Wed. Oct. 04, 2017

- Reading: For Friday:
  - Bugiolacchi et al. 2008
  - Laurence et al. 1998"

Makeup lecture time? Will Friday noon work for everyone?

  - No class Oct. 16, 18, 20?

Today:

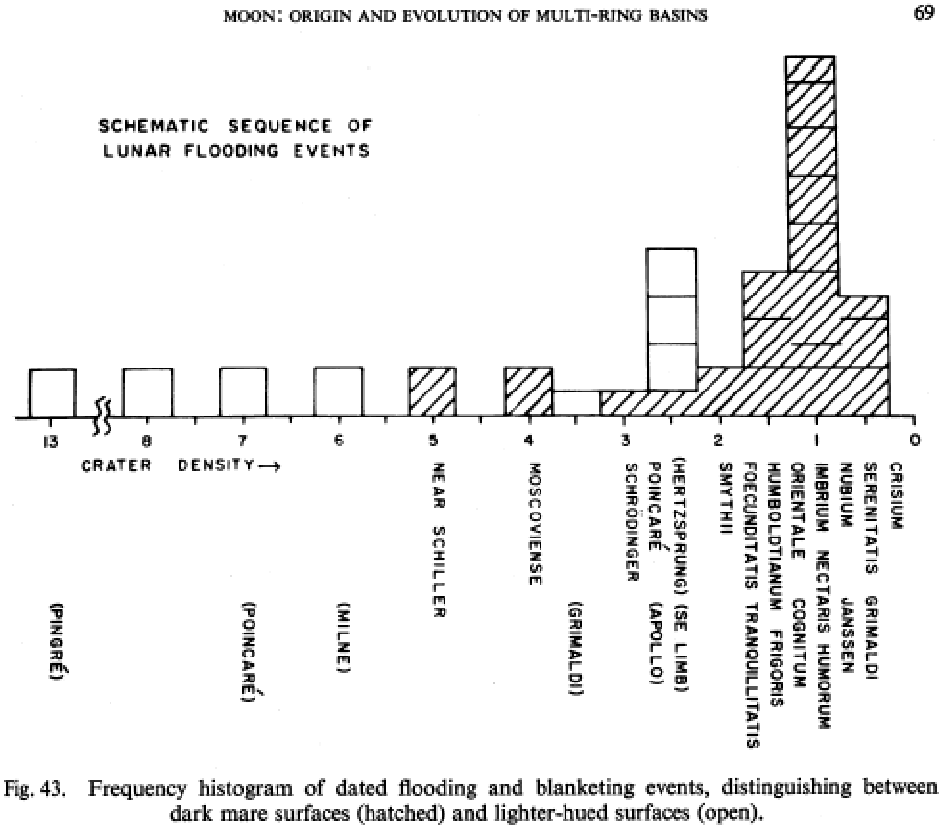
- Finish Lunar overview (from last set of PDF slides posted for Monday)
- Lunar Differentiation Part 1.

Differentiation of the early moon

- Harold Urey and some others originally believed moon primitive and undifferentiated
  mare basalts perhaps just impact melts
- Crater counts show mare much younger than basins
- Morphology of mare basalts indicate flows over time
- Anorthosite crust indicates major differentiation
- Complementary Eu anomalies in anorthosite and mare basalt source regions show they were in "equilibrium"
  - Global magma ocean

- Other effects of early differentiation?
- General timeline for activity?
- Comparison with other terrestrial planets?

Relative age of basins and mare



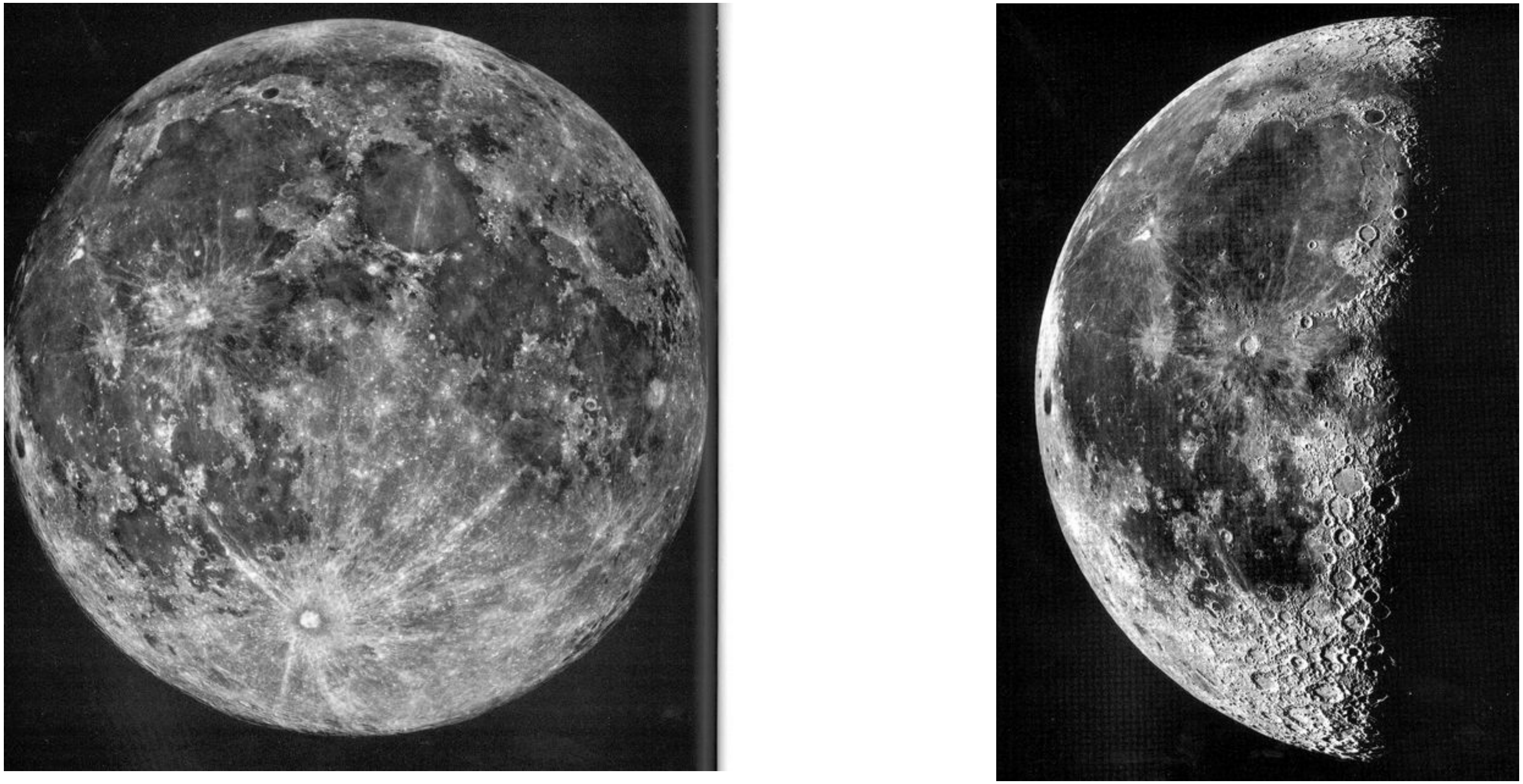
MOON: ORIGIN AND EVOLUTION OF MULTI-RING BASINS 69

Fig. 43. Frequency histogram of dated flooding and blanketing events, distinguishing between dark mare surfaces (hatched) and lighter-hued surfaces (open).

Hartmann & Wood 1971

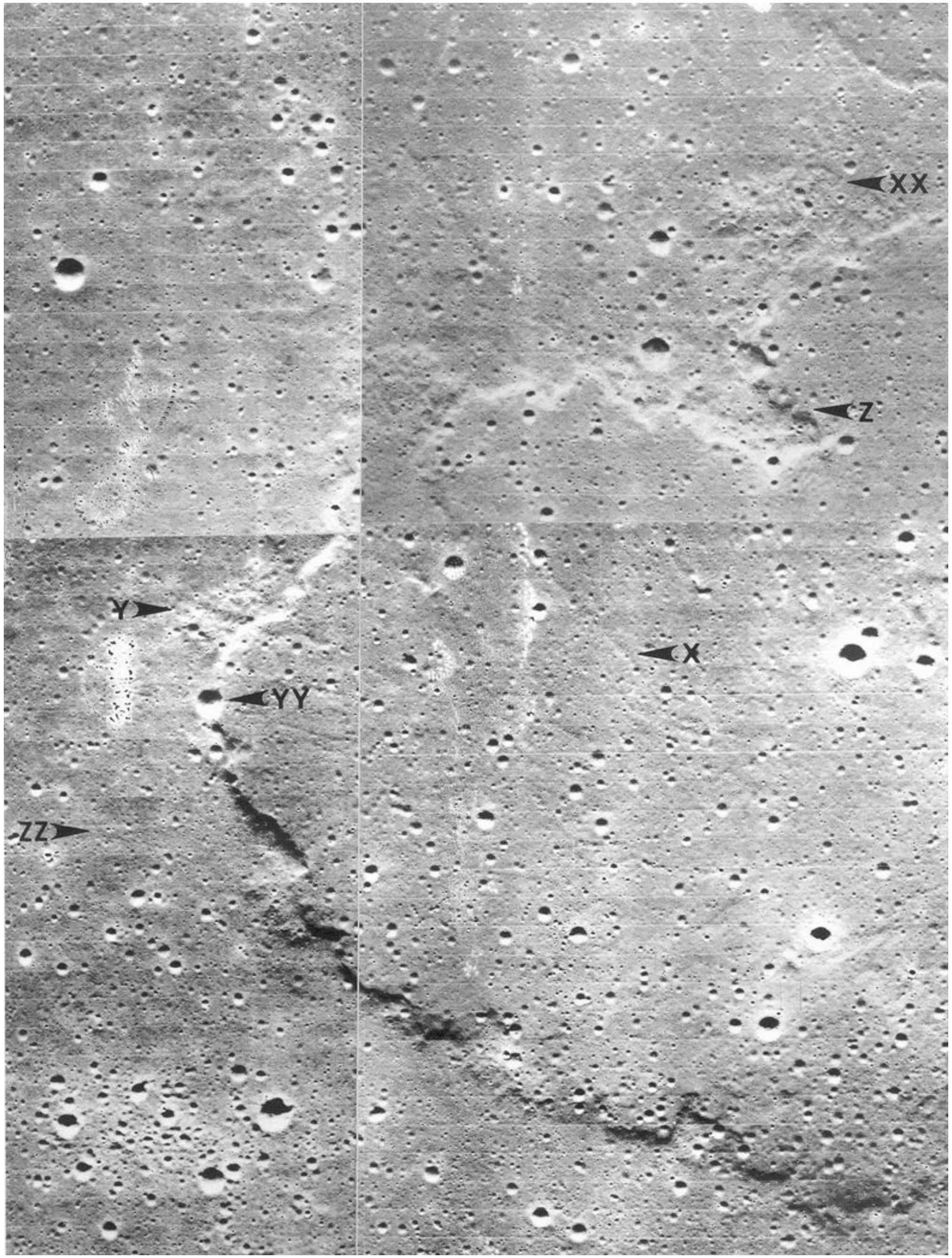
- Immediate conclusions
  - Mare are not simply impact melt (as some originally proposed)
  - Similar age of Mare suggests common cause related to lunar thermal evolution
  - Age of oldest lava uncertain
    - Some old ages suspect
    - Other “real” old lava could be hidden by later impacts
  - There is a clear “end” to the mare volcanism

