LUNAR LIPS: WHAT STORY ARE THEY TELLING US? C. R. Neal[1] Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu).

Introduction: The term "Large Igneous Province" (LIP) was initially proposed by Coffin and Eldholm [1-4] to represent a variety of mafic igneous provinces with areal extents >0.1 Mkm^2 that represented " massive crustal emplacements of predominantly mafic (Mg- and Fe-rich) extrusive and intrusive rock, and originated via processes other than "normal" seafloor spreading." This definition was revised by Bryan and Ernst [5] as follows: "Large Igneous Provinces are magmatic provinces with areal extents >0.1 Mkm^2, igneous volumes >0.1 Mkm^3 and maximum lifespans of ~50 Myr that have intraplate tectonic settings or geochemical affinities, and are characterised by igneous pulse(s) of short duration (~1–5 Myr), during which a large proportion (>75%) of the total igneous volume has been emplaced". This revision excludes seamounts, seamount groups, submarine ridges and anomalous seafloor crust from being classified as LIPs (Fig. 1).

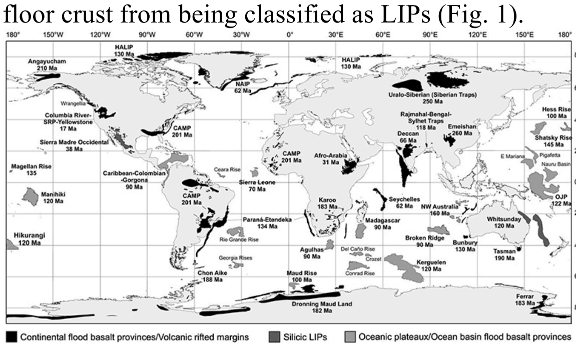

Figure 1: Revised LIP map of the Earth [5].

Expanding the definition of LIPs beyond the Earth, it is evident that such constructs are present on the other terrestrial planets: the northern smooth plains of Mercury [6]; Beta-Atla-Themis (BAT) and southern Lada volcanic provinces, Artemis and Lada Terra regions on Venus [7]; the Tharsis region on Mars [8]. Mantle plumes are the normal mode of volcanism on the terrestrial planets. On Earth, the situation is unique because of plate tectonics. However, terrestrial LIPs are enigmatic in their formation. For example, some LIPs form rapidly (3-5 m.y.; e.g., Ontong Java Plateau [9], Deccan Trapps [10], Columbia River [11], Siberian Trapps [12]), whereas others are built in stages (e.g., Kerguelen Plateau [13], Shatsky Rise [14]). On the other planets noted above, we do not have the luxury of samples taken from known locations to examine the duration of volcanism. We do have the luxury of samples from the Moon that define different compositional types that define a large age range, but have been defined as a comprising several LIPs [8].

The Moon: Most of the volcanic products produced on the Moon are present on the nearside (Fig. 2). These form the lunar maria that cover ~17% of the lunar sirface. The tota l area of the lunar maria (6.3 x I0^6 km^2 [15,16]) is considerably larger than typical terrestrial LIPs but only slightly larger than the area of the Ontong Java LIP. The estimated total volume is relatively small at 1 x 10^7 km^3 [15], comparable to the Deccan Traps alone. However, the estimates of volume need to be revised because mare thicknesses have only been determined via geophysical methods at a few locations [17].

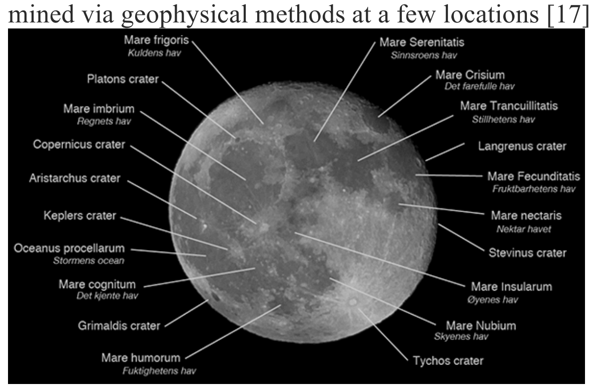

Figure 2: Map of the nearside lunar mare.

More recent relative age dating (using crater counts) of the lunar maria [18] show that relatively extensive (in lunar terms) eruptions occurred up until about a billion years ago (Fig. 3). This has important implications for the thermal evolution of the Moon. Given the small size of our nearest celestial neighbor, it is amazing that lunar flood basalt eruptions could still be generated after ~3.5 b.y. (red area in Fig. 3).

