

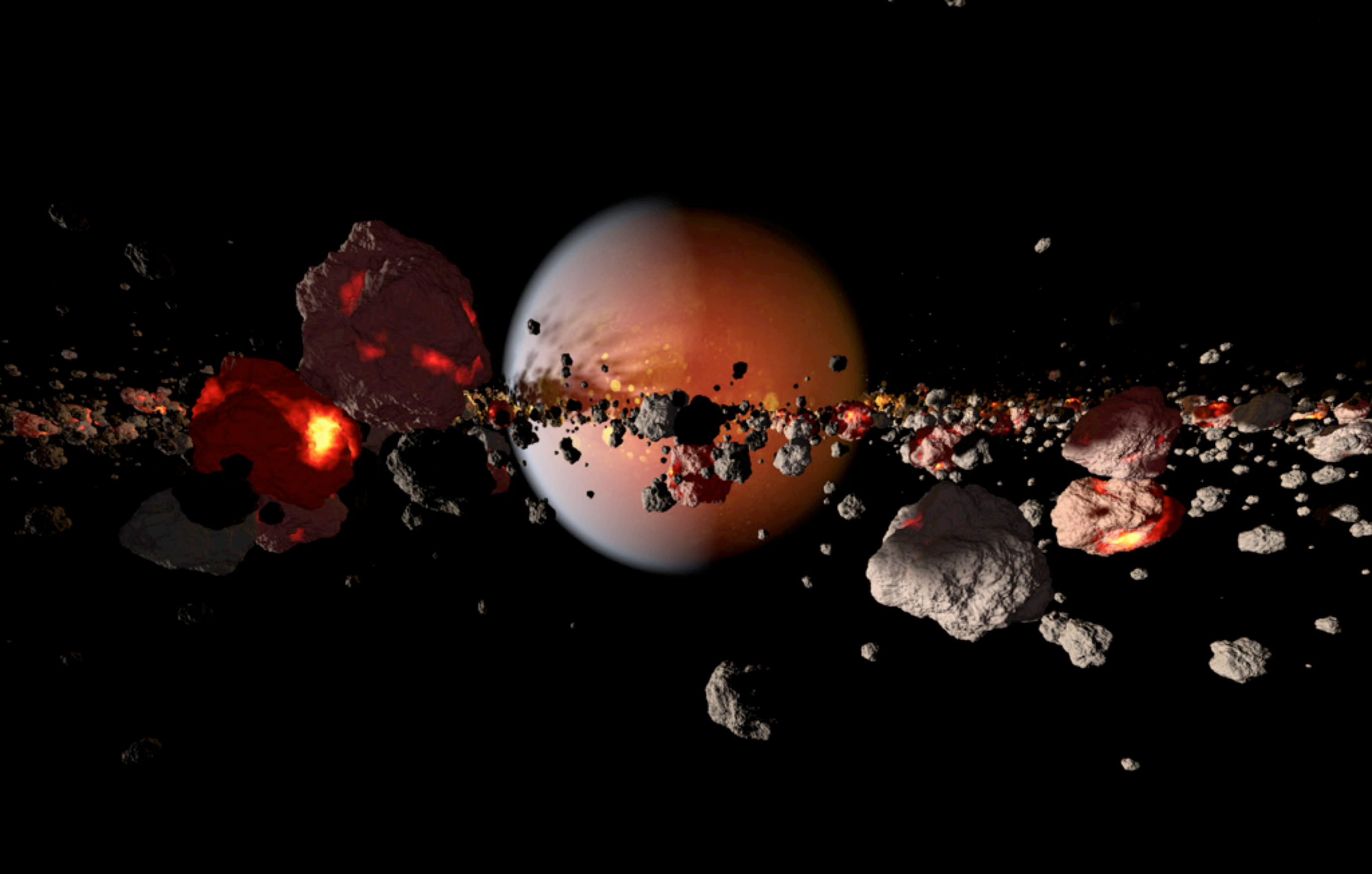
LUNAR MARE VOLCANISM

Evidence for a Magma Ocean



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Lunar Science Seminar
February 16, 2010





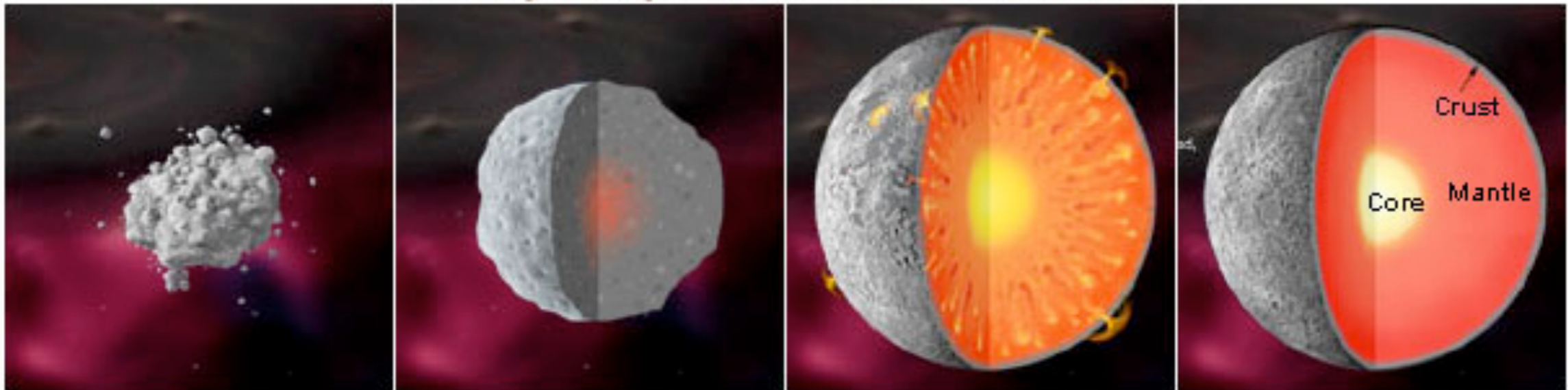
Moon Formation

Magma Ocean Hypothesis

- 4.52 Ga: Moon formation and magma ocean
 - 61 My later: Formation of most of anorthosite crust
 - 39 My later: End of crystallization
- ~4.4 Ga: Crust and mantle separation complete

