Understanding the Geochemical Evolution of an Asymmetric Moon

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Lunar Asymmetries & Consequences

- Crustal Terranes: PKT, FHT(A), FHT(O), SPA (Jolliff et al., 2000)
- Several maria are in or adjacent to the PKT
  - Surface FeO concentrations >~15%, Th >~3 ppm
  - Sampling sites for most returned mare basalts
- A few maria (e.g., Mare Crisium) and cryptomaria have lower Th <~3 ppm, but are poorly sampled
  - Lower Th in the basalts; Th in the mantle much lower still
  - Low heat production in parts of the mantle with low Th
- FHT(A) is unsampled except by lunar meteorites
  - Evidence for an expanded suite of crustal rocks in the meteorites
- Samples of FHT(O) (Apollo 16) complicated by basin impact effects
- Sample-based ideas of lunar differentiation and crust formation are based on observations for sites that are atypical of the lunar crust.
- Ideas of lunar thermal evolution and basaltic volcanism are based on observations for maria in atypical regions of the moon.
- Needed: A record of lunar evolution that applies to the entire moon.
  - Radiogenic isotopes take us “one step” back in time.
  - We need igneous rocks returned to our isotope labs.

Observations Mainly from Radiogenic Isotopes

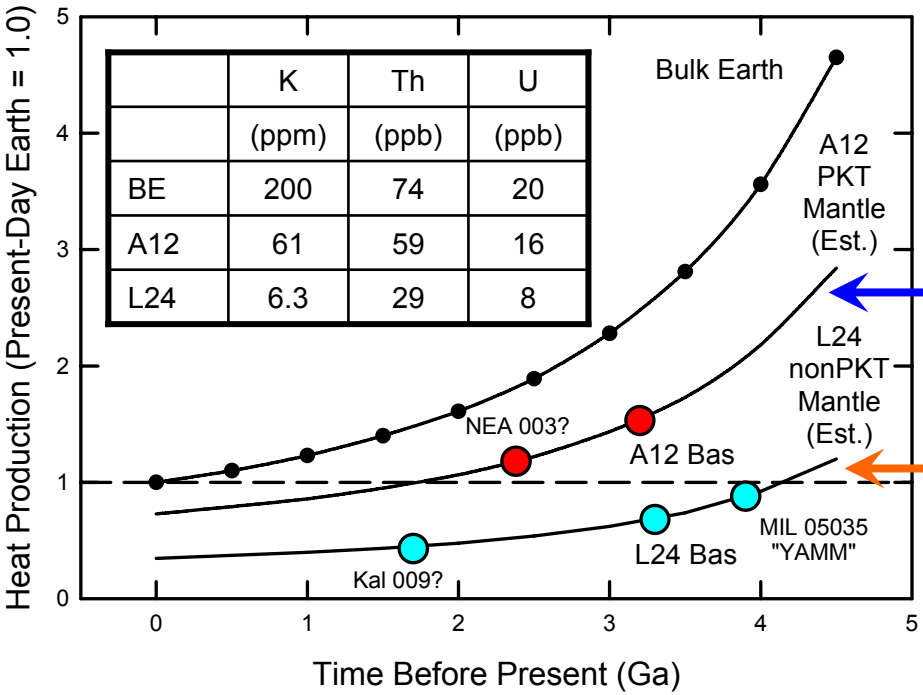
- The surface geochemical asymmetry is reflected in “initial” isotopic ratios of basalts as a result of radiogenic growth in the lunar mantle.
  - In particular, initial $^{87}Sr/^{86}Sr$ in basalts ~ Rb/Sr ~ [K] in the mantle
  - Mare basalts from outside the PKT have lower initial $^{87}Sr/^{86}Sr$, and must come from a mantle having lower [K], than basalts from the PKT.
  - Therefore, the PKT “anomaly” extends into the mantle.
  - Implies lateral variation in mantle heat production
  - What are the implications for mantle overturn and possibly convection?
- Radiogenic isotopes are ambiguous concerning A16 ferroan anorthosites (FANs) as flotation products on a lunar magma ocean
  - One A16 FAN appears to require the trace element abundances in its immediate precursor to differ from those expected for a magma ocean.
  - But, A16 FANs are non-ideal for isotopic studies, and impact-related complications to the isotopic data may arise
- Lunar meteorites suggest a greater variety of crustal rocks.
  - More magnesian, and thus more primitive anorthosites
  - Anorthosites with evolved feldspar compositions similar to those of the “Mg-suite”, but lacking a KREEP signature implying KREEP is regional.
- Geochemical asymmetries are “early” if not “primary”.
  - How do we explain large-scale lateral heterogeneity in the moon in a giant impact/magma ocean model?

