Mon. Oct. 09, 2017

- Reading: For Friday
  - Zuber et al. 2013   Grail Lunar Gravity
  - Andrews-Hanna et al. 2013   (GRAIL Procellarium region)

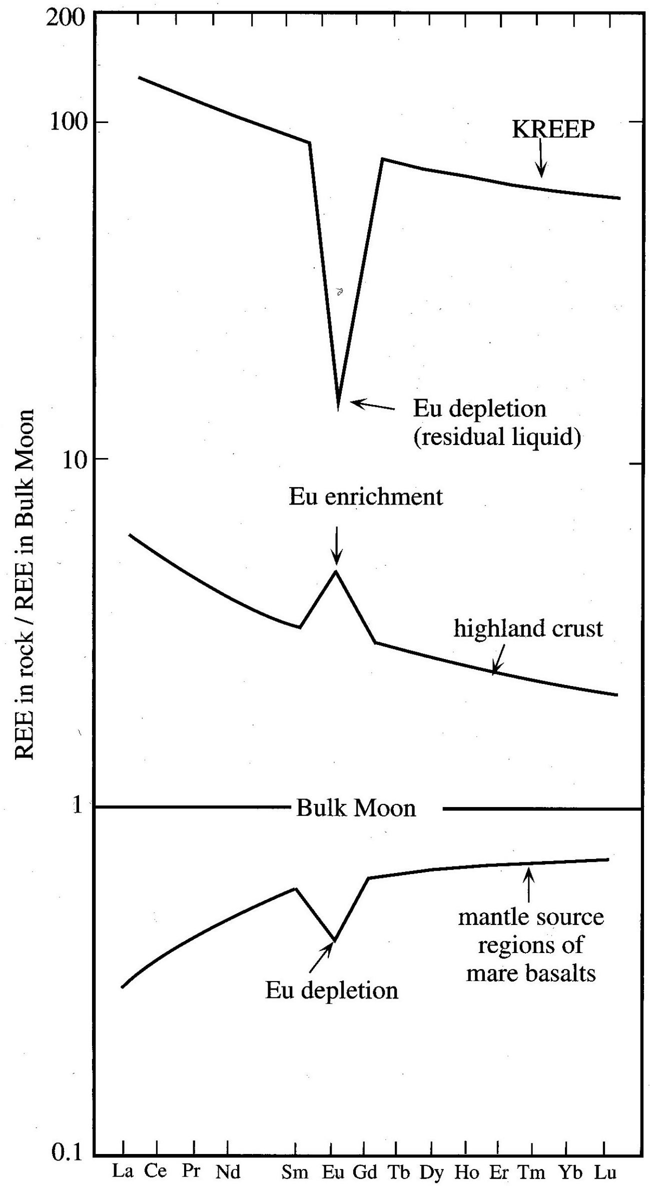
Makeup lecture days -- This Friday??

- No Class Oct. 16, 18, 20

Today:

- Lunar Differentiation Continued.
- Following includes some slides from those posted Wed., but not covered yet, plus some slides from the Mineralogy Summary, and finally, new slides.

Vertical and Horizontal Equilibration



Taylor, 2001 Fig. 13.2

Complementary patterns between highland crust and 400 km deep mare source regions shows equilibrium (and therefore melt) over that depth

Very similar isotopic composition of widely separated mare (and therefore their source regions) shows mixing (and therefore melt) over that horizontal distance

KREEP represents very last stages of residual melt

Variations among mare basalts

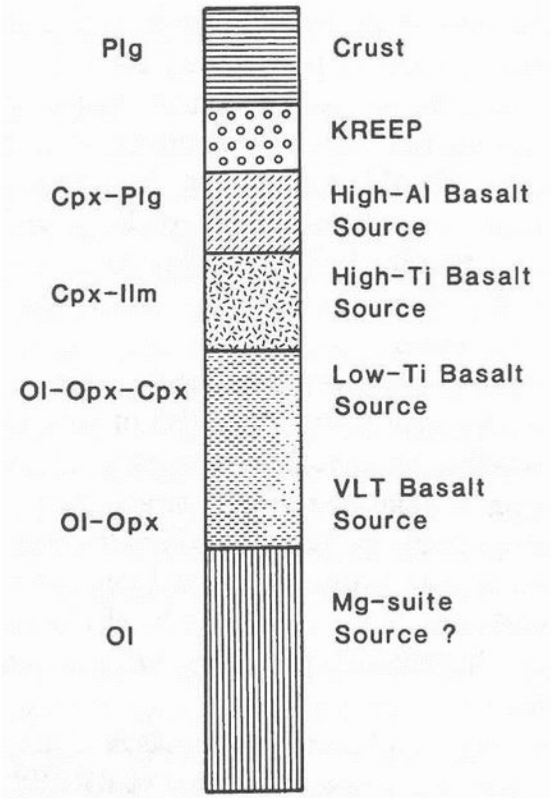
Three main groups of mare basalt

- High-Ti
- Low-Ti
- Very low Ti

In simplest model they come from slightly different depth source regions, which represent different stages of the residual magma ocean.

- Ti is incompatible, so is concentrated in last melt.

As described in Shervais & Taylor, simple model for high Al basalt is <u>too</u> simple.



Shervais & Taylor

Lunar Origin – Giant Impact

Possible sources

- Accretion in orbit around earth
- Capture from elsewhere in solar system
- Fission from earth
  - Giant Impact model

Tests

- Chemical composition
- Orbital dynamics

Earth vs. Moon Composition Similarities & Differences

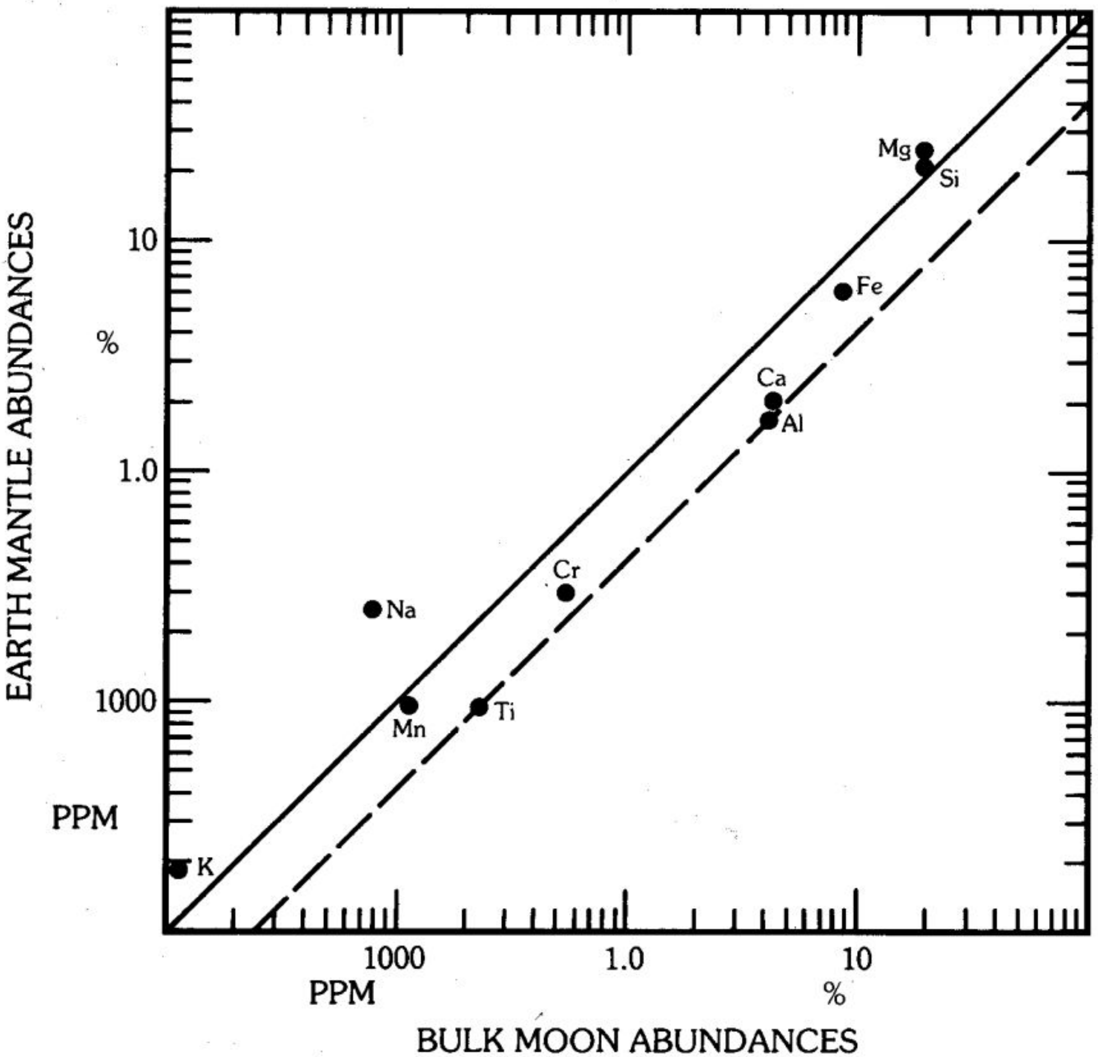
- Similarities
  - Major element bulk composition of moon similar to that of mantle
  - Oxygen isotopes in moon very similar to those in earth
    - Much more so than for random meteorites