Differentiation

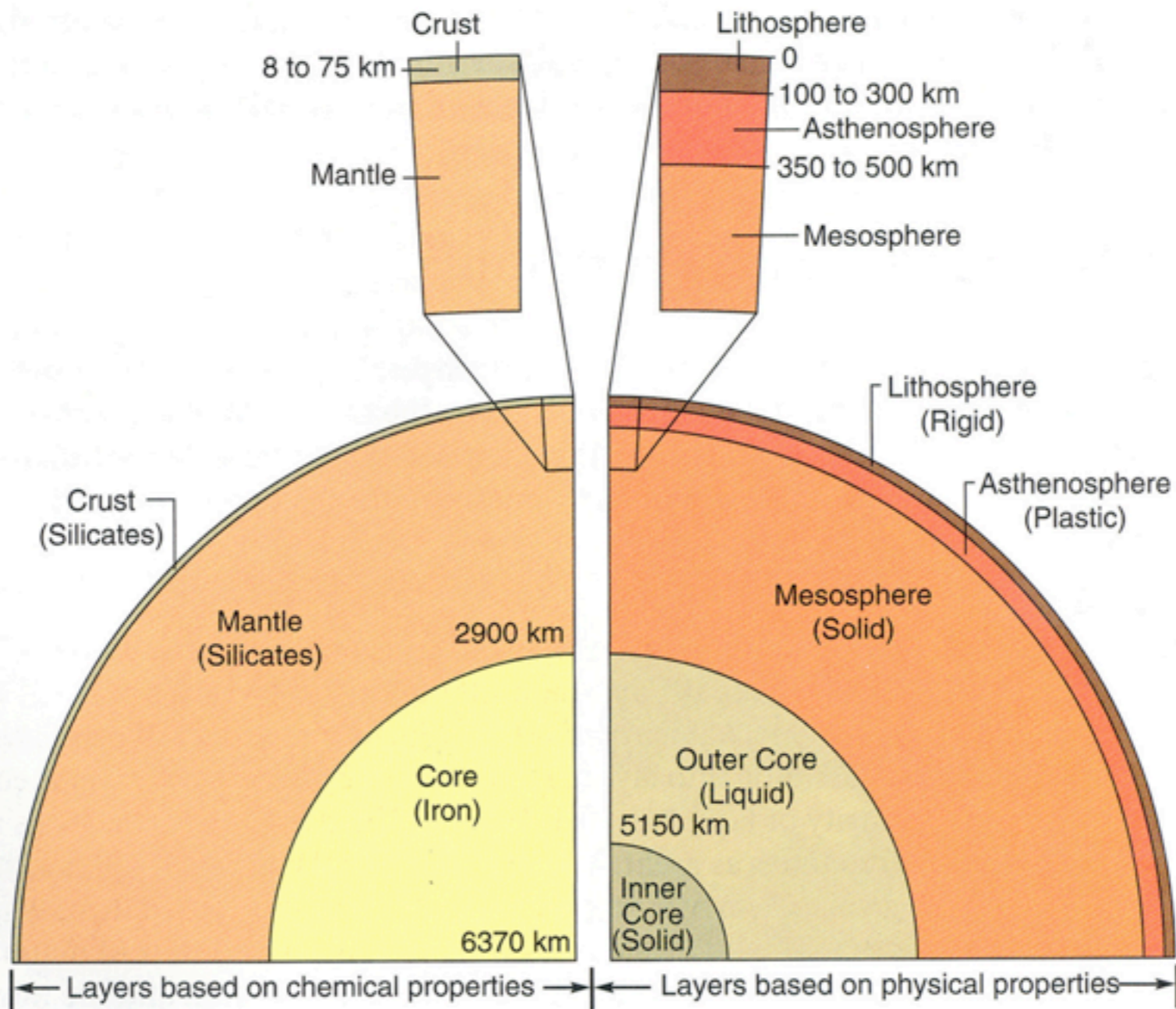
A Rocky Body Forms and Differentiates



(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

- Separation of constituents following accretion
- Based on density of materials
- Results in layers

