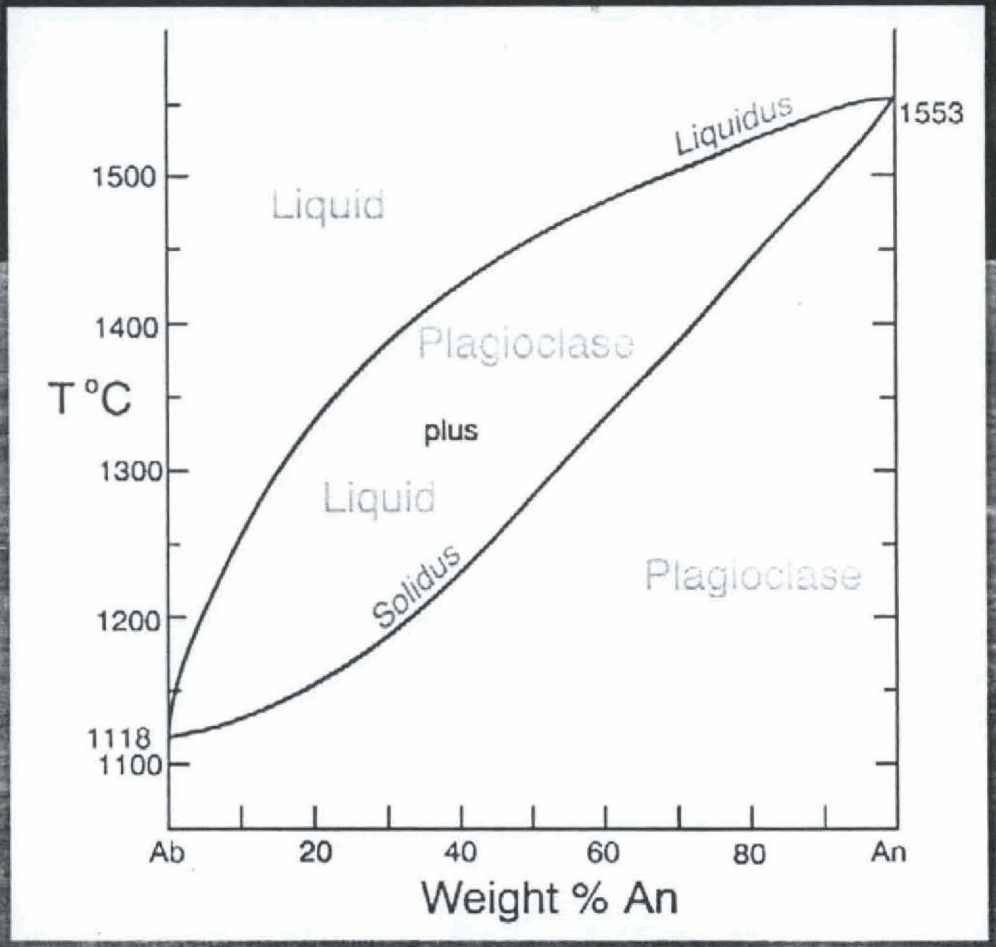
Minerals: Solid Solutions

Plagioclase feldspar

The most abundant mineral in the lunar highlands.

Albite $NaAlSi_3O_8$

Anorthite $CaAl_2Si_2O_8$



1 atmosphere diagram, from Bowen (1913)

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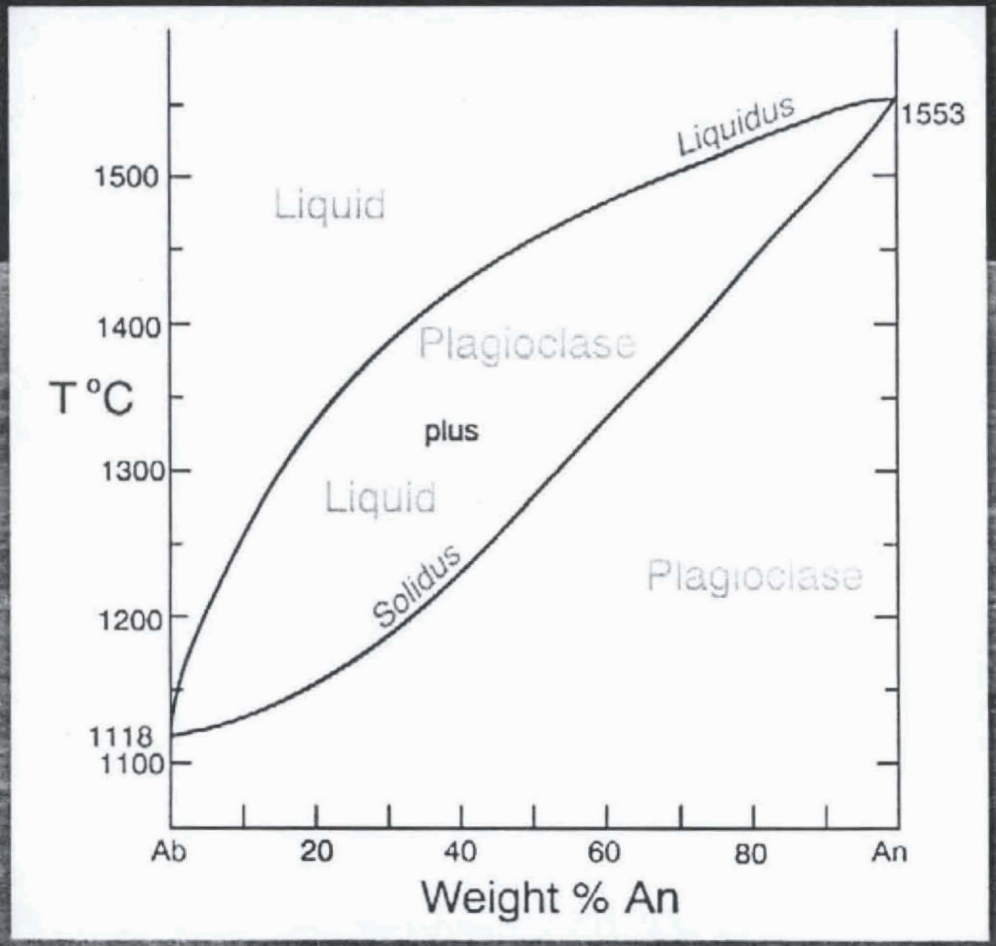
Na^+Si^{4+} ↑ ↓ $Ca^{2+}Al^{3+}$