- Differences
  - Moon is missing volatiles
  - Moon is highly reducing
  - Moon is missing siderophiles

- Basic problem: Why in some ways does it look so much like the Earth, but in other subtle but critical ways does it look so different?

Earth vs. Moon Composition

Lunar abundances similar to primitive terrestrial mantle

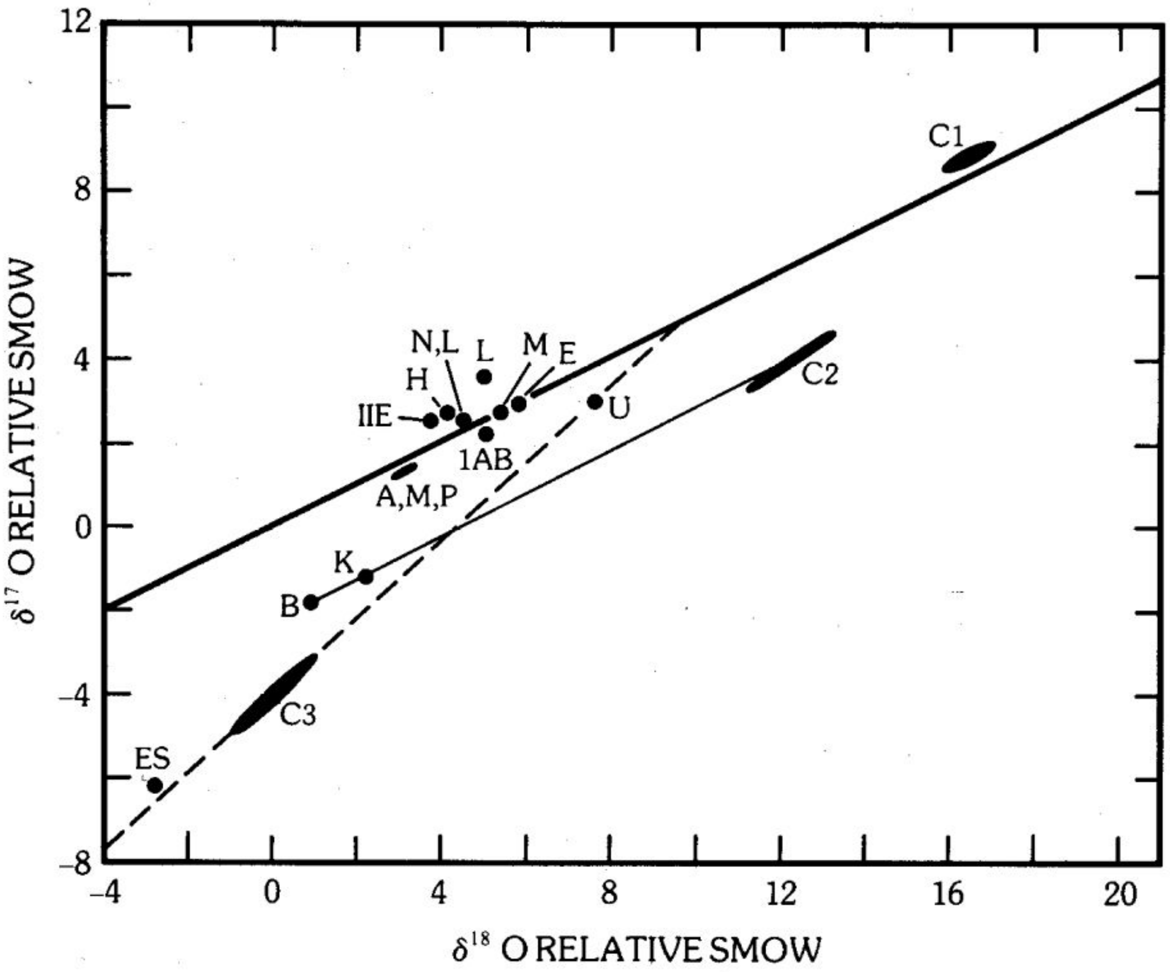


- Compare abundances to solid line at equal amounts earth (Y) = moon (X)
- Moon has similar abounds of Mg, Si, Mn
- Moon has less of volatiles like K, Na
- Moon has more of refractory elements like Ti, Al, Ca
- It also has slightly less Fe
- Trace elements confirm pattern

Taylor 1982 Fig. 8.5a

Earth vs. Moon Composition

Oxygen Isotopes very similar



- E = Earth
- M = Moon
- Oxygen isotopes almost identical, compared to differences seen among meteorites and other planets
- Minor differences are on slope ½ line which can be explained by chemical fractionation effects