Sampling to Better Understand Lunar Evolution

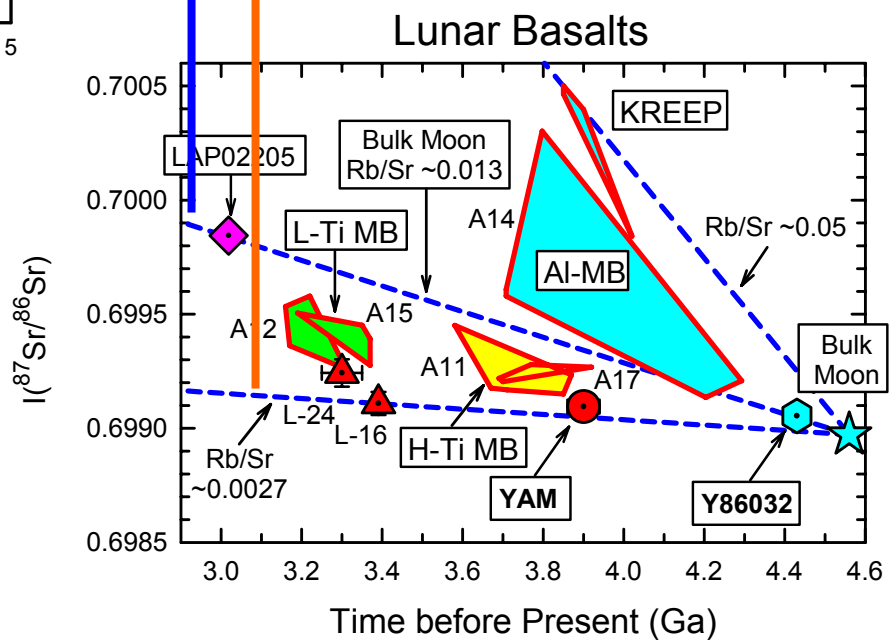
- Lunar magma ocean and crust formation
  - Sample low-Th, Feldspathic Highland Terranes
    - Sample FHT(A) rather than FHT(O)
    - Avoid the influence of the nearside impact-basins
    - Carefully select crustal samples (**astronauts**)
    - Sample igneous crustal rocks (**large boulders, drill**)
- Lunar heat generation, thermal evolution, and mare volcanism
  - Sample low-Th, mare basalt terranes
    - Young terranes based on crater densities are preferred.
    - Simpler rocks, less critical sampling methods (**robots**)
- From a South Polar Base
  - Detailed sampling of local terrane, possibly including SPA ejecta
  - Retrieve samples robotically from ever-more-distant terrane
    - Goal: Retrieve basalts from SPA, Mare Australe, and the Schiller/Schickard cryptomare