Anorthite $CaAl_2Si_2O_8$



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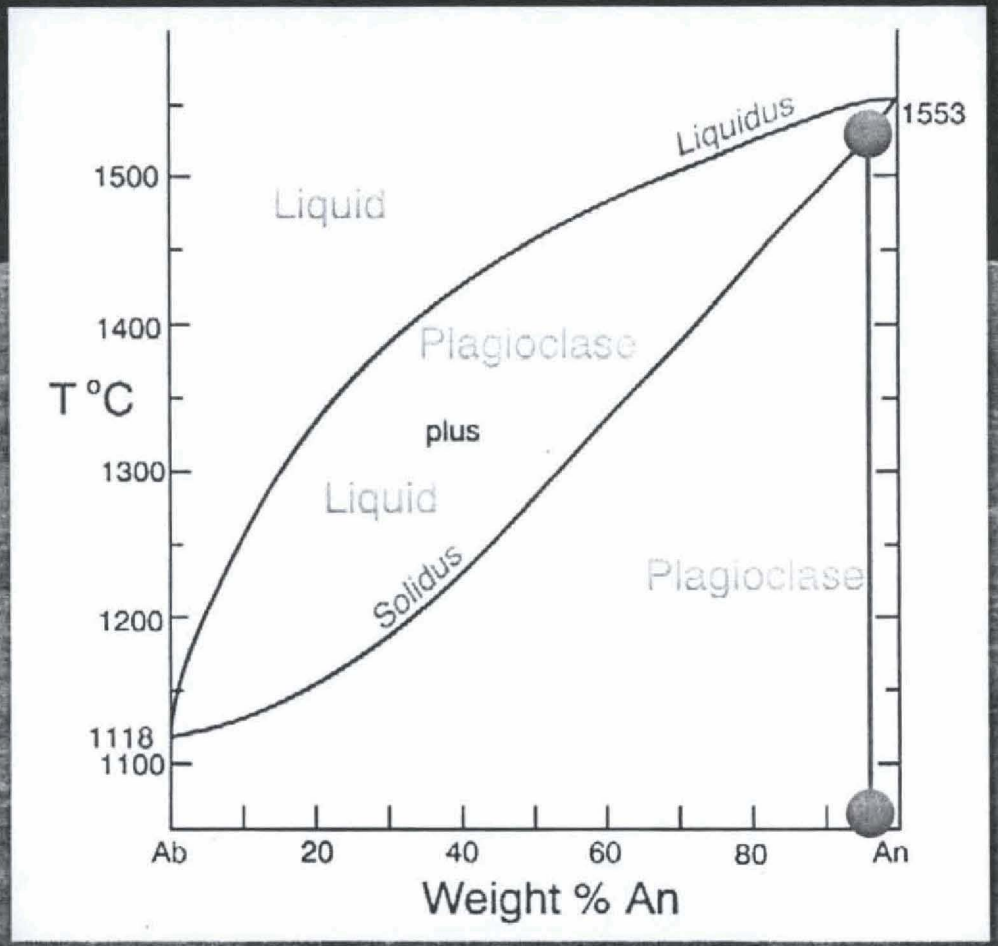
Most highlands plagioclase is An_{94-99}



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Minerals: Solid Solutions

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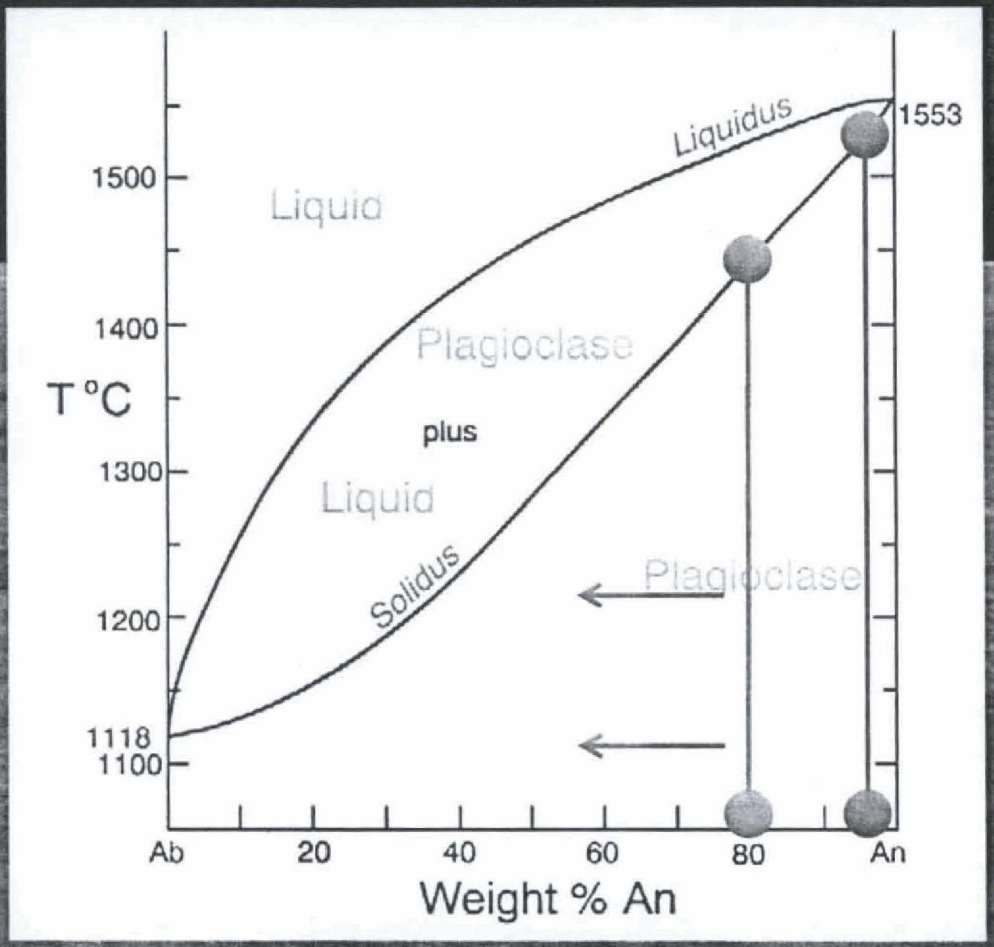
Most simulant plagioclase is $<An_{80}$



1 atmosphere diagram, from Bowen (1913)

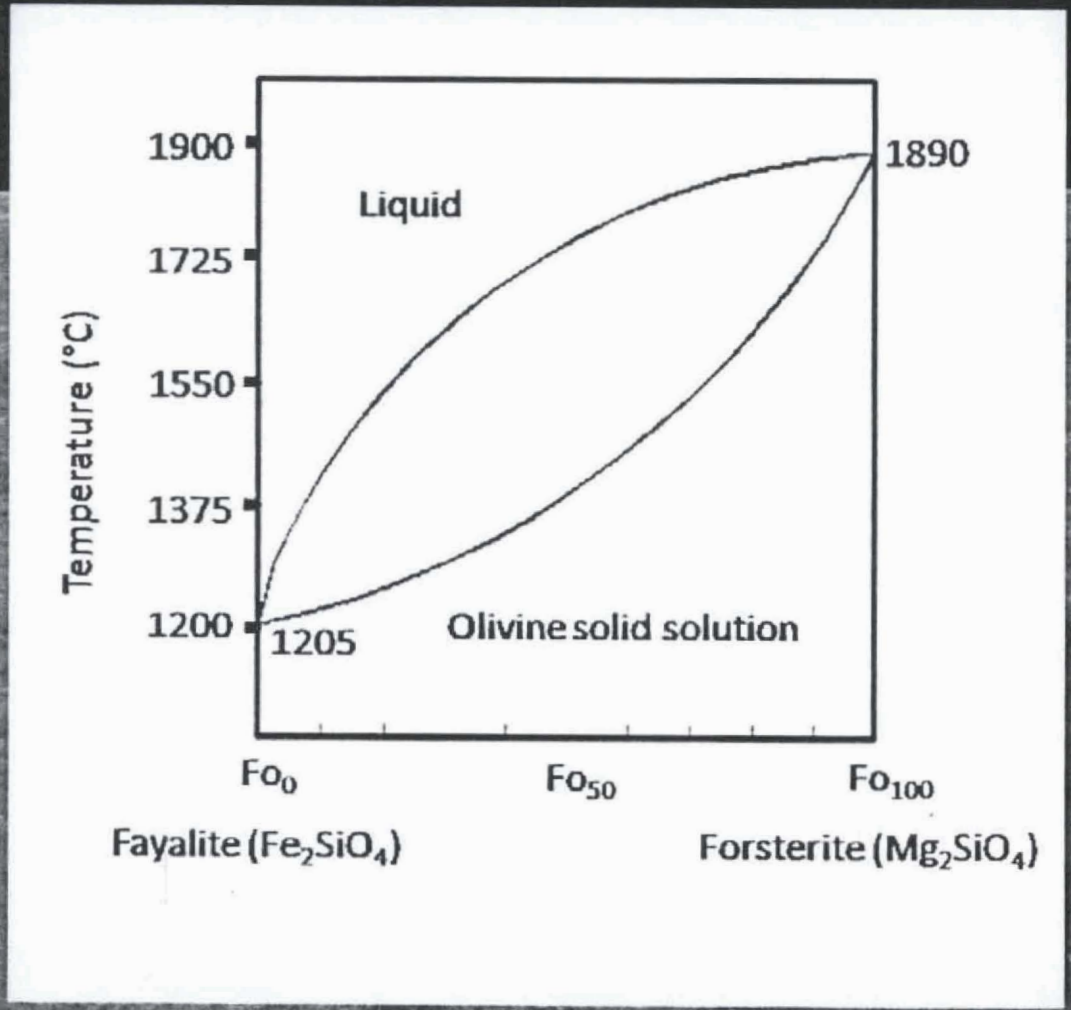
Minerals: Solid Solutions

Olivine
$(Mg,Fe)_2SiO_4$

Forsterite Mg_2SiO_4

Fayalite Fe_2SiO_4

Most lunar olivine is $Fo_{30\text{-}80}$.