Earth vs. Moon composition
Missing lunar volatiles

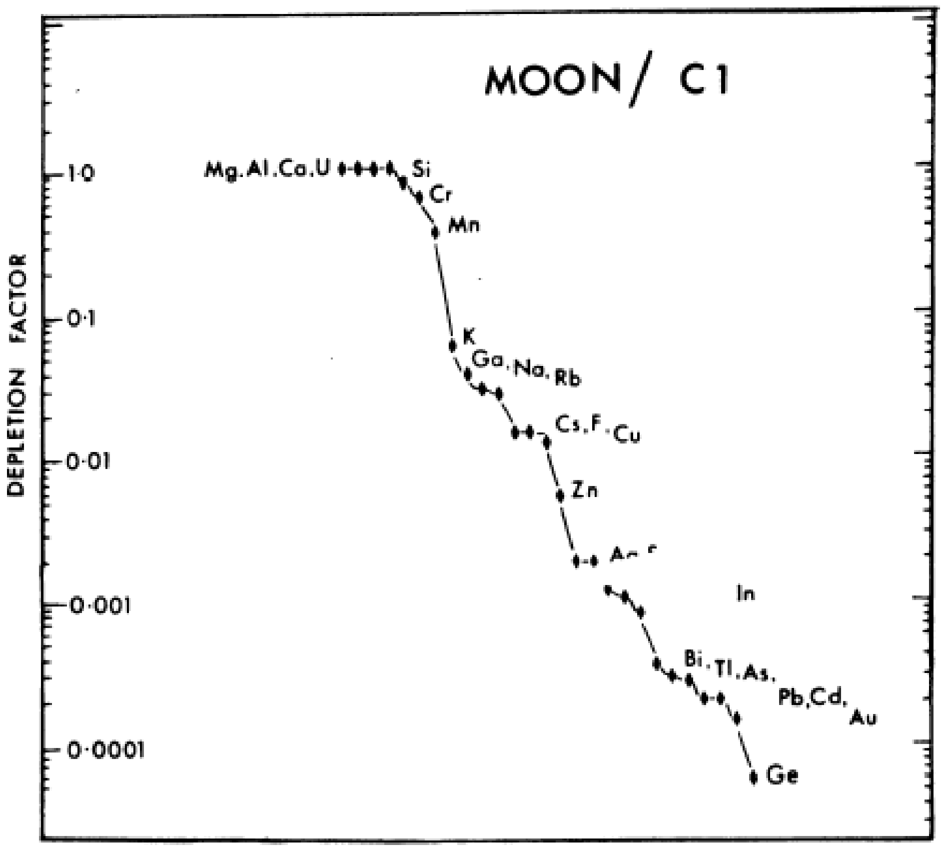
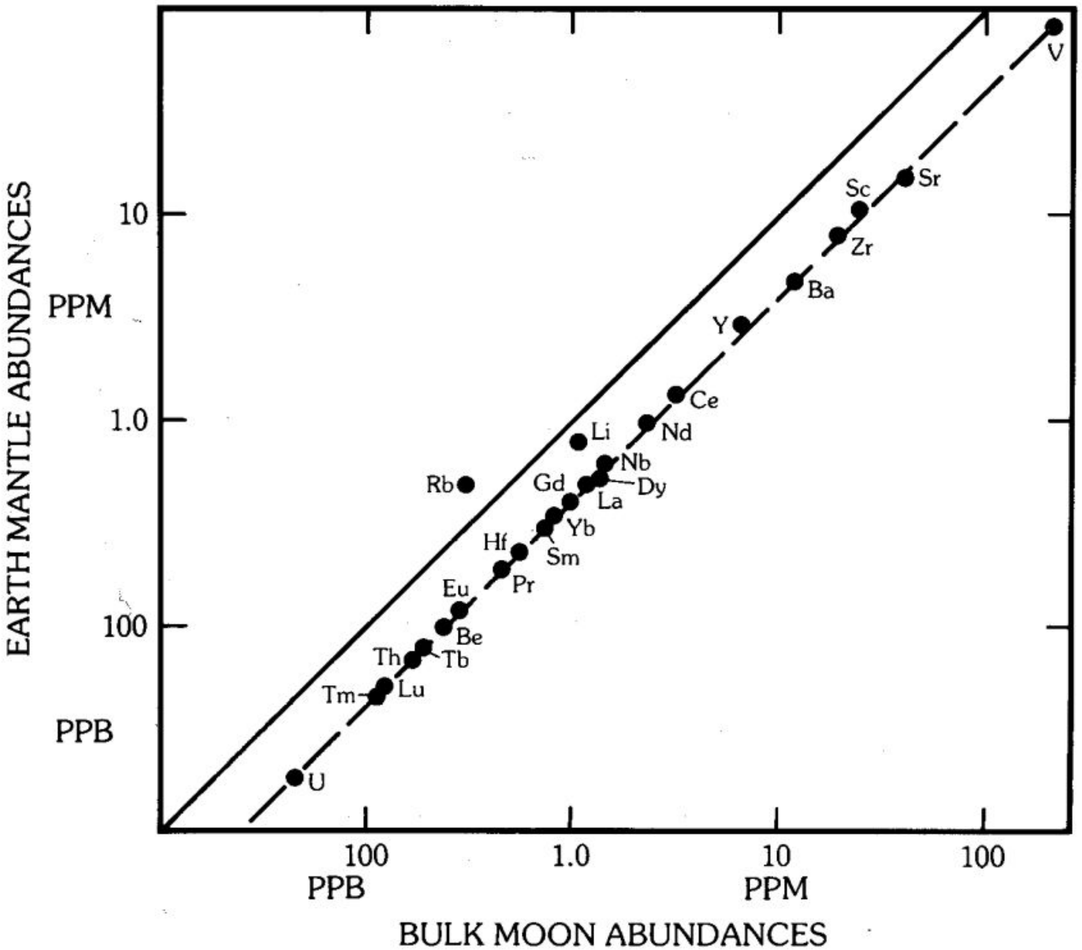


Fig. 2. Comparison of elemental abundances in the mantle source region of low-Ti mare basalts with abundances in C1 chondrites. Volatility of the elements tends to increase to the right. Figure from Ringwood and Kesson (1977).

Moon is missing volatiles
Moon is highly reducing
Moon is missing siderophiles

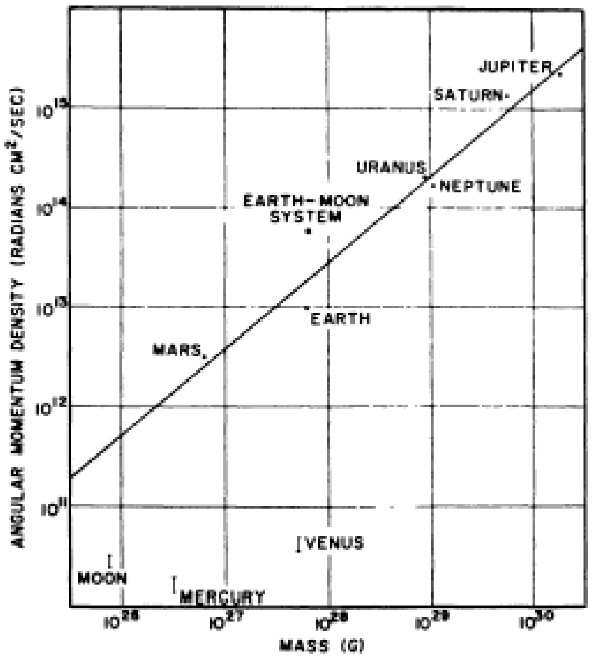
Earth vs. Moon composition
Trace element abundances



- Moon is depleted in volatile elements like Rb
-
- Once you limit discussion to just refractory elements, <u>relative amounts</u> in moon and earth are similar

