IMPLICATIONS FOR LUNAR HISTORY FROM ANCIENT BASALTS OF THE SECONDARY CRUST.

L. E. Nyquist[1], C.-Y. Shih[2], J. Park[3,4], G. F. Herzog[4], [1]XI/NASA-JSC, Houston TX 77058 (laurence.e.nyquist@nasa.gov), [2]16406 Locke Haven, Houston, TX 77059 (cshih2014@gmail.com). [3]Kingsborough Comm. Coll., Brooklyn, NY 11235. [4]Dept. Chem. & Chem. Biol., Rutgers Univ., Piscataway, NJ 08854.

Introduction: Recent work [1] has confirmed the existence of ancient volcanism on the moon predating formation of most of the currently observable major lunar basins. Earlier reports of such volcanism [2,3,4] were largely ignored. The existence of basalts produced by ancient volcanism is important evidence of development of a secondary crust [5] on the moon nearly contemporaneously with formation of its primary anorthositic crust [1,4]. Head and co-workers [5,6,7] have consistently cited evidence for the secondary lunar crust preserved in lunar cryptomaria, and have considered its implications for the chronology of lunar thermal evolution. That chronology differs significantly from a widely accepted four-step chronology omitting reference to a secondary crust: (a) lunar formation after impact of the Earth with another accreting, planetary-sized body; (b) solidification of a primary crust; (c) formation of major lunar impact basins; (d) basalt flooding of the impact basins following partial melting of a mantle formed contemporaneously with the primary crust. Basalt crystallization ages of 4369±7 Ma for Kalahari 009 (hereafter Kal 009) and 4332±2 Ma for MIL 13317 by the Pb-isotope technique [1] confirming ages for Kal 009 of 4300±50 Ma by the Sm-Nd technique [4] and 4286±95 Ma by the Lu-Hf technique [3] show basalt formation contemporaneous with (c) above, and perhaps with (b) rather than exclusively in (d). These observations call into question “established” paradigms of lunar evolution, and are most consistent with the lunar global thermal model of [8].

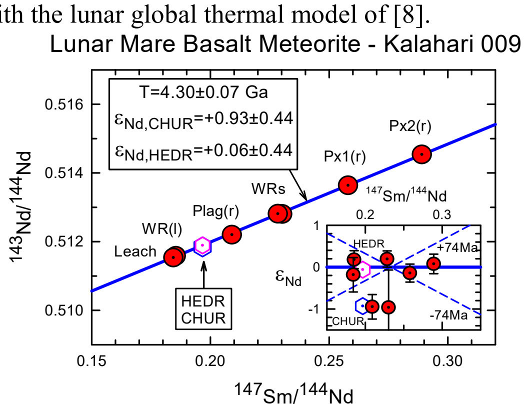

Fig. 1. Sm-Nd data for Kal 009 updated from [4].

Radiogenic Isotope Data for Kalahari 009: The radiogenic isotope data considered here emphasize those previously reported for Kal 009 by [4]. Fig. 1 shows updated Sm-Nd data. Those data yield an age of 4303±74 Ma for $\lambda(^{147}Sm)$ = 0.00654 Ga^{-1} and initial ε_{Nd} =+0.93±0.44 relative to the chondritic reservoir [9] and ε_{Nd} =+0.06±0.44 relative to the eucritic reservoir (HEDR) of [10]. Minor changes in the results and uncertainties from [4] reflect a new isochron regression with Isoplot [11].

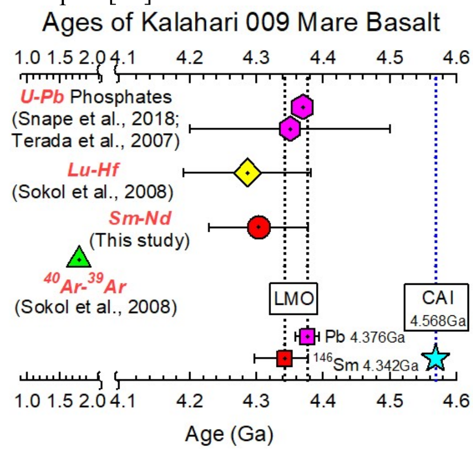

Fig. 2. Summary of ages for Kal 009.

.

Fig. 2 summarizes radiogenic isotope ages reported for Kal 009. With exception of the ^{40}Ar-^{39}Ar age, all agree within analytical uncertainty. Also shown are two estimates of the date of the Lunar Magma Ocean (LMO) by the U-Pb [12] and ^{146}Sm-^{142}Nd techniques (Fig. 3 this study). Borg et al. [12] also suggest an age of 4355±32 Ma as the likely age of lunar solification in essential agreement with the Pb model differentiation age of 4376±18 Ma [13]. Our Sm-Nd age for Kal 009 would allow its formation slightly after lunar differentiation, but as noted in [1], its U-Pb age of 4369±7 Ma makes it contemporaneous with the foregoing estimates of the time of lunar differentiation.