1 atmosphere diagram, from Bowen & Schairer (1935)

Minerals: Solid Solutions

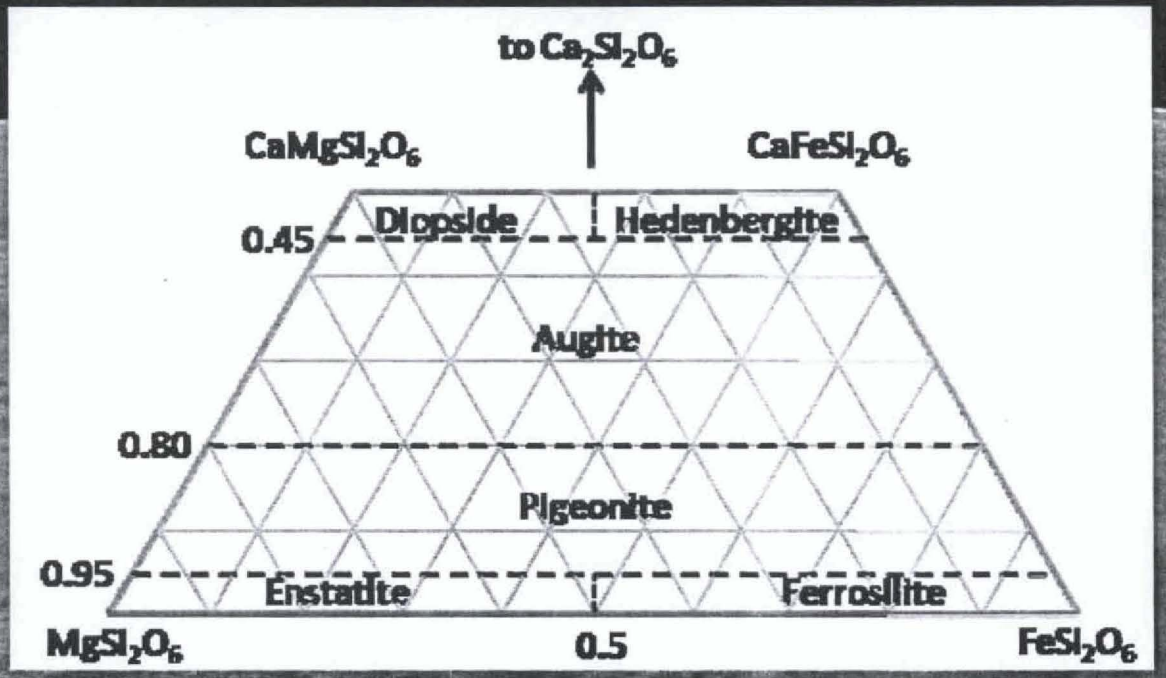
Pyroxene
$(Ca,Mg,Fe)_2Si_2O_6$

Clinopyroxene series

$Ca(Mg,FeO)Si_2O_6$

Orthopyroxene series

$(Mg,Fe)_2Si_2O_6$



Pyroxene quadrilateral and classification fields

Minerals: Solid Solutions

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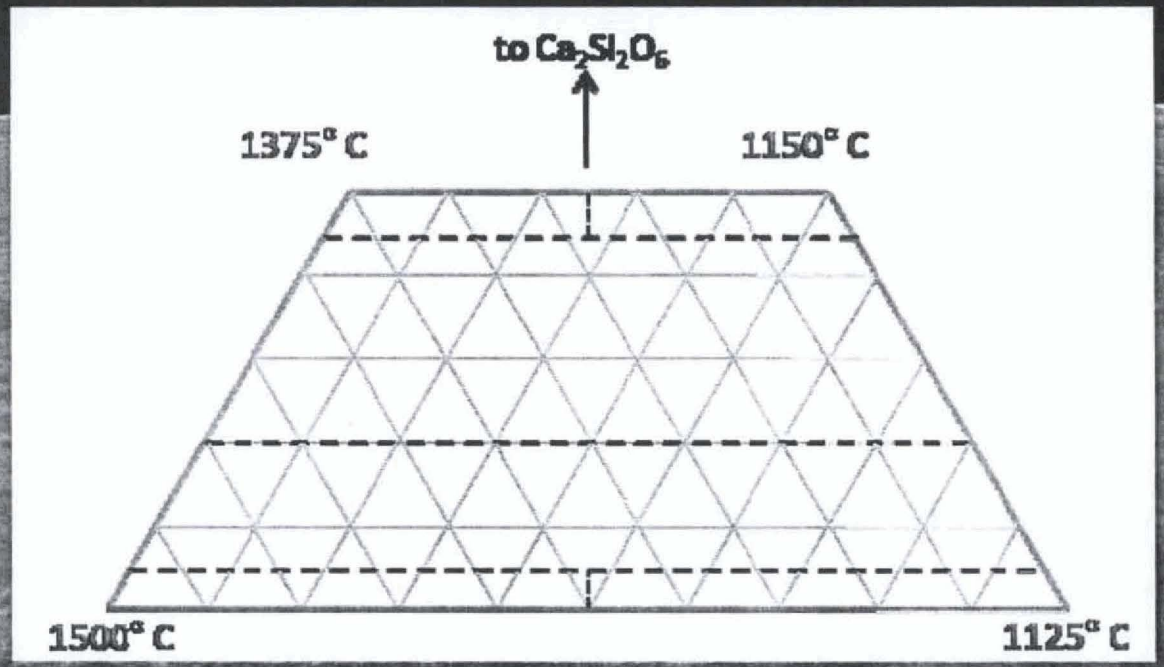

Approximate solidus temperatures of endmember pyroxenes, from Huebner and Turnock (1980, figure 9)

Minerals: Solid Solutions

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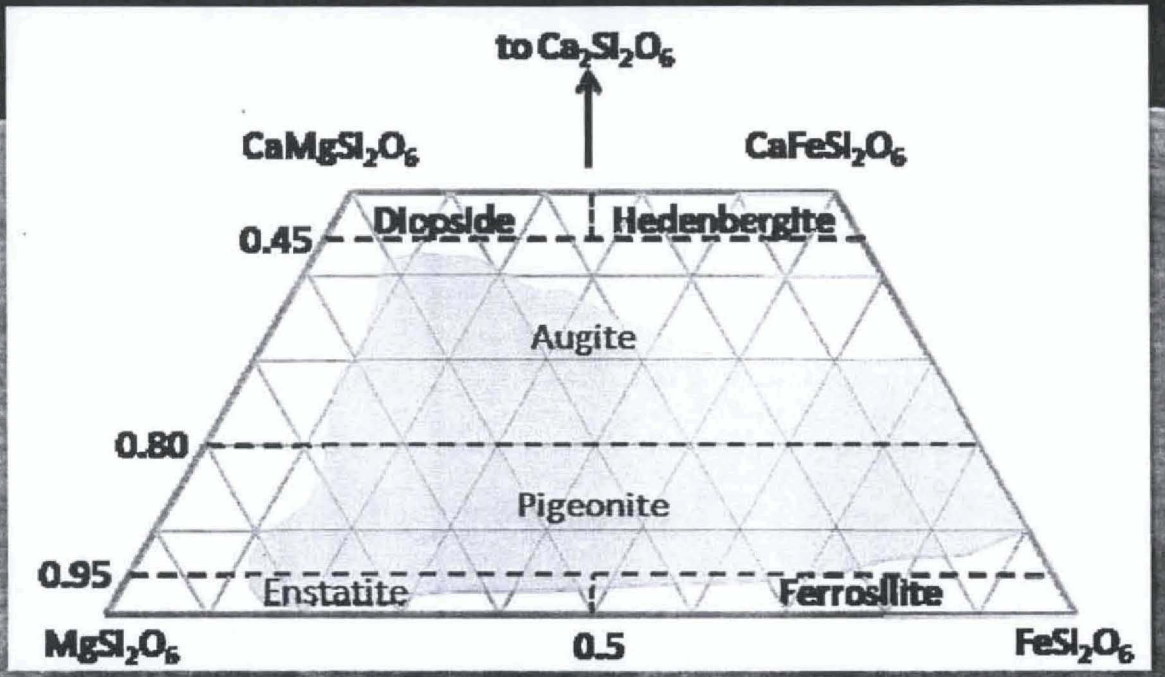

