

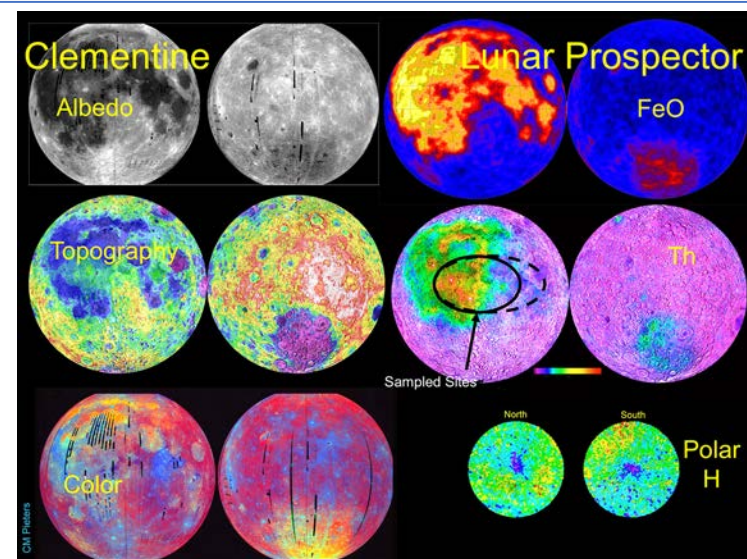
**GLOBAL COMPOSITION OF THE MOON (AS WE'RE LEARNING TO KNOW IT).** C. M. Pieters<sup>1</sup> <sup>1</sup>Dept. Earth, Environmental, and Planetary Sciences, Brown Univ., Providence RI 02912 (Carle\_Pieters@brown.edu)

**Introduction:** Lunar samples returned 40-50 years ago by the US and the former Soviet Union (Russia) continue to provide immeasurably valuable information constraining the character of the Moon and the evolution of the Earth-Moon system at 1 AU. Initial global compositional information was not obtained for the Moon until several decades later by the small Clementine and Lunar Prospector missions. (**Fig. 1**).

orbital missions carrying a diverse range of instruments starting in 2007: SELENE (Japan), Chang'E (China), Chandrayaan-1 (India), and LRO/LCROSS (USA). These orbital spacecraft achieved global coverage and provided a rich pulse of new and diverse compositional data. Two different aspects of the composition of the lunar surface are amenable to evaluation from an orbiting spacecraft: *elemental abundances* (e.g., Fe, Al, Si, Mg, Th, U, K, and H [2]) and *mineral composition* (e.g., plagioclase, pyroxenes of different composition, olivine, glass, spinel, ilmenite [3]). Elemental data are measured by neutron, gamma-ray, and X-ray spectrometers and the mineralogy is measured at higher resolution by optical instruments in the visible, near-infrared, and mid-infrared.

Although elemental abundance and mineralogy of the lunar surface are of course directly related, there are fundamental differences in how they are assessed and interpreted: in particular whether the surface is dominated by well-developed soils or rock fragments. Major changes occur as rocks are gradually transformed into soils (through space weathering [4]) altering the mineralogy dramatically. A well-developed mature soil has had the majority of its original minerals (50-80%) transformed into glassy aggregates called agglutinates. In contrast, the measured elemental abundance is relatively insensitive to changes in physical form, but both measurement types are affected by a degree of lateral (and vertical) mixing of different lithologies during regolith evolution.

For the Moon, an accurate albedo measurement can be a first order assessment of both elemental abundance and mineralogy. This is because anorthositic plagioclase is an Al-rich (Fe-poor) silicate that dominates much of the ancient highland crust as a relatively transparent (bright) mineral. In contrast, the basaltic maria contain Fe-rich minerals (pyroxenes, olivine) and variable amounts of opaque ilmenite and are relatively dark. This is apparent even in the Clementine albedo data where the ancient highlands are bright and the maria are dark. More importantly, the non-mare interior of SPA is a dark smudge on the farside reflecting its bulk composition is both Fe-rich and contains abundant Fe-bearing minerals (pyroxene). One of the most unusual and useful measurements of albedo of the Moon was obtained with the laser altimeter on LRO [5] which supplied both the light source and the detector, providing

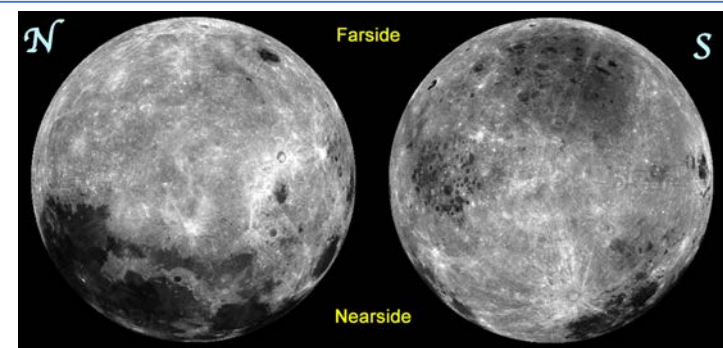


**Fig. 1.** Summary of global lunar data returned by the Clementine and Lunar Prospector missions that orbited the Moon 1994-1998. Integrated analyses of the data (nearside-left; farside-right) are discussed throughout [1]. Shown on the nearside Th map is the approximate area sampled by Apollo (solid) and Luna (dashed) landers.

Highlights from these small missions include: a) The lunar farside is *quite* different from the nearside (previously studied via telescopes) and contains the most extreme topography, the largest and oldest basin on the Moon (South Pole-Aitken, SPA), and the most iron-poor as well as the most iron-rich non-mare regions of the Moon. b) The largest concentration of heat-producing elements such as Th, however, were found to occur on the nearside and are associated with a wide diversity of mare basalt compositions and ages. c) The polar areas are special and exhibit enhanced concentrations of Hydrogen, presumed to be OH or H<sub>2</sub>O trapped or buried in the cold shadowed areas. It became evident that samples from the six Apollo and three Luna sites represent only a fraction of global lunar lithologies.