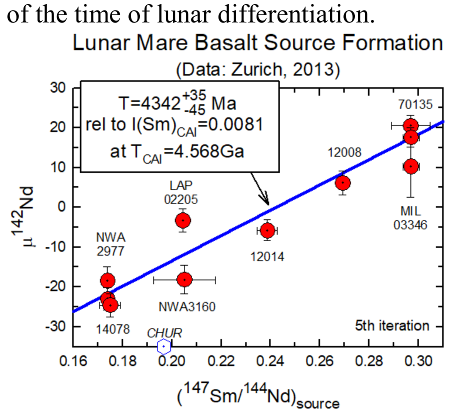

Fig. 3. ^{146}Sm-^{142}Nd isochron for formation of mare basalt sources. Basalts from LREE-enriched sources plot to the lower left ($^{147}Sm/^{144}Nd$<CHUR), those from LREE-depleted sources plot to the upper right ($^{147}Sm/^{144}Nd$>CHUR).

The ^{146}Sm-^{142}Nd lunar mantle differentiation age [14] is another measure of the time of lunar global differentiation. By recording mantle-scale geochemical processes of element partitioning it differs qualitatively from other measures of this event, which rely on averaging ages of individual lunar rocks. That is, the data shown in Fig. 3 [15] record processes leading to depletion and enrichment, respectively, of the geochemically important Light Rare Earth Elements (LREE)

Geological Expression of Global Differentiation: Lunar highlands composed of feldpathic rocks – the so-called Feldspathic Highlands Terrain (FHT) - provide geochemical as well as geological evidence of global lunar differentiation. But, what is the evidence for contemporaneous basaltic volcanism having formed a very early secondary crust? Photogeologists studying the lunar surface remotely cite the existence of low lying cryptomaria partially filled with ejecta from the surrounding highlands as evidence of a "secondary" lunar crust. To estimate the starting time and duration of basalt extrusion into the cryptomaria, Head and Wilson [5] cited a thermal model by [8] that accounts for the lunar volume change due to differentiation. Kirk and Stevenson [8] had applied their model to basalt production and eruption rates. Some results following this approach are summarized in Fig. 4.

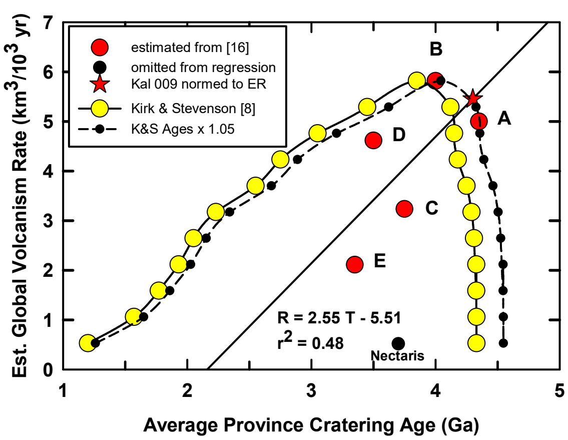

Fig.4. *Estimated lunar global volcanic eruption rate (red) derived from Table 8.9.1 of [16] compared to volcanic production rates [8] after normalizing the estimated maximum production rate to the estimated maximum eruption rate. Horizontal axis shows time in the past (T, Ga) with estimated volcanic 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).*

Seeking the Cryptomare Source of Kal 009: The locations of cryptomaria have been increasingly well defined by a number of lunar orbiting spacecraft from the United States and other nations. Nevertheless, the identity of the cryptomare source of Kal 009 remains elusive. We previously noted possible geochemical and isotopic linkages between Kal 009 and the Apollo 14 aluminous mare basalts (A14 AMB) [4]. We further suggested that the crytomare in the Lomonosov-Fleming (L-F) basin northeast of Mare Marginis might be a place where the AMB and Kal 009 might coexist, since Kal 009 is aluminous, and some of the A14 AMB also are Very Low Titanium (VLT) like Kal 009. The geochemical connections are subtle, however, and the large distance between the L-F basin and the Apollo 14 landing site is a challenge to the hypothesis of a physical relationship between these two types of ancient VLT/AMB basalts. The close chronological and geochemical affinity between Kal 009 and MIL 13317 is a strong hint that the two may share a place of origin on the lunar surface. Their ancient ages and *relatively* high frequency of occurrence among otherwise rare basaltic lunar meteorites continue to favor the L-F cryptomare among other possible candidate sources (Table 1).

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	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	
Kal 009					~4.30[c]

[a]($10^4 km^2$) [b]($10^4 km^3$) [c]Sm-Nd

Footnote: Data summarized in Table 1 are from [6].

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] Lugwig 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.