Pyroxene quadrilateral and classification fields, with lunar pyroxene distribution from Heiken et al. (1991)

Minerals: Oxide minerals

Spinel minerals

- Spinel $Mg_2Al_2O_4$
- Hercynite $Fe_2Al_2O_4$
- Ulvöspinel $TiFe^{2+}{}_2O_4$
- Chromite $Fe^{2+}{}_2Cr_2O_4$
- Magnetite $Fe^{2+}Fe^{3+}{}_3O_4$

Ilmenite

- Ilmenite $Fe^{2+}TiO_3$
- Hematite $Fe^{3+}{}_2O_3$

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There is almost always Fe3+ in terrestrial oxide minerals, and it may be the dominant species. It does not occur in lunar rocks.

Minerals: Phosphates

<u>Apatite</u>

- Fluorapatite $Ca_5(PO_4)_3F$
- Chlorapatite $Ca_5(PO_4)_3Cl$
- Hydroxyapatite $Ca_5(PO_4)_3OH$

<u>Whitlockite (merrillite)</u>

- $Ca_{16}(Mg,Fe^{2+})_2(^{*}REE)(PO_4)_{14}$

*Rare Earth Element

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<u>Whitlockite (merrillite)</u>

- $Ca_{16}(Mg,Fe^{2+})_2(^{*}REE)(PO_4)_{14}$

*Rare Earth Element

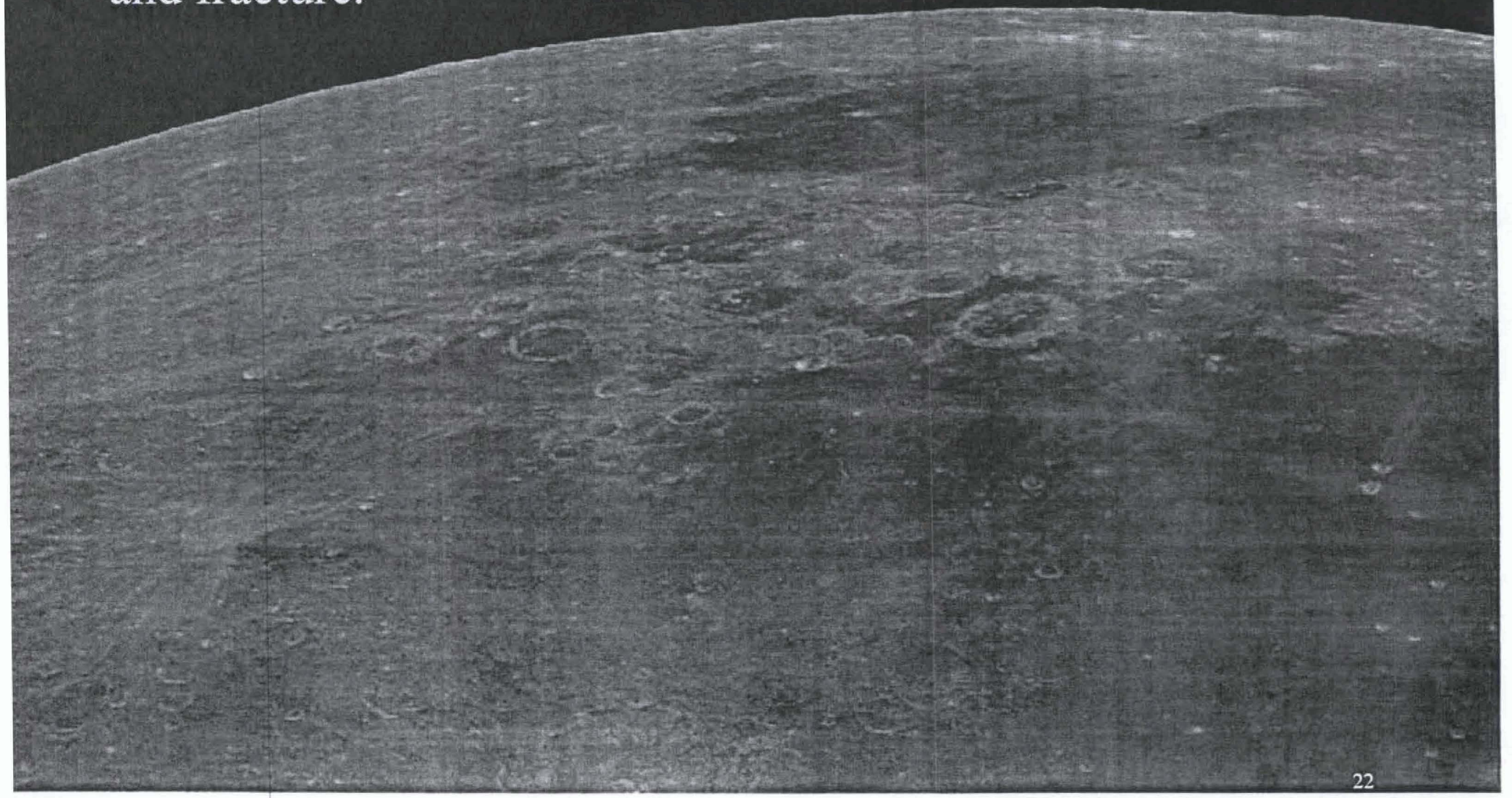
Minerals: Specific gravity

Lunar minerals have S.G. from ~2.7 (anorthite plagioclase) to ~4.75 (troilite and ilmenite). Native iron (Fe^0) has an S.G. of 7.87.

Specific gravity varies by as much as 1 unit within solid solutions as Ca/Na or Mg/Fe changes or as Cr, Ti, Al, etc. substitute.

Minerals: Abrasiveness

A mineral's abrasiveness is derived from its hardness, cleavage, and fracture.



Minerals

Speaking very generally:

- For applications involving melting, reactivity, and spectral reflectance, the chemistry of the minerals matters. Mg/Fe strongly affects melting T and reflectance (Cahill and Lucey, 2007). Ca/Na affects melting T and possibly reflectance.

- For some geotechnical behavior, the kind of minerals and the abundance matters (e.g., abrasivessness).

- Spinels may be the exception, as the endmembers have substantially different hardness and fracture.

- For applications dependent on specific gravity, assemblage and composition matters.

Glass

- Glass is material that crystallizes from a molten state without developing crystallinity. Thermodynamically, it is disordered like a liquid but is rigidly bound.

