Mon. Oct. 23, 2017

- Reminder -- extra lecture next Friday (not this Friday) at noon
- Reading: Ch. 4 (Atmospheres) from Wood plus lunar papers for Friday

- Today:
  - Plans for midterm (preliminary discussion)
  - Topics for last 1/3 of semester (preliminary discussion)
  - Recent results for moon

- Wednesday:
  - Wed.: Magma oceans on other planets, and Atmospheres Pt. 1

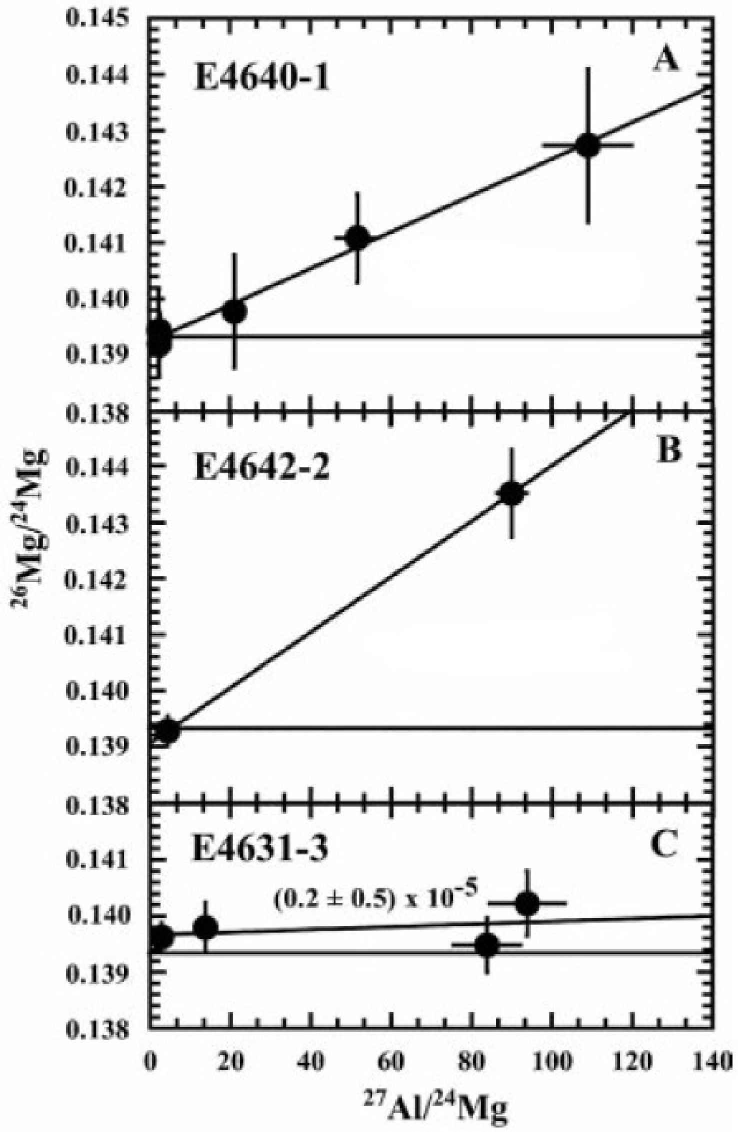


Fig. 2. Mg-Al isotopic systematics for three CAIs from E chondrites. (**A**) and (**B**) are hibonite-spinel inclusions. (**C**) is the hibonite-pyroxene microspherule that shows no resolvable $^{26}Mg^*$ excess. The $(^{26}Al/_{27}Al)_o$ ratios are listed on the plot for each inclusion.