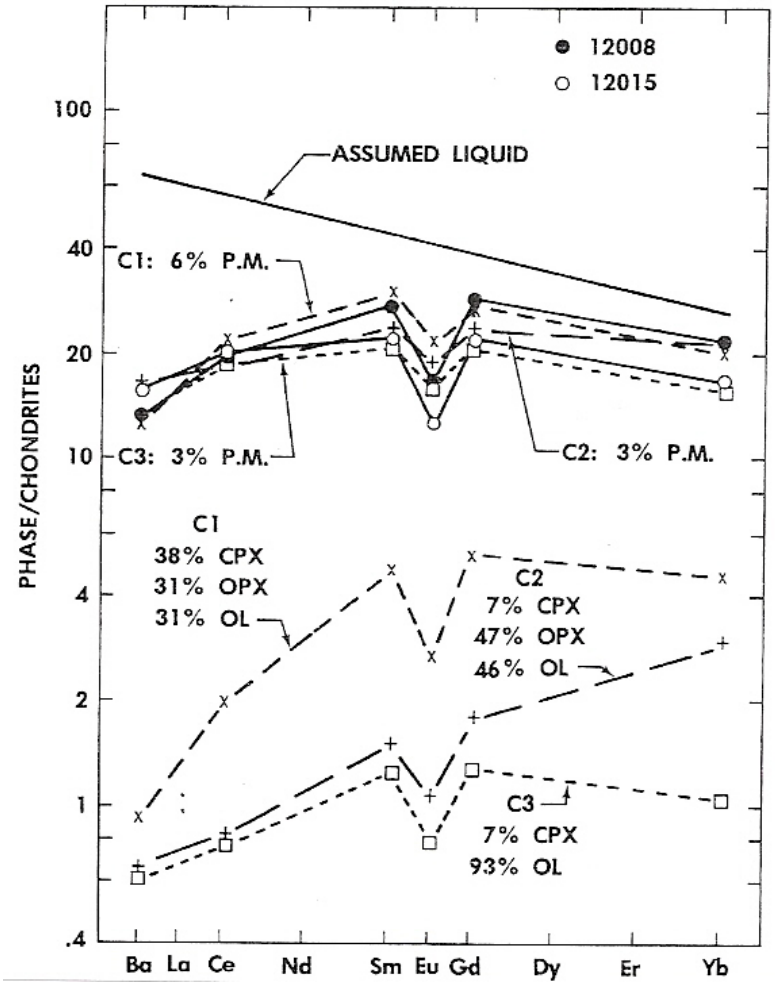
Relative Total Radiogenic Heat Production
(after Van Schmus, 1995)

	K	Th	U
	(ppm)	(ppb)	(ppb)
BE	200	74	20
A12	61	59	16
L24	6.3	29	8

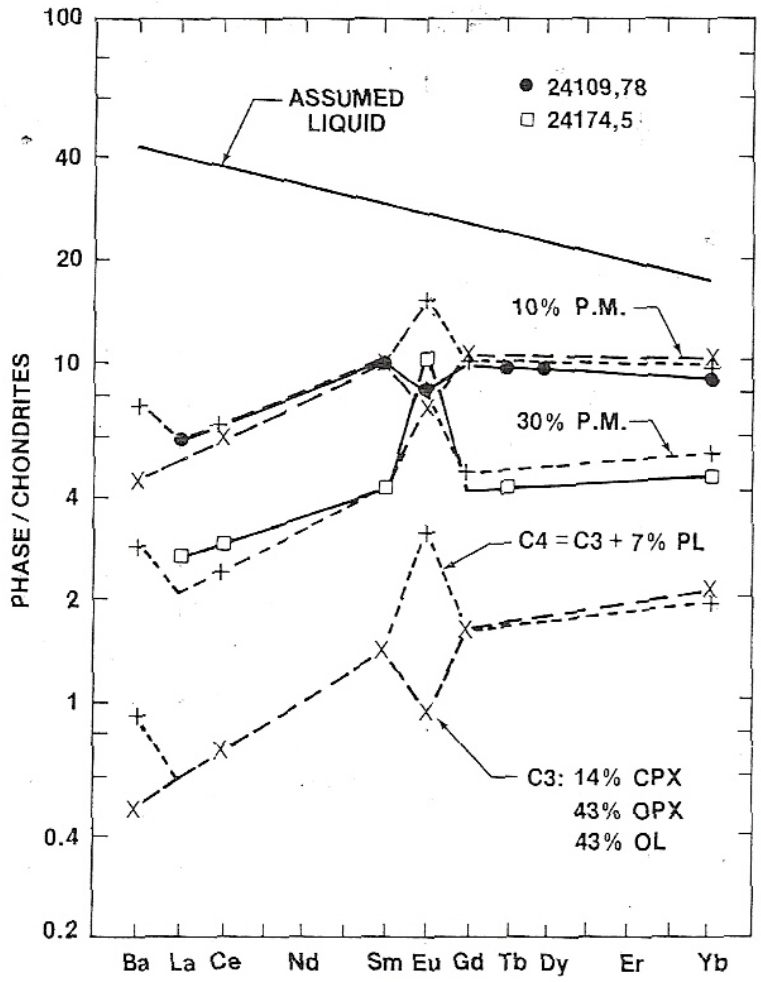


Data from Nyquist et al. (2007) LPSC 38, Abstract #1702 and white paper to this workshop. See those references for further discussion.