- Glass on the Moon is either:
  - volcanic, which is Mg- and Fe-rich, with variable TiO_2,
    or
  - impact-related, in which case it will reflect the composition of the melted material

Glass: How composition affects properties

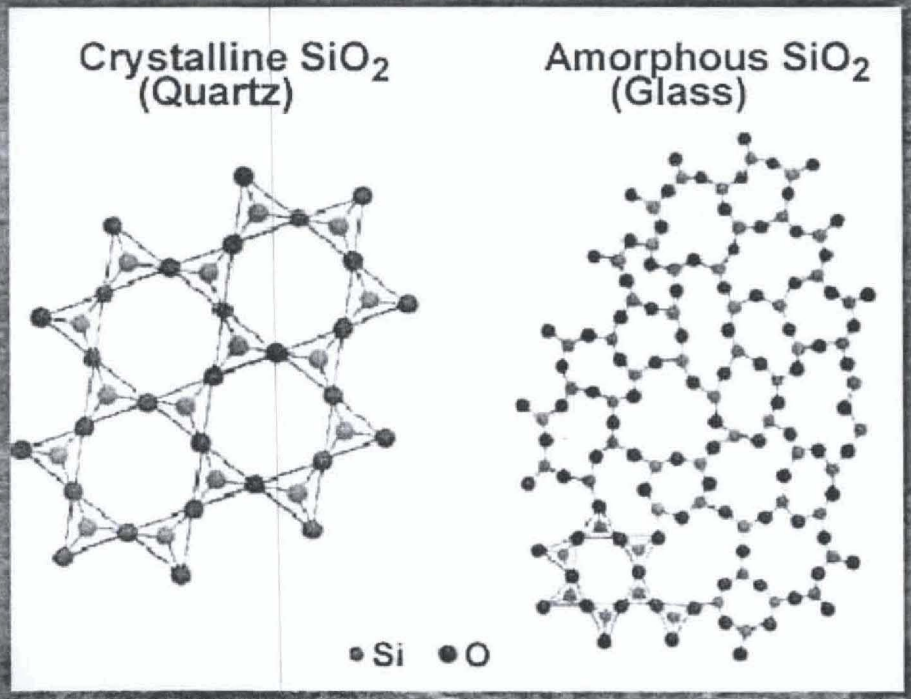
Glass that concerns us is silica-based (35-75 wt.% SiO_2)

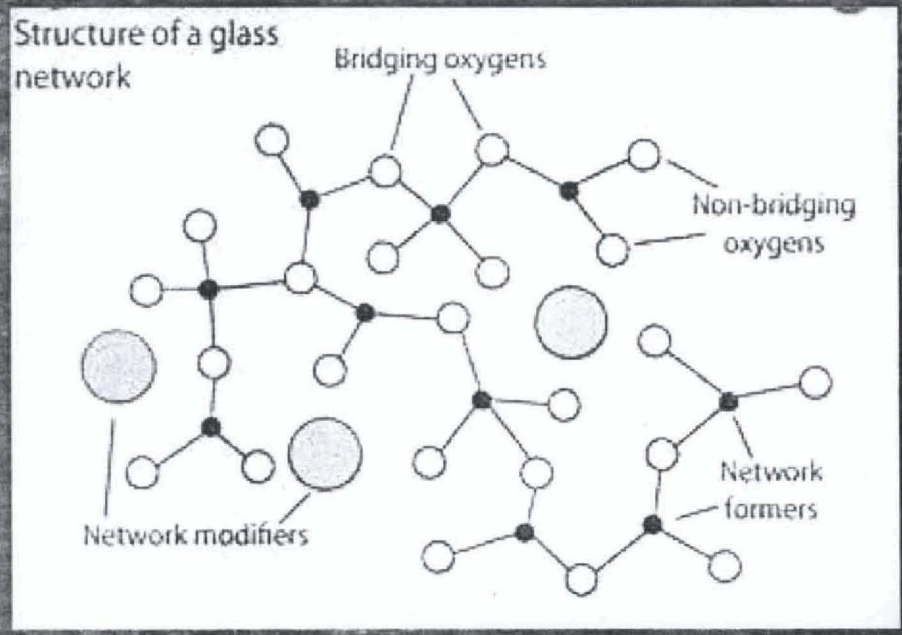
Pure SiO2 glass is amorphous but highly polymerized.

It is viscous and relatively unreactive.

Elements may join the network (Al^{3+}) or modify (Na^+, K^+).

These will change viscosity, reactivity, and thermal response.





Glass

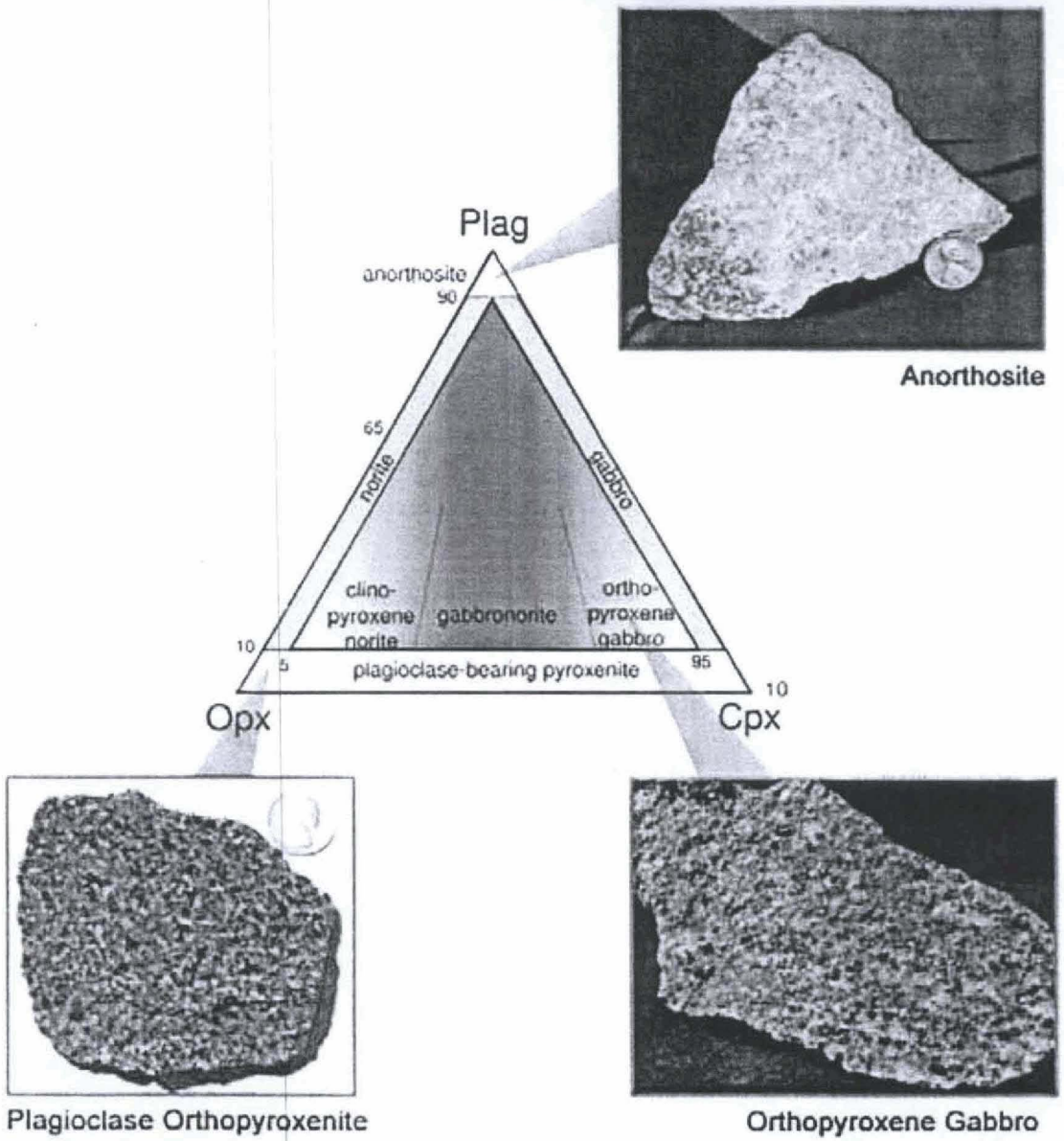
- Glass does not have an ordered internal structure, and thus has no singe melting point
  - Annealing point, at which its internal strain is relaxed
  - Softening point, at which it can be worked, and a
  - Molten point, at which it is entirely liquid.
- These points may spread over 100's or >1000° C
- These position of these points depend on composition (e.g., Mg/Fe, the presence of flux elements like Na, B...)