Effect of phase angle



- Use low phase angle (noon) pictures to emphasize albedo
- Use high phase angle (sunset/sunrise) pictures to emphasize topograph

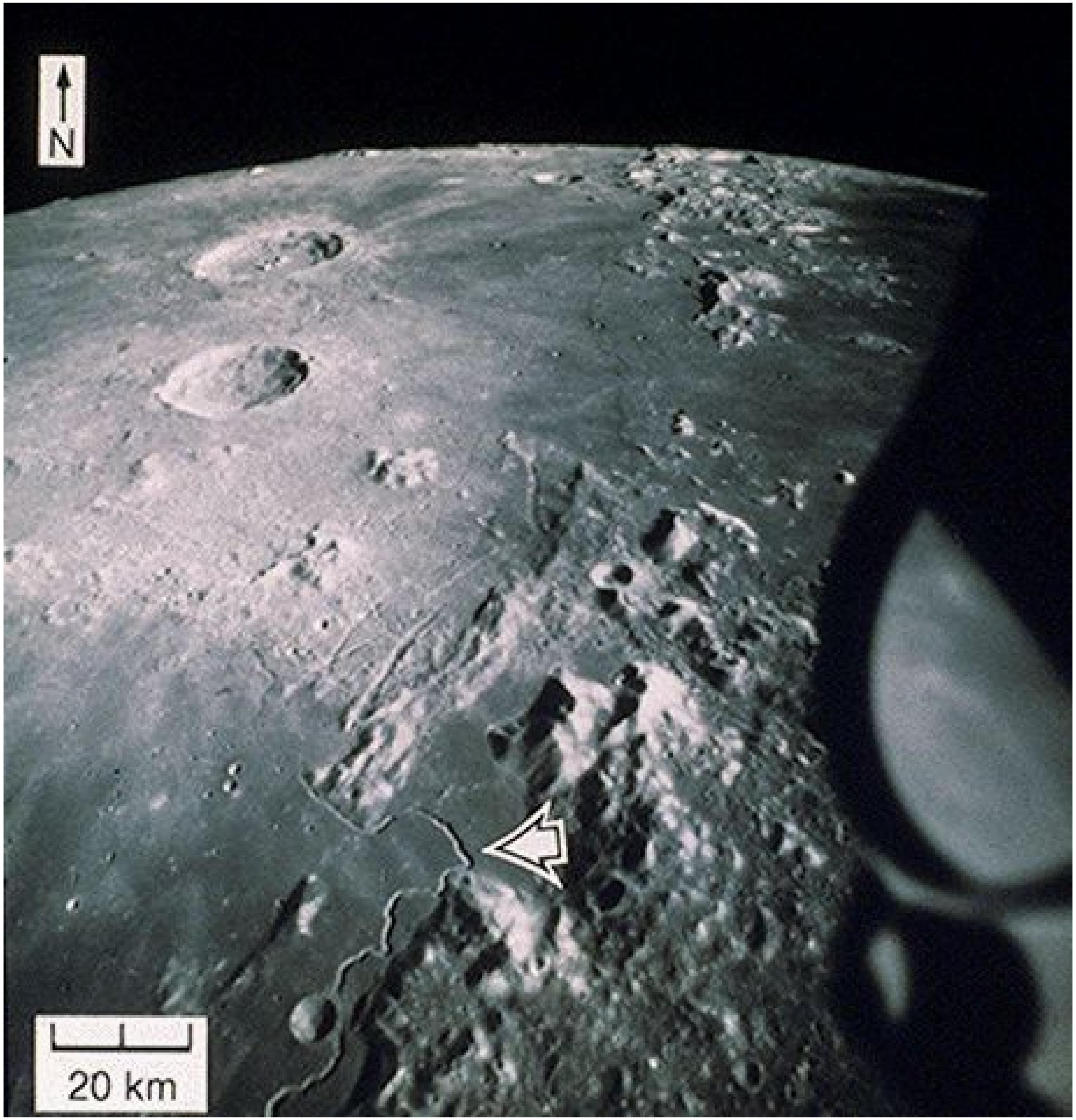
Composite pictures



Evidence of mare lava flows

- Lobate flow front characteristic of low viscoscity lava
- Flow thickness from size of smallest craters showing "concentric" structure
  - ~ 5 meters
- Can also place limits from shadows at flow margin
  - < 25 meters
- In this not much crater density difference across boundary, so preexisting surface not much older than flow