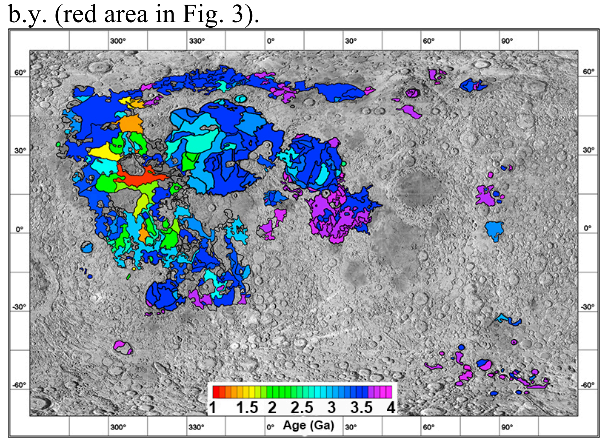

Figure 3: Mare basalt ages from [18].

The samples returned by the Apollo program show eruptions occurred over an almost 800 m.y range (Fig. 4a,b). The high-Ti basalts returned by Apollo 11 and Apollo 17erupted over 120 m.y. (Apollo 11) and 220 m.y. (Apollo 17). However, the range of ages for Apollo 11 basalts are encompassed by that for Apollo 17 high-Ti basalts – 3.89-3.67 Ga.The high-Ti basalts are younger than the high-Al, low-Ti Apollo 14 basalts

(4.27-3.95 Ga) and older that the low-Ti Apollo 12 (3.35-3.16 Ga) and Apollo 15 (3.43-3.34 Ga) basalts.

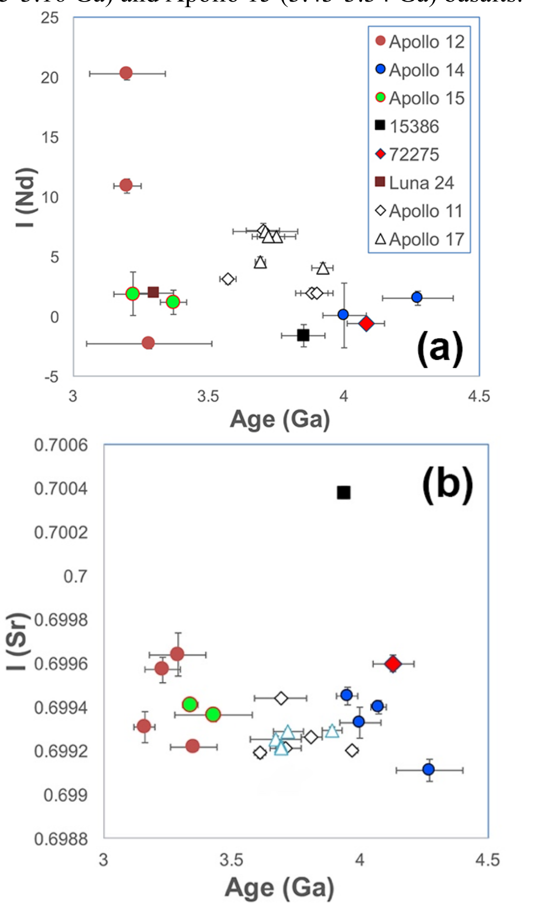

Figure 4: (a) I(Nd) vs Age (Ga) and (b) I(Sr) vs. Age (Ga) for all mare basalt groups. Data from [19-33].

In viewing the isotope and age data in this way, the high-Ti basalts erupted during a time when, at least in the Apollo and Luna sample collection, no low Ti mare basalts were erupting. KREEP basalts 72275 and 15386 do overlap the older end of the high-Ti basalt range and extend into the older Apollo 14 high-Al basalts.

The source regions for the mare basalts indicate that in terms of Nd, there are all derived from depleted sources, except for the KREEP basalts and Apollo 12 feldspathic (high-Al) basalt 12038. For I(Sr) the Apollo 11 and 17 high-Ti basalts define a narrow range of 0.69924+/-4, except for Apollo 11 Group A basalts (0.69944+/-2). The low-Ti basalts from Apollo 12, 14, and 15 define broader ranges of I(Sr).

The isotope data indicate that the different types of mare basalts were derived from generally distinctive sources, sometimes even for basalts returned from the same landing site (e.g., Apollo 12). Terrestrial LIPs generally show uniform initial isotope ratios because they are generally erupted over a short time period. However, the later eruptions are generally isotopically distinct from earlier eruptions (e.g., Ontong Java Plateau). Such relationships are not apparent in the mare basalts from the Apollo and Luna collections.