Rock

- A rock is a naturally occurring solid aggregate of consolidated minerals, with or without glass.

- Igneous rocks are those that cool from magmas.
  - volcanic rocks erupt and cool quickly; they are fine-grained and may be glassy
  - plutonic rocks cool underground and develop coarser crystals

- Rocks are classified by their mineral contents or their chemistry.



International Union of Geological Sciences (IUGS) classification

Relative amounts of :

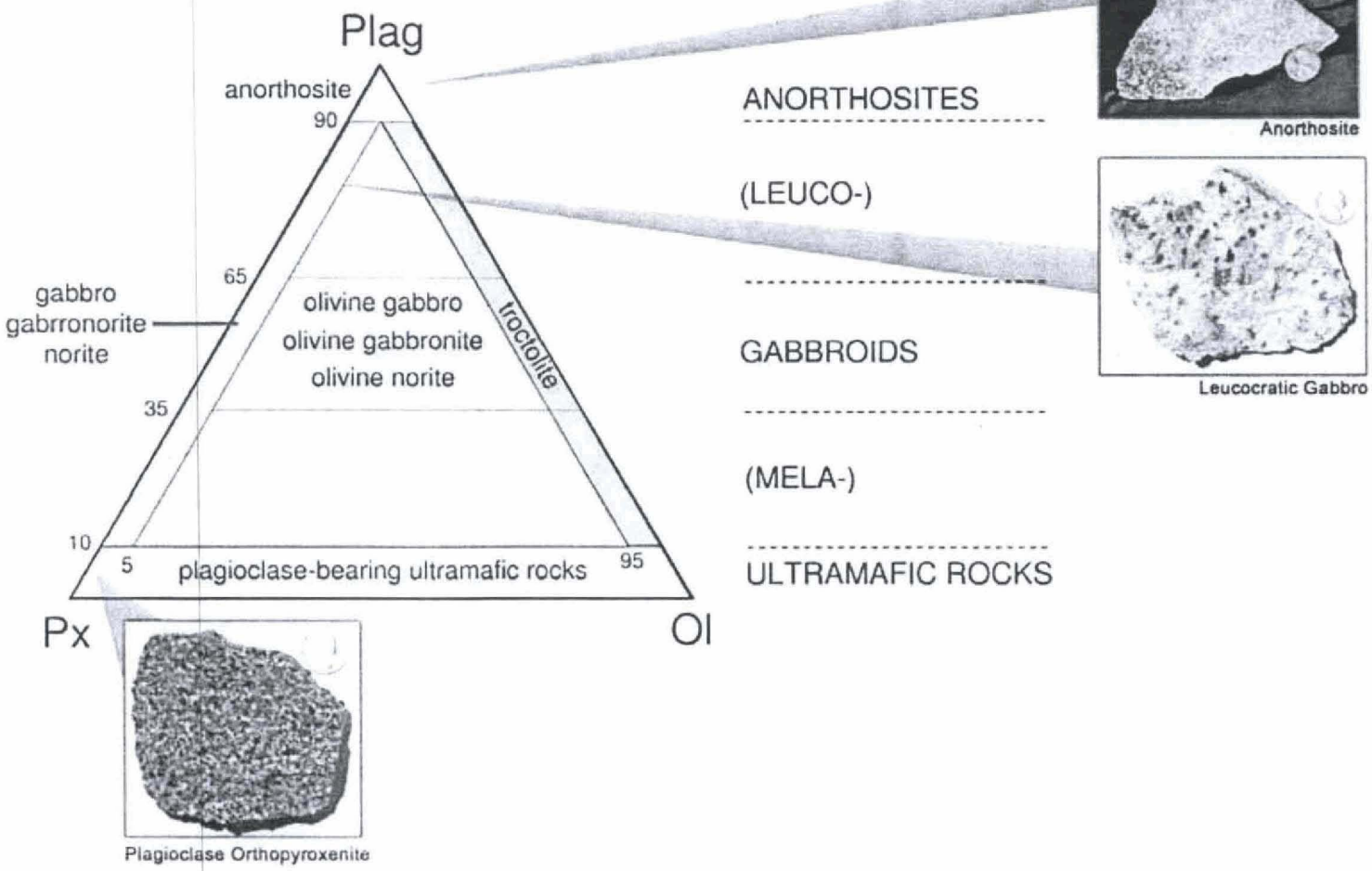
plagioclase

clinopyroxene (Ca-bearing)

orthopyroxene (little to no Ca)

(IUGS) classification

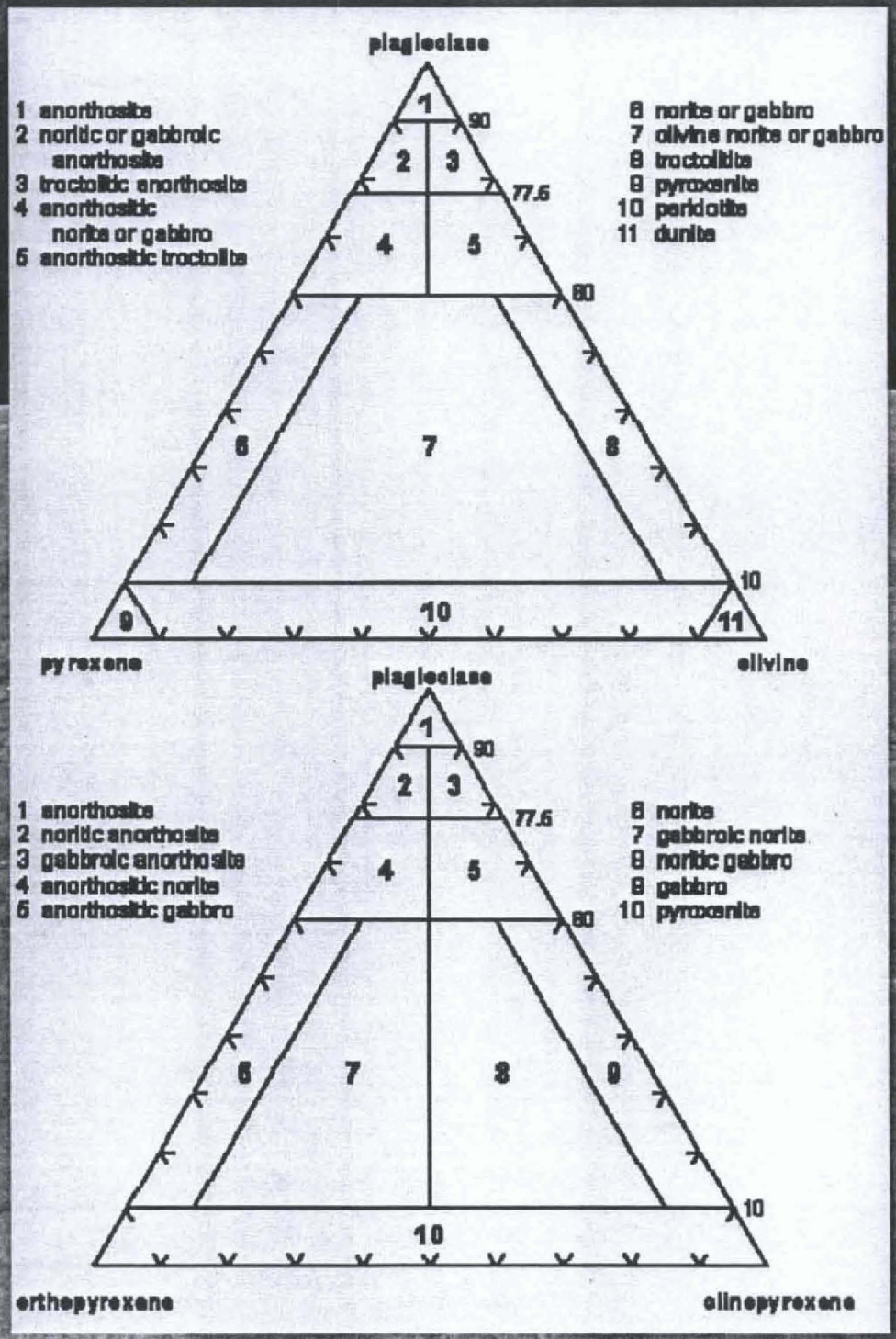
Relative proportions of plagioclase, total pyroxene, and olivine