HW 3 comments

- Determining slope -- widely spaced x
- Determining intercept -- read it directly, don't extrapolate if x=0 is on plot.
- Need for high accuracty in Y_0

- δ Notation -- both + and - numbers

Cratering Rates

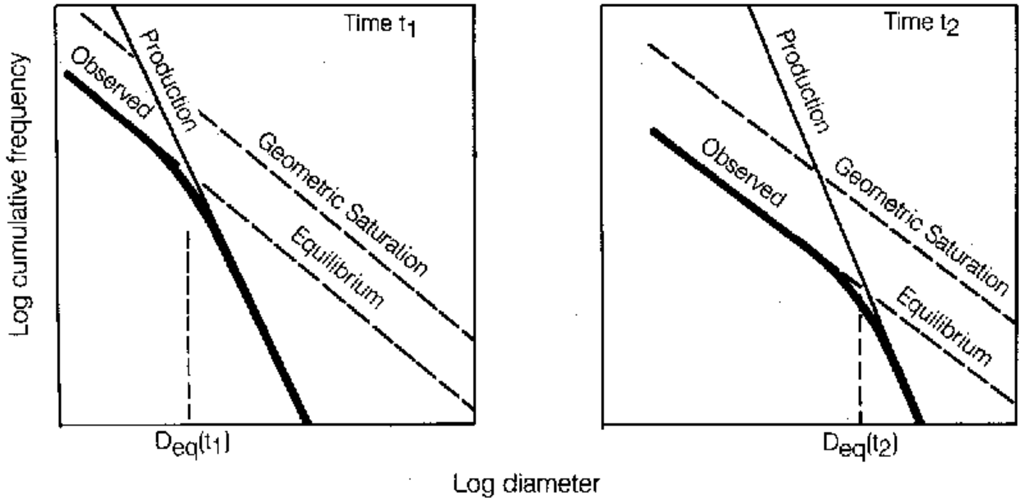


Fig. 10.5 Evolution of a crater population with slope $b > 2$. The production population exceeds the equilibrium line at small crater diameters. Small craters are thus in equilibrium up to some diameter D_{eq}, above which the observed population follows the production population. The left panel illustrates the population at a relatively early time t_1 and the right panel shows how the population has changed at a later time t_2. The equilibrium diameter D_{eq} clearly increases as a function of time, although this increase is generally not linear.

From Melosh1989: *Impact Cratering: A Geological Process*

- These plots assume a steep production power law $N \propto D^{-b}$ (i.e. relatively few large impactors compared to small ones)

- The saturation curve has the form $N \propto D^{-2}$ where the “2” comes from the fact that Area $\propto$ (Diameter)^2 so the number of craters you can fit in a given area must go down as D^{-2}.

Ages and Depths of resurfacing

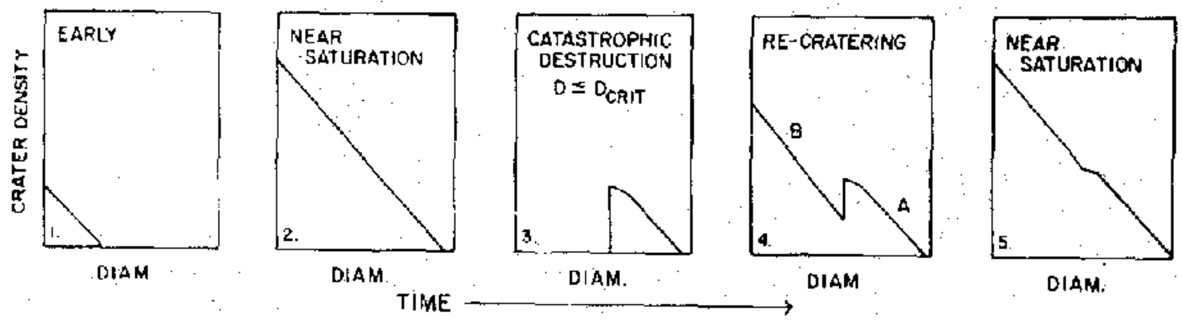
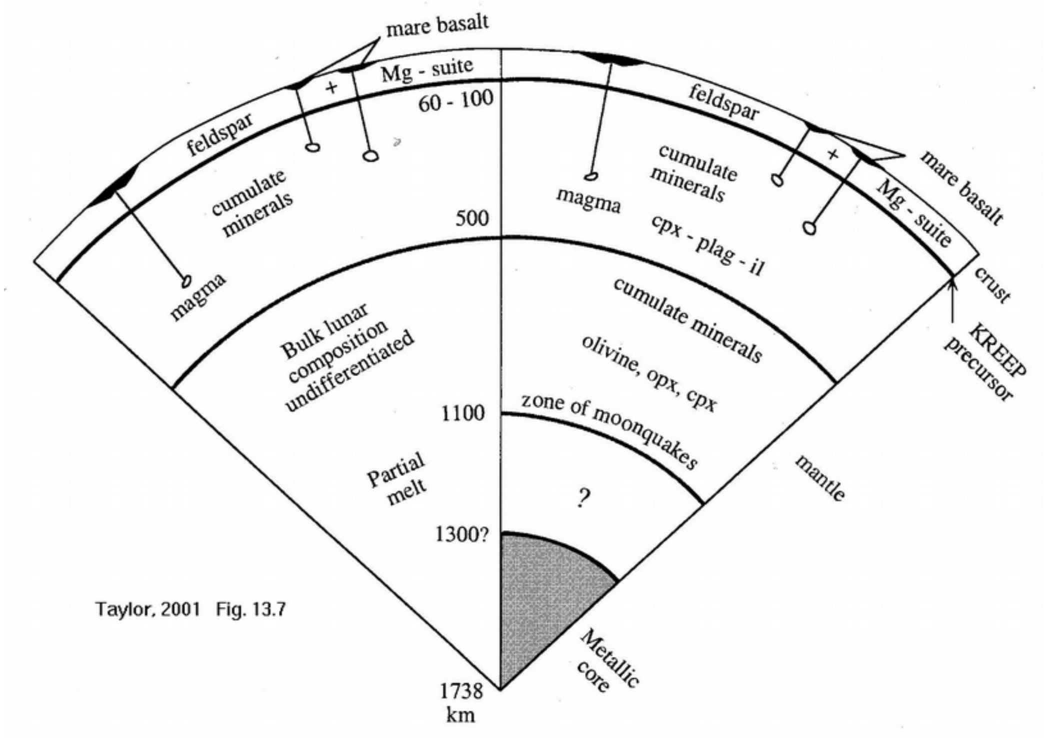