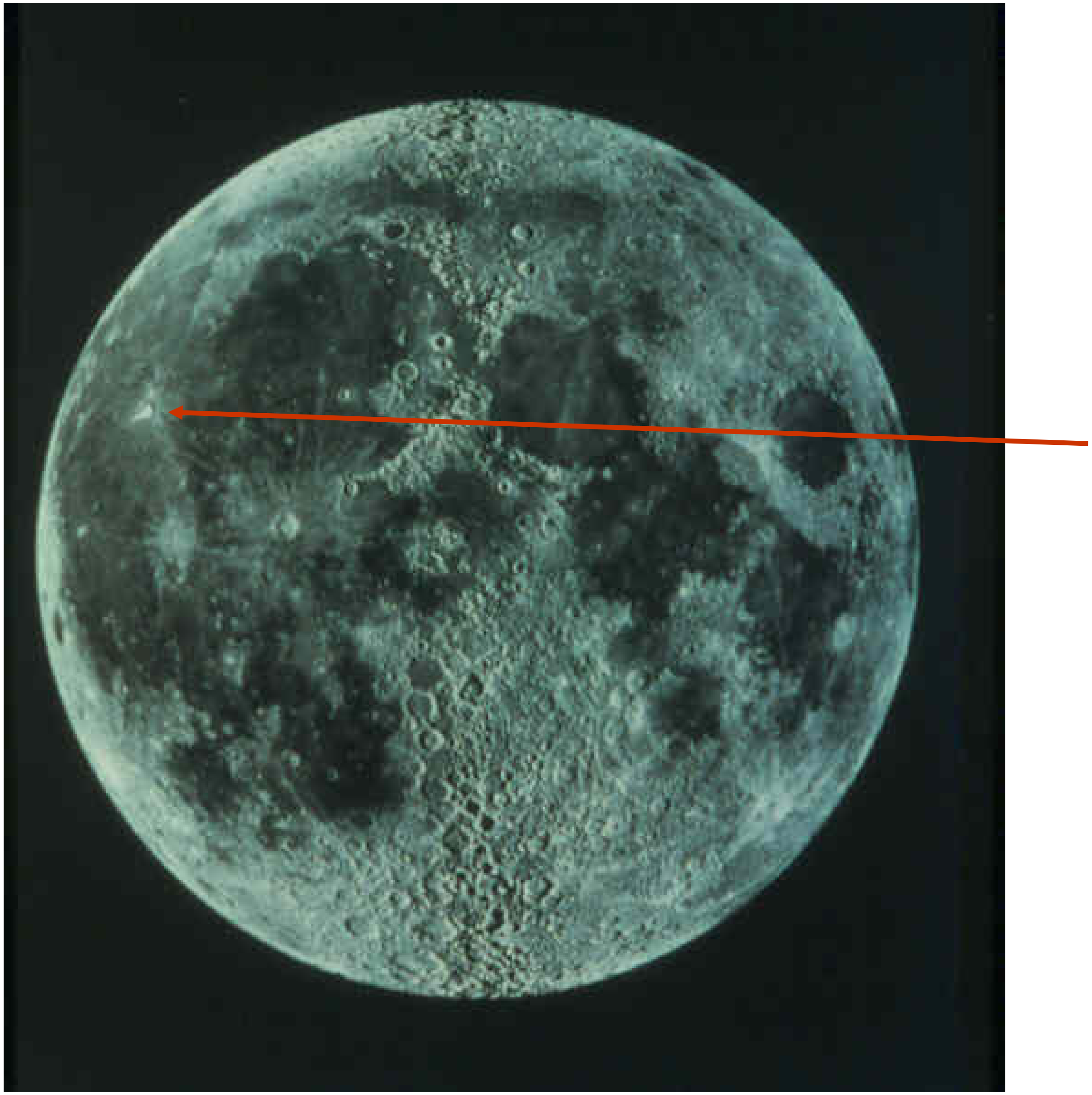
Lunar Orbiter photo from Shultz 1974



Sinuous rilles

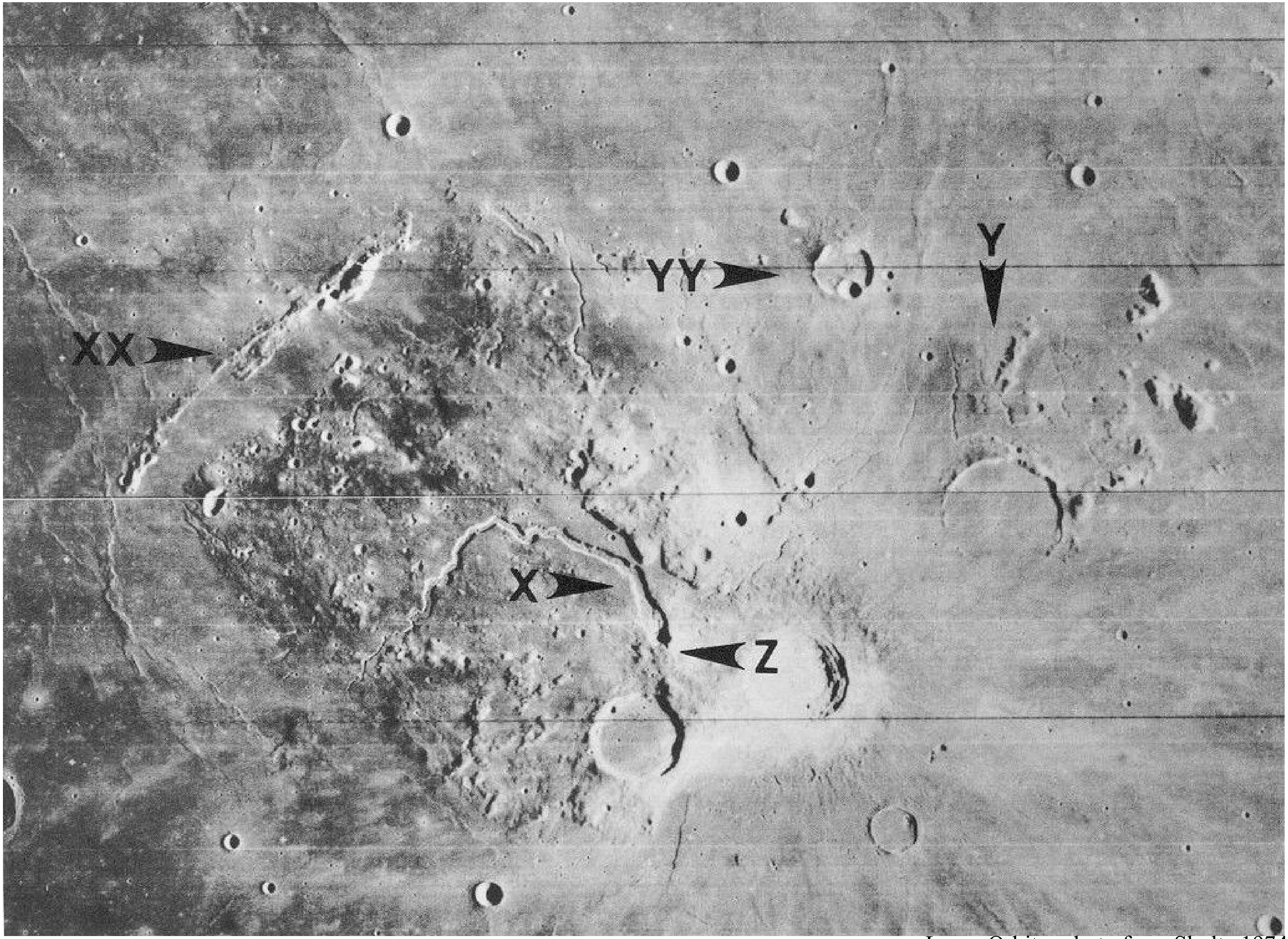
- Hadley rille at Apollo 15 landing site

Aristarchus plateau



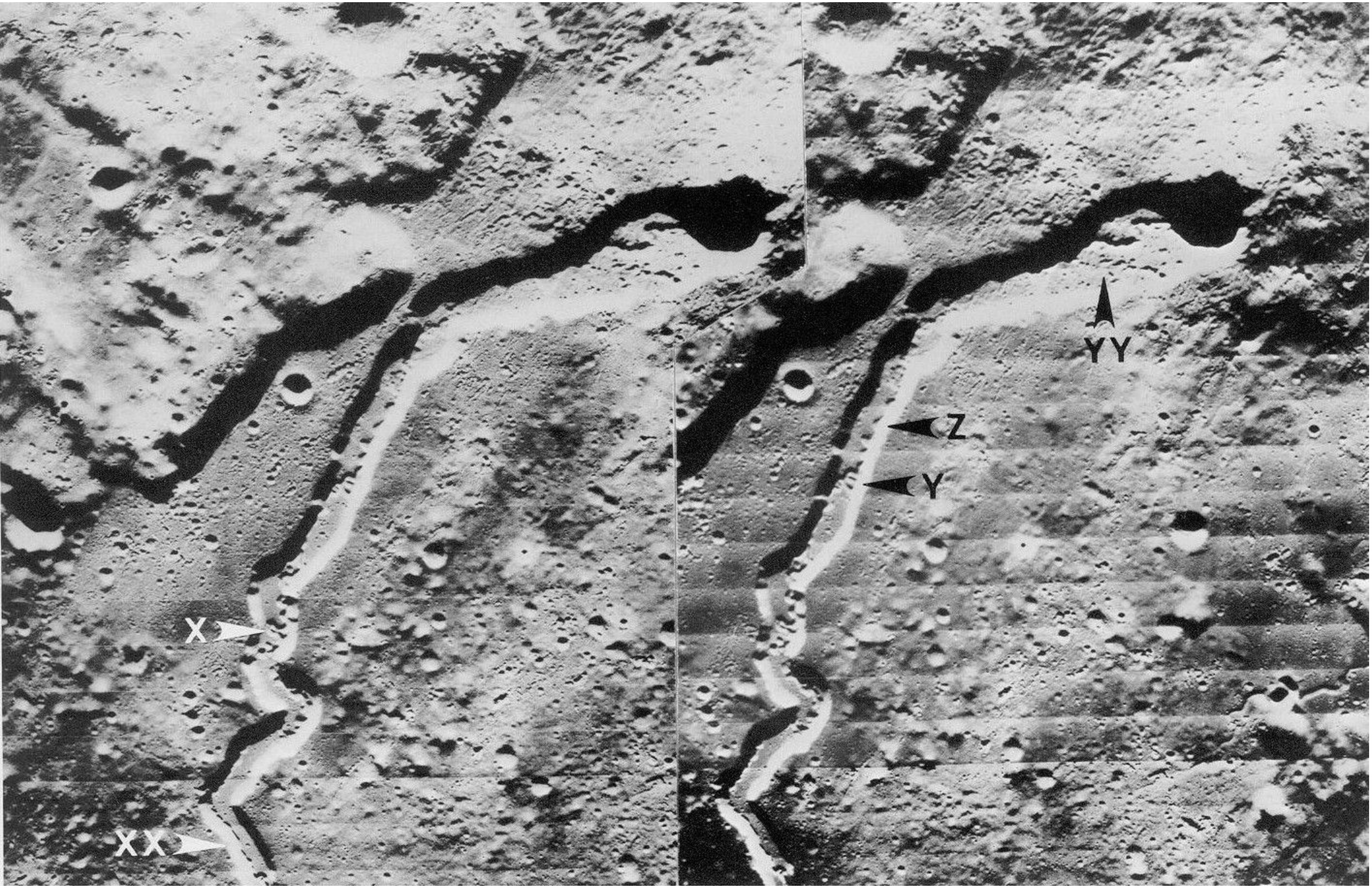
- Located near bright new crater Aristarchus – but that came much later

