REGOLITH COVERAGE INFERRED FROM OPTICAL MATURITY AND SLOPE DATA FOR THE MAJORITY OF REPORTED LUNAR PURE PLAGIOCLASE SURFACES.

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On the basis of reflectance spectroscopy observations (comparison between iron absorption band strengths in plagioclase versus mafic silicate), numerous locales have been identified where the lunar surface reportedly contains a remarkably high abundance of plagioclase. Ohtake et al. [1] and Yamamoto et al. [2] reported many locales as being "PAN" (purest anorthosite, ≥98% plag). Donaldson Hanna et al. [3] identified many additional locales as "pure crystalline plagioclase" (≥99% plag; to minimize confusion, we will hereafter refer to "pure crystalline plagioclase" as PAN99). So widespread are the reported PAN and PAN99 locales that [2] suggested that most of the lunar crust is PAN, and [3] inferred "an extensive zone of highly pure (≥99% plagioclase) … anorthositic crust" associated with "most of the nearside and farside multiring and peak ring basins." Such inferences have profound implications for the bulk composition of the lunar crust, for the gross evolution of the Moon, and particularly for the hypothesis that a magma ocean produced the initial crust by buoyant flotation of plagioclase [4, 5].

In a paper in press [5] we urge caution regarding the PAN and PAN99 claims. There is little reason to doubt that the locales in question feature relatively low mafic abundances. But just how low, quantitatively, is not so clear. Nonuniform FeO content in plagioclase [6] is just the simplest, most easily understood of several potential complications. In any case, the broad lunar-science significance of the PAN and PAN99 observations depends in large measure on whether the surfaces in question are exposures of bare rock, or mixed regolith. If regolith, the materials have been systematically blended, with significant dilution of the underlying solid crust by debris of distant provenance. The efficiency of this horizontal mixing is highly uncertain, but one estimate [7] is that 20-30% of typical lunar regolith material originates from >100 km horizontal distance. Survival of a PAN99 composition in regolith form is thus even more remarkable than its existence in rock form at the scale (0.4-0.7 km) of the PAN99 [3] measurements.

Ohtake et al. [1] claimed that their PAN locales are mostly "fresh and nearly regolith-free". However, as noted by [8], the rate of growth of regolith is initially quite rapid; the growth rate gets slower and slower as thickening of the regolith shields underlying rock against continued impact disaggregation. In the model of [8] the thickness Z grows according to $Z = kt^{0.64}$, where t is time and the constant k is assumed to be 208 to match early regolith thickness observations (higher k by a factor of 3 or more is suggested by more recent observations, e.g. [9]; the model does not account for regional slope).

Figure 1 shows the regolith thicknesses implied (sticking with $k = 208$) for the features where [1] and [3] reported finding PAN and PAN99 compositions, translated from age estimates taken from the vast crater-count literature. For PAN99 [3] locales, only those of the freshest "degradation" class are shown. The age estimates employed are not averages or preferred values; to be conservative we employ the youngest age in any case where multiple estimates have been published. Admittedly some of the precise PAN locales might be fresher than the listed features as a whole (e.g., a younger crater within the cited crater). Nonetheless, considering that the spectral reflectance technique *measures less than a millimeter deep*, only very extraordinarily young features are predicted to be close to regolith-free.
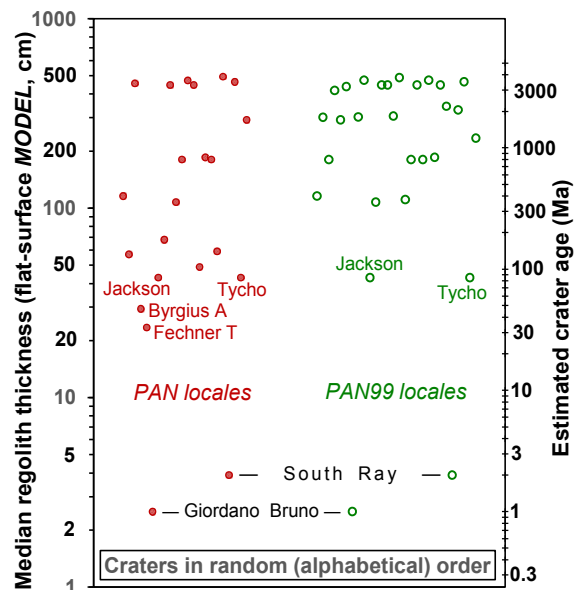

Fig. 1. Age and age-implied regolith thickness predicted by the model of [8] for various PAN/PAN99 locales.

We have also evaluated the PAN99 locales for two other relevant parameters, optical maturity "OMAT" [10] and slope [11], using the excellent LROC

"QuickMap" web app. We studied all the locales in Table 1 of [3] for which the descriptions are unambiguous (a location designated as "ejecta" for example, is considered too vague).

Regolith maturity is relevant if only because bare rock, or locales dominated by bare rock, ought to evince very little indication of optimal maturation. Most of the lunar surface has OMAT between 0.15 and 0.25, but OMAT in a regolith-free surface should in principle be far higher than 0.625, the value found by [10] for uncommonly immature regolith sample 15401, or anyway far higher than 0.48, the OMAT of immature regolith sample 61221.