Fig. 1. Time sequence of crater diameter distributions, starting with a nearly-uncratered surface (1) which accumulates craters, undergoes an event which destroys small craters, and then is re-cratered.

From Hartmann and Wood 1971

- Crater counts for diameters below the break give the age of the resurfacing
- The diameter of the break (when multiplied by the depth-to-diameter ratio of the craters) gives the depth of resurfacing

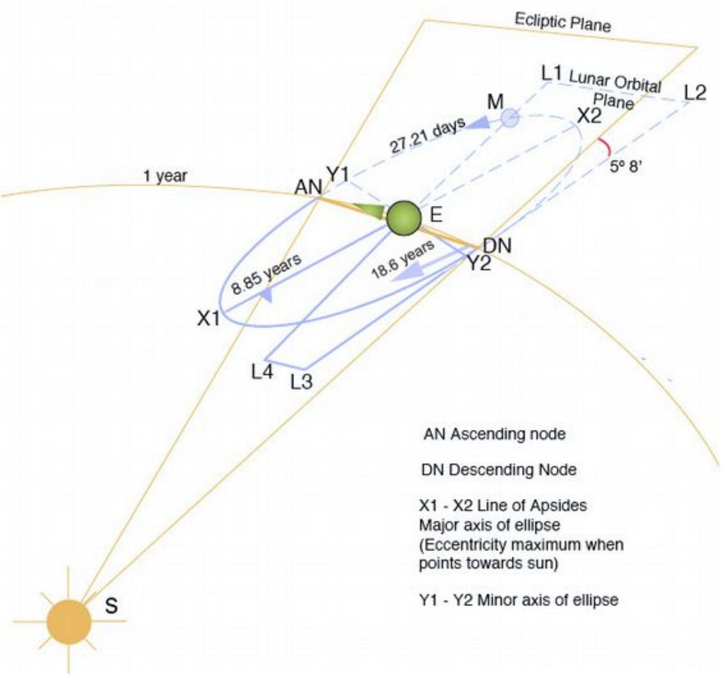
Deep structure not (originally) well constrained