Lunar missions this century have added a new aspect to understanding LIP magmatism on the Moon and that is the present of silicic magmatic constructs [34,35]. Some of these are situated in mare basalt regions [34] while others are in highlands terrains [35]. Those in mare terrains are broadly similar to the terrestrial LIPs that have mafic-silicic constructs (e.g., Carribean Plateau – Aruba [36]). The presence of the silicic "domes" in mare terrains is enigmatic but the study of such dichotomies can be studies through comparative planetology with terrestrial LIPs.

Summary: Plume volcanism is the norm for terrestrial planets except Earth. However, the Earth has experience such eruptions throughout geologic history. Comparing terrestrial LIP magmatism with magmatic provinces on the Moon shows broad differences and also similarities. There are two important next steps in exploring lunar magmatism: 1) quantifying the thicknesses of mare deposits in the various basins; 2) sampling and age dating mare basalts from 1-2.5 Ga (Fig. 3). Then we will truly understand the magntidufe of lunar LIPs as well as the thermal history of the Moon.

References: [1] Coffin M.F. & Eldholm O. (1992) *Geol. Soc. Lond. Spec. Pap. 68*, 17-30. [2] Coffin M.F. & Eldholm O. (1993) *Geology 21*, 515-518. [3] Coffin M.F. & Eldholm O. (1993) *Sci. Amer. 269*, 42-49. [4] Coffin M.F. & Eldholm O. (1994). [5] Bryan S.E. & Ernst G. (2008) *Earth Sci. Rev. 86*, 175-202. [6] Head J.W. et al. (2011) *Science 333*, 1853-1856. [7] Hansen V.L. (2007) *Chem. Geol. 241,* 354-374. [8] Head J.W. & Coffin M.F. (1997) *Geophys. Monogr. 100*, 411-438. [9] Tejada M.L.J. et al. (2002) *J. Petrol. 43*, 449-484. [10] Chenet A.-L. et al. (2009) *JGR 114*, B06103, doi:10.1029/2008JB005644. [11] Mahood G.A. & Benson T.R. (2016) *EPSL 450*, 340-351. [12] Reichow M.K. et al. (2002) *Science 296*, 1846-1849. [13] Duncan R.A. (2002) *J. Petrol*. 43, 1109-1119. [14] Tejada M.L.J. et al. (2016) *GCA 185*, 302-327. [15] Head J.W. (1975) *Origin of Mare Basalts, Proc. Lunar Sci. Conf. 234*, 66-69. [16] Head J.W. (1976) *Rev. Geophys. Space Sci. 14*, 265-300. [17] Cooper M.R. et al. (1974) *RGSP 12*, 291-308. [18] Hiesinger H. et al. (2010) *JGR 115*, 10.1029/2009JE003380. [19] Snyder G.A. et al. (1994) *GCA 58*, 4795-4808. [20] Shih C.-Y. et al. (1999) *LPSC 30*, #1787. [21] Nyquist L.E. et al. (1981) *EPSL 55*, 335-355. [22] Nyquist L.E. et al. (1979) *PLPSC 10*, 77-114. [23] Dasch E.J. et al. (1987) *GCA 51*, 3241-3254. [24] Dasch E.J. et al. (1991) *LPSC 32*, 275-276. [25] Papanastassiou D.A. & Wassrburg G.J. (1971) *EPSL 12*, 36-48. [26] Snyder G.A. et al. (1997) *LPSC 28*. [27] Snyder G.A. et al. (1998) *LPSC 29*, #1141. [28] Paces J.B. et al. (1991) *GCA 55*, 2025-2043. [29] Shih C.-Y. et al. (2000) *LPSC 31*, #1667. [30] Lunatic Asylum (1978) *Mare Crisium: View from Luna 24*, 657-678. [31] Carlson R.W. & Lugmair G.W. (1979) *EPSL 45*, 123-132. [32] Nyquist L.E. et al. (1975) *PLSC 6*, 1445-1465. [33] Shih C.-Y. et al. (1992) *EPSL 108*, 203-215. [34] Glotch T. et al. (2011) *GRL 38*, 10.1029/2011GL049548. [35] Jolliff B.L. et al. (2011) *Nat. Geosci. 4*, 566-571. [36] White R.V. et al. (1999) *Lithos 46*, 43-68.