

CAVEAT! CALIBRATION COMPLEXITIES FOR REFLECTANCE SPECTROSCOPY OF ANORTHOSITIC LUNAR SOILS. P. H. Warren¹ and R. A. Korotev², ¹Earth, Planet. & Space Sci., UCLA, Los Angeles, CA 90095, pwarren@ucla.edu, ²Earth & Planet. Sci., Washington Univ. St. Louis, MO 63130, korotev@wustl.edu.

Introduction: Major advances in lunar science have been achieved through remote sensing of the Moon's surface composition. Unfortunately, however, in circumstances of limited ground truth, compositional extremes may pose calibration challenges for remote sensing. Results from visible-near-IR reflectance spectroscopy (RS) have been interpreted as showing that "purest anorthosite" (PAN) is the preponderant material in most of the lunar crust [1,2], with PAN somewhat inconsistently defined as having "~ 98" or ">98" vol% or "≥98" plagioclase [3,1,2]. Kaguya (KSP) reflectance data were also used to construct a map for mafic silicate abundance (MSA) for ~55% of the Moon's surface, indicating that MSA of the global median surface is only about 9.7%, and at the Apollo 16 site 7.5% [4]. Other, less extreme, claims for abundant crustal PAN include [5, 6]. In this work, we first document how badly the KSP [4] calibration appears to under-measure MSA, and then explore possible causes of systematic miscalibration of spectral reflectance data for MSA in anorthositic soils.

Evidence of miscalibration: The MSA calibration was checked by [4], who found fairly good agreement between RS-measured and "real" (lab-measured) MSA for four Apollo 16 soils. However, the "real" MSA data plotted by [4] are of mysterious provenance and egregiously incorrect (Fig. 1). Very helpful in this connection is a new large data set for MSA in Apollo soils determined using XRD [7]. *For purposes of relating RS results to crustal rock-type abundances* [1,2], even the XRD results need to be interpreted with care, because in typical lunar soils a huge proportion of the MSA has been transformed into impact-engendered glass. The disparity between the MSA results of [4] and the MSA implied by applying CIPW to bulk-soil composition data [from various literature sources] averages about a factor of *four*.

Next, consider the entire ~30 km² area of the Apollo 16 site, for which the KSP result is explicitly given as 7.5% [4]. The average XRD [7] result for MSA in 33 soils from all across the site is (converted to vol%) 10.7%, or 15.1% on a nonglass basis. The average CIPW result (converted to vol%) is 18%. Analogous treatments of CIPW and modal data from the anorthositic Luna 20 site indicate similar, factor of 3, discrepancy; as do data from the anorthositic South Massif soils from Apollo 17.

Bulk-compositional data for 81 lunar meteorites, as a statistical population, constrain the median global

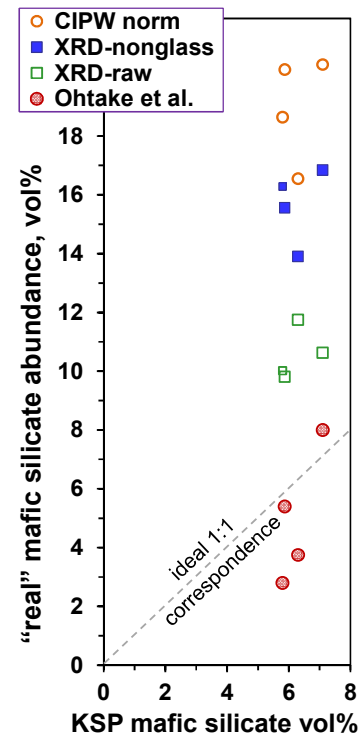


Fig. 1: Calibration check for MSA in soils 62231, 64801, 66041 and 67601. In the case of 64801, the closest XRD [7] counterpart is 64421 (smaller symbols), acquired 65 meters to the northeast.

surface mineralogy. The median Al₂O₃ content, 25.9 wt%, translates (precise methodology too complex to cover here; the data of [7] are again helpful) to a MSA (ignoring the impact-glass complication) of 20.3%, more than twice the median MSA, 9.7%, found by [4].

Comparison with other remote sensing results is also revealing. The global median Al₂O₃ found by Lunar Prospector's Gamma-Ray Spectrometer, 24.7 wt% [8], implies a MSA of 22.8%. The Chang'E-2 X-Ray Spectrometer [9] found 22.6 wt% Al₂O₃, implying for MSA 27.4%, nearly 3 times the KSP result [4].

Possible causes of miscalibration: How could a straightforward technique like spectral reflectance engender such misleading results? Part of the problem is that RS does not measure, in a representative way, the bulk soil. It only measures the crystalline portion (sometimes less than half) of the soil. Worse, RS data are predominantly derived from the volumetrically minor (typically ~15 wt%) <20 μm grain-size fraction; the 10-20 μm fraction "is the most similar to the overall spectral properties of the bulk soil" [10].

Some older studies show only limited mineralogical difference between coarse, moderate, and fine grain-size fractions in lunar soils. However, the last and most comprehensive single study of this type [10] found that in six anorthositic soils (the only type of

interest here) the 10-20 μm fraction shows very strong and consequential fractionations.