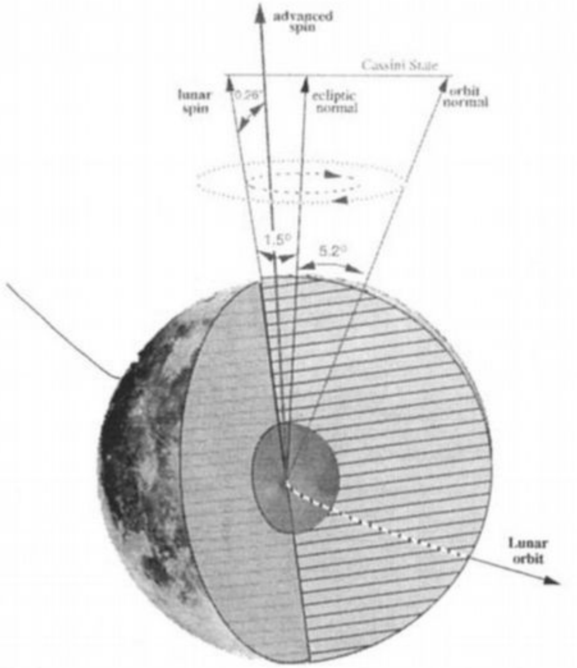


Taylor, 2001 Fig. 13.7

- Crust and upper mantle known from gravity and from sample mineralogy
- Structure uncertain below “olivine cumulus” zone
  - Apollo seismic observations limited
  - Lunar Prospector suggests core so may be fully differentiated
  - Lower gravity in first part of assembly could limit melting to later (outer) parts
- Important for thermal models (does inner part provide heat?)
- Important for secondary differentiation
  - olivine cumulus denser than underlying “primitive” region – could overturn
  - (Similarly, ilmenite layer will be denser than underlying olivine – could overturn)

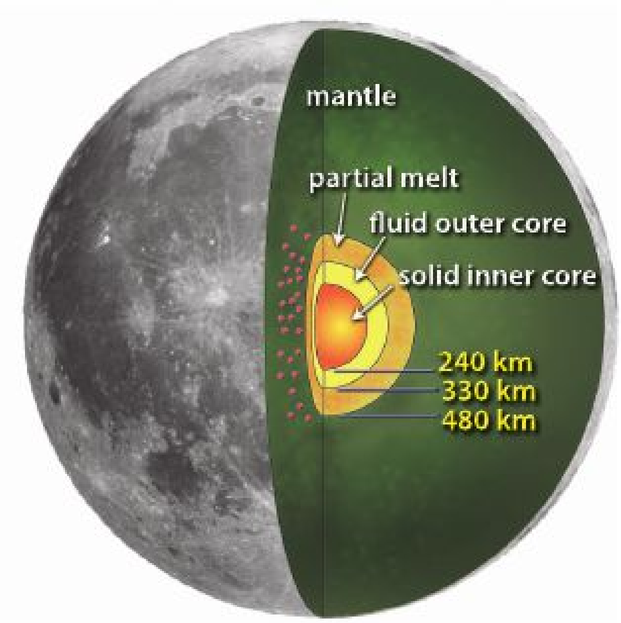
Recent work on deep structure (rotation)