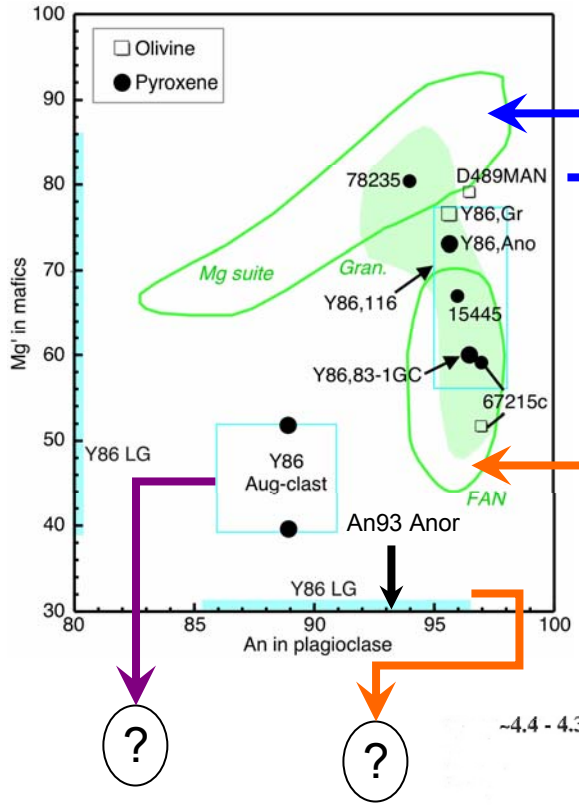


Nyquist et al. (1977) Sr-isotopic constraints on the petrogenesis of Apollo 12 mare basalts. PLSC8, p. 1383-1415. Fig. 9.

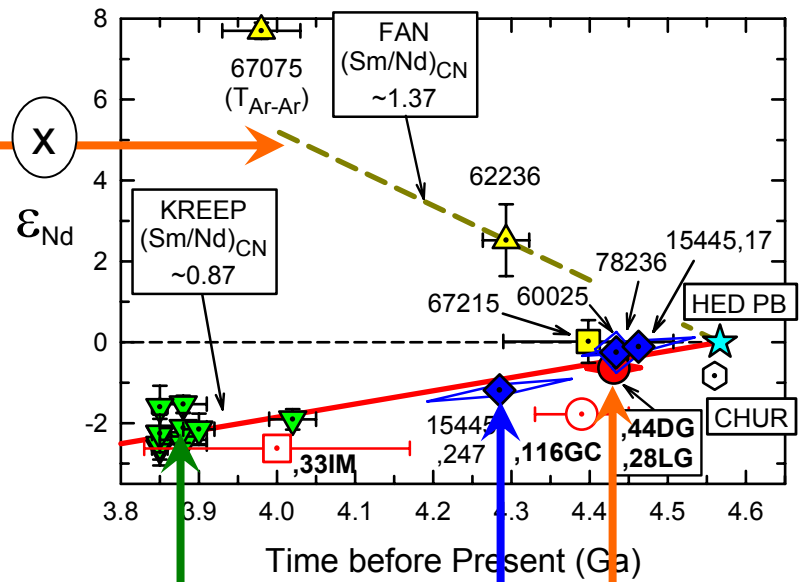


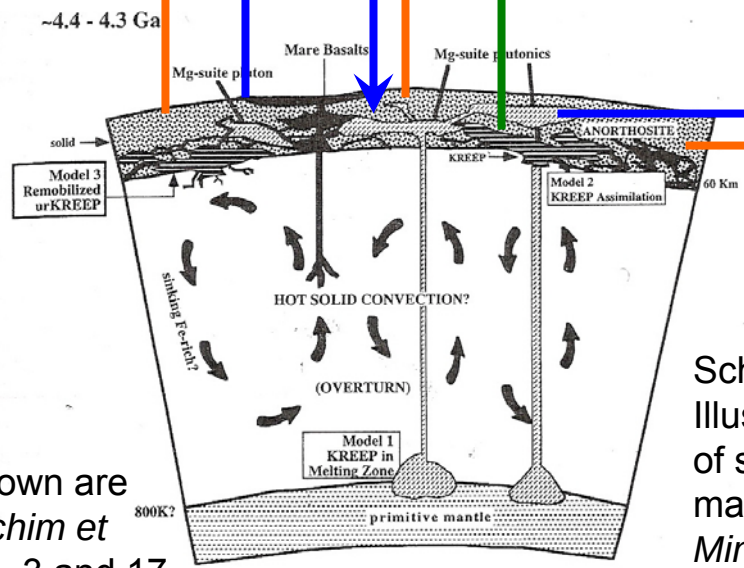
Nyquist et al. (1978) Chemical and Sr-isotopic characteristics of the Luna 24 samples. Mare Crisium: The view from Luna 24, p. 631-656, . Fig. 7.