Taylor 1982 Fig. 8.5b

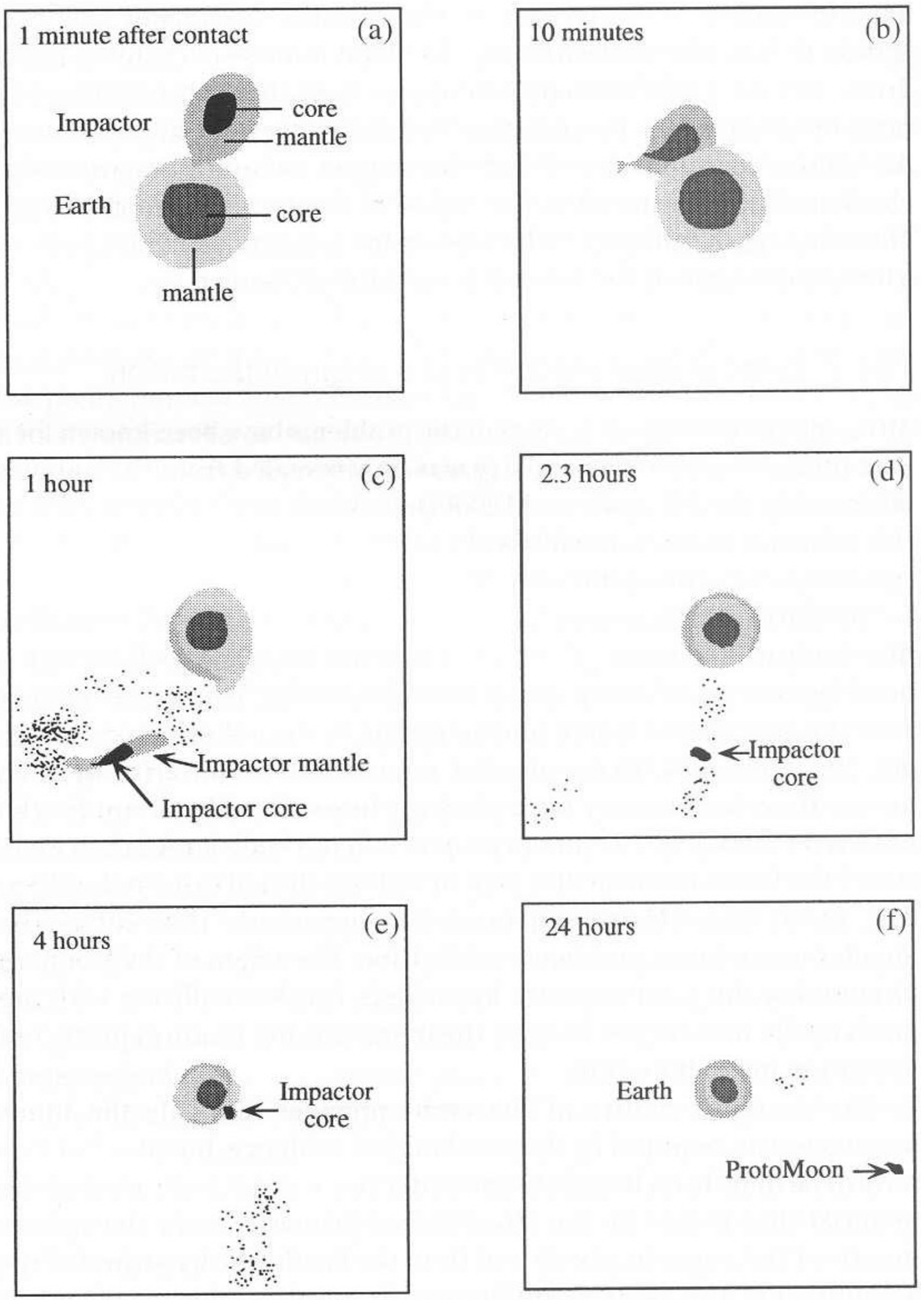
Dynamical (i.e. orbital) Constraints



MacDonald 1966

- Earth-Moon system has much more angular momentum than expected.

- Orbital capture very hard – most close passes will result in incoming object just flying by earth without losing enough energy to stay in orbit



Taylor 2001 Fig. 13.10

Giant Impact mechanism

- Moon made not just from impactor remnant, but also from ejected earth mantle so get similarity in bulk composition and O isotopes
- Volatiles lost from high temperatures caused by impact
- Siderophiles lost because terrestrial core already formed, and impactor core may remain with earth
- Impact explains high angular momentum of the system

Deviations from simple differentiation model

- Deviations from simple differentiation model:
  - Regional variations in composition
  - Hemispheric asymmetries
  - Secondary Differentiation:
    - Instabilities in mantle
    - Mare basalts
      - Basalt (and highland) ages: general timeline
      - Varying depth of mare basalt source region

Lunar Observations: 1980-present Part 1.

- Few lunar missions after final Apollo mission (Apollo 17) in 1972
  - A couple Russian rover/sample returns in 1970's
  - Variety of earth-based remote sensing programs during 1980's and 1990's
  - Galileo flew by Earth and Moon twice (1990, 1992) on way to Jupiter
- Clementine Mission: Jan. – June 1994 ~Polar Orbit
  - Joint mission between Strategic Defense Initiative Organization ("Star Wars") and NASA
  - UV, Visible, and Infrared cameras
  - LIDAR for precise topography
  - Gravity measurements to test isostacy
  - Radar to search for frozen polar volatiles
- Lunar Prospector 1998-1999 Polar Orbit
  - X-Ray, Gamma Ray, Neutron experiments: Composition (including ice at poles)
  - Refined Doppler Gravity Experiment
  - Electron/Magnetometer Experiment
- Recent missions by Japan, India, China
  - SELENE (Selenological and Engineering Explorer) or "Kaguya" 2007-2009
  - Chandrayaan-1 2008-2009

Lunar Observations: 1980-present   Part 3

- Lunar Reconnaissance Orbiter   June 2009 through present
  - LCROSS impactor (impact Oct. 2009)
  - High resolution camera (LROC)
  - Neutron Experiment
  - Lyman Alpha (UV) mapper
  - Lasar Altimeter
  - IR Thermal Radiometer
- GRAIL (Gravity Recovery and Interior Laboratory) Sept. 2011 – May 2012
  - Launched Sept. 10, 2011 on low energy lunar trajectory – arrives Jan. 2012
  - Twin spacecraft – map lunar gravity Mar. - May 2012
  - Science objectives:
    - Map the structure of the lithosphere.
    - Understand the Moon's asymmetric thermal evolution
    - Determine the subsurface structure of impact basins and the origin of mascons
    - Ascertain the temporal evolution of crustal brecciation and magmatism
    - Constrain deep interior structure from tides
    - Place limits on the size of a possible solid inner core