Schröter's Valley
sinuous rille with a smaller one inside



Lunar Orbiter photo from Shultz 1974

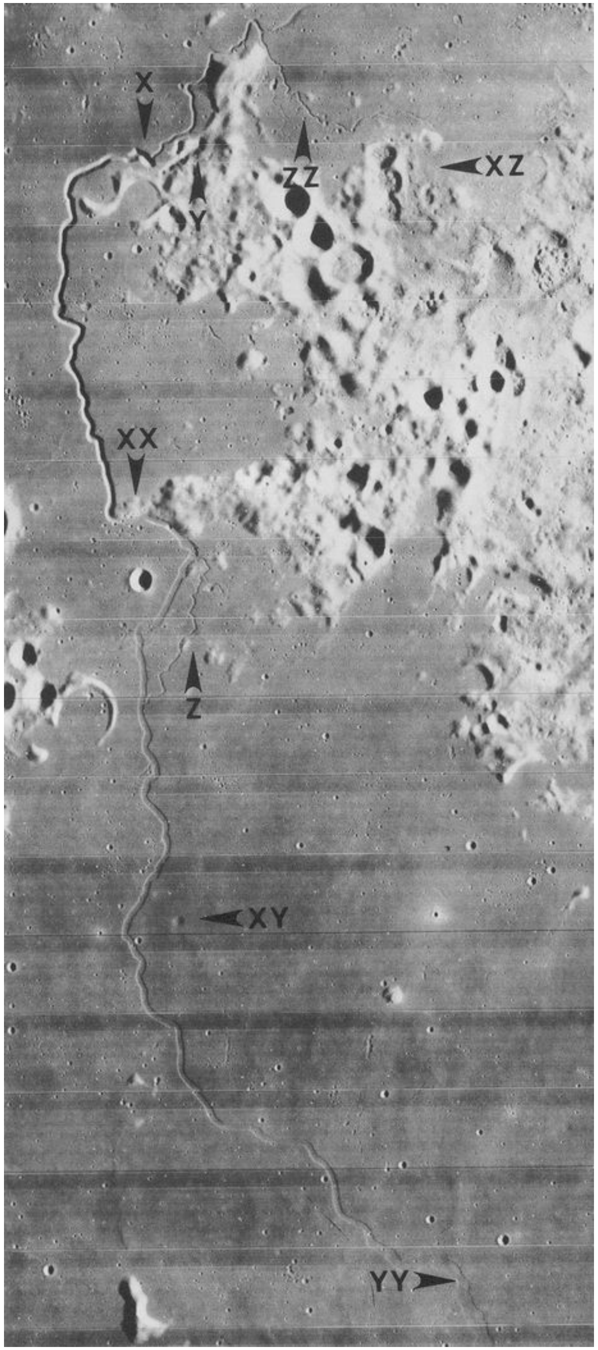
Schröter's Valley-close up view

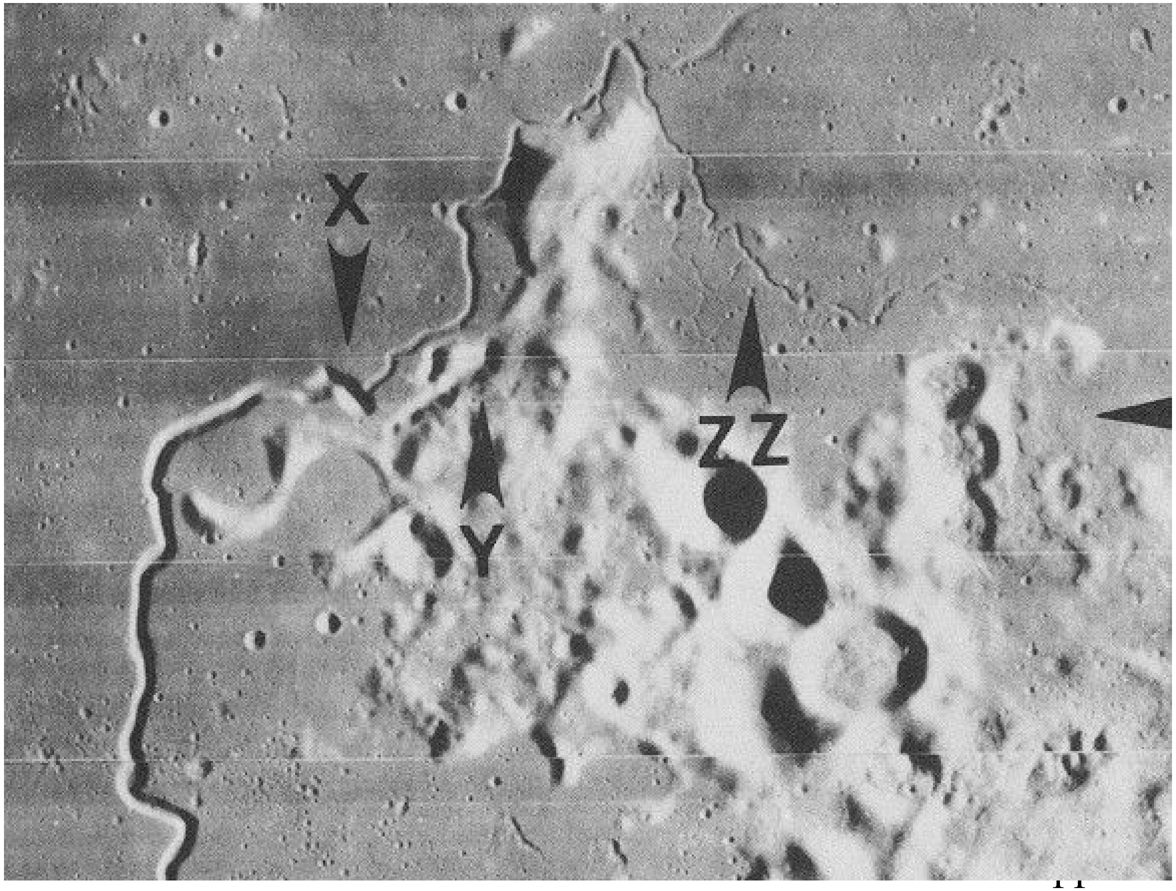


Lunar Orbiter photo from Shultz 1974

Rima Sharp

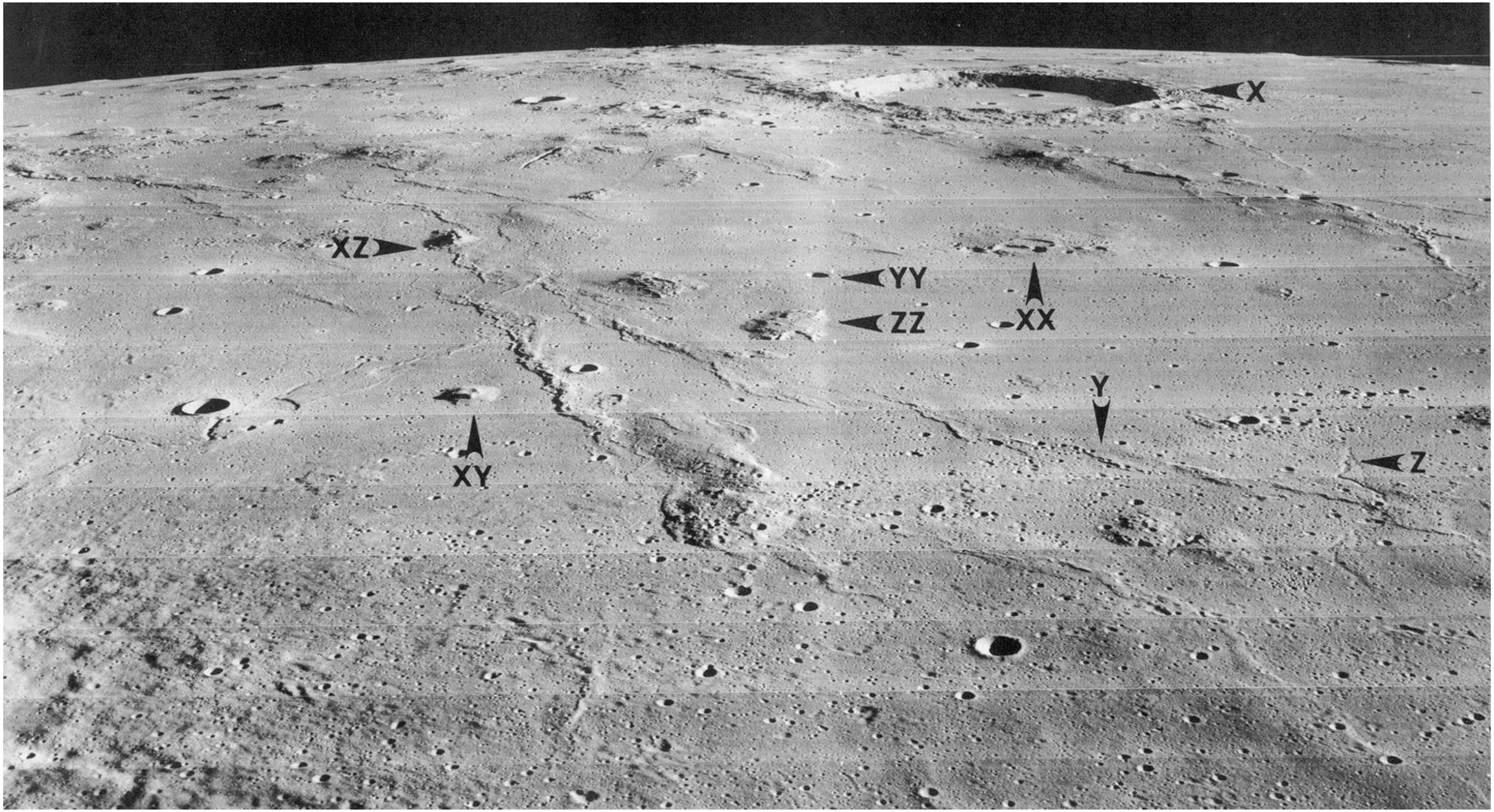
- Two rills originate in same elongated “crater”
- Lower rill extends 360 km in this picture, and a similar distance below the bottom cutoff