Differentiation: Earth



Important Minerals



pyroxene



olivine

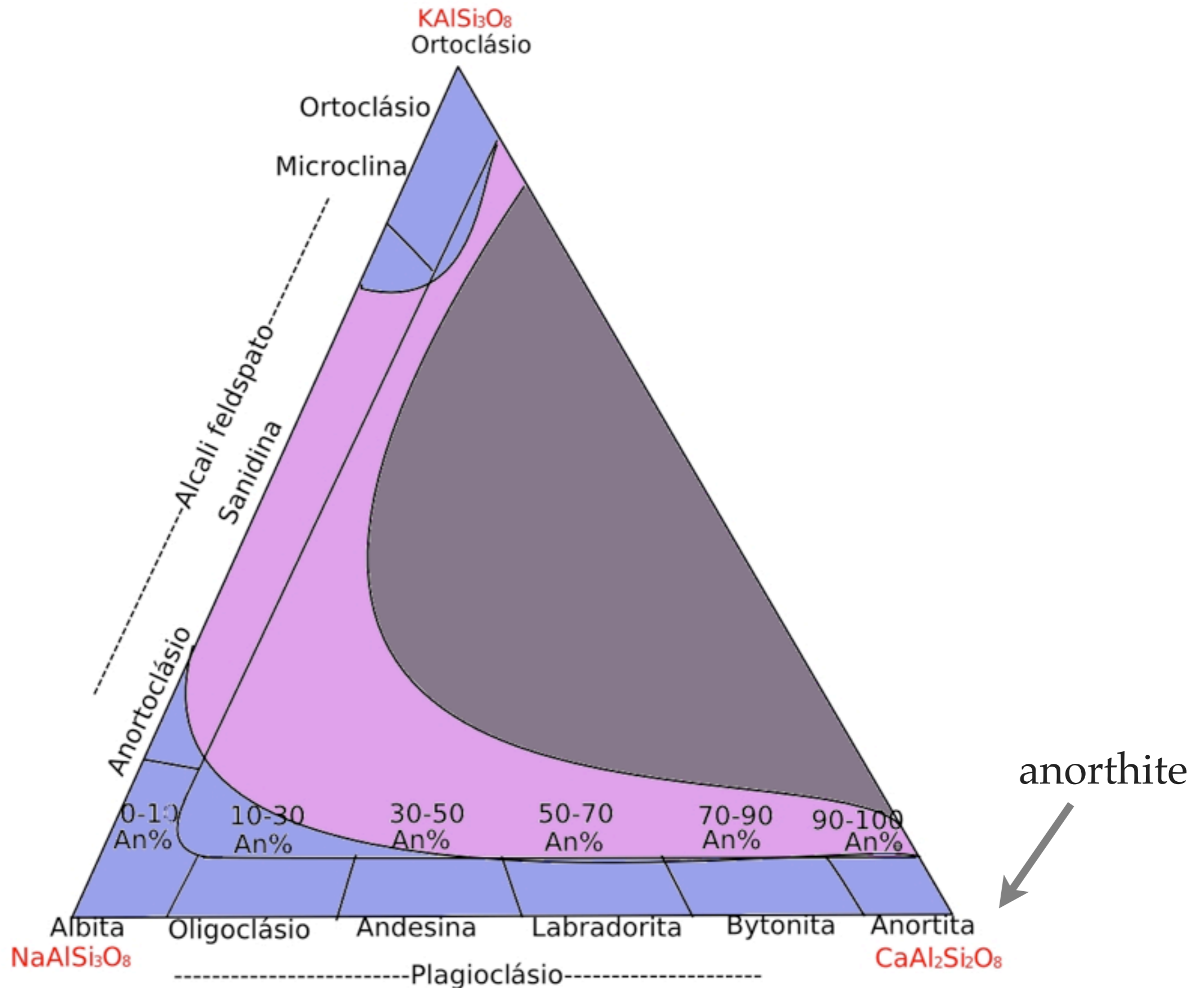


plagioclase
feldspar

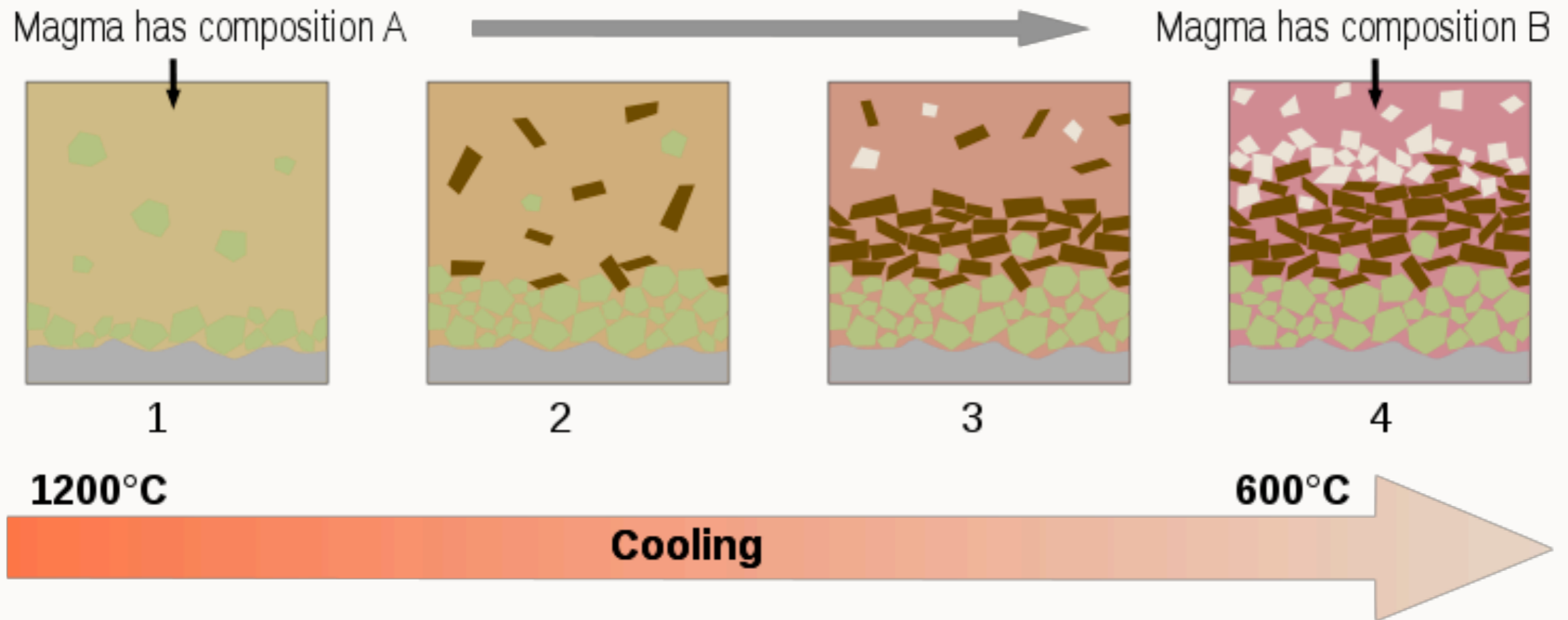
pyroxene and olivine: rich in Mg
and Fe

plagioclase feldspar: rich in Ca,