Major Element Composition of Lunar Crustal Rocks



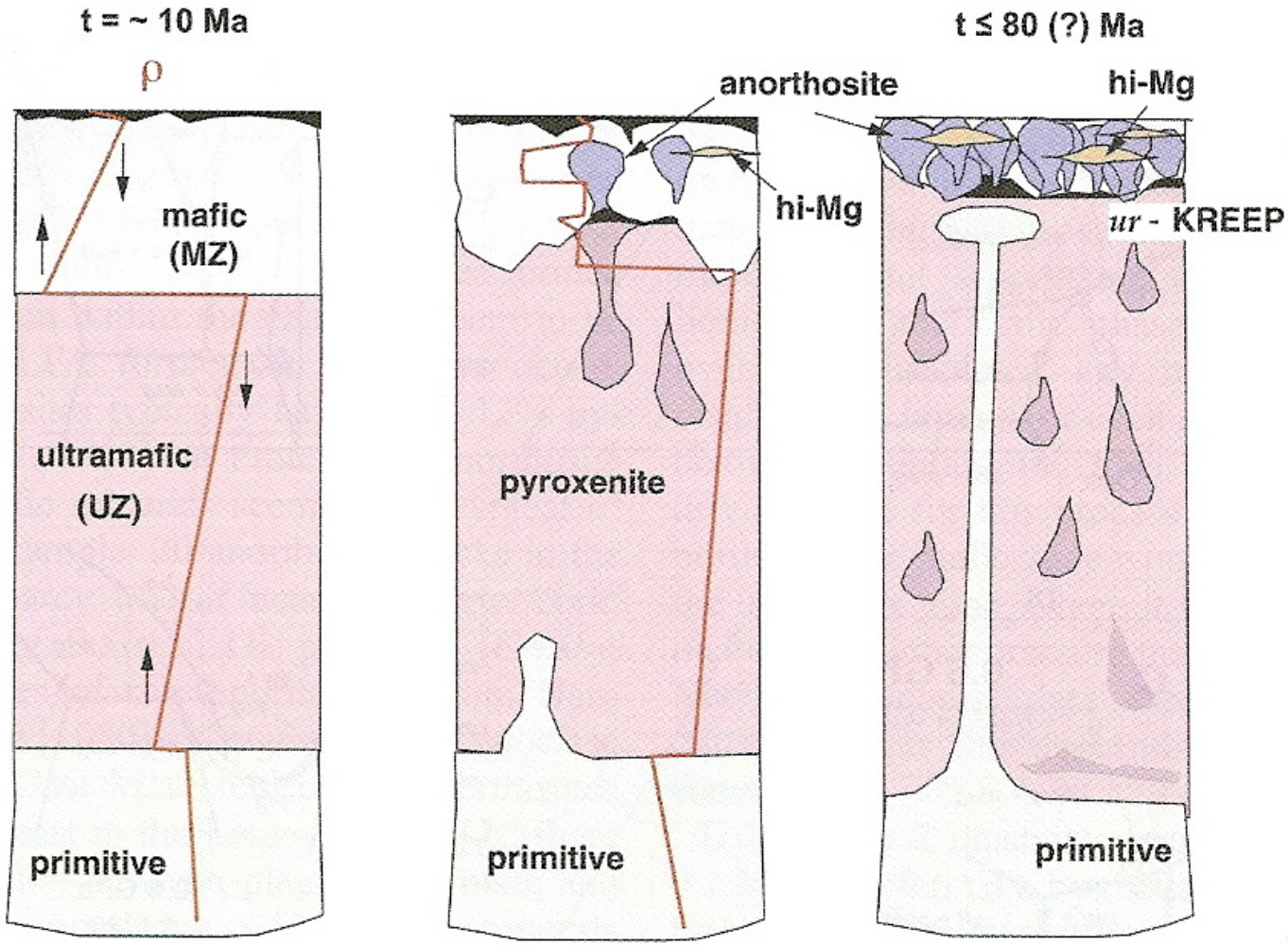
Initial Nd-isotopic Composition of Lunar Crustal Rocks