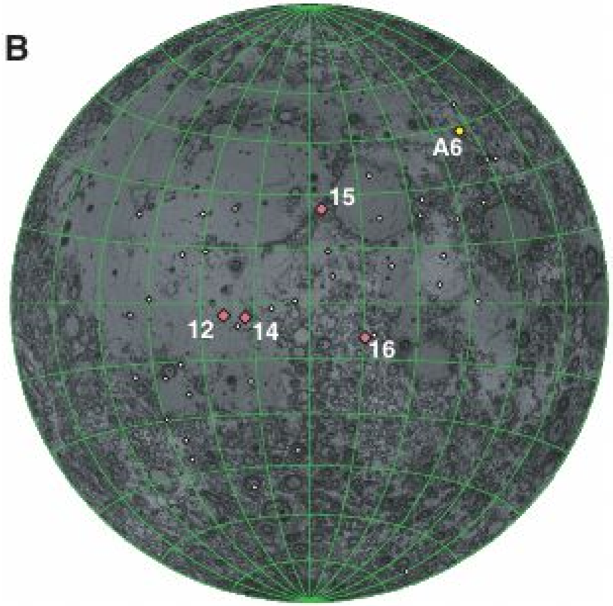




- The orbit of the moon is tilted 5.2° relative to the ecliptic plane (i.e. the earth's orbital plane)
- Because of solar and lunar tides that lunar orbital plane precesses once every 18.6 years
- Because of the continually changing orbital plane, the rotation axis of the moon cannot remain perpendicular to that orbital plane
  - With extremely large dissipation (internal friction) tides would quickly adjust the rotational axis to be perpendicular to the orbit plane
  - With extremely small dissipation it would relax to an "average" (so called Cassini) state where the rotational pole would lie in the same plane as the normal to the ecliptic and the normal to the orbit
  - The actual rotational pole is 0.26° out of the plane containing the ecliptic and orbit normals, and as detailed in Williams et al. (2001) this indicates a moderate amount of dissipation -- suggesting a small liquid lunar core with radius roughly 370 km.

Recent work on deep structure (seismic)





Weber et al. 2011

- Initial analysis of data from Apollo seismometers was inconclusive regarding central structure:
  - Scattering of seismic waves from regolith confuses interpretation
  - Small number of quakes, and even smaller number which would have had wave paths through inner 500 km.
  - Indicated attentuation within deep interior, but without firm evidence of a core.
- Recent reanalysis of old Apollo data (especially that by Weber et al. 2011) suggests:
  - Presence of fluid outer core with radius 330 km
  - Possible inner solid core with radius 240 km
  - Possible partial melt layer outside fluid core, with radius 480 km
- Regardless of details, lunar core (as a percent of volume) is much smaller than the terrestrial Fe core

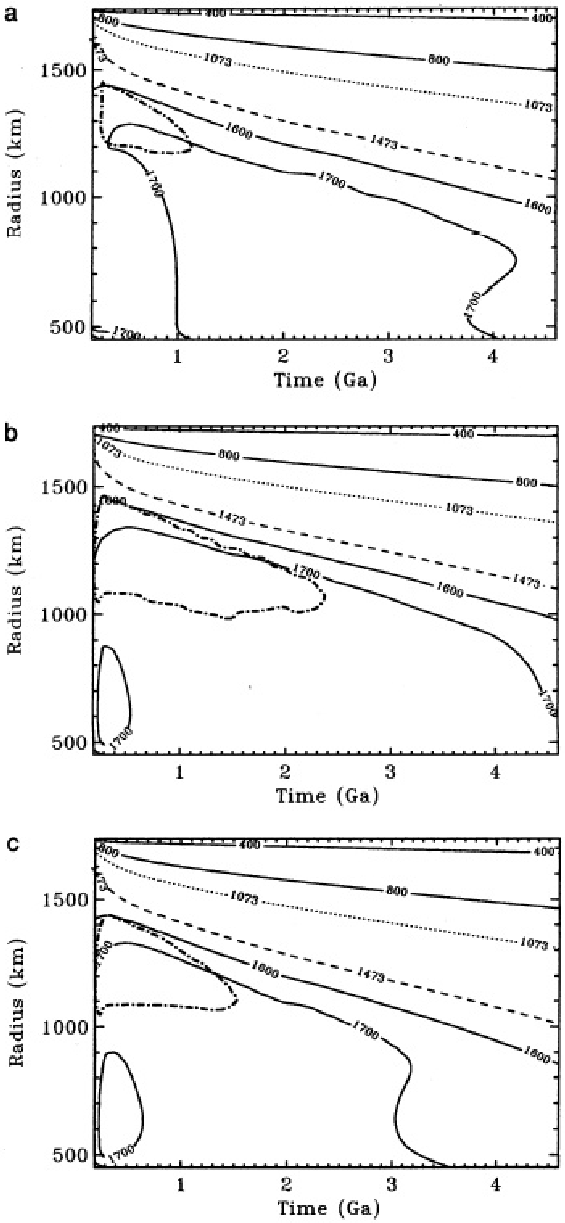


FIG. 2. Evolution of the mean radial temperature profile for models 1 (a), 2 (b), and 3 (c). The isotherms are in K. The dash-dotted contour lines encircle the areas where the mean radial temperature profile exceeds the solidus and partial melting occurs.

Thermal models from Spohn et al.