Slope is relevant because a sufficiently steep locale might not be able to form, or sustain, regolith. The static angle of repose of lunar regolith is variously estimated at from 40 to 50 degrees [12], although the dynamic angle of repose is closer to 30 degrees. However, the Apollo missions closely approached locales, Hadley Rille and the mountains (North Massif and South Massif) adjacent to the Apollo 17 site, that in all cases indicate slopes locally (on a scale of 60+ m) as high as 33 degrees develop and sustain regoliths. The regolithic covering over most of the two massifs (whose overall average slopes are about 27 degrees) is documented by OMAT measurements (generally 0.2-0.3), and by the many boulder tracks, which are typically near-continuous, and feature widths comparable to the widths of the boulders; i.e., the boulders did not bounce off the ground as much as they would have over solid-rock steep slopes, and they plowed deep into the soft surface as they slid down. See, for example, LROC image M134991788RE.

In utilizing the available data for OMAT and slope, it is necessary to ignore scattered instances where a long column of pixels (series of orbital observations) is clearly out of calibration, either far too high or far too low, relative to the background. Although we exclude such obvious calibration artifacts, we seek to find the very highest slope, and highest OMAT, within the general area of each PAN99 locale described by [3]. This approach is likely conservative, inasmuch as in some instances PAN99 might have been located at a detailed position with lower OMAT and/or slope than the regional maximum.

Results for (maximal) OMAT and (maximal) slope are shown in Fig. 2. For most of the investigated locales, OMAT is too low ($\ll 0.6$) to be consistent with a surface not dominantly covered by regolith. For some of the locales where (maximal) OMAT is only known to be > 0.49, a major presence of regolith is also inferred because slope is only moderate; i.e., not greater than about 33 degrees (assuming the Hadley Rille and Massif slopes happen to be at the limit). Out
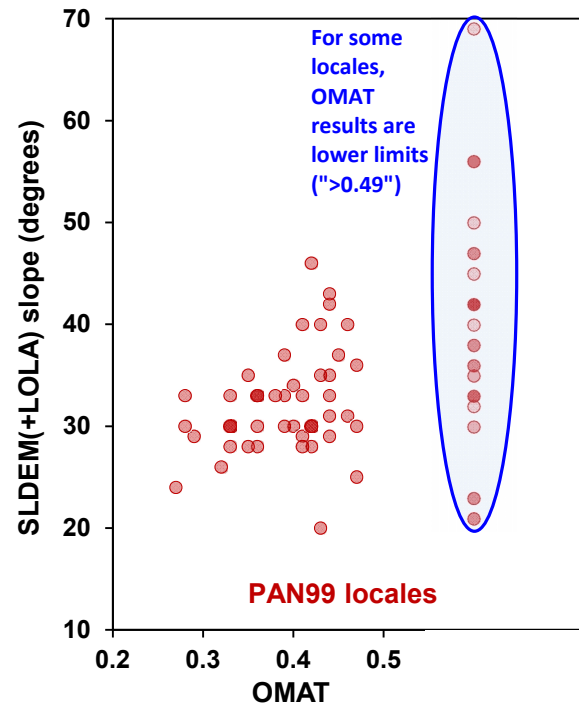

Fig. 2. Results for maximum regolith optical maturity index (OMAT, lower is more mature [10]) and slope at reported [3] PAN99 locales.

of 110 PAN99 locales investigated, only 21 have (maximal) OMAT > 0.47, and only 15 of those 21 have (maximal) slope > 33 degrees. Only a total of 11 locales (10%) have OMAT > 0.47 coupled with slope > 36 degrees. We infer that *the vast majority of the PAN99 locales are surfaced predominantly by regolith*, not bare rock.

One of the best documented PAN99 locales ([3], also well documented as PAN by [1]) is the central peak of Jackson. This is one of only a handful of locales where combinations of high slope and OMAT > 0.49 are not just present, they are widespread. However, even here, and apart from Fig. 1, there are complications. For example, the highest levels of the Jackson central peak are more mafic-rich: pyroxene is 10% and $\geq 20\%$ at two locales measured by [1].

References: [1] Ohtake M. et al. (2009) *Nature*. [2] Yamamoto S. et al. (2012) *GRL*. [3] Donaldson Hanna K. L. et al. (2014) *JGRP*. [4] Wood J. A. et al. (1970) *Proc. Apollo 11 LSC*. [5] Warren P. H. and Korotev R. L. (2022) *MAPS*, in press. [6] Helz R. T. and Appleman D. E. (1973) *Proc. LSC4*. [7] Li L. and Mustard J. F. (2005) *JGRP*. [8] Quaide W. L. and Oberbeck V. R. (1975) *Moon*. [9] Qian Y. et al. (2021) *EPSL*. [10] Lucey P. G. et al. (2000) *JGRP*. [11] Smith D. E. et al. (2010) *GRL*. [12] Khademian Z. et al. (2019) *JGRP*.