Na, and Al

Feldspar Phase Diagram



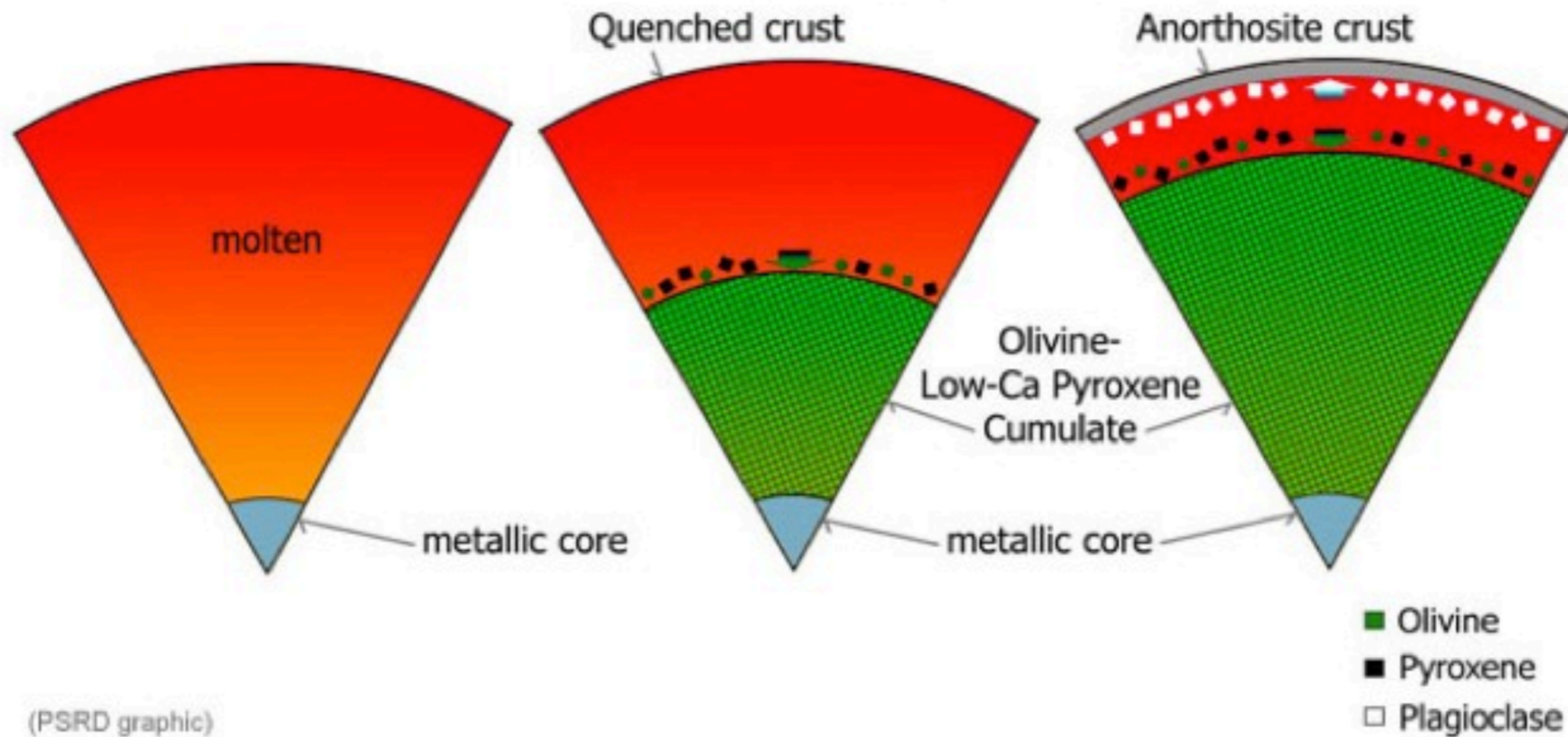
Fractional Crystallization



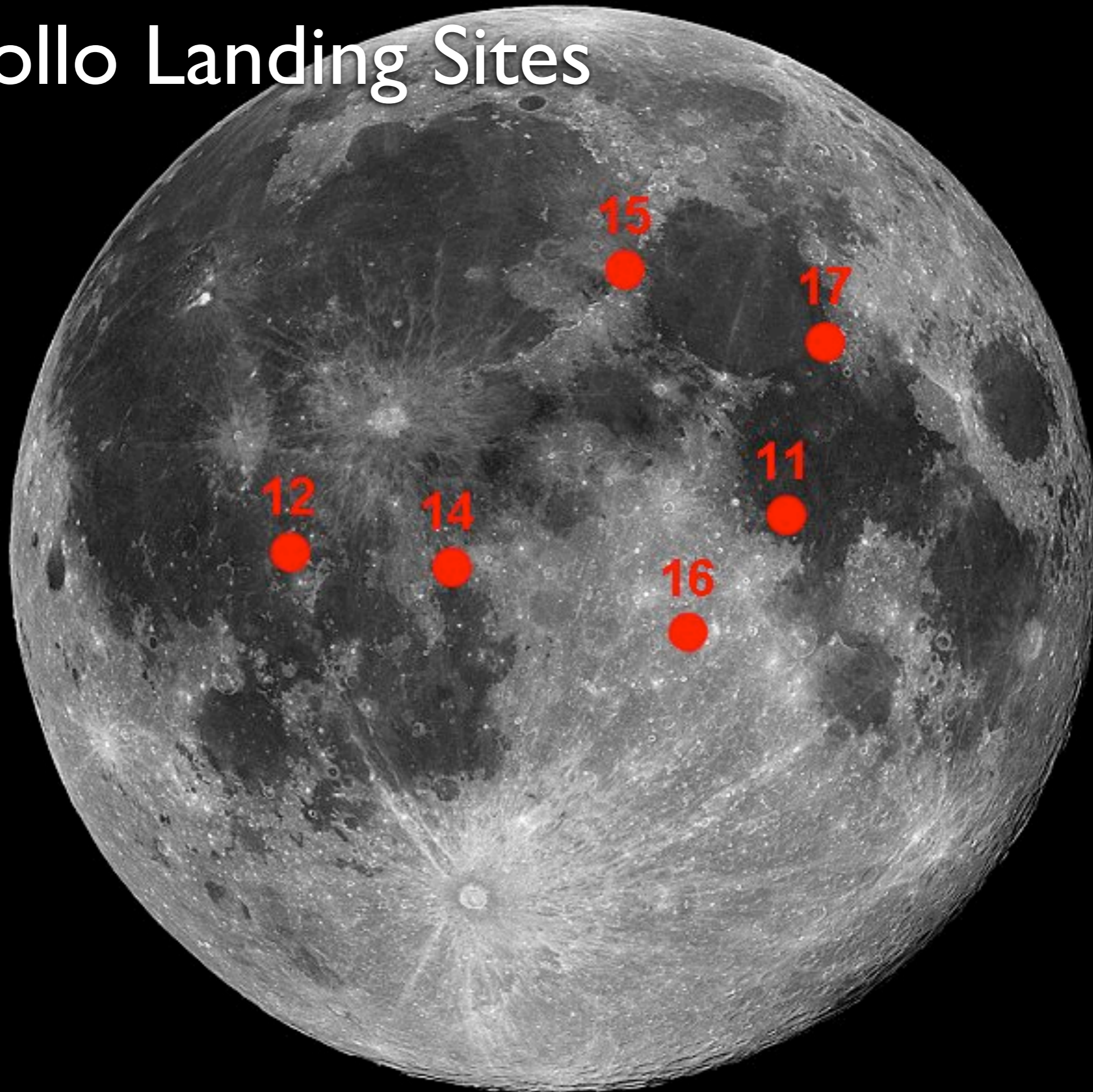
green = olivine | brown = pyroxene | white = plagioclase

Magma Ocean Concept