- Dash-Dot Contour is melt region
- Dotted line = 1073 K (base of elastic lithosphere)
- Dashed line = 1473 K (base of thermal lithosphere)

- 3 Models with different assumptions
  - Model 1: 350 km deep initial magma ocean
  - Model 2&3: 700 km deep initial magma ocean
  - Models 2 & 3 differ on treatment of core boundary
  - All assume a hot interior

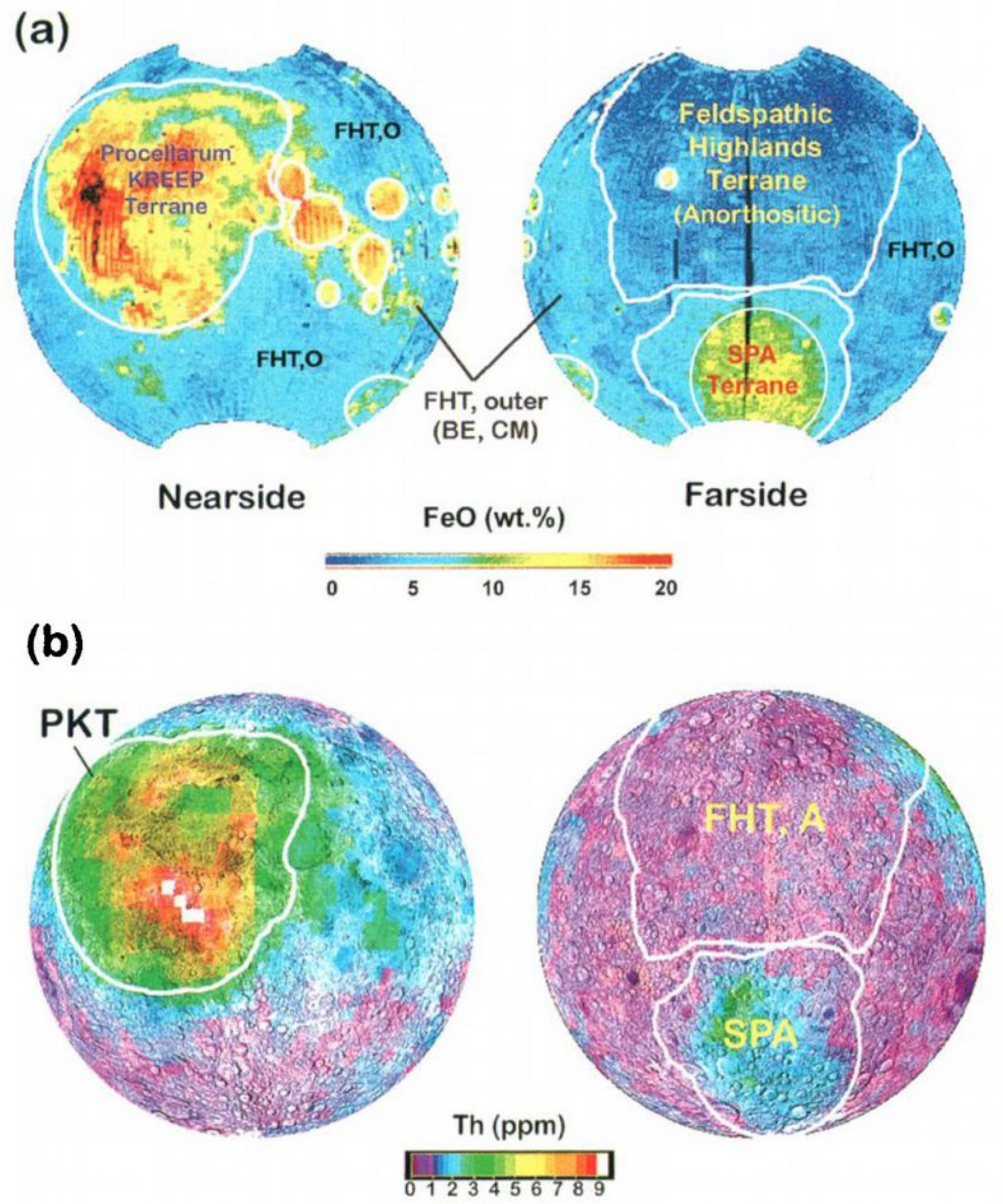
- Partial melt zone persists 1-2 AE
  - It solidifies from the top
  - The lower boundary is approximately constant

