Implications for Lunar History from Ancient Basalts of the Secondary Crust.

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Introduction & Overview

- Ancient volcanism (>4.35 Ga) on the Moon confirmed
  - Recently: Kalahari 009 and Miller Range 13317 by SIMS Pb-isotopes [1].
  - Previously: Apollo 14 Aluminous Mare Basalts, then Kal 009
    - A14 AMB: Rb-Sr (*e.g.* [2]), Kal 009: Lu-Hf [3] & Sm-Nd [4].
- Here: Extend and expand our report on Kal 009 [4].
  - Kal 009 in the context of "secondary lunar crust"
    - A concept introduced by Head and Wilson [5] and continued recently by Whitten and Head [6,7].
    - Here we mean the "original" secondary crust volcanically produced prior to the currently identified lunar basins.
- Important because the timeline for secondary crust formation may not follow the usual paradigm.
  - *i.e.*, Formation of LMO then Anorthositic crust then Impact Basins then Mare volcanism into the impact basins.
- When, where, how could such a crust begin forming?
  - Will borrow heavily from prior work on this topic (*e.g.* [5]-[8]).

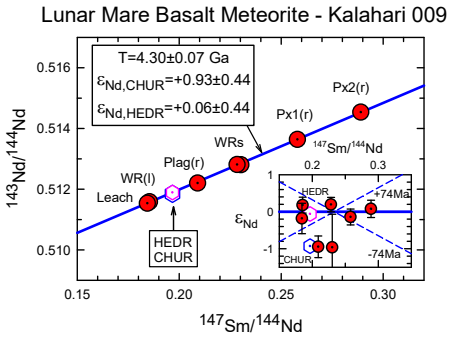

Fig. 1. Sm-Nd age for Kal 009. Data of [4] newly regressed with Isoplot [11].

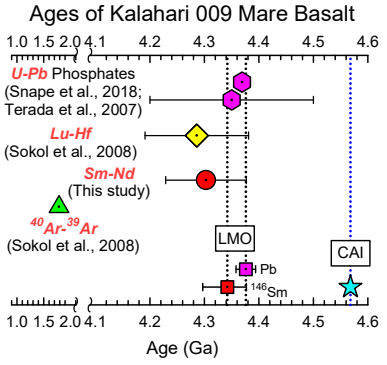

Fig. 2. *Upper portion (5 data)*: Summary of radiometric ages for Kal 009. *Lower portion (2 data)*: Radiometric ages for lunar differentiation ("LMO" age) compared to the solar system age ("CAI" age).

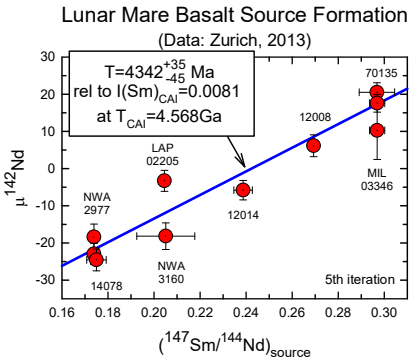

Fig. 3. ^{146}Sm-^{142}Nd isochron for lunar differentiation and formation of mare basalt sources ([14, [15]). Basalts from LREE-enriched sources are at the lower left ($^{147}Sm/^{144}Nd$<CHUR), those from LREE-depleted sources are at the upper right ($^{147}Sm/^{144}Nd$>CHUR).

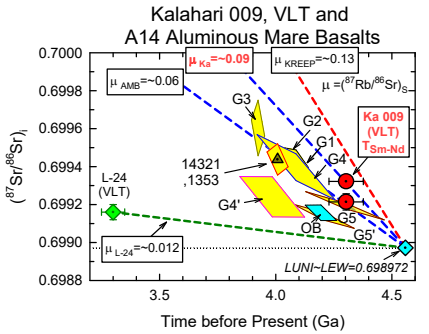

Fig. 4. Conventional (T,I_{Sr}) plot for Kal 009, A14 AMB, and Lunar 34 VLT basalts. Comparatively high I_{Sr} values for Kal 009 and A14 AMB suggests derivation from similar, high $^{87}Rb/^{86}Sr$ (μ) sources.