The Lunar Magma Ocean



Apollo Landing Sites

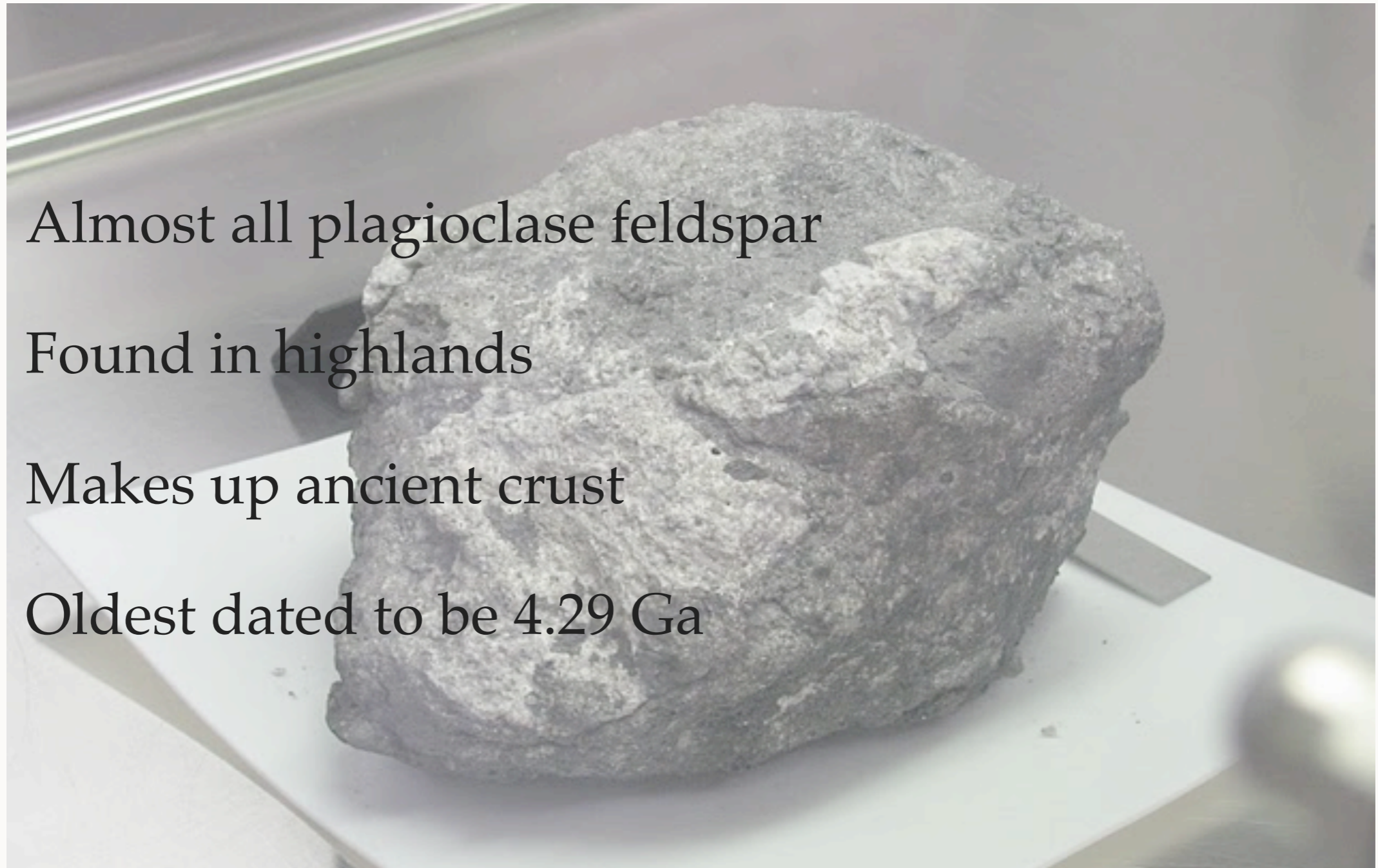


Anorthosite



Anorthosite

- Almost all plagioclase feldspar
- Found in highlands
- Makes up ancient crust
- Oldest dated to be 4.29 Ga