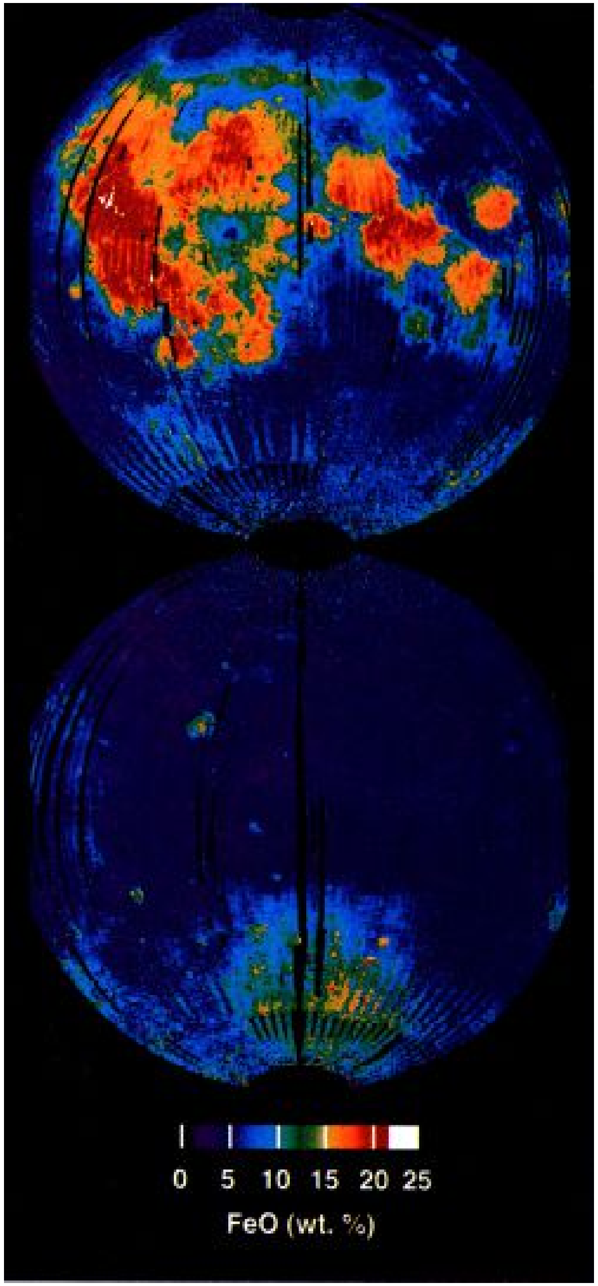
Simple Albedo/Color Effects

Edge of Mare Serenitatis is darker, bluer

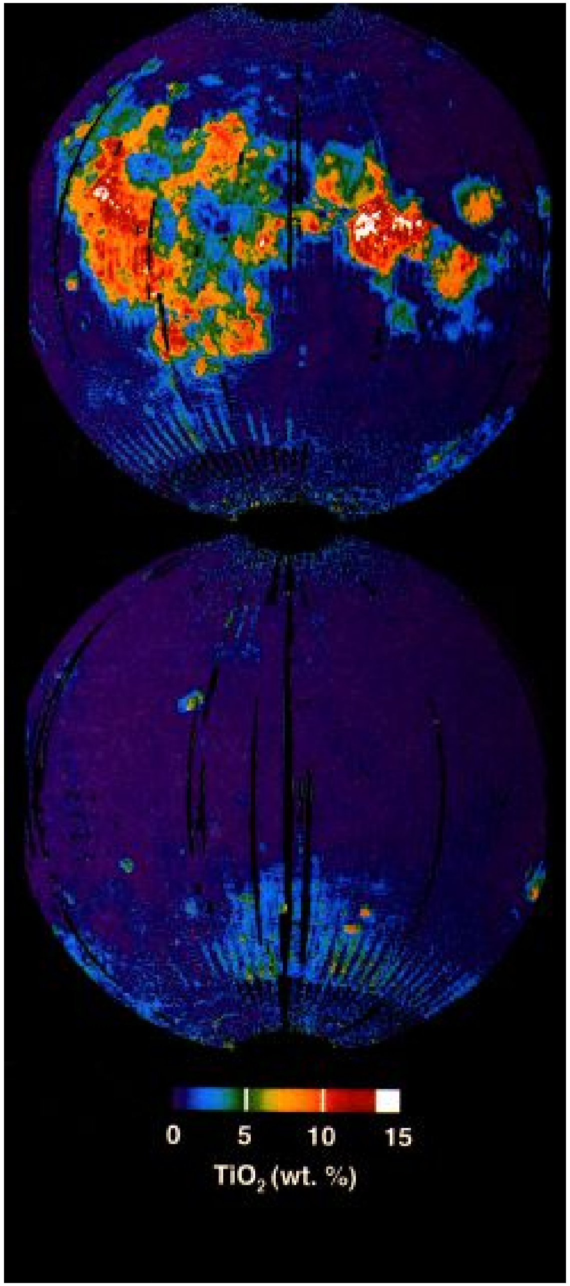
Several flows of different albedo, color in Mare Tranquillitatis

Olympus E-620 Image 2009_10_03 Contrast stretched slightly

Spectral mapping



Fe abundance



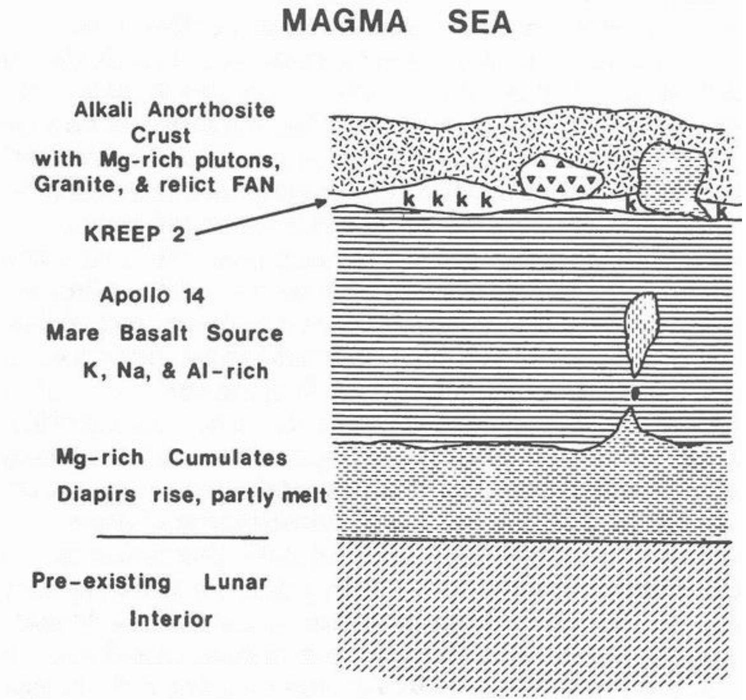
Ti abundance

- Lucey et al , based on Clementine images
- Note high Ti abundance in Tranquillitatis and the rim of Serenitatis

Uncertainties in Lunar Structure

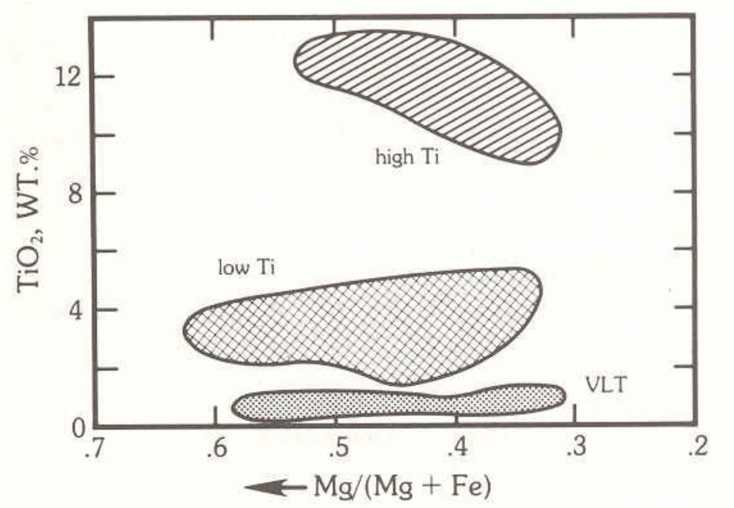
- Mg-rich (troctolite, norite) rocks from lower anorthosite crust
  - Do they represent plutons intruded from lower Mg rich cumulates?
  - Could they be imperfect settling of denser minerals?

- Is the lower mantle differentiated or original primitive material?
  - Might expect lower heat (since smaller gravity) when central portions assembled
  - If it is primitive, then also have unstable situation once liquids solidify:
    Late forming Fe rich solids can be higher density then later melts from Mg-rich cumulates



Shervais & Taylor

Basalt Ti content most variable factor



- High Ti (tend to be old)
- Low Ti (tend to be young)
- High Al (both young and old)

Table 6.1 Classification of lunar basaltic rock types.

Group	Basalt class	Mission	Sample Numbers
Low Titanium Basalts	Emerald Green Glass	Apollo 15	15426
	Very low Titanium (VLT)	Luna 24	24174
		Apollo 17	70007, 70008, 78526
	Olivine	Apollo 12	12002, 12004, 12006, 12009, 12012, 12014, 12015, 12018, 12020, 12040, 12075, 12076
		Apollo 15	15016, 15445, 15555
	Pigeonite	Apollo 12	12007, 12011, 12017, 12021, 12039, 12043, 12052, 12053, 12055, 12064, 12065
		Apollo 15	15058, 15499, 15597
	Ilmenite	Apollo 12	12005, 12008, 12016, 12022, 12036, 12045, 12047, 12051, 12054, 12056
High Titanium Basalts	Low-K	Apollo 11	10003, 10020, 10029, 10044, 10047, 10050, 10058, 10062, 10092
		Apollo 17 A	75055, 76136
		B	70215, 70275
		C	74245, 74255, 74275
		U	70017, 70035
	Orange glass	Apollo 17	74220
	High-K	Apollo 11	10017, 10022, 10024, 10032, 10049, 10057, 10069, 10071, 10072, 10085
High Aluminum Basalts		Apollo 12	12031, 12038, 12072
		Luna 16	B-1
		Apollo 14	14053, 14072, 14321

Sources: Rhodes, J. M., and Blanchard, D. P. (1980) *PLC 11:* 49 (Apollo 11).
Beaty, D. W., and Albee, A. L., (1978) *PLC 9*: 359 (Apollo 11).
Rhodes, J. M., et al. (1977) *PLC 8:* 1305 (Apollo 12).
Rhodes, J. M., et al. (1976) *PLC 7:* 1467 (Apollo 17).

Compiled in Taylor 1982

Table 6.6 Radiometric ages of lunar basalts, listed in approximate order of age.