Averages of data from [10] for these six soils indicate that impact glass (“agglutinitic glass”) is more abundant in the 10-20 μm fraction than in bulk soil [7; and other sources] by an average factor of 1.54; and MSA is lower in the 10-20 μm fraction than in the next coarsest (20-45 μm) fraction by a factor of 0.69. The 10-20 μm fraction is depleted in MSA relative to the bulk-soil CIPW norm MSA by factor of 0.33. The latter fractionation may seem incredible, but displacement of crystalline pyroxene and olivine by impact glass is only part of the story. Trends in a separate set of FeO-compositional data from [10] suggest that mafic silicates are preferentially destroyed (and plagioclase is preferentially preserved) by the agglutinate-formation process: Within the relevant 10-20 μm size fraction, FeO content (a proxy for MSA) is about twice as high in the impact glass component as in the nonglass component (Fig. 2).

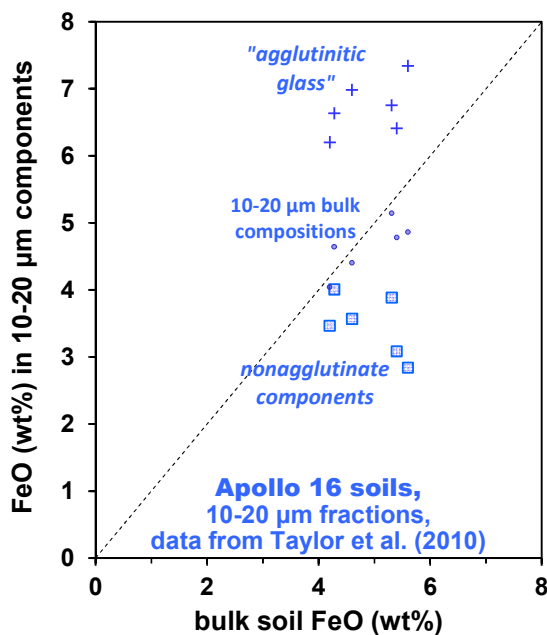


Fig. 2: FeO content comparison, between the bulk soil and the two separate, nonagglutinate (square symbols) and agglutinate (+ symbols), components of the 10-20 μm fraction, for six Apollo 16 soils (61221, 61141, 62231, 64801, 67461 and 67481). The 10-20 μm (y-axis) data are derived entirely from Taylor et al. (2010), including by mass balance for the nonagglutinate FeO (assuming that agglutinates are less dense than bulk 10-20 μm matter by a factor of 2/3). Bulk soil data are from the literature, mainly the Lunar Sample Compendium.

These results from [10] cry out for testing and confirmation. But support for a glass/nonglass chemical fractionation can also be found in the Apollo

16 soil XRD data of [7], which show otherwise puzzling systematic enhancements in plagioclase/MSA (in the surviving nonglass components) relative to the ratios implied by a wealth of literature bulk-compositional (and CIPW) results.

These patterns are found in anorthositic Apollo 16 soils. In more extremely anorthositic soils such fractionations might be commensurately more pronounced. The mechanism that engenders the fractionations is far from obvious, but an old model inspired by an admittedly dubious data set [11] may still be valid. This model assumes that the porous, fine-grained nature of the lunar surface, and the small scale of relevant impacts, causes impact melt (glass) to form largely due to dispersed superheated impact melt+vapor splashes, and preferentially where grains of roughly cotectic mineralogy (subequal mafic and plagioclase) meet. In an anorthositic soil, this translates into a tendency to preferentially melt mafic silicates.

“PAN” locales are still interesting: The inferred need for recalibration does not nullify the fact that some regions of the Moon’s highland surface appear from RS especially anorthositic. The distribution of these locales is far from random [2,5,6]. The Apollo samples include 60015, a 28×15×10 cm rock that, apart from a thin impact-melt glass coating, is 99 vol% plagioclase (the second largest Apollo anorthosite, 60025, has ~10 vol% mafic minerals). However, the volume of 60015 is lower by a factor of roughly 10^{15} than the smallest region measureable by orbital RS.

Apart from the RS calibration issue, extrapolating from a few scattered “PAN” locales to the wider crust [2,3] is hazardous without careful appreciation for statistical effects that arise when a very large dataset with significant uncertainty is employed near an extreme of the measurement range. The LPGRS data set [8] supplies a convenient analog. In this fine but not highly precise set of results, the sum of oxides, which in reality is surely never above 100 wt%, is for 2% of the measured regions greater than 103.5 wt%. The true composition of the identified “PAN” locales may be only mildly exceptional; and true PAN may be nonexistent, at orbital RS scale, in the lunar crust.

References: [1] Yamamoto S. et al. (2012) *GRL*. [2] Yamamoto S. et al. (2015) *JGRP*. [3] Ohtake M. et al. (2009) *Nature*. [4] Ohtake M. et al. (2012) *Nature Geosci.* [5] Cheek L.C. et al. (2013) *JGRP*. [6] Hanna K.L.D. et al. (2014) *JGRP*. [7] Taylor G.J. et al. (2019) *GCA*. [8] Prettyman T.H. et al. (2006) *JGRP*. [9] Dong W-D. et al. (2016) *Res. Astron. Astroph.* [10] Taylor L.A. et al. (2010) *JGRP*. [11] Rhodes J.M. et al. (1975) *Proc. Lunar Sci. Conf.*, 6.