Lunar (non-IUGS) classification

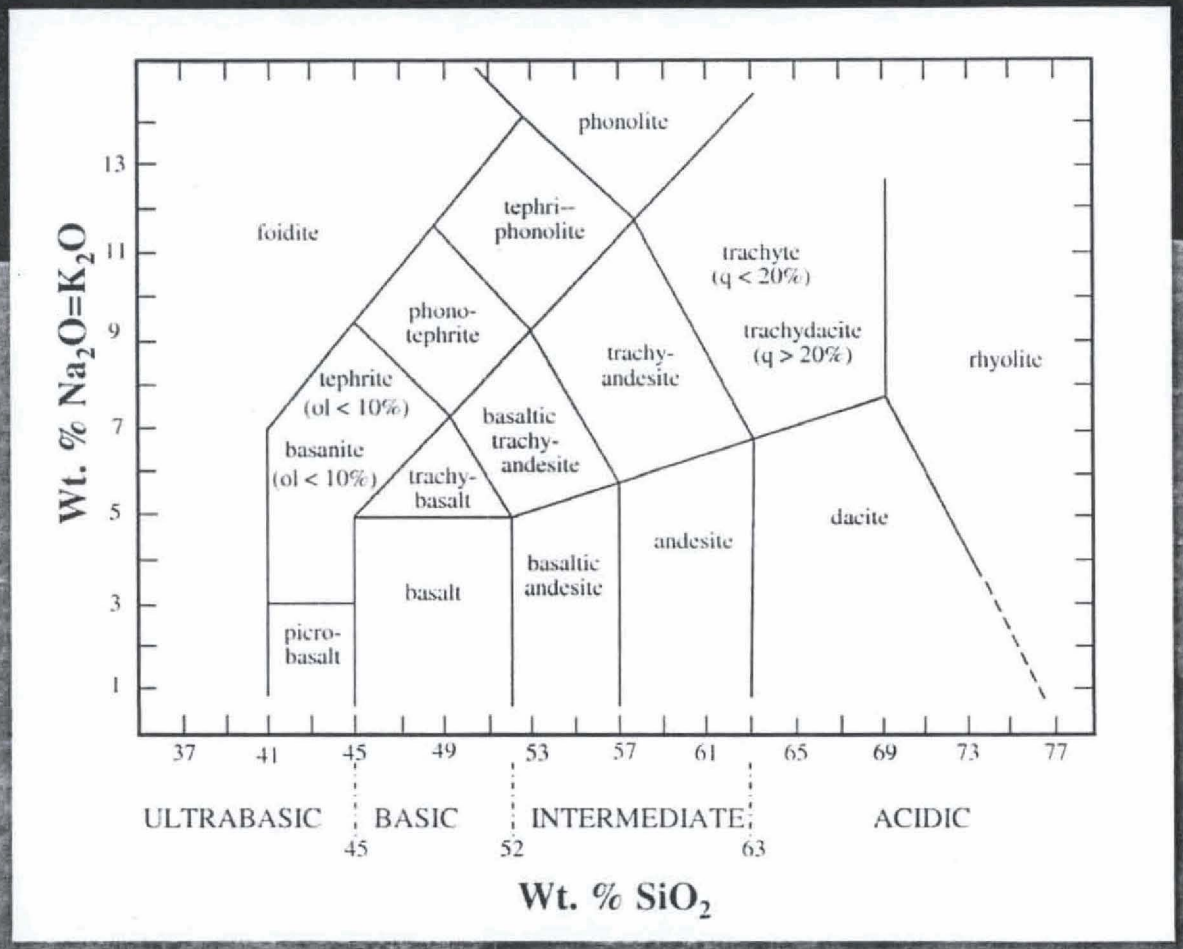
You may see this classification from Stöffler et al (1980) used.

It expands the anorthosite to transitional fields by the use of modifiers.



Total alkali-silica diagram ($[Na_2O+K_2O]-SiO_2$)

Useful for volcanic rocks that are glassy or too fine-grained for mineral identification



T.A.S. diagram after LeBas et al., 1986

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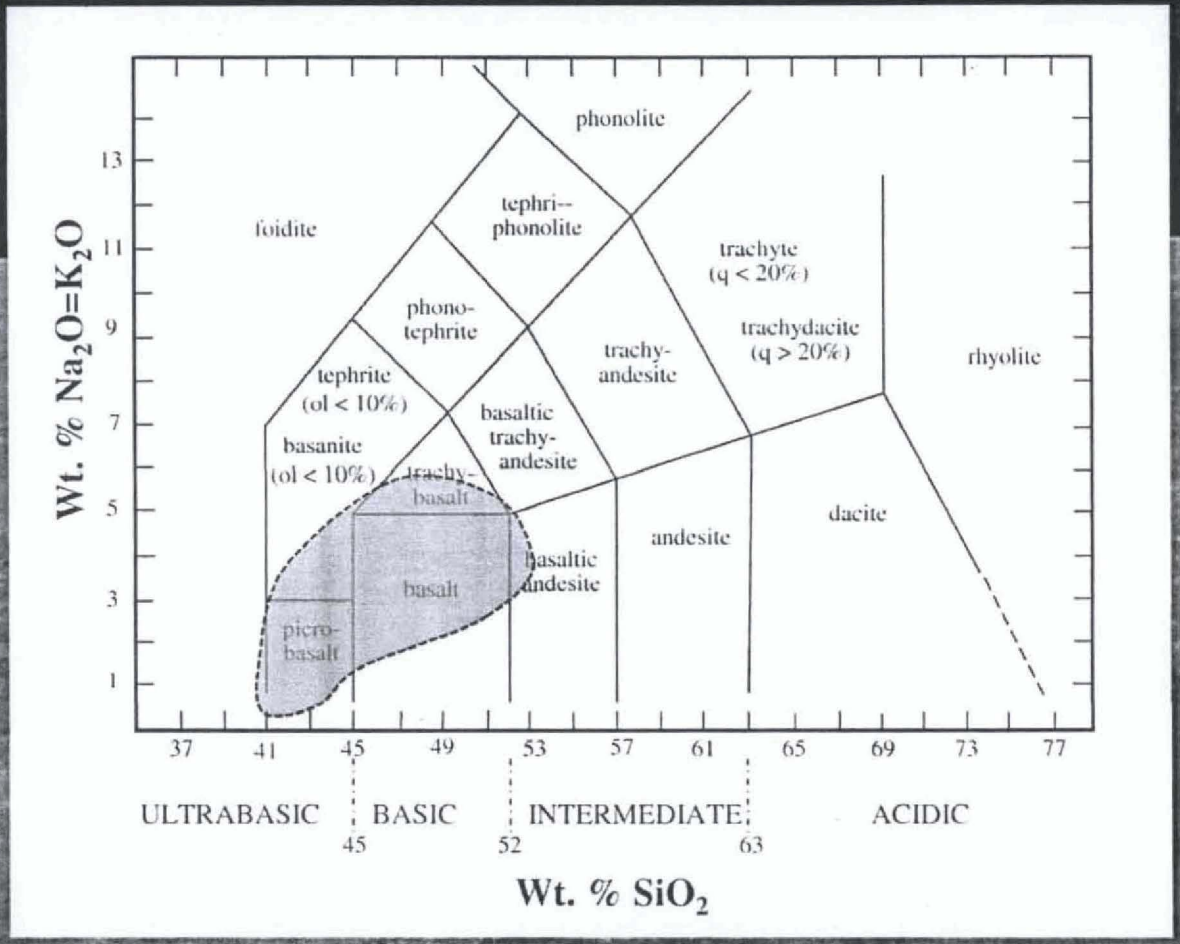
Terrestrial "basalts" have a range of composition.