- Not well explained: ~100 My “delay” between basin formation and onset of mare volcanism

- Not considered: Concentration of heat generating K, Ur, Th in the residual “KREEP” layer

Spohn et al 2001

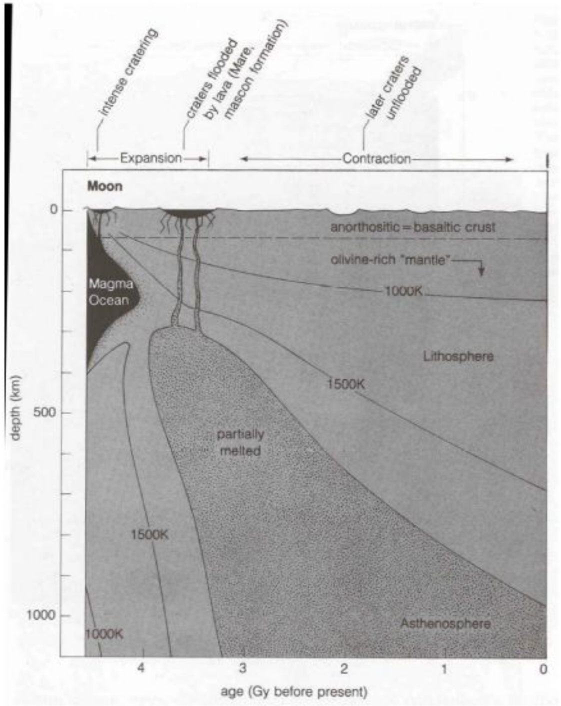
Global Terranes now typically defined



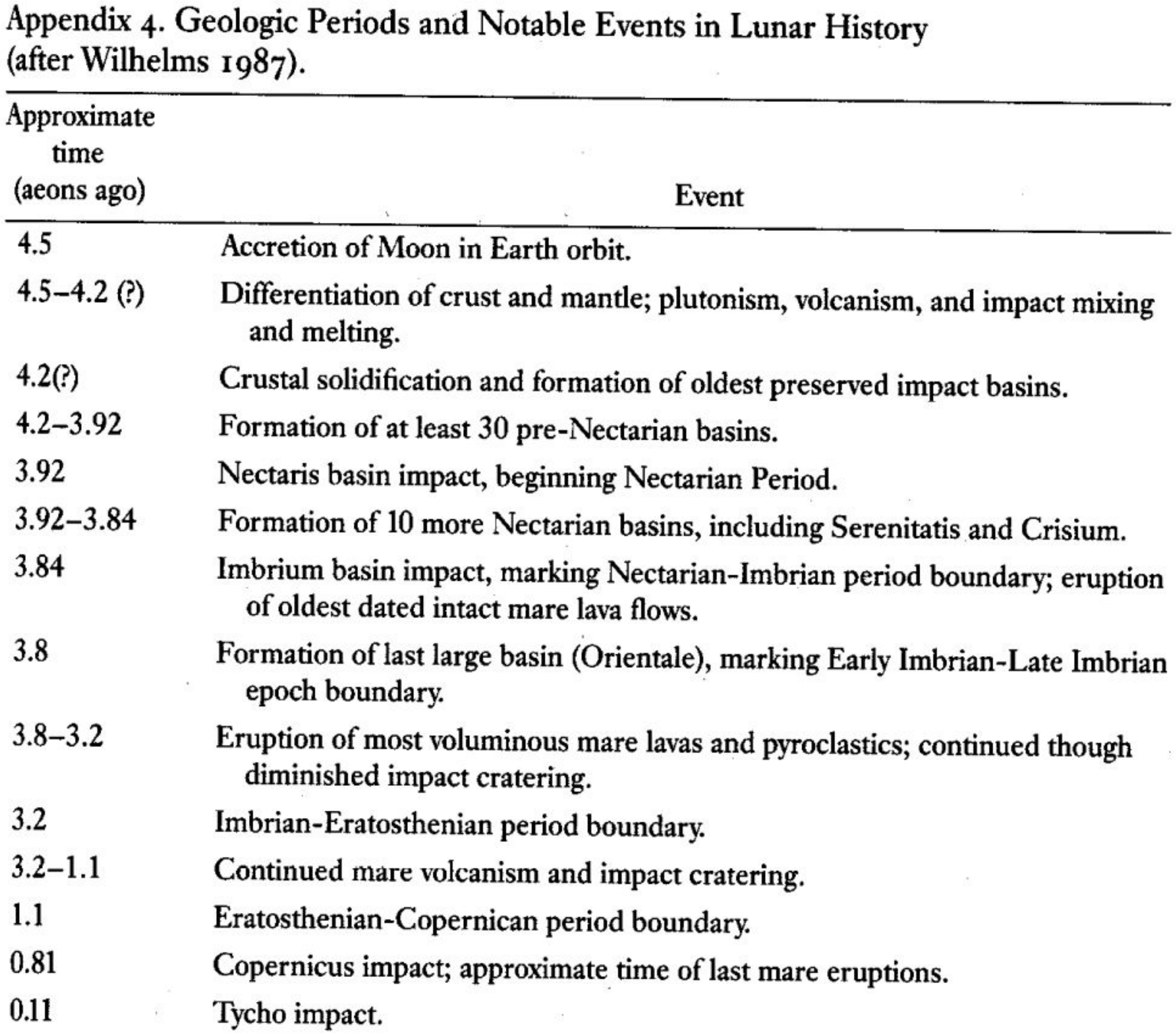
- FHT: Feldspathic Highlands Terrane
  - A: Anorthositic
  - O: Outer (contaminated with mare material, etc.)
- PKT: Procellarum KREEP Terrain
- SPA: South Pole – Aitken basin