The taste of global information from these two small missions stimulated an appetite for broader global lunar data using more modern instruments, and the international community responded with a series of successful

normal albedo data of the surface with no shadows. This allows a unique view of lunar albedo across high latitudes and the lunar poles as shown in **Fig. 2**. The dark Fe-rich nature of SPA interior on the southern farside is evident (and later shown to be due to abundant low-Ca pyroxene [6,7]). The brightest areas are related to feldspathic very immature soils (low weathering).



**Fig. 2.** Normal albedo of the Moon at 1064nm obtained without shadows from LRO-LOLA [5]: (Left) North pole; (Right) South pole. (orthographic projection). Fe-rich lunar areas have lower albedo.

The scale and geologic context of lunar composition measured globally is critical for understanding relations between components of the crust and processes responsible for their origin. Evolution of the regolith (and mega-regolith) produces a breccia dominated surface affected by wide-spread mixing and abundant (weathered) soils across the surface. Nevertheless, these processes have not obliterated inherent compositional variations that have been retained and are exposed within many craters and basins and are accessible by high spatial and high spectral resolution data. The walls and central peaks of large craters, inner rings of basins, and individual fresh craters often provide particularly well preserved exposures of diverse primary lithologies. With high spatial resolution their relation can be discerned and the geologic context unraveled. An example is shown for Theophilus in **Fig. 3** where nearby (pyroxene-rich) mare basalt is exposed in the northern wall while deep-seated materials (Mg-spinel, pure plagioclase, and olivine), perhaps originally associated with Nectaris inner ring, are exposed in the central peaks [8, 9].

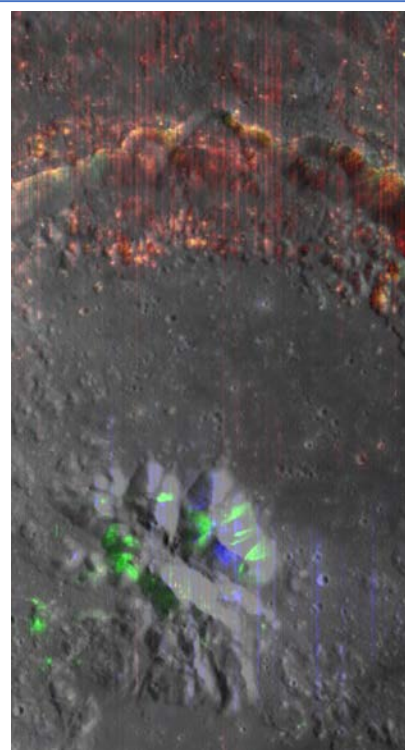
Over the last decade, sensors on orbiting spacecraft have documented and mapped a first-

order assessment of several rock types that form the global character of the lunar crust. Extensive pure anorthosite (PAN) with <3% mafics is identified in rocky areas across the highlands [10,11], strongly supporting the Magma Ocean hypothesis. PAN is particularly well exposed across the inner ring of the Orientale Basin [12]. Olivine-rich exposures, commonly as troctolite, are found near the Crisium, Moscoviense, and Imbrium basins [13]. Mg-spinel anorthosite, a new rock type [14] (not represented in current lunar samples), is exposed in diverse highland environs suggestive of excavation from the lower crust or upper mantle [9]. The principal mafic component identified throughout the upper megaregolith is low-Ca pyroxene (noritic anorthosite) [15], presumably the cumulative result of the early basin heavy bombardment and mixing. A similar highly noritic composition forms the bulk of the non-mare interior of the enormous SPA basin [6,7].

What is *not yet known* is how the olivine, troctolites, norites, or Mg-spinels are associ-

ated with the enigmatic “Mg-suite” identified in lunar samples. Most important for understanding the evolution of the lunar crust (and potential resources) are spatial relations and scale of diverse crustal materials that occur together in near-pristine geologic context (**Fig. 3** example). Progress in such investigations awaits the next generation of lunar exploration.

**References:** [1] Jolliff et al., Eds, 2006, *New Views of the Moon*. [2] Prettyman et al. 2006, *JGRP* 111. [3] Pieters, Klima, Green, 2019, in *Remote Compositional Analysis* (Bishop et al. eds) in press. [4] Pieters and Noble, 2016, *JGRP* 121, 1865-1884. [5] Lucey et al., 2014, *JGRP* 119, 1665-1679. [6] Moriarty and Pieters, 2018, *JGRP* 123, 729-747. [7] Ohtake et al., 20014, *GRL* 41, 2738-2745. [8] [Dhingra et al., 2011, *GRL* 38, L11201 [9] Pieters et al. 2014, *Am Min* 99, 1893-1910 [10] Ohtake et al., 2009, *Nature* 461, 236-240. [11] Donaldson Hanna et al. 2014, *JGR* 119, 1516-1545 [12] Cheek et al. 2013, *JGR* 118, 1-16 [13] Yamamoto et al., 2010, *Nat. Geoscience* 3, 533-536 [14] Pieters et al. 2011. *JGR* 116, E00G08 [15] Lucey et al. 2014, *Am Min.* 99, 2251-2257.



**Fig. 3.** Processed M<sup>3</sup> data across the ~100 km crater Theophilus [9]. The northern wall exposes pyroxene-rich materials (red), while the central peaks expose neighboring unusual Mg-spinel (green) and pure plagioclase (blue) materials