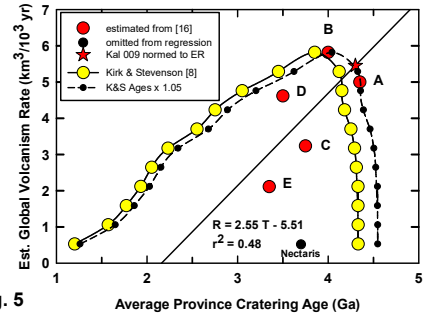

Fig. 5

Fig.5. Estimated lunar global volcanic eruption rate (red) derived from Table 8.9.1 of [16] compared to volcanic production rates [8] after normalizing the estimated maximum production rate to the estimated maximum eruption rate. Horizontal axis shows time in the past (T, Ga) with estimated volcanic extrusion rates (R) from [16] plotted versus the ages of the lunar provinces considered. With terminology from [16]: **A** = Uplands, **B** = Procellarum + Tranquilitatis + Fecunditatis + Mendeleev + Schiller, **C** = Smythii + Humorum + Balmer, **D** = Serenitatis + Crisium + Humbodtianum + Grimaldi + Schroedinger, **E** = Imbrium + Orientale. Nectaris is not assigned. The ~4.3 Ga age of Kal 009 is plotted on a linear fit to the extrusion rate estimates omitting Nectaris (star) and would represent some of the oldest secondary volcanic crust in this model.

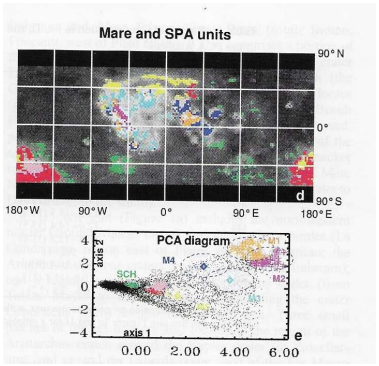

Fig. 6

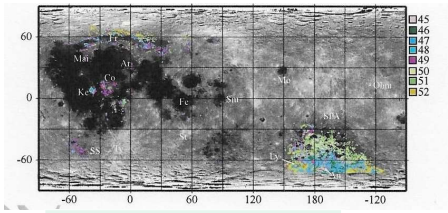

Fig. 8

Fig. 6. Lunar global composition from Chevrel et al. [17]. **Fig. 7.** Principle Component Analysis (XLSTAT®) for remotely-sensed Fe, Ti, and Th abundances. Fig. 8. Lunar global FeO, TiO2 and Th abundances determined by Hareyama et al. [18] via remote sensing. Fig. 9. PCA applied to the data of Hareyama et al. [18]. Compared to the remote-sensing data, Kal 009 and the Apollo 14 Aluminous Mare basalts have "intermediate" compositions between the lunar crust and mare basalts with high abundances of both Fe and Ti. Higher TiO_2 abundances in the A14 AMB of ~2 wt. % and reference to remote sensing data [19] lead us to redefine "V-LT" with TiO_2 <3 wt. % when considering origins of ancient mare basalts.

Summary and Conclusions

- Lunar cryptomaria are characterized mostly by VLT basalt compositions.
  - Variations in VLT basalt ages are apparent both photo-geologically and in sample data.
- The variation in ages suggests the "secondary lunar crust" probably formed rather continuously in early lunar history.
- The Schiller-Schickard (SS) region is a type example of a cryptomaria, but the older, more heavily obscured Lomonosov-Fleming remains favored as a source for the oldest VLT basalts like Kal 009.
- Principal Components Analysis (PCA) is a useful method to **compare** the compositions of samples to those of geologic provinces.
  - See Smith et al. (1985), Blewett et al. (1995), Chevrel et al. (2006), etc.
  - But, interpretations of PCA are "non-absolute".
- A paucity of data suitable for "absolute" comparisons persists.
  - Remotely sensed Th abundances are systematically higher than laboratory values for corresponding samples.
    - ✓ Remotely sensed surfaces may be contaminated with high-Th ejecta.
- One or more additional parameters remotely determined with "good" analytical and spatial resolution are needed.
  - Careful evaluation of Al/Fe ratios from spacecraft gamma ray spectrometry instruments may be useful.