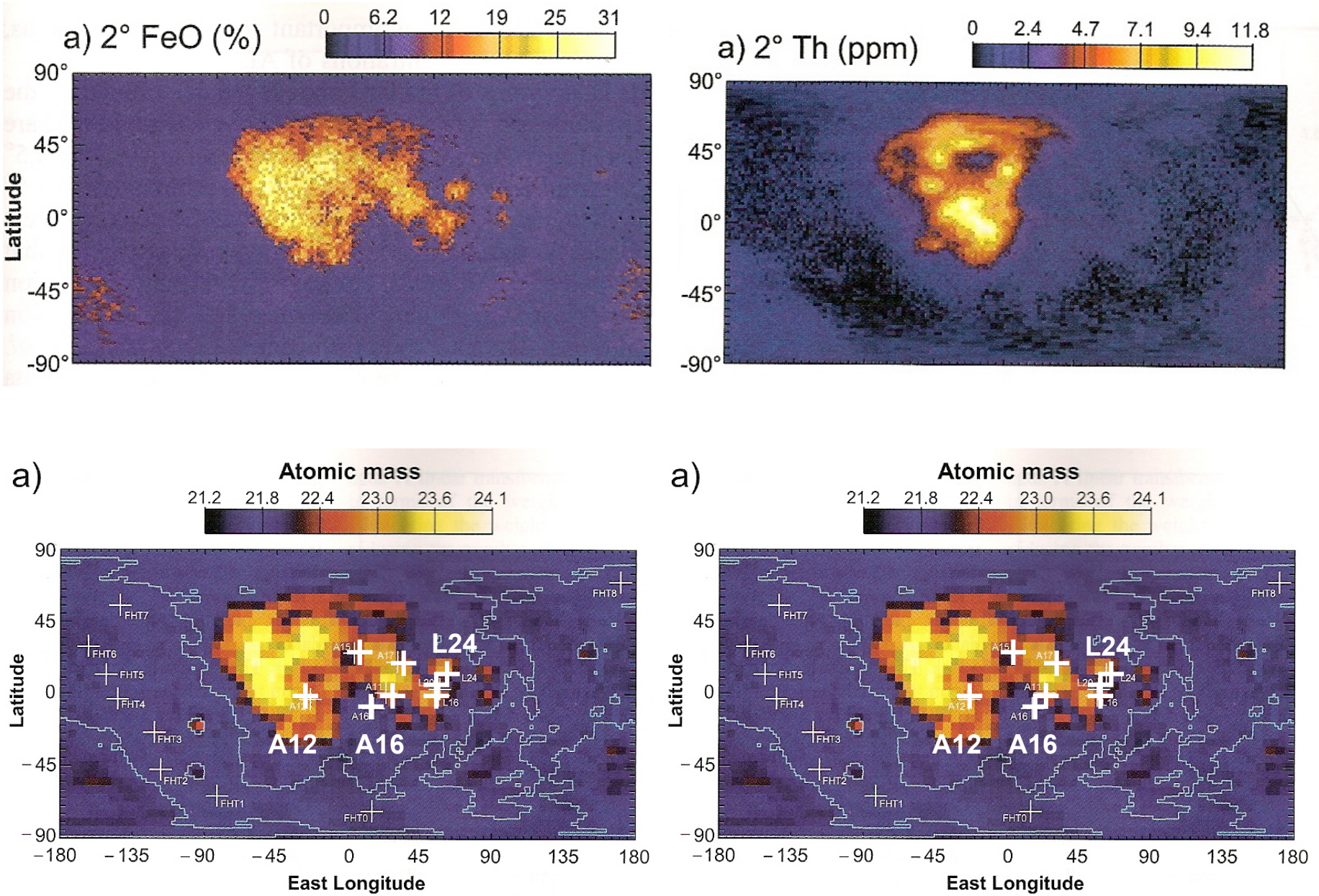
Elemental and isotopic data shown are from Nyquist et al. (2006) *Geochim et Cosmochim Acta,* vol. 70, Figs. 3 and 17.

Schematic cross section of the Moon Illustrating hypothetical consequences of solidification of a 800 km deep magma ocean. From *Reviews in Mineralogy,* J. J. Papike (ed.) vol. 36, Fig. 4, p. 5-5.