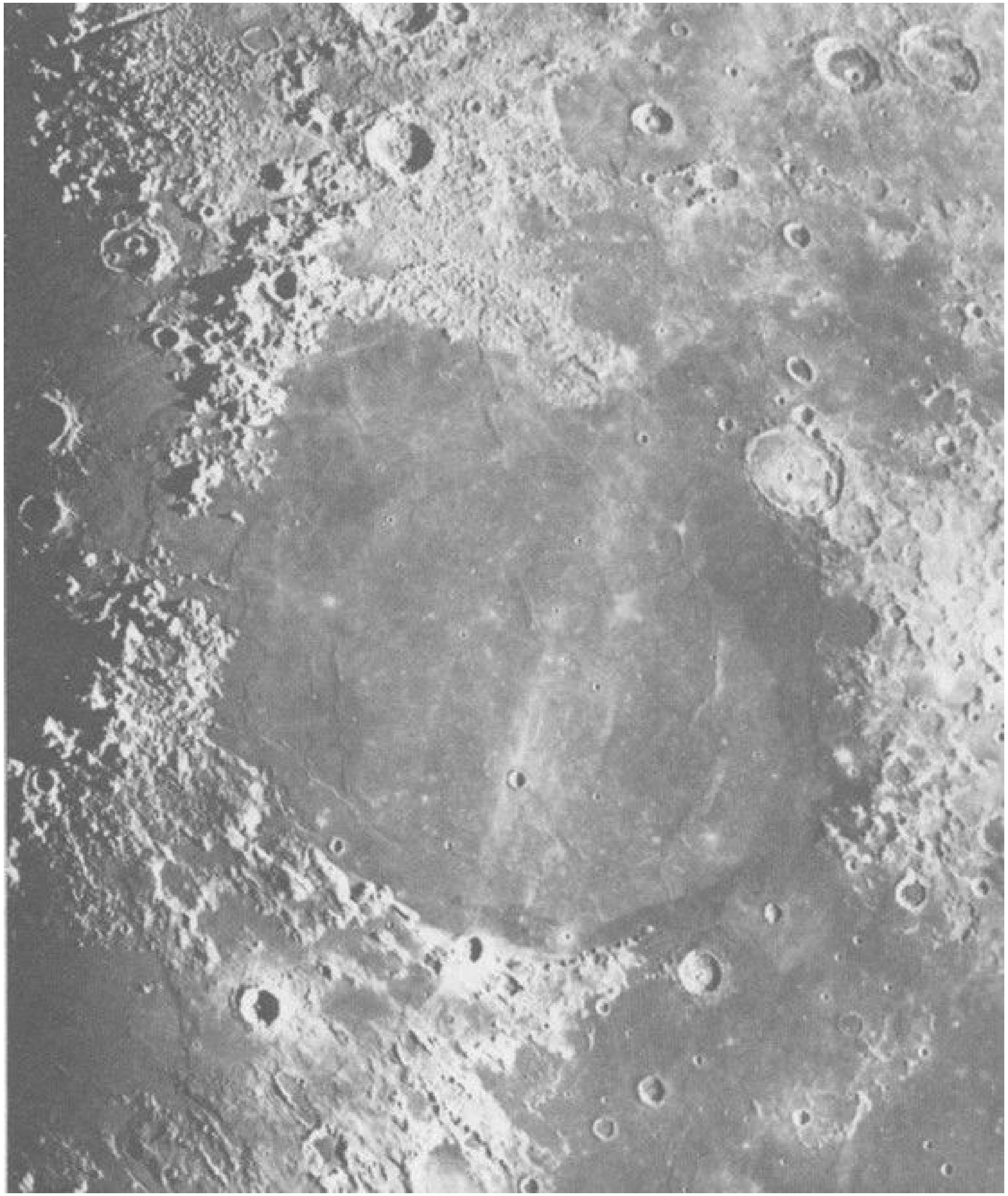
Lunar Orbiter photo from Shultz 1974

Marius Hills



- Z = Sinuous rilles
- XX = Caldera like depressions on low-relief mounds
- YY = Rimless pits
- ZZ = Isolated platforms
- XY = mounds with summit pits
- XZ = mounds without summit pits

Lunar Orbiter photo from Shultz 1974



Mare Serenitatis

Low sun angle to measure albedos

Note different albedo flows, almost concentric to the basin

Very low albedo region in SE corner (Apollo 17 landing site)

Taylor 1982 Fig. 6.9a

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Classifications of elements

Lithophile elements	
Refractory	Be, Al, Ca, Ti, V*, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th and U
Transitional	Mg, Si and Cr*
Moderately volatile	Li, B, Na, K, Mn*, Rb and Cs*
Highly volatile	F,Cl, Br, I and Zn
Siderophile elements	
Refractory	Mo, Ru, Rh, W, Re, Os, Ir and Pt
Transitional	Fe, Co, Ni and Pd
Moderately volatile	P, Cu, Ga, Ge, As, Ag, Sb and Au
Highly volatile	Tl and Bi
Chalcophile elements	
Highly volatile	S, Se, Cd, In, Sn, Te, Hg and Pb
Atmophile elements	
Highly volatile	H, He, C, N, O, Ne, Ar, Kr and Xe

** At high pressure these elements may develop siderophile behaviour and partition into the core.*

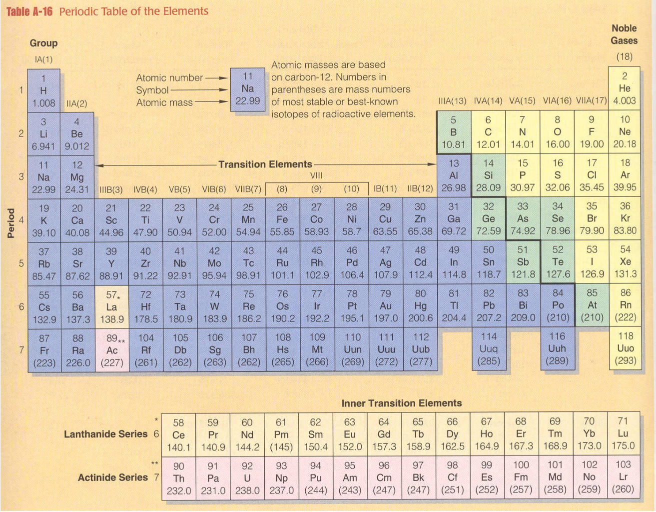


Table A-16 Periodic Table of the Elements

Atomic number → 11
Symbol → Na
Atomic mass → 22.99

Atomic masses are based on carbon-12. Numbers in parentheses are mass numbers of most stable or best-known isotopes of radioactive elements.

Transition Elements

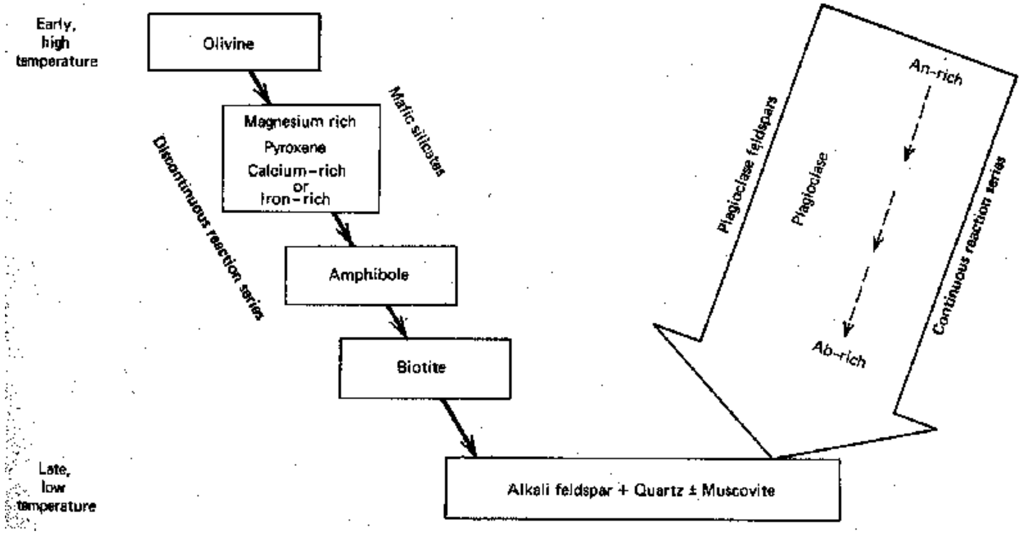
Period	IA(1)	IIA(2)	IIIB(3)	IVB(4)	VB(5)	VIB(6)	VIIB(7)	VIII (8)	VIII (9)	VIII (10)	IB(11)	IIB(12)	IIIA(13)	IVA(14)	VA(15)	VIA(16)	VIIA(17)	Noble Gases (18)
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.7	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57* La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.0	89** Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 Uun (269)	111 Uuu (272)	112 Uub (277)		114 Uuq (285)		116 Uuh (289)		118 Uuo (293)

Inner Transition Elements

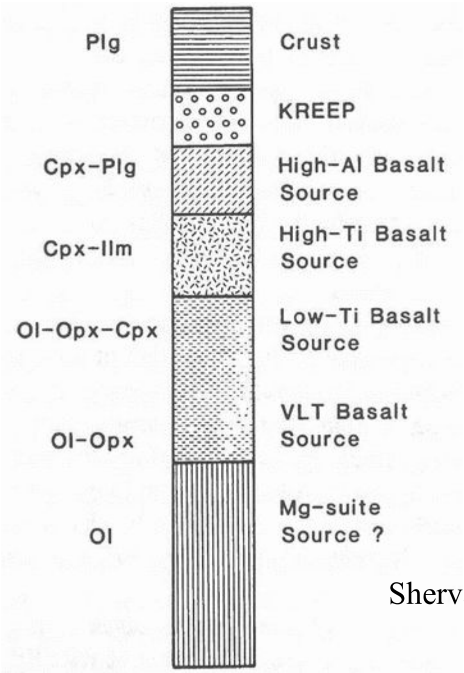
* Lanthanide Series	6	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
** Actinide Series	7	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.0	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

Incompatible elements:	Those elements which like to remain behind in the melt as a magma crystallizes
Compatible elements:	Those elements which like to go into the crystals.

Origin of the Anorthosite?
Bowen reaction series



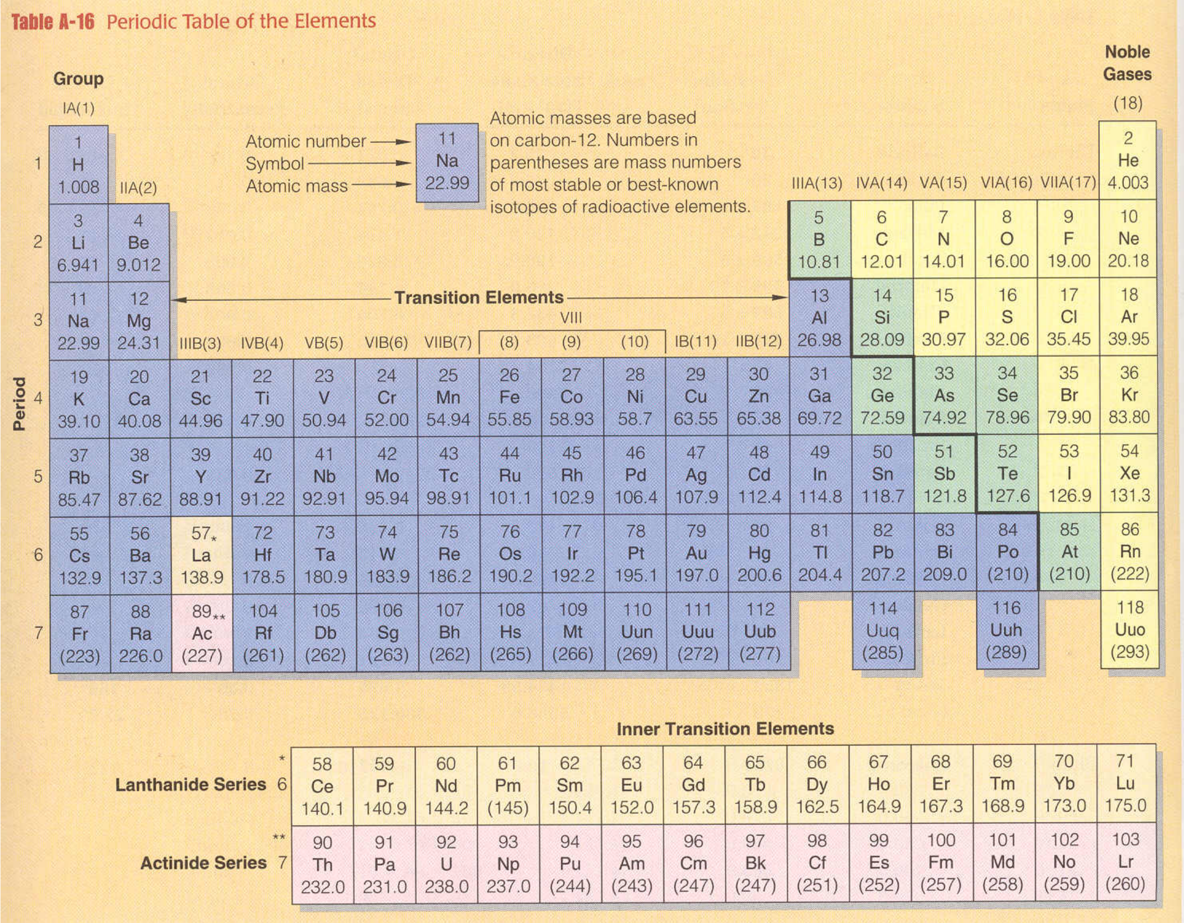
Bowen reaction series from Dietrich and Skinner1979