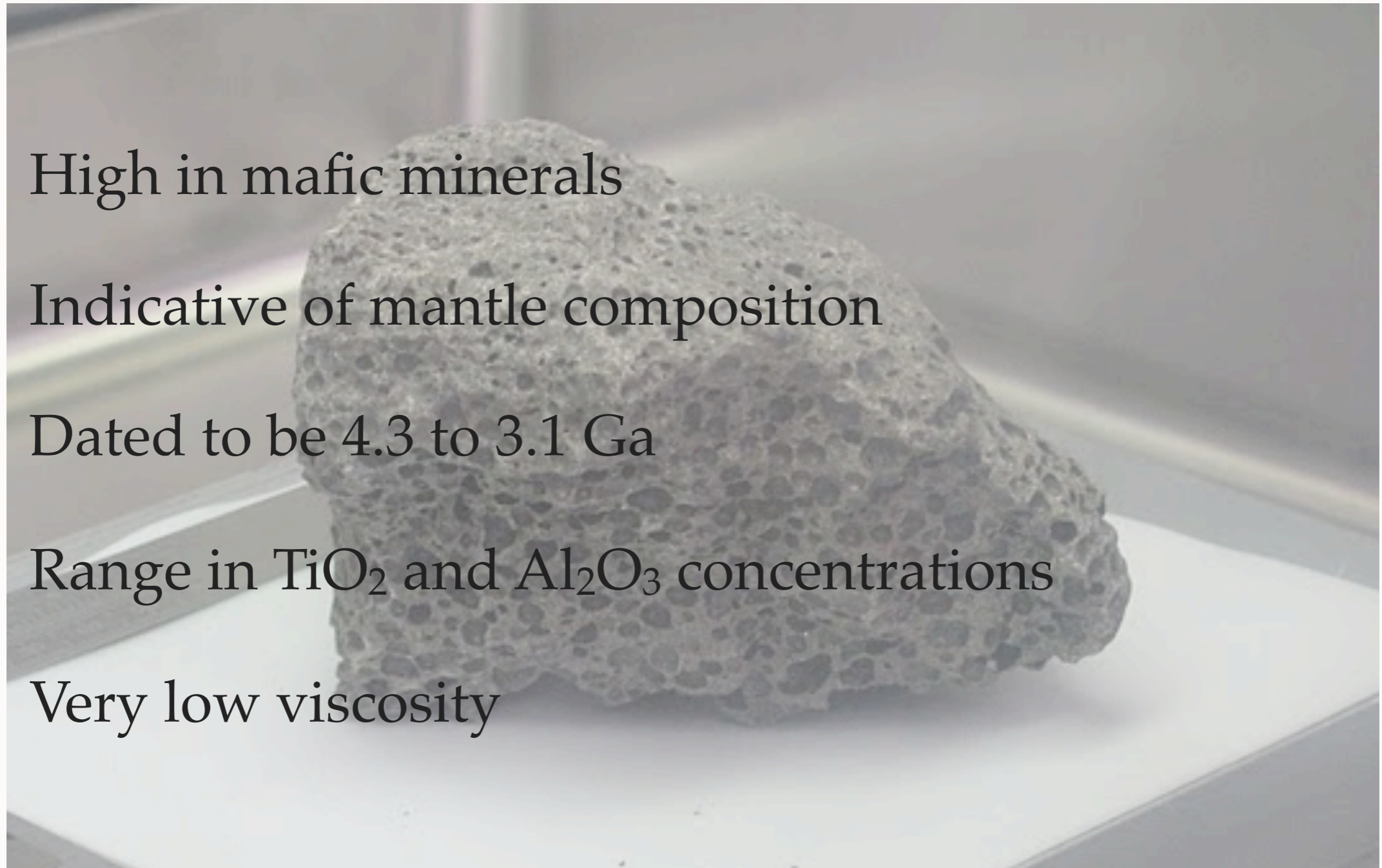


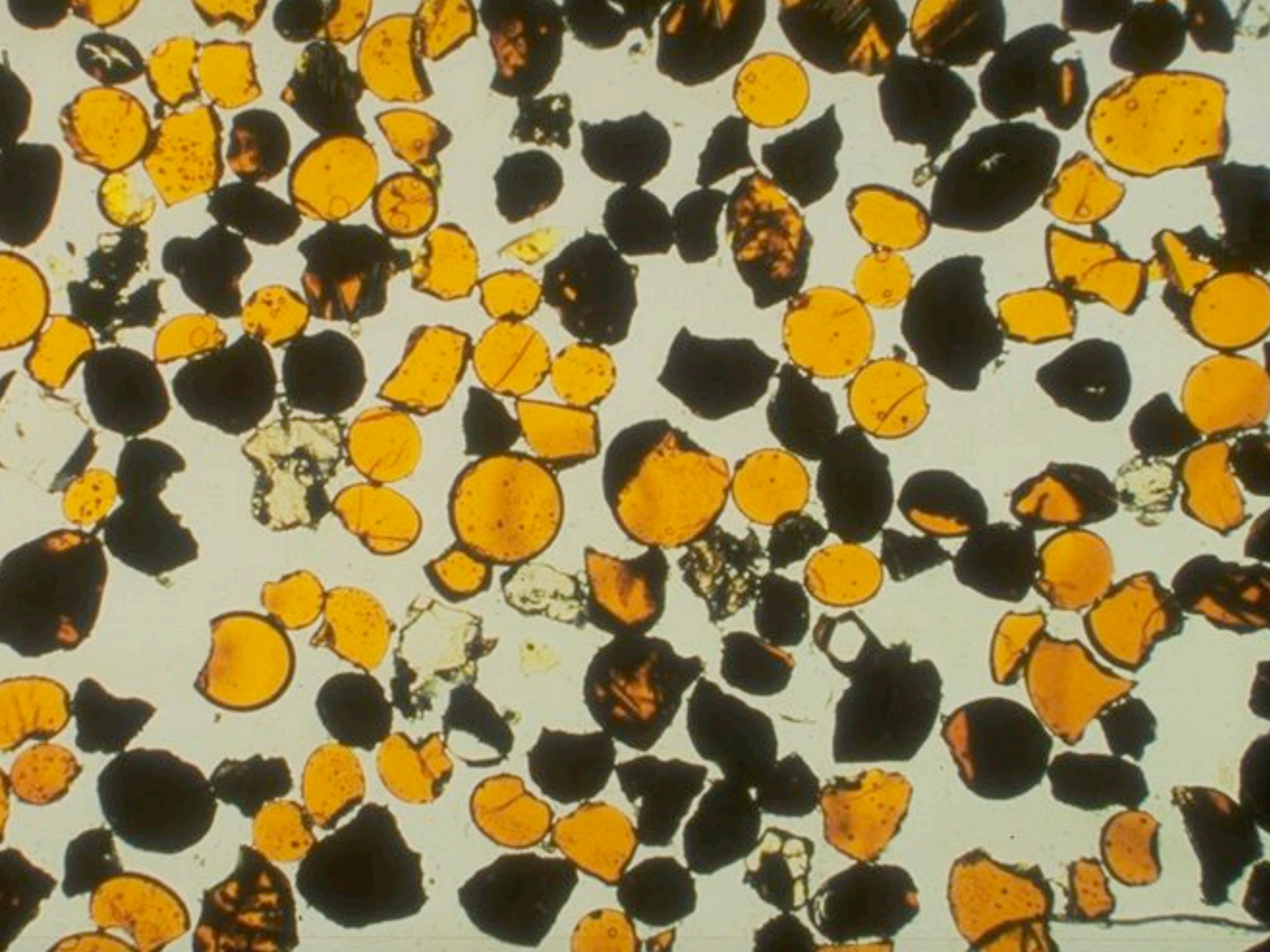
Mare Basalt



Mare Basalt

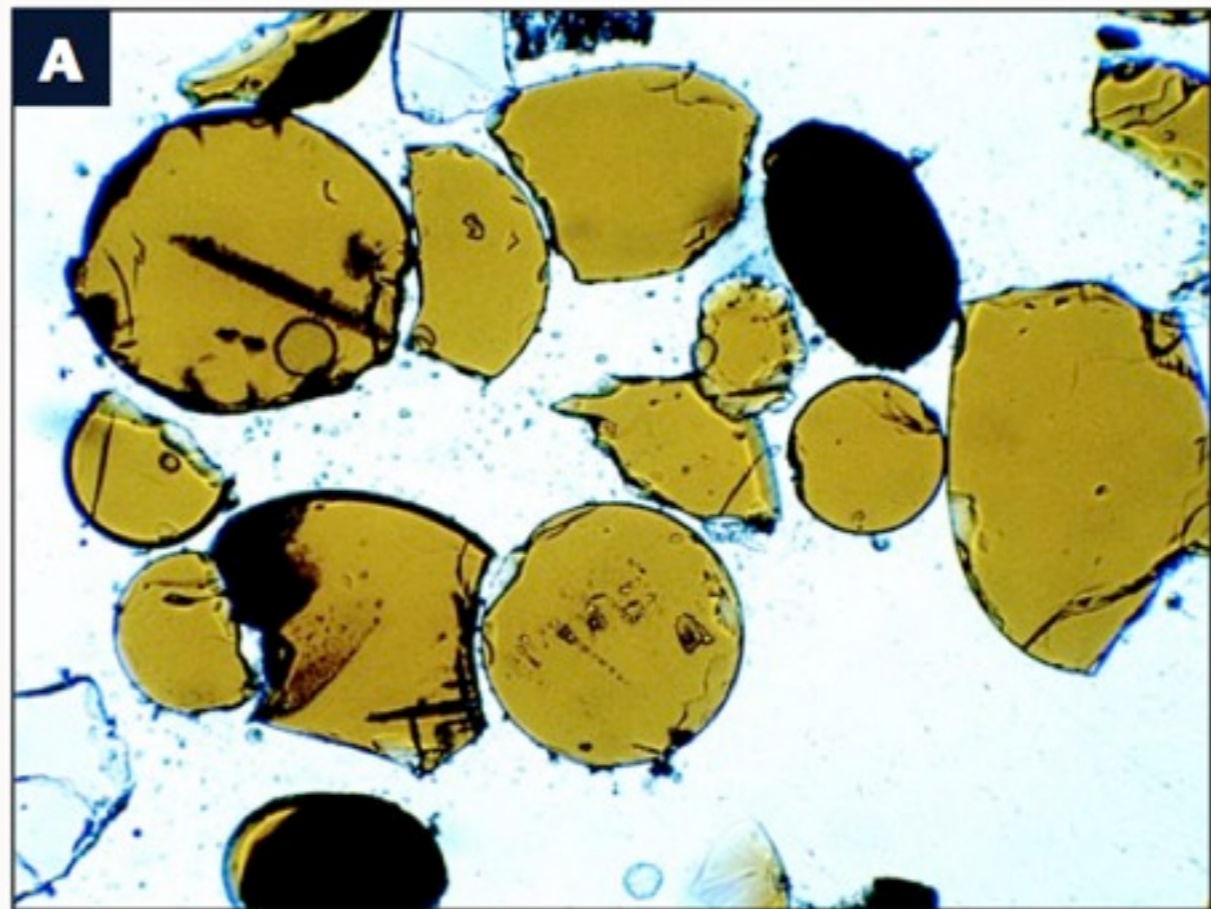
- High in mafic minerals
- Indicative of mantle composition
- Dated to be 4.3 to 3.1 Ga
- Range in TiO_2 and Al_2O_3 concentrations
- Very low viscosity





Volcanic Deposits

- Fire fountain source
- Ubiquitous
- Ultramafic
- Color based on TiO_2 content
- Evidence for varied mantle composition



Apollo 17 orange glass
Horizontal width is 0.5 mm

Rare Earth Elements (REE)

Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
LANTHANIDE SERIES		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
ACTINIDE SERIES		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