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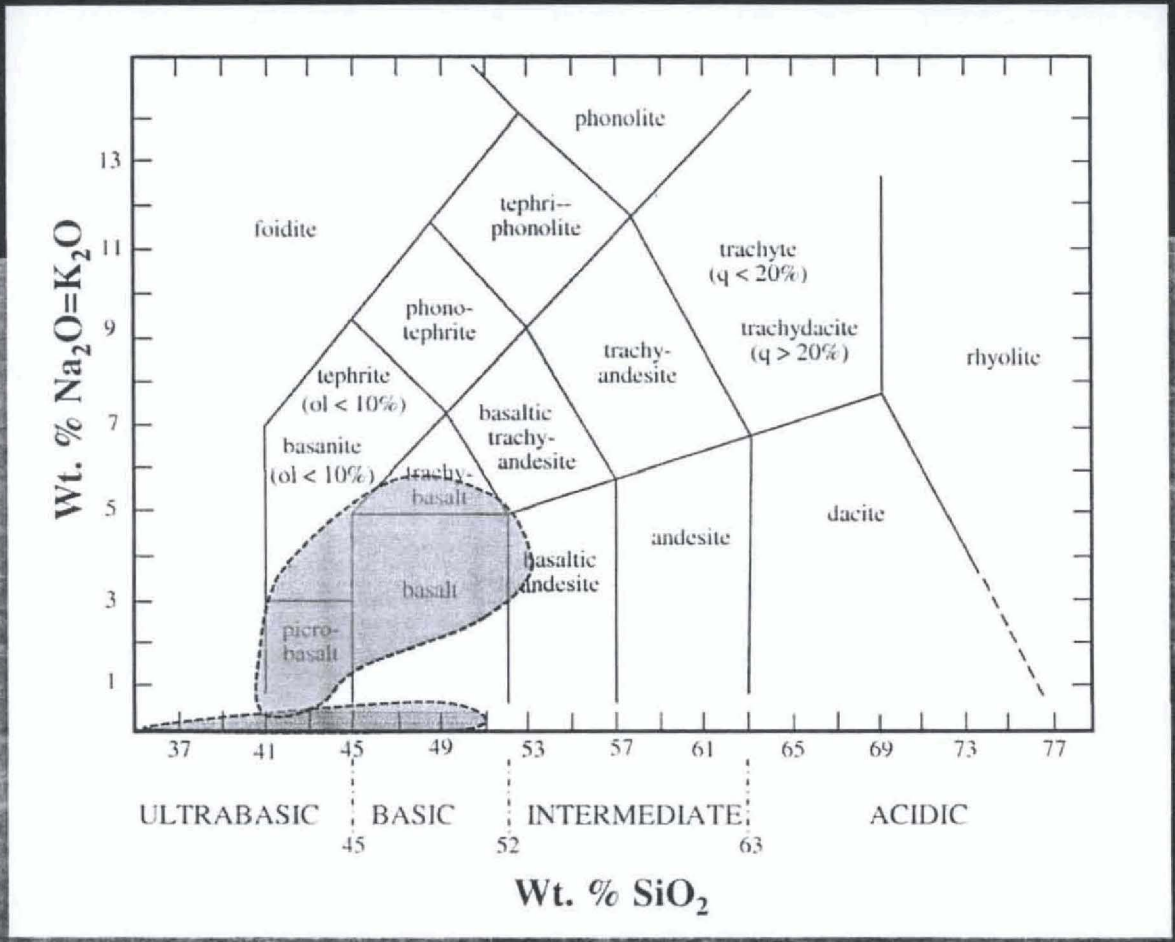
Lunar basalts are depleted in alkalis, so this diagram does not discriminate them well.



T.A.S. diagram after LeBas et al., 1986

Impact Rocks

- Almost all rocks on the lunar surface have experienced shock and/or thermal effects from impact.
- If they were completely molten, then they are, for our proposes, igneous.
- If they are partially molten or partially broken, they form a spectrum of ***breccias.***

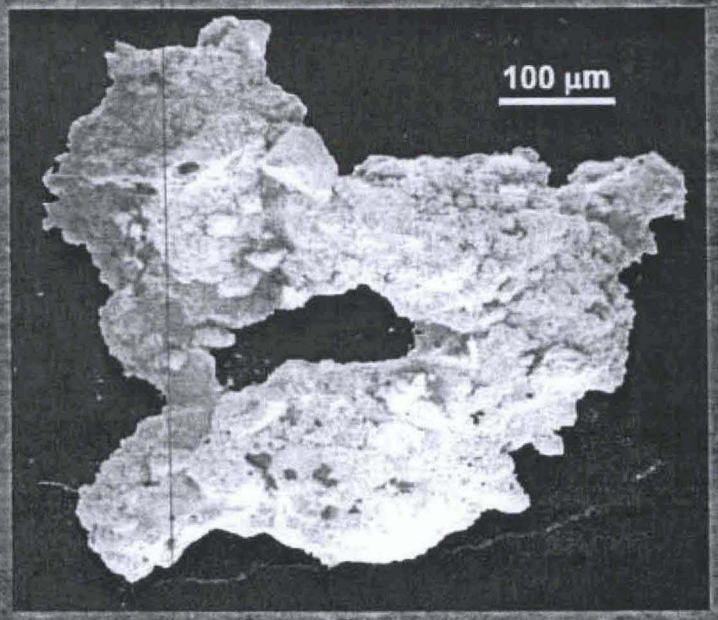
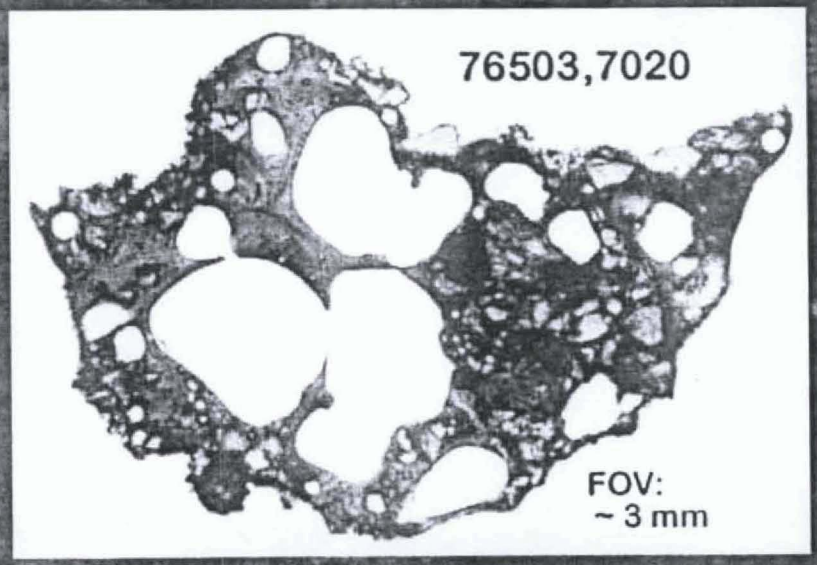
Impact Rocks

Suffice to say, there is a spectrum of rock types with variable shock, crushed rock, and glass.

The effect of these on the reactivity and geomechanical properties of the regolith are unknown.

porous dark matrix breccia
compact dark matrix breccia
porous light matrix breccia
compact light matrix breccia
crystalline matrix breccia
equant plagioclase poikilitic breccia
acicular plagioclase poikilitic breccia
variliolitic basalt-textured breccia
subophitic basalt-textured breccia
intergranular basalt-textured breccia
intersertal basalt-textured breccia
porphyritic basalt-textured breccia
granulitc breccia

Agglutinates

- Agglutinates are small glassy breccias formed when micrometeorites (< 1 mm in diameter) strike the lunar regolith.

- They contain minerals, lithic fragments, and vesicles (gas bubbles) in a glass matrix. Agglutinates are typically 10's of μm to a few mm in size.