Mission	Location	Basalt Type	Sample Number	Age (aeons)	±	Method
Apollo 14 (Fra Mauro	Cone	High-Al	14072	3.96	0.05	Ar–Ar
			14072	3.91	0.09	Rb–Sr
	Cone	High-Al	14321	3.87	—	Ar–Ar
			14321	3.87	0.04	Rb–Sr
	Cone	High-Al	14053	3.85	0.05	Ar–Ar
Apollo 11 (Mare Tranquillitatis)	LM	Low-K	10003	3.86	0.07	Ar–Ar
			10003	3.76	0.08	Rb–Sr
	LM	Low-K	10020	3.72	—	Ar–Ar
	LM	Low-K	10047	3.69	0.03	Ar–Ar
	LM	Low-K	10062	3.79	0.04	Ar–Ar
			10062	3.92	0.11	Rb–Sr
			10062	3.88	0.06	Sm–Nd
Apollo 17 (Taurus-Littrow)	Camelot	High-Ti (A)	75055	3.73	0.04	Ar–Ar
			75055	3.69	0.06	Rb–Sr
			75055	3.70	0.07	Sm–Nd
	Camelot	High-Ti (A)	75075	3.69	0.02	Ar–Ar
			75075	3.70	0.07	Sm–Nd
	LM	(B)	70215	3.79	0.04	Ar–Ar
	LM	(U)	70017	3.59	0.08	Rb–Sr
	LM	(U)	70035	3.69	0.07	Ar–Ar
			70035	3.67	0.09	Rb–Sr
			70035	3.77	0.06	Sm–Nd
Apollo 11 (Mare Tranquillitatis)	LM	High-K	10072	3.57	0.05	Ar–Ar
			10072	3.56	0.05	Rb–Sr
			10072	3.57	0.03	Sm–Nd
Luna 16 (Mare Fecunditatis)	—	High-Al	L26-B1	3.41	0.04	Ar–Ar
			L26-B1	3.35	0.18	Rb–Sr
Apollo 15 (Hadley-Apennines)	Rhysling	Olivine	15016	3.34	0.08	Ar–Ar
			15016	3.33	0.04	Rb–Sr
	Hadley Rille	Olivine	15555	3.27	0.03	Ar–Ar
			15555	3.25	0.04	Rb–Sr
	Dune	pigeonite	15499	3.30	0.08	Ar–Ar
	Hadley Rille	pigeonite	15597	3.37	0.07	Rb–Sr
Luna 24 (Mare Crisium)	—	VLT	24170	3.26	0.04	Ar–Ar
			24170	3.30	0.05	Sm–Nd
Apollo 12 (Oceanus Procellarum)	N of Head	Olivine	12002	3.21	0.05	Ar–Ar
			12002	3.29	0.10	Rb–Sr
	Bench	Olivine	12040	3.23	0.04	Rb–Sr
	NE of Head	pigeonite	12021	3.26	0.06	Rb–Sr
	Head	pigeonite	12052	3.15	0.09	Rb–Sr
	Bench	pigeonite	12056	3.20	0.14	Sm–Nd
	Surveyor	pigeonite	12064	3.15	0.01	Ar–Ar
			12064	3.11	0.04	Rb–Sr
	N of Head	Ilmenite	12022	3.08	0.06	Ar–Ar
	Surveyor	Ilmenite	12051	3.23	0.05	Ar–Ar
				3.09	0.09	Rb–Sr
				3.13	0.06	Ar–Ar
				3.19	0.10	Rb–Sr
	Bench	High-Al	12038	3.08	0.05	Ar–Ar

Sources: All data from *Basaltic Volcanism* (1981) p. 950, Table 7.3.1, except Apollo 14 values from Ryder, G. and Spudis, P. (1979) *Lunar Highlands Crust*, p. 360, Table 3.

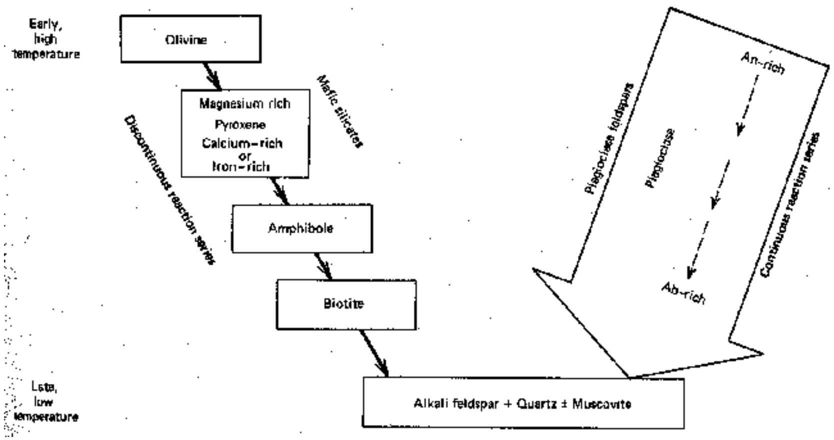
Compiled in Taylor 1982

Range of Ages for Mare

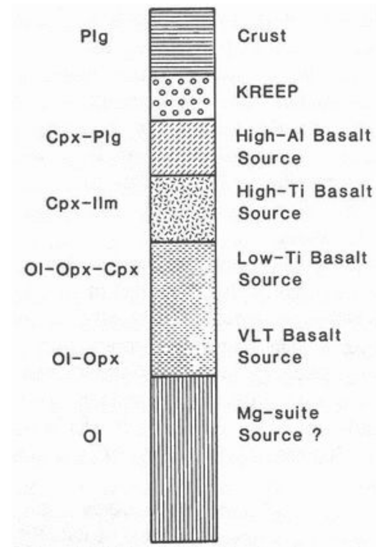
- Highland basalt (Apollo 14) — 3.9 AE
- Mare Tranquillitatis (Apollo 11) — 3.8 AE
- Mare Serenitatis rim (Apollo 17) — 3.7 AE
- late M. Tranquillitatis (Apollo 11) — 3.57 AE
- Mare Fecunditatis (Luna 16) — 3.4 AE
- Mare Imbrium rim (Apollo 15) — 3.3 AE
- Mare Crisium (Luna 24) — 3.28 AE
- Oceanus Procellarum (Apollo 12) — 3.15 AE
- No younger basalts sampled, but crater counts (if believable) suggest some limited flows occurred as late as 2 or 1 AE

Shervais and Taylor (1980's)

- Form following crust by crystallization from global magma ocean
- Note order of cumulates (up through Ca rich pyroxene) follows Bowen reaction series



Dietrich & Skinner



Shervais & Taylor

- Once crystallization is complete, remove upper parts of An to create crust seen in "Eastern" regions
- In western regions closer to center of "Procellarum basin" pressure release from removal of An crust causes partially melting in the KREEP or underlying CPX, Ol cumulates resulting in more complicated secondary differentiation

Variations among highland rocks

Highland rocks all dominated by anorthosite (Ca feldspar)

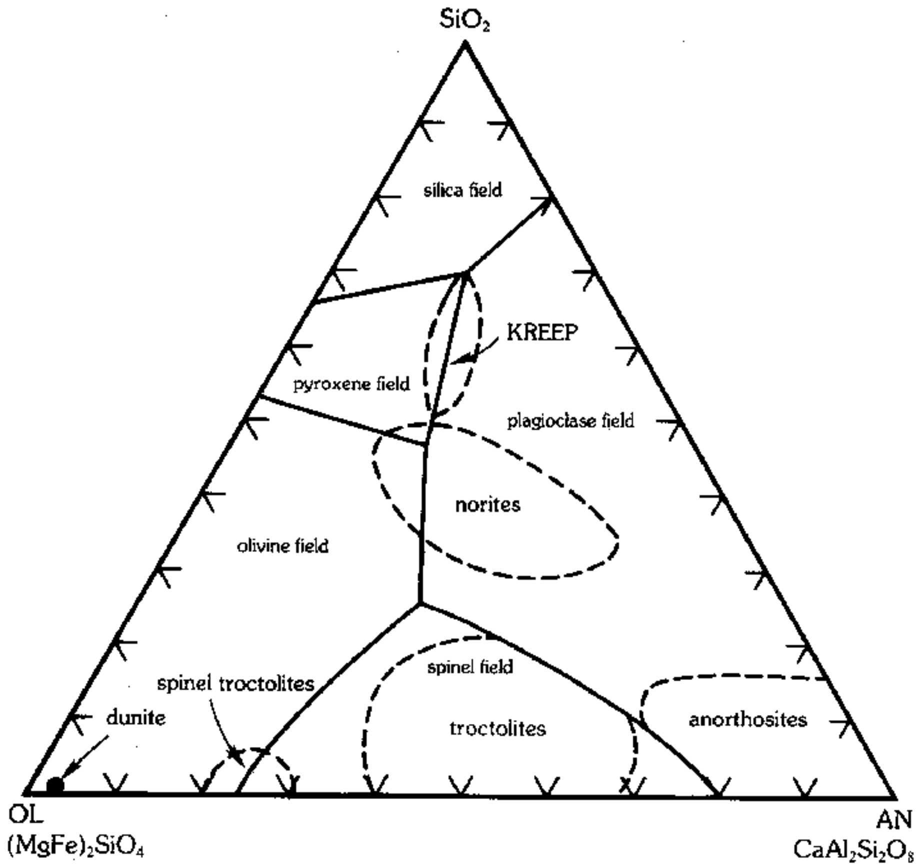
Some highland rocks show various amounts of KREEP signature