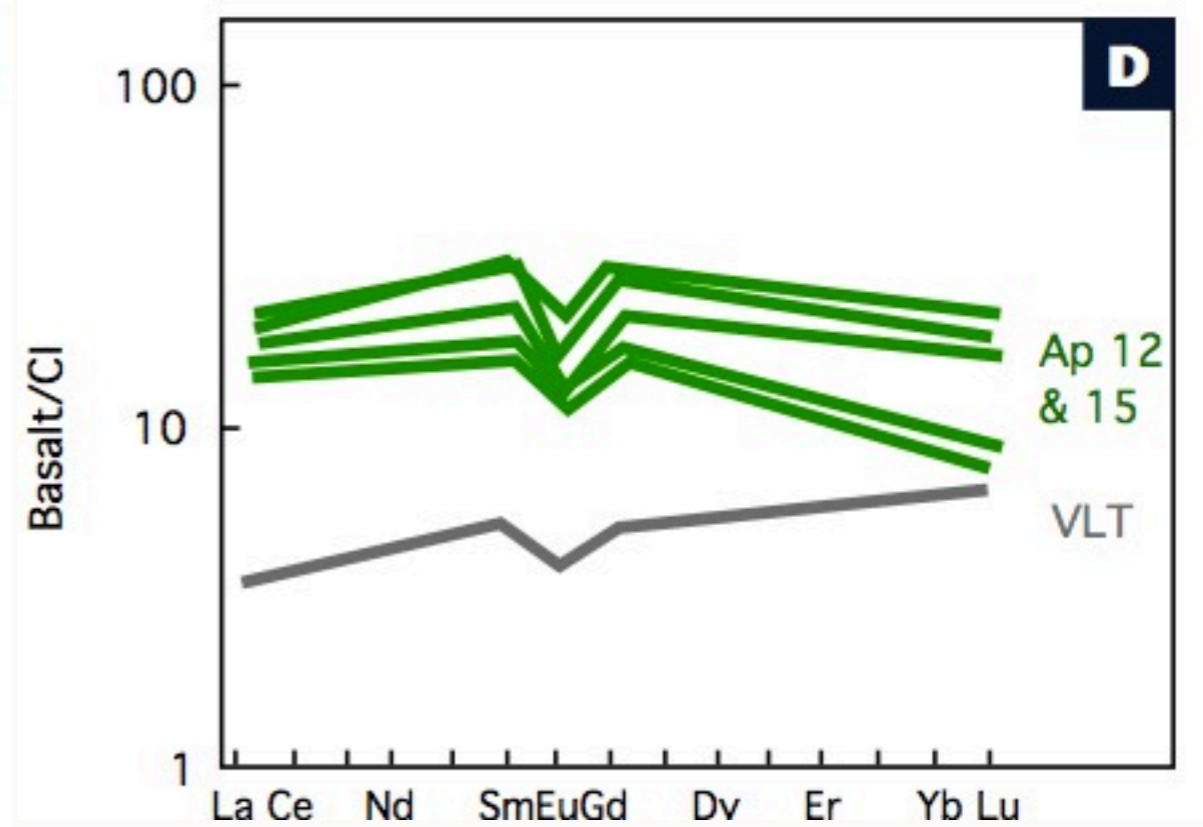
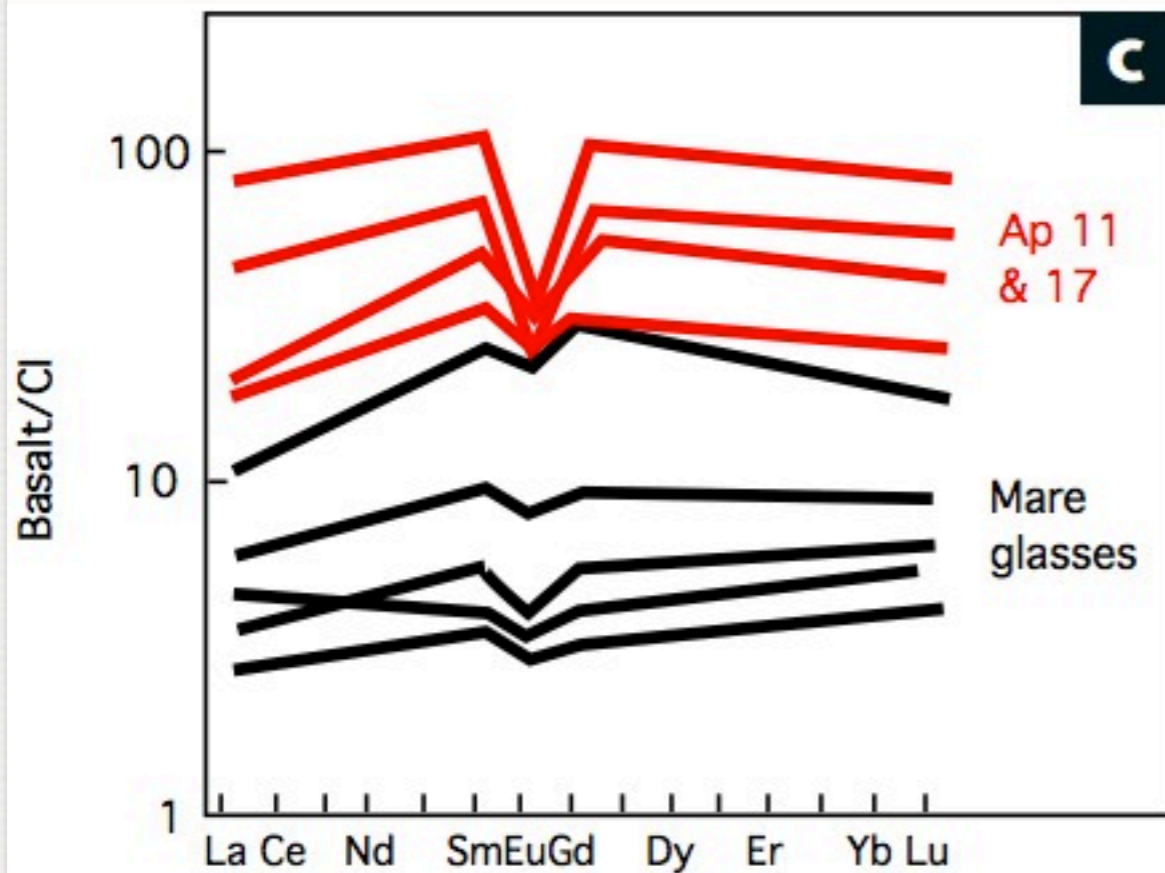
- Predictable behavior in terrestrial rocks
- Usually trivalent
- Mare basalts surprisingly enriched

Europium

- Depleted in mare lavas
- Divalent under reducing conditions
- Substitution for Ca in plagioclase