Fe, Ti (wt%) Th (ppm) Averages Table 1 of Chevrel et al. (2002)				
Province	Units	Fe	Ti	Th
Highlands	H1	2.7	0.2	0.9
	H2	4.8	0.2	1.3
Th-rich	H3	6.5	0.2	3.5
	H4	9.0	0.4	5.8
	H5	10.3	0.9	8.0
Mare	M1	14.9	6.5	2.5
	M2	15.3	6.3	3.7
	M3	14.1	3.5	4.0
	M4	13.5	3.5	2.0
	M5	11.4	0.6	3.3
SPA	S1	9.8	0.3	2.3
	S2	11.0	0.55	2.0
	SS	7.2	0.25	1.3

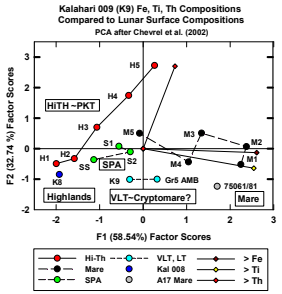

Fig. 7

Hareyama et al. (2018) classes		
K-mns	TiO_2	ISODATA
K1	VHT, HT, IMT	N=21
	LT, VLT	
K2		N=8
K3	VHT, HT, IMT	N=14
	LT, VLT	
K4	VHT, HT, IMT	N=9
	LT, VLT	
K5	Highlands	N=8
K6	Highlands	N=2
K7	Highlands	N=3
	UVHT	00
S = 9	S = 19	S = 66

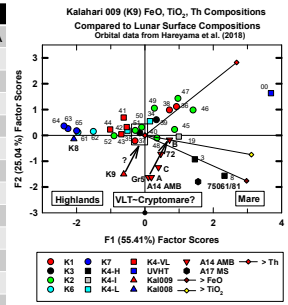

Fig. 9

Table 1. Candidate sources of Kal 009 & MIL 13317

Name	Lat. N°	Long. E°	Area[a]	Vol.[b]	Age (Ga)
Balmer	-18.74	68.78	6.11	18.3	~3.84
L-F[d]	19.3	106.9	11.3	22.6	~4.01
Smythii	-1.94	85.12	3.88	15.5	~3.90
W. Hum.	-21.52	-56.87	0.32	0.16	
SS[e]	-48.8	-51.75	13.2	39.7	~3.77
Kal 009					~4.30[c]

[a](10^4 km^2) [b](10^4km^3) [c]Sm-Nd isochron
[d]Lomonosov-Fleming [e]Schiller-Schickard

References: [1] Snape J. F. et al. (2018) *EPSL, 502*, 84-95. [2] Taylor L. A. (1983) *EPSL, 66*, 33-47. [3] Sokol A. K. et al. (2008) *GCA, 72*, 4845-4873. [4] Shih C.-Y. et al. (2008) LPS XXXIX, abstract #2165. [5] Head J. W. and Wilson L. (1992) *GCA, 56*, 2155-2175. [6] Whitten J. L. and Head J. W. (2015), *Icarus, 247*, 150-171. [7] Whitten J. F. and Head J. W. (2015) *Planet. Space Sci., 106*, 67-81. [8] Kirk R. L. and Stevenson D. J. (1989) *JGR, 95*, 12,133-12,144. [9] Jacobsen S.B. and Wasserburg G.J. (1984) *EPSL 67*, 137-150. [10] Nyquist L. E. et al. (2010) *GLUC*, 2010.1.1.A.4. [11] Ludwig K. R. (2008) *Isoplot/EX ver. 3.70*, Berkeley B. G. Center. [12] Borg L. E. et al. (2015) *Meteoritics & Planet. Sci., 50*, 715-732. [13] Snape J. F. et al. (2016) *EPSL, 451*, 140-158. [14] Nyquist L. E. et al. (1995) GCA 59, 2817-2837. [15] This study (Touboul M. and Kleine T. (2018) pers. comm.) [16] Hartman W. K. et al. (1981) in *BVSP*, 1049-1127. [17] Chevrel S.D. et al. (2002) *JGR, 107*, No E12, 15-1 to 15-14. [18] Hareyama et al. (2019) *Icarus* 321, 407-425. [19] Prettyman T.H. et al. *(2006) J. Geophys. Res.*, Vol. **111,** No. E12, E12007.