- KREEP: High in K (potasium) REE's P (phosphorous)
- Incompatible elements so concentrated in last liquid of magma ocean
- Two end-member ways to explain KREEP in anorthosite:
  - Erupt as "basalt" just before last of ocean solidifies, or by slightly later remelting
  - Trap residual melt among anorthite crystals as they float to form crust
- In either case heavy impacts mix crust, destroying original texture

Two main types of highland rocks described by Shervais and Taylor

- First – they describe the obsolete designation of "ANT" suite rocks
  - Anorthosite: anorthite dominated rock)
  - Norite: plagioclase (usually anorthite) plus pyroxene
  - Troctolite: plagioclase (usually anorthite) plus olivine
- Next they describe the two new main components
  - **FAN suite = Ferroan Anorthosite =** Anorthosite containing Fe-rich mafic minerals
  - **Mg suite** (Norites and Troctolites containing Mg-rich pyroxene and olivine
  - A third "minor" suite contains more alkali feldspar rich rocks

“Primary Rocks”



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

Taylor 1982

- Detailed origin of lower “anorthosite” crust not completely clear
  - 1) Anorthosite crust intruded by mafic components from below
  - 2) Imperfect settling of mafic components during the initial crystallization

  On earth secondary differentiation happens in two primary ways
  - 1) continental crust intruded/heated by mantle material from below
  - 2) island arcs & subduction zones following interaction of subducted material (and H_2O) with mantle material

  On moon do not have plate tectonics – need to make simple heating & impact processes to all the work
  - Use large impacts to unroof regions differentiated once before
  - Can also have slow radioactive heating of cumulates produced by original magma ocean. Perhaps have overturn of gravitationally unstable cumulate pile and resulting melting..
  - May have global circulation/asymmetry patterns in global magma ocean (more on this later)

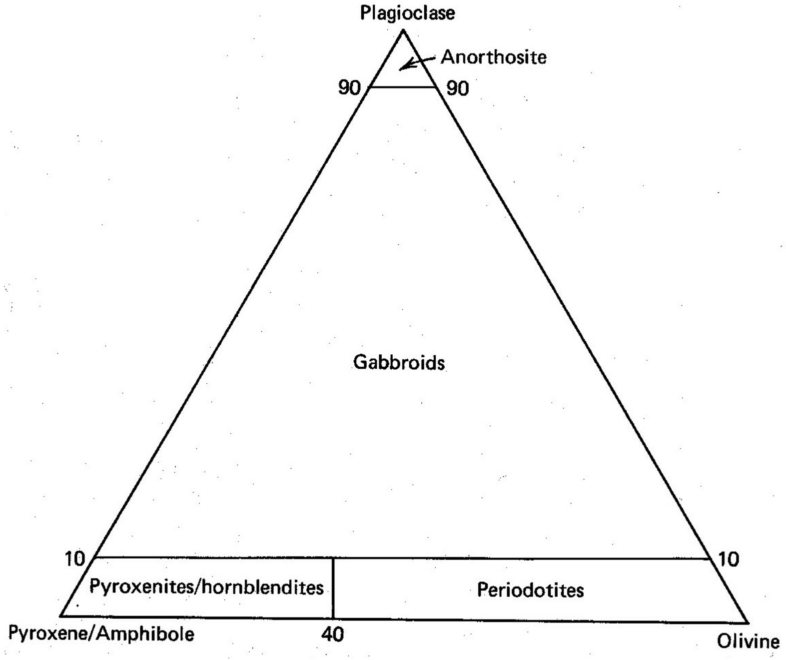
Classification used for Highland Rocks: "Gabbroids"

- 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

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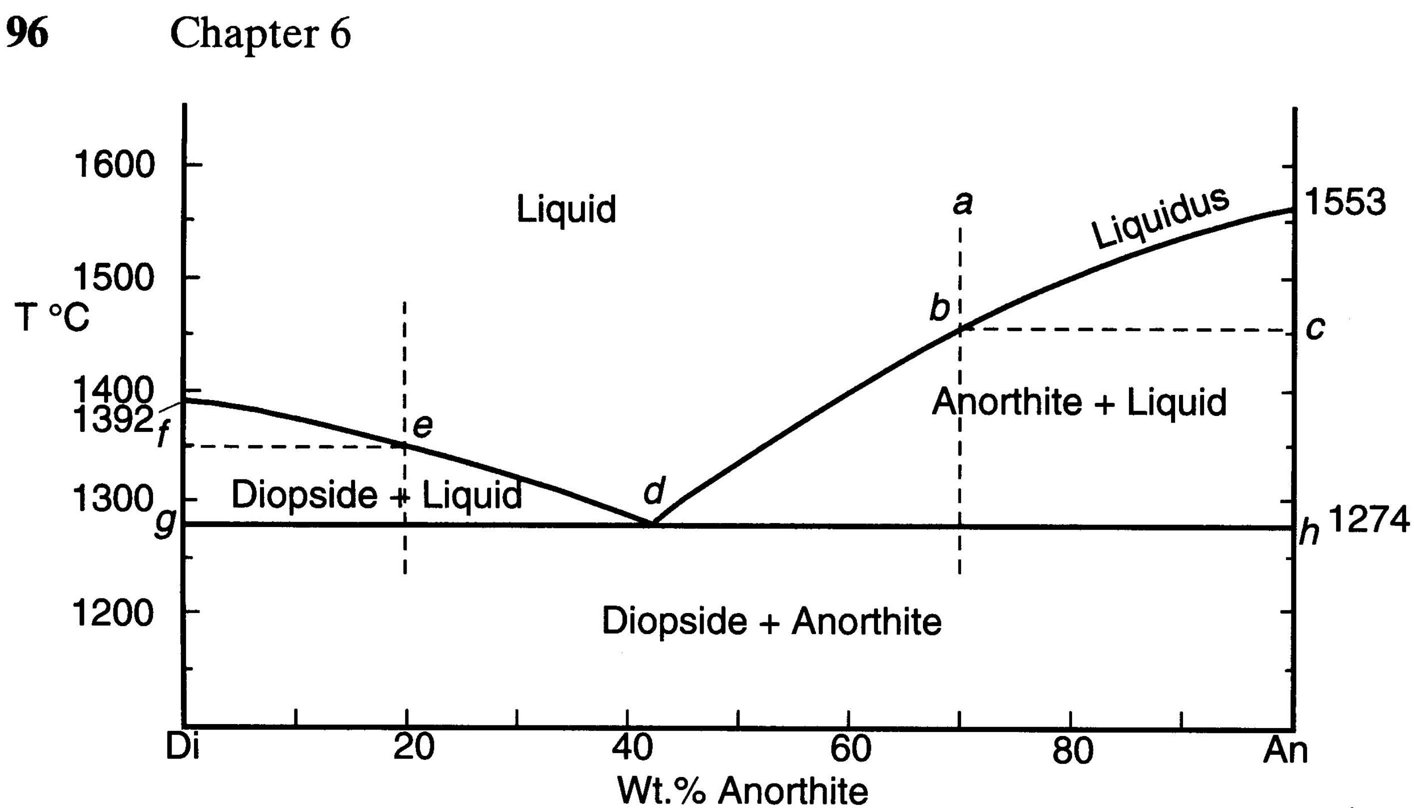
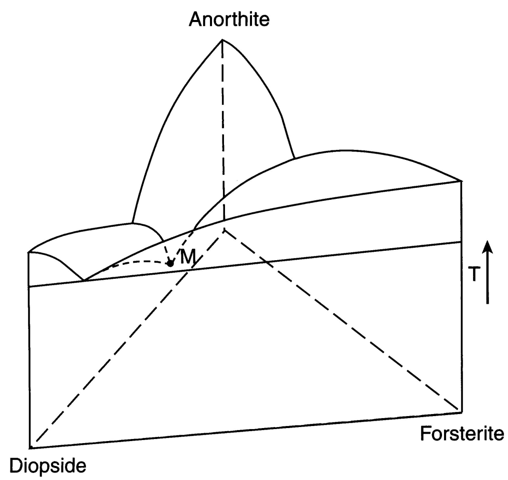
Melting: Immiscible Solids (Diopside + Anorthite)