Shervais & Taylor

- Anorthite and olivine are first minerals to crystallize
- Anorthosite is lower density than the melt and will float (especially for dry lunar melts)
- Olivine and pyroxene are denser and will sink

Rare Earth Elements (REE)



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← Transition Elements →

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- Order of shells filled:
  - 1s
    2s 2p
  - 3s 3p
  - 4s 3d 4p
  - 5s 4d 5p
  - 6s 4f 5d 6p
  - 7s 5f 6d 7p

All REE's = Lanthanides behave chemically almost the same – usually in +3 state

Light REE's = LREE's slightly larger than Heavy REE's = HREE's because increasing nuclear charge makes outer electron orbits smaller

- La^{3+} = 0.106 nm
- Lu^{3+} = 0.085 nm
- Different minerals may prefer large over small, leading to linear trends

"Spidergrams" plot abundance of each REE / chondritic abundance

Preference of some minerals for larger/smaller ions gives linear trends

Eu can be +2 as well as +3

- Eu^{2+} can replace Ca^{2+} in anorthite

Evidence of global magma ocean

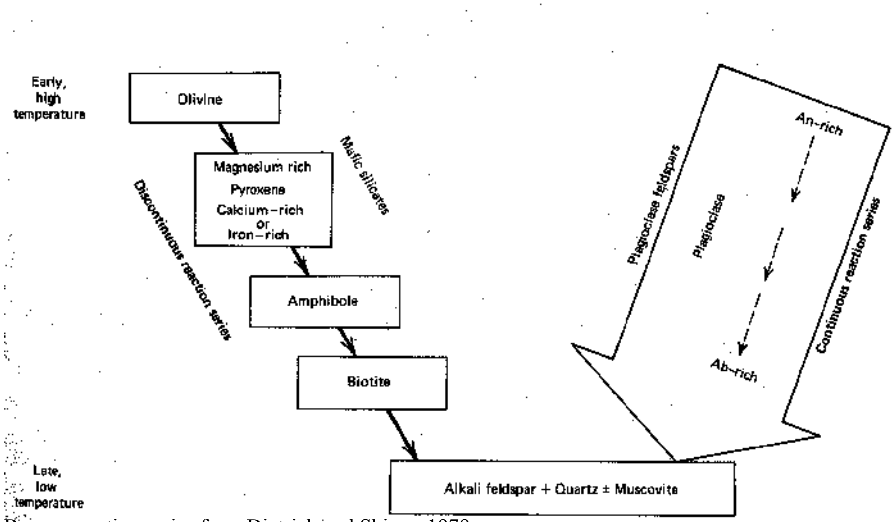
- Presence of anorthosite crust shows moon differentiated
  - Crust makes up 10% of volume so requires major event
  - To generate Anorthosite = 10% of volume requires differentiation of 40% of total volume of material

- Presence of mare <u>basalt</u> supports this idea but doesn't require full differentiation
  - Mare basalts only make up 0.1% of volume
  - Require partial (10%) melting of 1% of volume – so "minor effect"

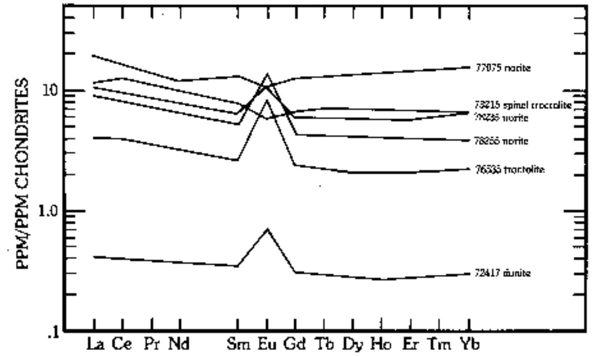
- Existence of complementary Eu anomalies in crust and mare source regions show that those regions were in chemical "equilibrium" which indicates connection between surface and (~400 km) deep layers

- Similar isotopic signatures in all mare suggest lateral connection between source regions when they formed

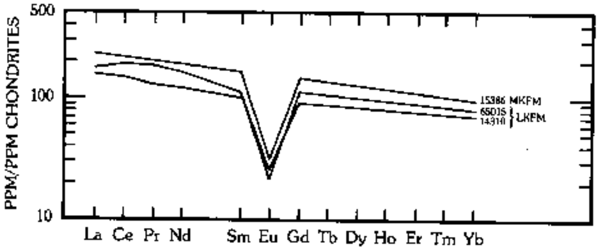
Evidence of global magma ocean



Bowen reaction series from Dietrich and Skinner1979



Highland rocks

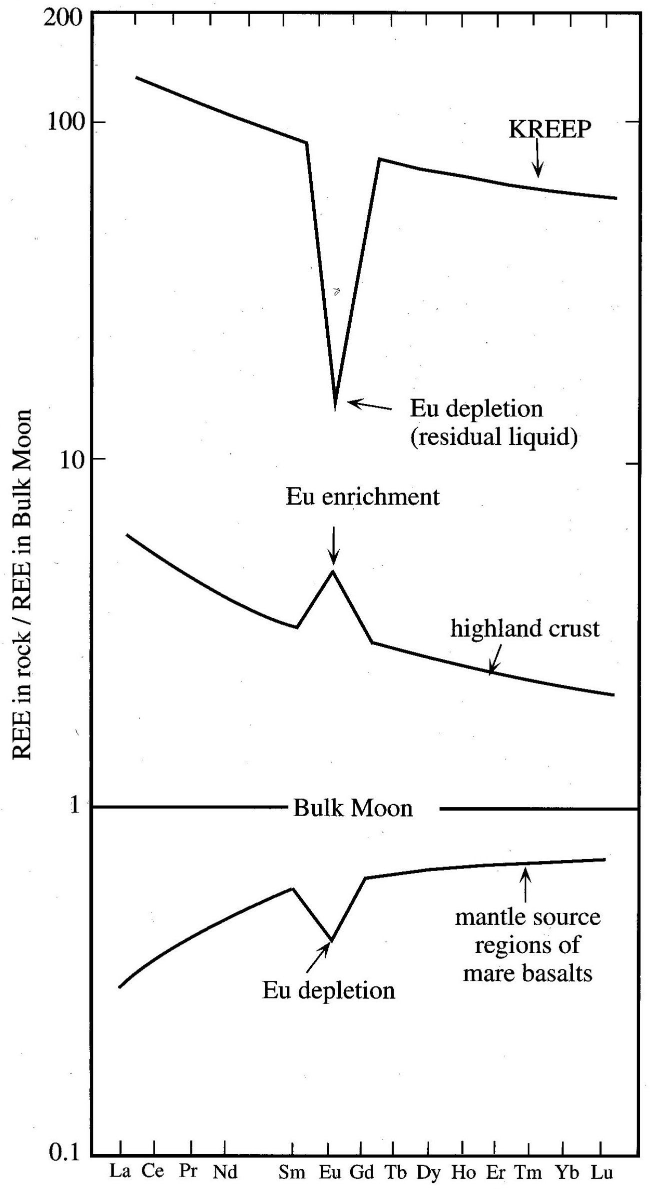


Basalts

5.19 Rare-earth element abundances in Fra Mauro basalts. Note the extreme enrichment of the total REE and the deep depletion in europium, forming a pattern reciprocal to that of the anorthosites in Fig. 5.15.

- Olivine and anorthite are first minerals to crystallize
- Anorthite is lower density than the melt and will float (for dry lunar melts – not for wet terrestrial ones)
- Olivine (and pyroxene) are denser and will sink
- A layer of residual melt will be trapped between the two
  - Will concentrate “incompatible” elements such as +3 REE’s, K, Th, U, etc.