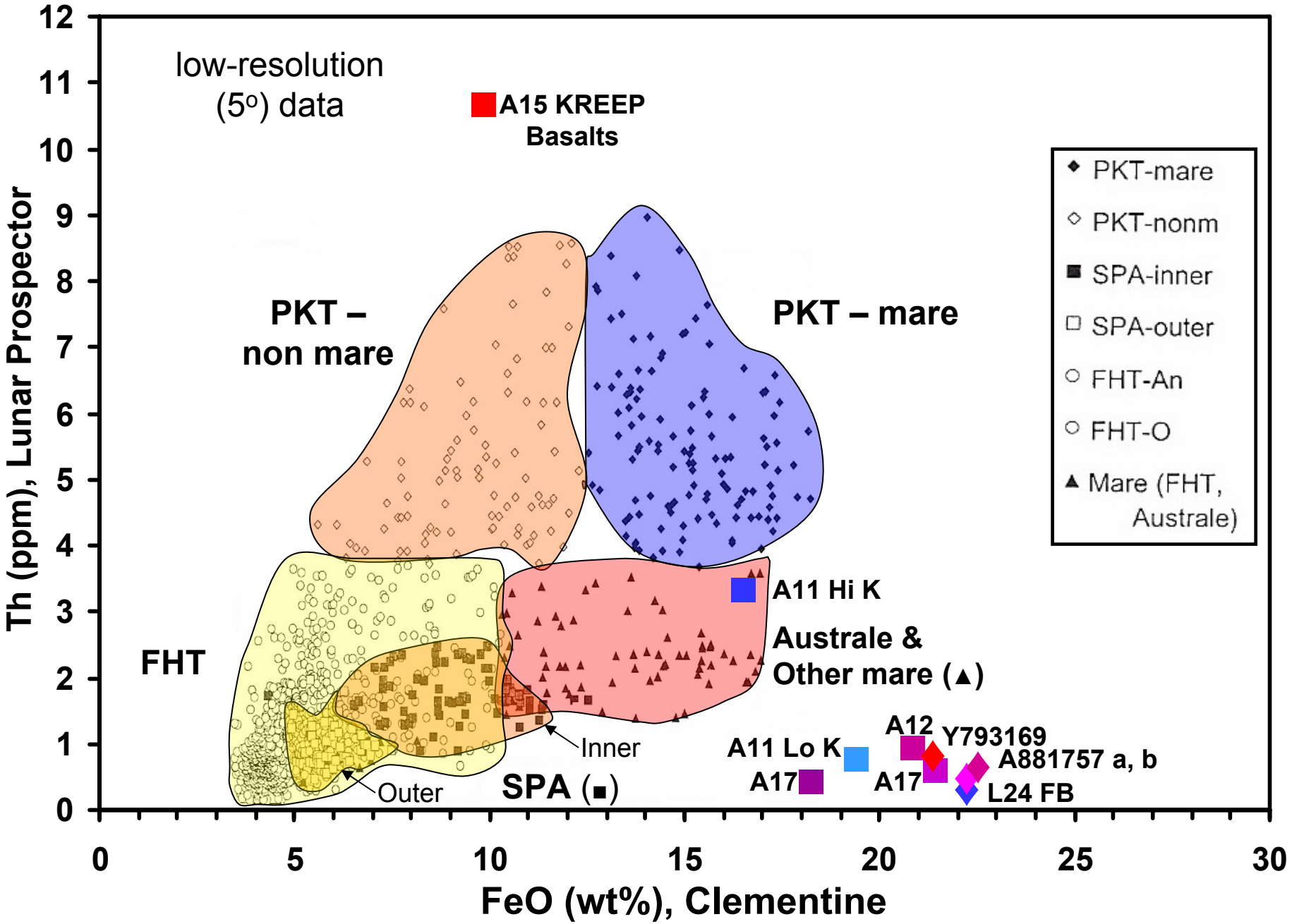


Longhi, J. (2003) A new view of lunar ferroan anorthosites: Postmagma ocean petrogenesis. JGR 108, E8, 5083

Fig. 8. Early lunar differentiation in which FAN formation follows rapid crystallization of the magma ocean.



Adapted from Prettyman et al. (2007) JGR 111, E12007



Adapted from Jolliff et al. (2000) JGR 105, E2, 4197-4215, Fig. 6.