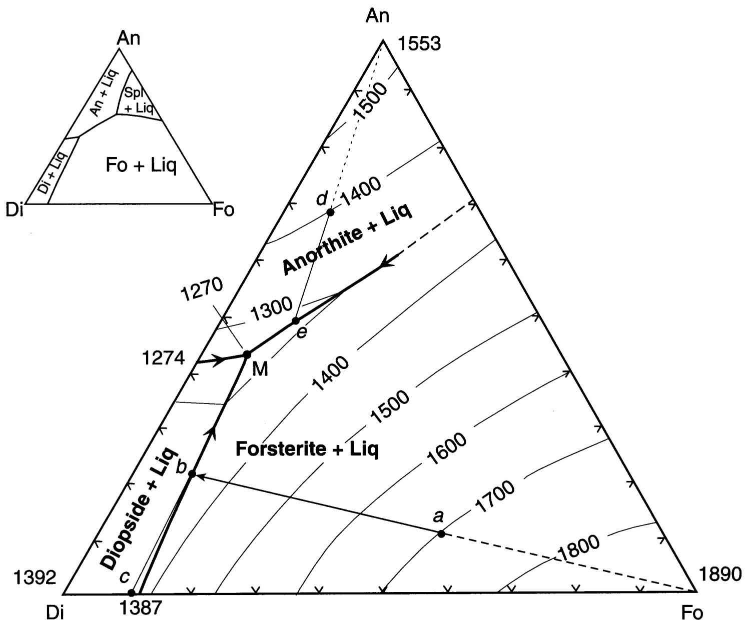
From Winter 2001

- Crystals of the pyroxene Diopside ($MgCaSi_2O_6$ and the feldspar Anorthite ($CaAl_2Si_2O_8$) are immiscible and so have a phase diagram similar to that of the simplified salt.

Melting: 3 Component Phase Diagrams

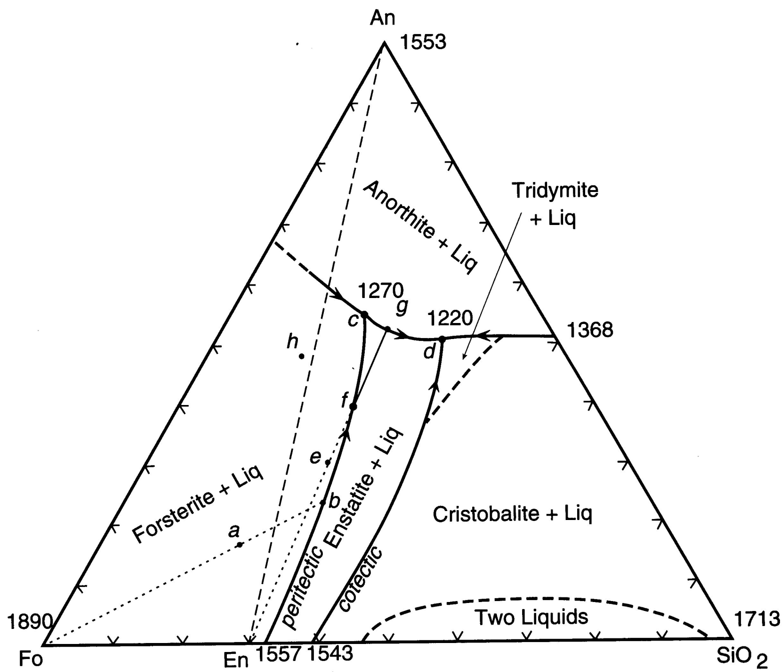


- For 3 component systems could plot composition in x-y plane using a triangle plot, and temperature in Z.
- Along any outside edge it looks like the two component plots we have studied:
    - The two curved liquid + crystal curves meet at a eutectic
- In 3-D those curved lines become curved surfaces – 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



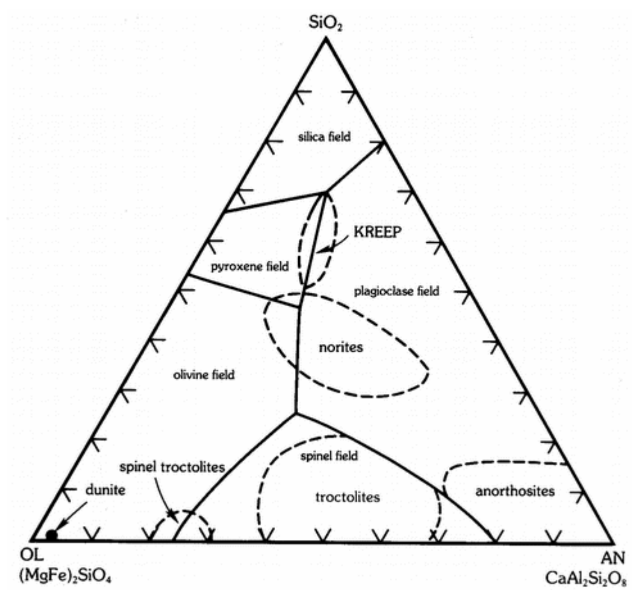
From Winter 2001

Melting: The An, Fo, SiO_2 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 SiO_2 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].)

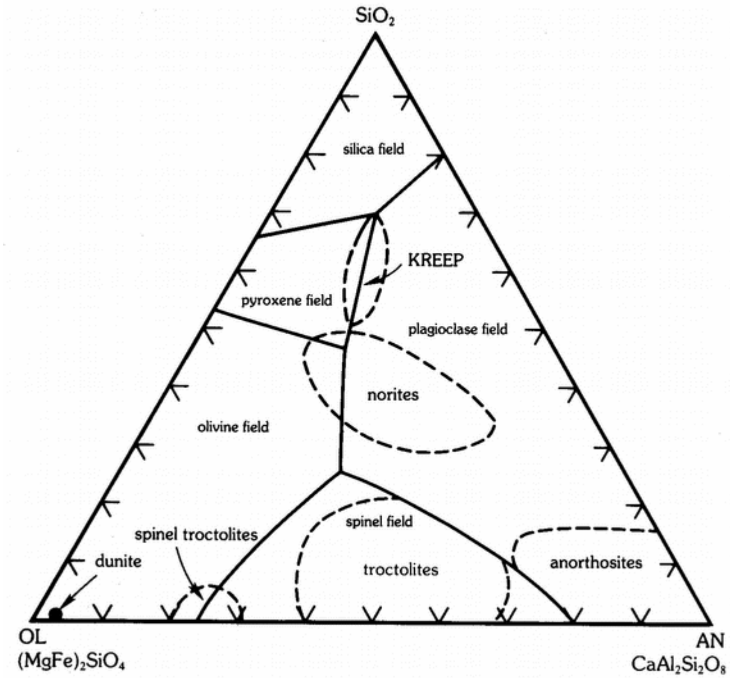
Classification used for Highland Rocks: More refined names for Gabbroids

- 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



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Taylor 1982