THE EARTH-LIKE, AND WÄNKE-LIKE, BULK COMPOSITION OF THE MOON

P. H. Warren[1] and M. A. Siegler[2], [1] Dept. Earth, Planet. & Space Sci., University of California, Los Angeles, CA 90095, USA, pwarren@ucla.edu, [2]Planetary Science Institute, Tucson AZ 85619, USA.

Heinrich Wänke was renowned for a wide spectrum of cosmochemical research, but perhaps his greatest contribution was made in constraining the bulk compositions of terrestrial planets, in the broad sense including Mars, the Moon and the eucrite parent body (Vesta, probably). For the Moon, Wänke [1] inferred a composition similar to that of the bulk silicate Earth (BSE), except depleted in volatiles and enriched in FeO. How does this issue stand today?

Apart from the undoubted Fe-metal disparity, basically three aspects of putative lunar bulk-compositional peculiarity were once popular [e.g., 2], and to varying extents remain semi-plausible. (1) In terms of major elements, relative to BSE, the bulk silicate Moon (BSM) was inferred by some to feature roughly 1.5× enrichments in Al_2O_3, CaO, TiO_2, along with some 25 other refractory lithophile elements, most notably the heat-producers Th and U. The only other heat-producing element, K, albeit not refractory conveniently correlates with Th and U among lunar materials. (2) FeO was inferred to be enriched by a similar (albeit basically unrelated) factor in the BSM relative to the BSE. (3) The Moon was for nearly four decades "known" to be depleted by immeasurable orders of magnitude in water (OH), along with less drastic but still large depletions in all other volatiles, relative to the Earth. The demise of model/prejudice (3) was rather sudden and dramatic, starting with [3]; such that today debate centers more on the 180° opposite hypothesis that the Moon and the Earth may contain nearly equal proportions of water [e.g., 4, 5]. Still, and despite their importance for understanding lunar origin and evolution, the water, refractory-lithophile and FeO issues remain in need of clarification.

Isotopic composition is a significant, genetically diagnostic aspect of bulk composition. As advances in technique (and sampling) have furnished more and more precise constraints, the stable isotopes have tended to reveal a remarkable degree of Earth-Moon similarity. Oxygen isotopes [6] are the most precisely constrained, but the Earth-Moon similarity is most impressive because other stable isotopes that manifest great diversity among planetary materials, such as those of Cr and Ti (which are not in any simple way overall-correlated with O isotopes), also show indistinguishable Earth and Moon compositions [7, 8]. A match in any one of these isotopic systems, even a very close match, is conceivably a statistical fluke. Consistent match-up among several different systems greatly compounds the improbability of some such fluke. The isotopic evidence implies that Earth and its Moon came preponderantly from a single distinctive reservoir of solar system material.

Heat flow is an excellent means of constraining bulk-Moon Th and U (and probably with them, Al_2O_3, CaO, etc., as well as K). Yet until this year [9], heat flow had only been measured at two central nearside sites. The new measurement is only an upper limit, but it greatly clarifies the Moon's global heat flow. It is now clear that heat flow correlates with variations in crustal composition. Assuming that most of the Moon's Th and U are in its crust [10], the new result [9] is difficult to reconcile with BSM Th any higher than 90 ng/g; which leaves only modest potential for disparity vs. the BSE (~75 ng/g). GRAIL's finding of a lower crustal mass [11] has also destroyed the old mass-balance incentive for high BSM Al_2O_3 and CaO.

The traditional way of constraining both FeO and water is by analogy between mare basalts and terrestrial basalts such as MORB. However, the mare source was not a tectonically stirred near-uniform reservoir but a grossly heterogeneous magma-ocean cumulate pile. It may be wishful thinking to assume that melting is as composition-independent (especially for a melting-fluxer like water) in the latter case as in the former. A simple density modeling approach [8] enabled by the GRAIL data-bonanza suggests that FeO is *mildly* enriched in the BSM. As evidence accumulates for Earth-Moon similarity in water content, it should be borne in mind that plenty of evidence shows the Moon is at least mildly depleted in most volatile elements. The lunar K/U ratio is tightly constrained to be about 1/4 that of the BSE [12]. The major element sodium is clearly depleted by a similar factor. Mare and KREEP basalts consistently show F/Nd depleted by about an order of magnitude, and Cl/Nb depleted by nearly two orders of magnitude, versus MORB [13].

References: [1] Wänke H. and Dreibus G. (1982) In *Tidal Friction and the Earth's Rotation II*, ed. by Brosche P. and Sündermann J., pp. 322–344. [2] Taylor S. R. et al. (2006) *Geochimica Cosmoch. Acta*, 70, 5904-5918. [3] Saal A. E. et al. (2008) *Nature* 454, 192-196. [4] Hui H. et al. (2013) *Nature Geosci.* 7, 177-180. [5] Chen Y. et al. (2015) *Earth and Planetary Sci. Letters* 427, 37-46. [6] Young E. D. et al. (2016) *Science* 351, 493-496. [7] Warren P. H. (2011) *Earth and Planetary Sci. Letters* 311, 93-100. [8] Dauphas N. et al. (2014) *Philosophical Transactions Royal Soc*. 372: 20130244. [9] Paige D. A. and Siegler M. A. (2016) *Lunar and Planetary Sci.* 42 abs. #2753. [10] Warren P. H. (2005) *Meteoritics and Planetary Sci.* 40, 477-506. [11] Wieczorek M. A. et al. (2013) *Science* 339, 671–675. [12] Eldridge J. S. et al. (1974) *Proceedings of the Fifth Lunar and Planetary Sci. Conference,* 1025-1033. [13] Greenwood J. P. et al. (2016) *Lunar and Planetary Sci.* 42 abs. #2484.