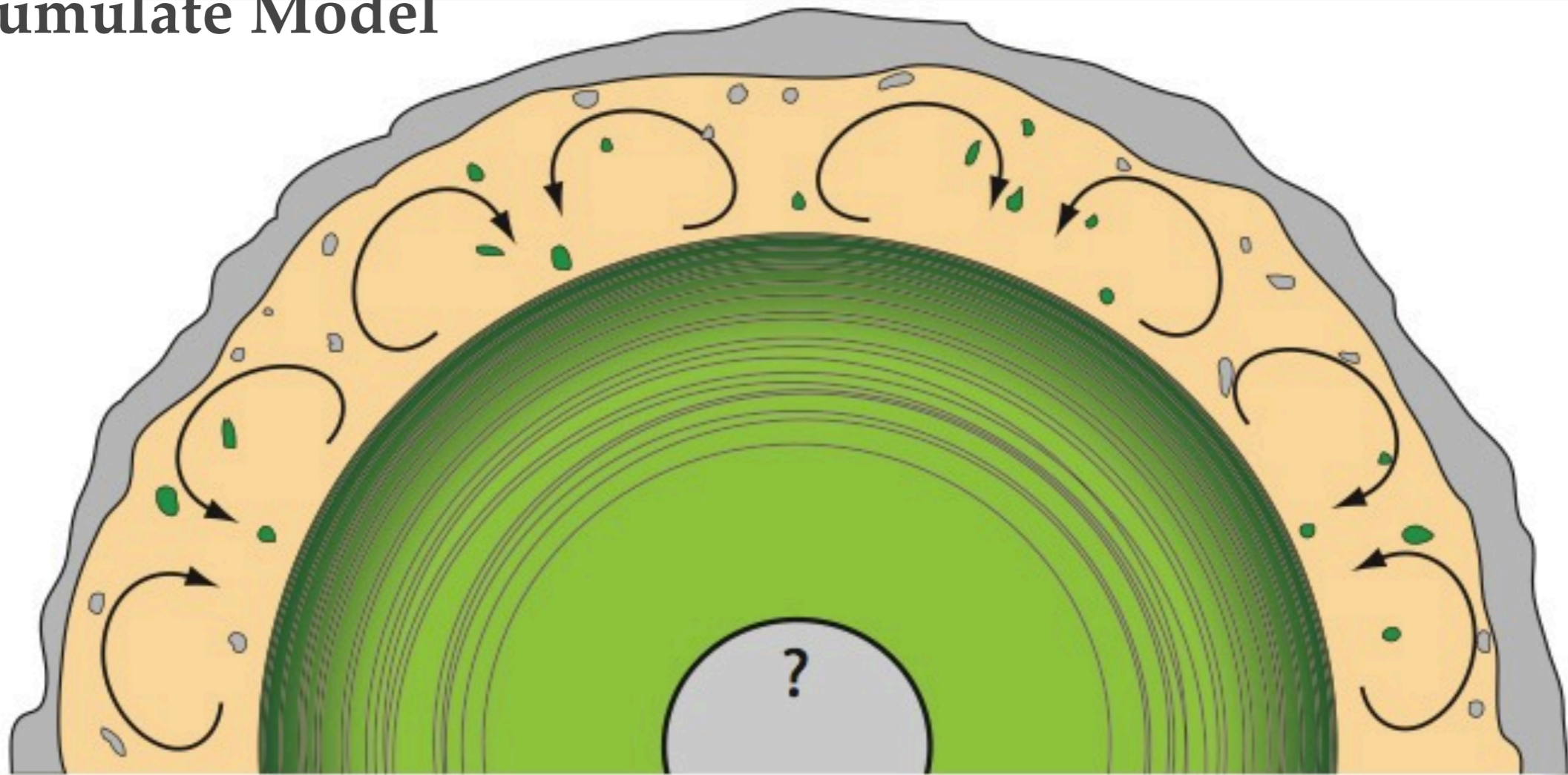


Europium Anomaly



Early Crystallization

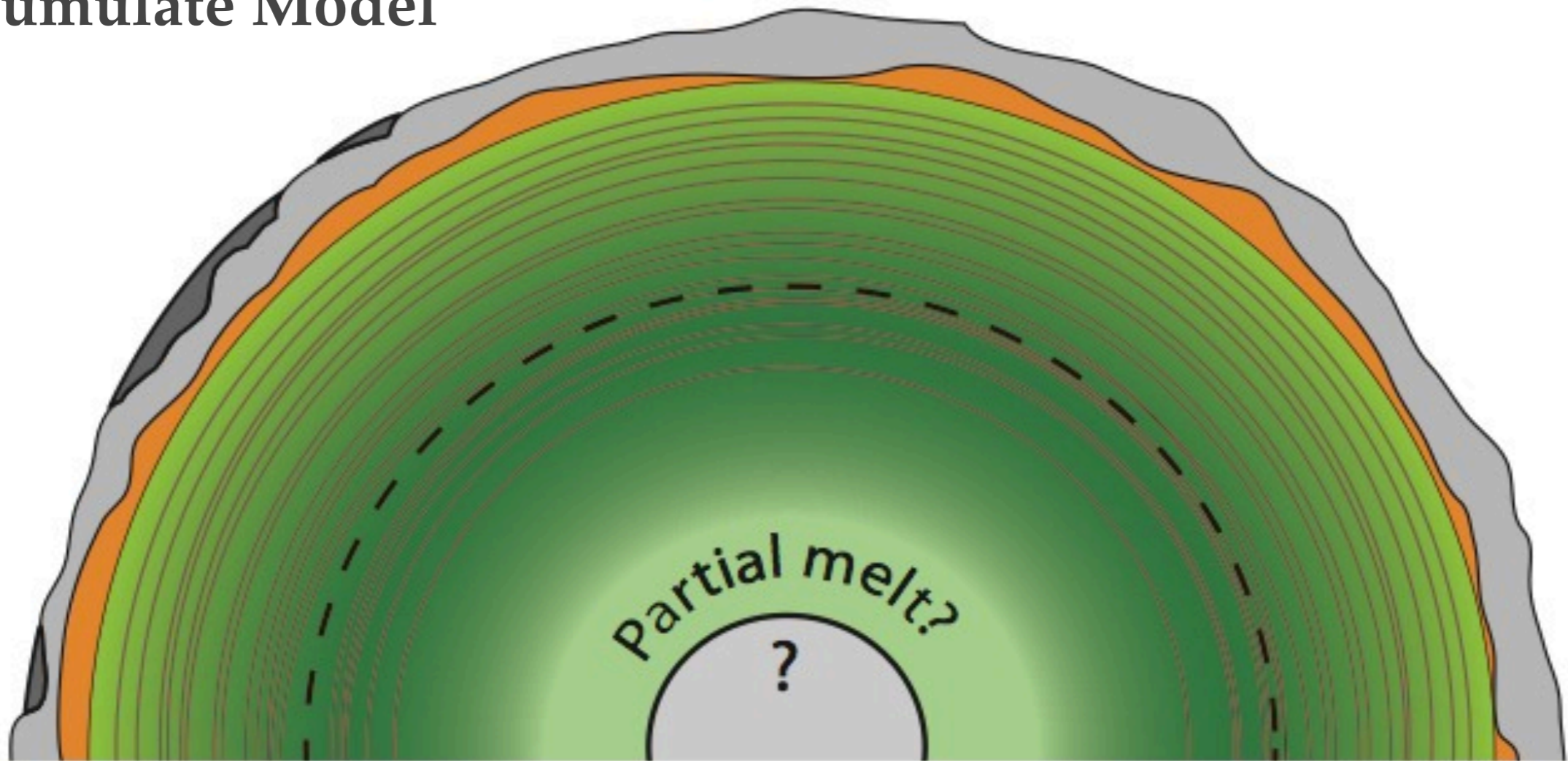
Cumulate Model



grey = plagioclase | tan = magma ocean
green = olivine and pyroxene

Late Crystallization

Cumulate Model



grey = plagioclase | orange = TiO₂-rich magma
green = olivine and pyroxene

Summary

- Post-accretion magma ocean
- Ancient anorthosite crust
- Evidence from basalts
 - Mineral distribution
 - TiO_2 and Al_2O_3 concentration range
 - Europium depletion
- Cumulate model

References

- Grove, T.L. and Krawczynski, M.J. (2009) Lunar Mare Volcanism: Where Did the Magmas Come From? *Elements* 5: 29-34.
- Norman, M. (2004) The Oldest Moon Rocks. PSRD Discoveries Research. Hawaii Institute of Geophysics and Planetology. Accessed 1 February 2010. <<http://www.psr.d.hawaii.edu/April04/lunarAnorthosites.html>>.
- Spudis, P. (1996) *The Once and Future Moon*. Washington: Smithsonian Institute Press. p. 131-156.
- Taylor, G.J. (2009) Time to Solidify an Ocean of Magma. PSRD Discoveries Research. Hawaii Institute of Geophysics and Planetology. Accessed 1 February 2010. <<http://www.psr.d.hawaii.edu/Mar09/magmaOceanSolidification.html>>.

Questions?



*Jack Schmitt, the only
geologist to walk on
the Moon*