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 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

Variations among mare basalts

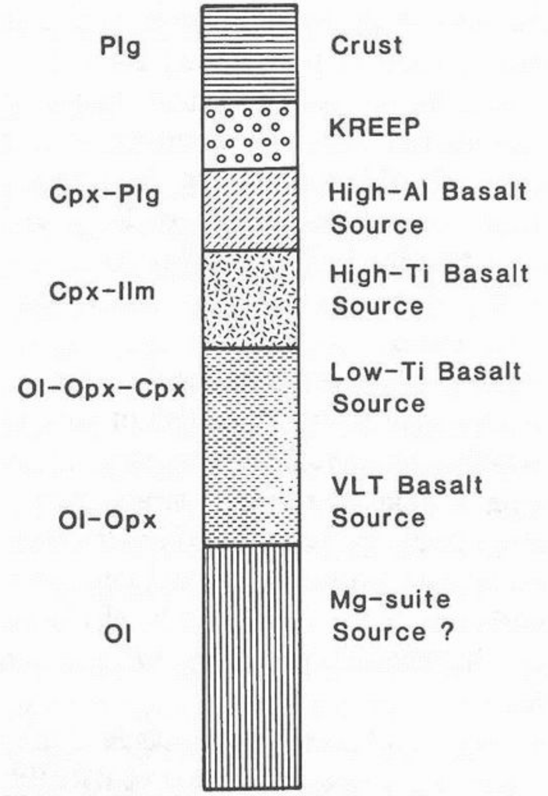
Three main groups of mare basalt

- 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

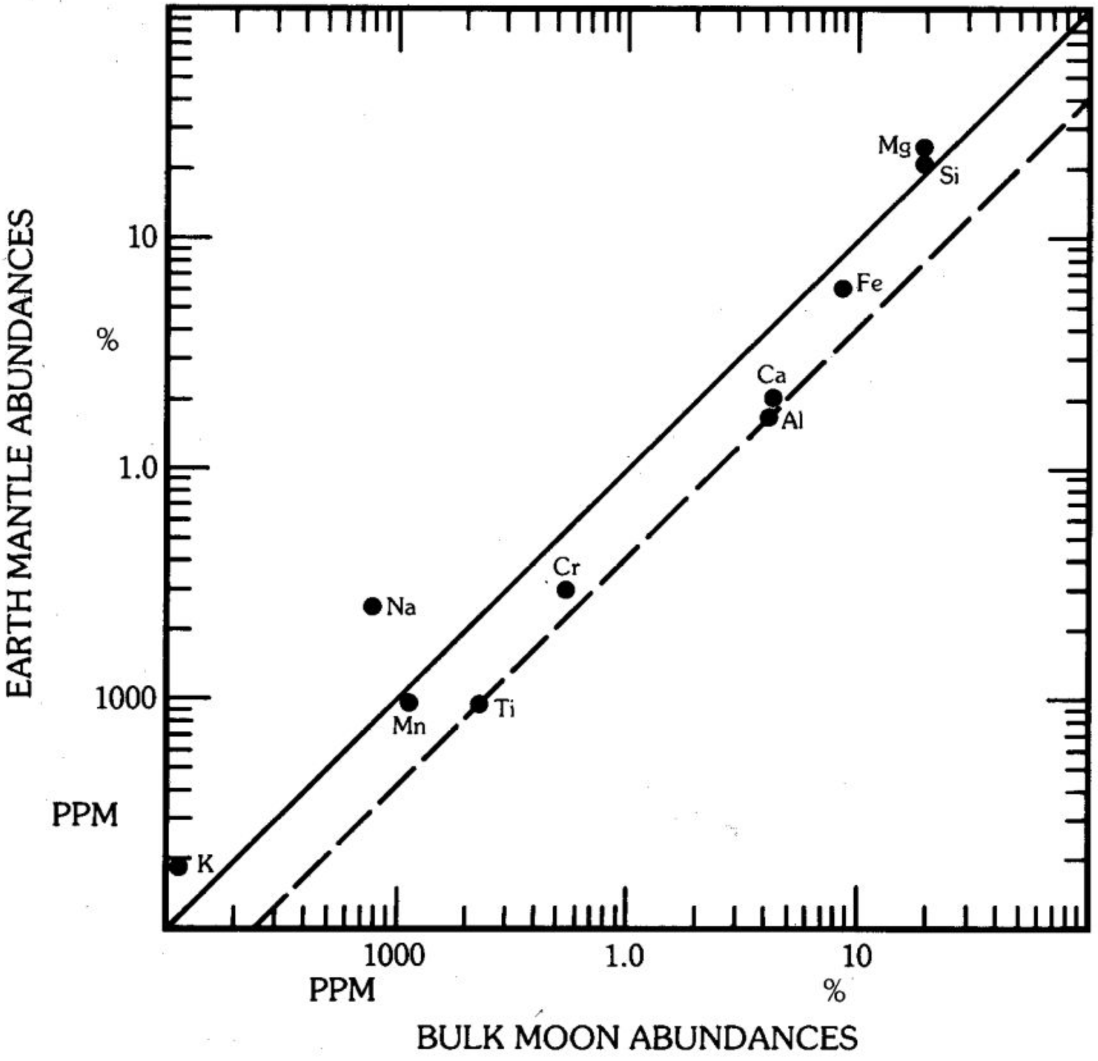
- Possible sources
  - Accretion in orbit around earth
  - Capture from elsewhere in solar system
  - Fission from earth
    - Giant Impact model
- Tests
  - Chemical composition
  - Orbital dynamics

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

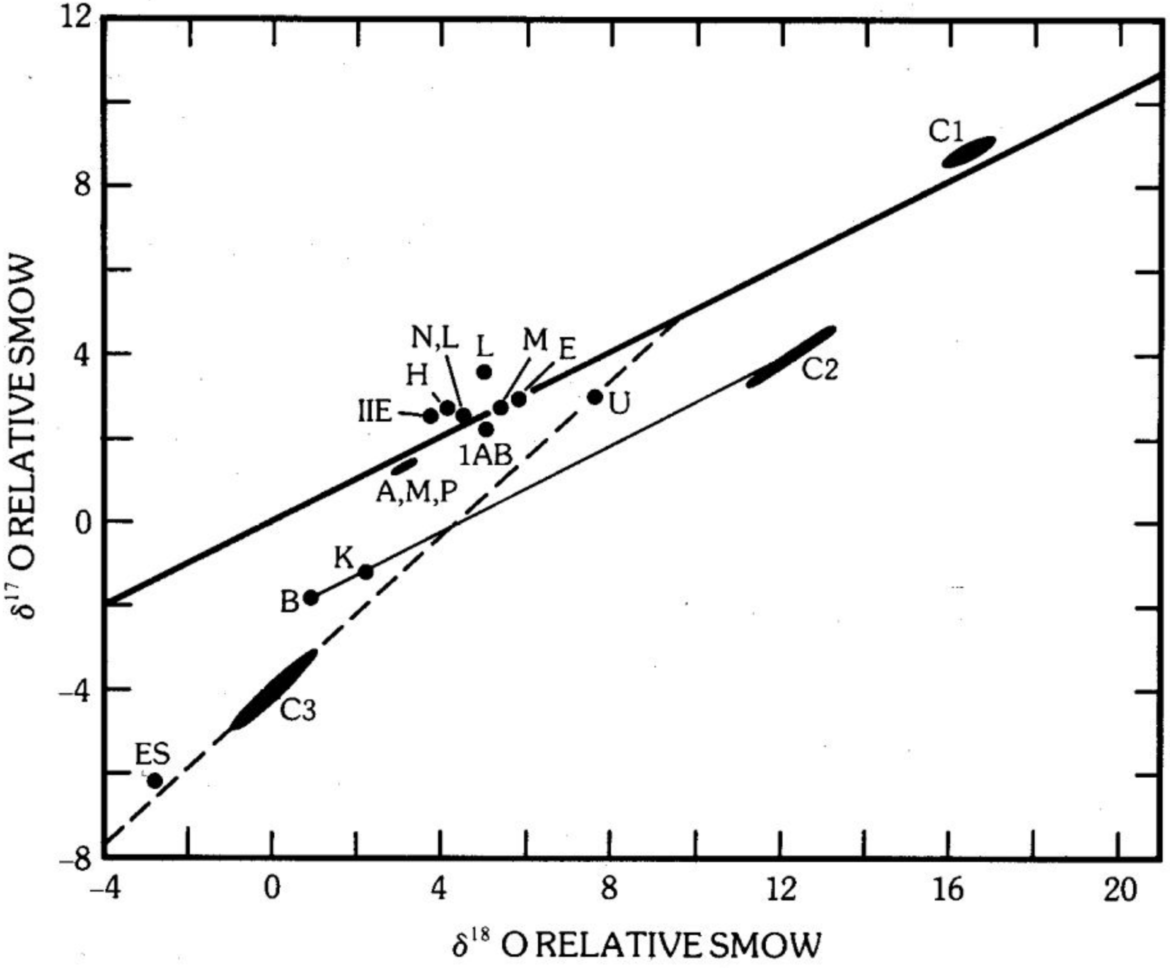


- Compare abundances to solid line at equal amounts earth (Y) = moon (X)
- Moon has similar abounds of Mg, Si, Mn
- Moon has less of volatiles like K, Na
- Moon has more of refractory elements like Ti, Al, Ca
- It also has slightly less Fe
- Trace elements confirm pattern