Jolliff et al. 2000

Timing of Activity on the Moon



From "Moons and Planets" by Hartmann



Appendix 4. Geologic Periods and Notable Events in Lunar History (after Wilhelms 1987).

Approximate time (aeons ago)	Event
4.5	Accretion of Moon in Earth orbit.
4.5–4.2 (?)	Differentiation of crust and mantle; plutonism, volcanism, and impact mixing and melting.
4.2(?)	Crustal solidification and formation of oldest preserved impact basins.
4.2–3.92	Formation of at least 30 pre-Nectarian basins.
3.92	Nectaris basin impact, beginning Nectarian Period.
3.92–3.84	Formation of 10 more Nectarian basins, including Serenitatis and Crisium.
3.84	Imbrium basin impact, marking Nectarian-Imbrian period boundary; eruption of oldest dated intact mare lava flows.
3.8	Formation of last large basin (Orientale), marking Early Imbrian-Late Imbrian epoch boundary.
3.8–3.2	Eruption of most voluminous mare lavas and pyroclastics; continued though diminished impact cratering.
3.2	Imbrian-Eratosthenian period boundary.
3.2–1.1	Continued mare volcanism and impact cratering.
1.1	Eratosthenian-Copernican period boundary.
0.81	Copernicus impact; approximate time of last mare eruptions.
0.11	Tycho impact.

From "To A Rocky Moon" by Wilhems

Key "Current" Questions in Lunar Science
(Jolliff 2006: New Views of the Moon, Preface)

1. What is the vertical and lateral structure of the lunar crust and how did that crust evolve?
   (general structure now measured by GRAIL)

2. What is the composition and structure of the lunar mantle?

3. What was the extent of a lunar magma ocean?

4. How is the surface expression of lunar materials related to the Moon's internal structure and evolution (or Where exactly do the different rock types come from?)
   (partly answered by GRAIL related models)

5. What is the nature of the Moon's asymmetry, what caused it, and what are the implications for the Moon's internal evolution and present-day distribution of materials?

6. What is the origin, evolution, and distribution of mare volcanism?

7. What were the timing and effects of the major basin-forming impacts on lunar-crustal stratigraphy? What is the nature of the South Pole-Aitken Basin and how did it affect early lunar crustal evolution?
   (LRO and other missions now provide better crater counts, but absolute ages still uncertain)

8. What are the origins of lunar paleomagnetism?

9. What are the Moon's important resources, where are they concentrated, and how can they be accessed?
   (presence of polar volatiles better understood as a result of LCROSS)