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

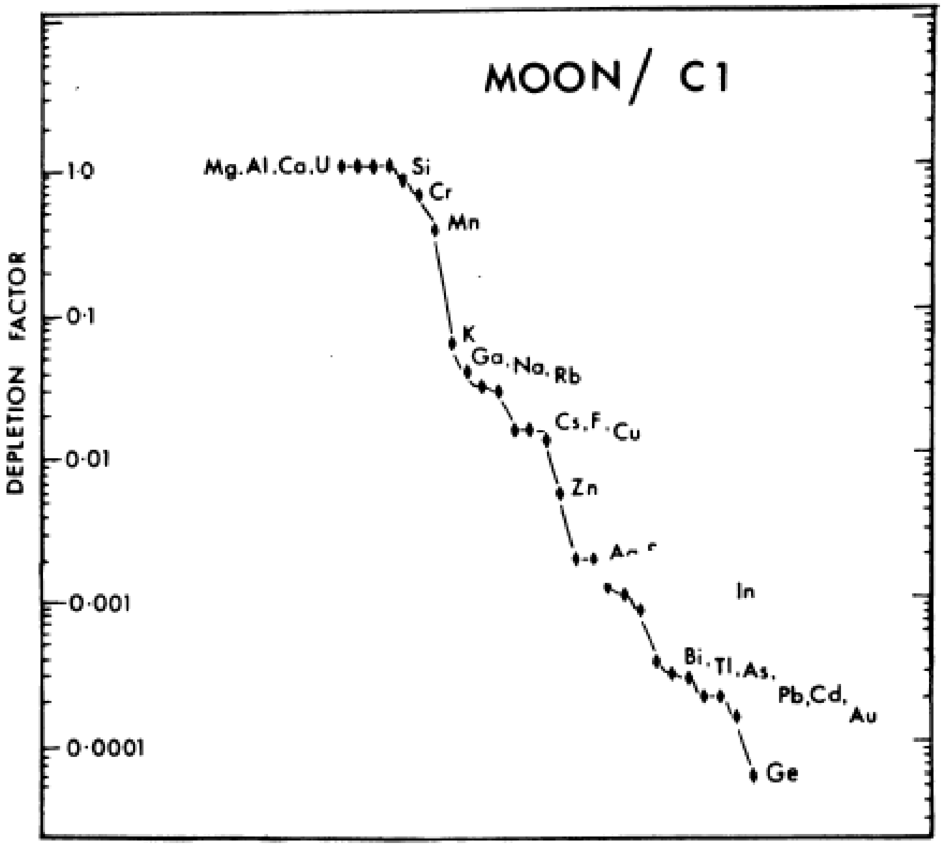
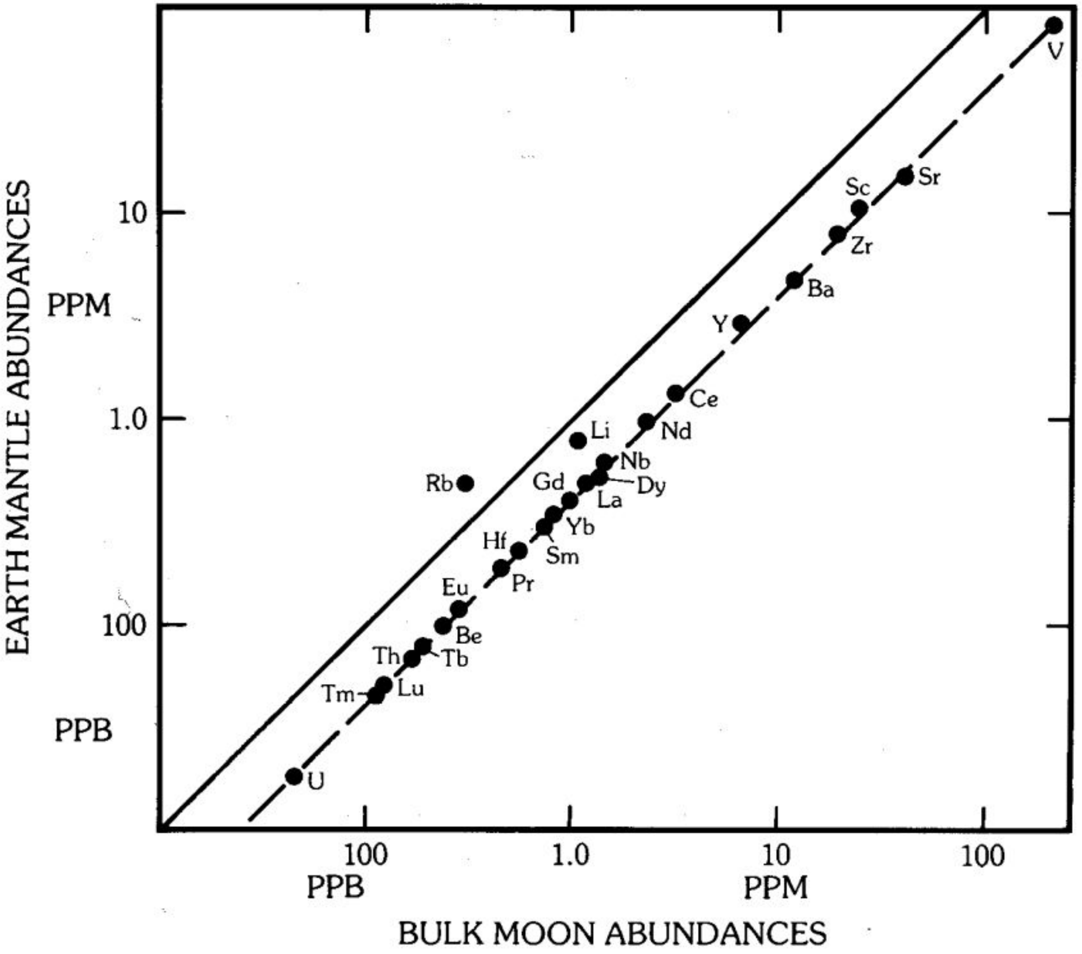


Fig. 2. Comparison of elemental abundances in the mantle source region of low-Ti mare basalts with abundances in C1 chondrites. Volatility of the elements tends to increase to the right. Figure from Ringwood and Kesson (1977).

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

Earth vs. Moon composition

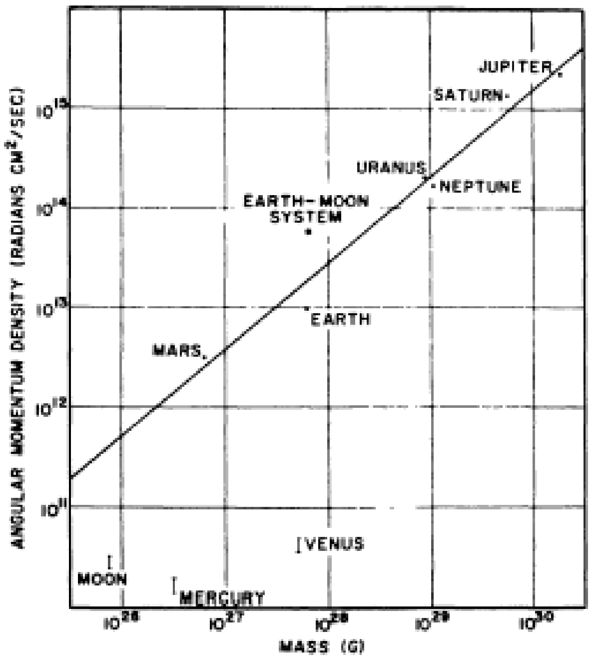
Trace element abundances



- Moon is depleted in volatile elements like Rb
- Moon is enhanced in volatile elements like U, Th, REE, Sr
- Once you limit discussion to just refractory elements, relative amounts in moon and earth are similar

Taylor 1982 Fig. 8.5b

Dynamical (i.e. orbital) Constraints

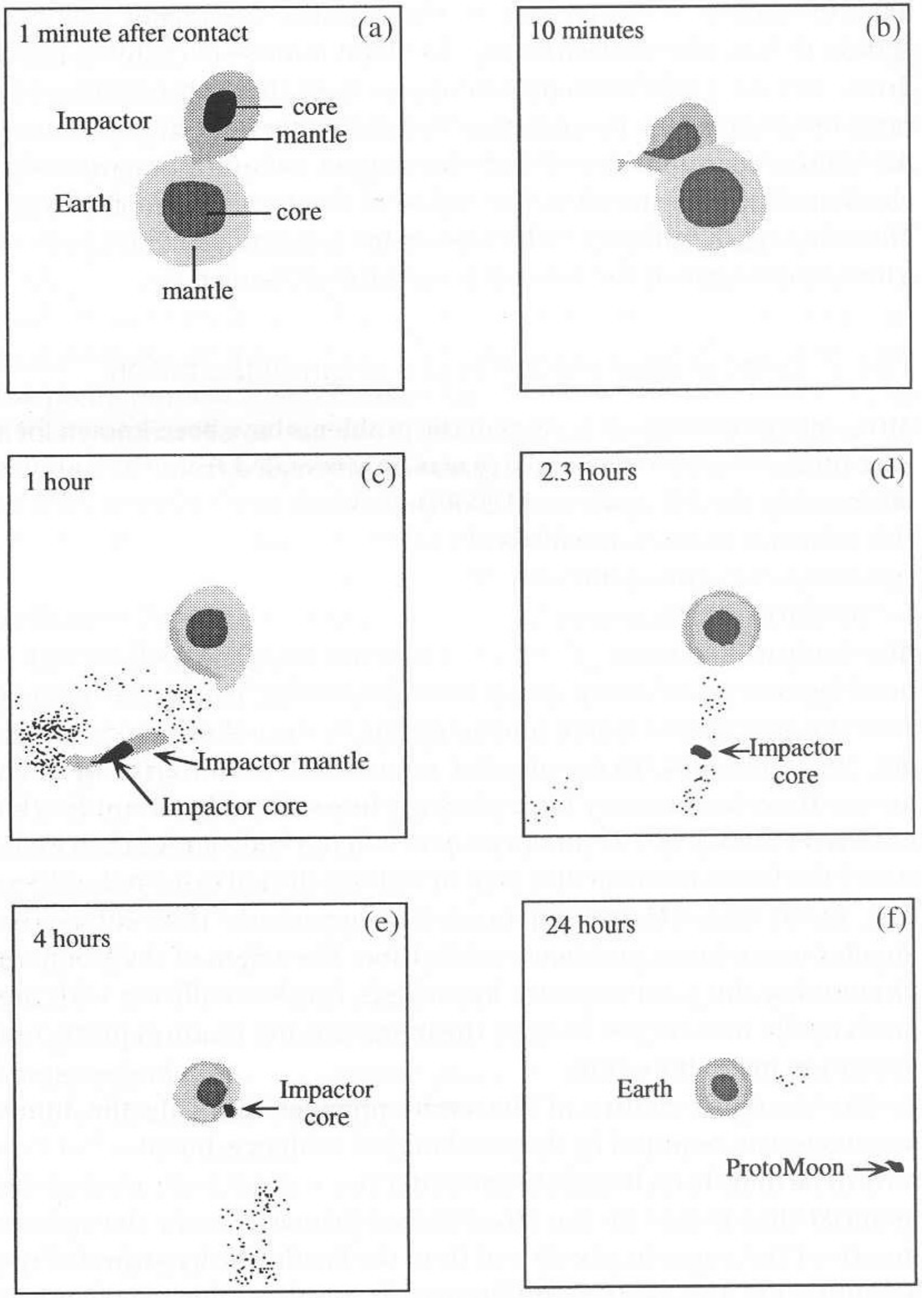


MacDonald 1966

- 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

Giant Impact mechanism



Taylor 2001 Fig. 13.10

- 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