ABUNDANCE AND DISTRIBUTION OF LUNAR PRIMARY CRUST ANORTHOSITE: THE FEATURELESS PLAGIOCLASE CHALLENGE.

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Introduction: Spectroscopic analyses of lunar materials (samples in the laboratory and the lunar surface using remote sensors) have been quite successful in identifying several iron-bearing minerals and mapping their distribution across the Moon [1, 2]. The origin of diagnostic absorption features is well founded in mineral physics [3], and for lunar materials is most commonly linked to ferrous iron. However, the principal crustal component derived from lunar magma ocean crystallization, cumulate plagioclase, was initially identified by the lack of any discernible mafic absorption features across the near-infrared (NIR) region [2, 4]. Since these featureless areas occurred in the Al-rich highlands [5], and plagioclase dominates the returned highland samples, the logic for plagioclase identification by a *lack* of ferrous features in remote sensing data was generally accepted.

Nevertheless, when mafic minerals are absent, NIR spectra of relatively transparent crystalline plagioclase measured in the laboratory exhibits a regular absorption band centered near 1.25 µm (1250 nm) [6], even when the FeO content of plagioclase is only 0.1-0.3%. All available laboratory spectra of lunar anorthosite samples, some of which contain shock effects (planar fractures, maskelynite) [7, 8], exhibit the diagnostic absorption properties of crystalline plagioclase (Fig. 1).

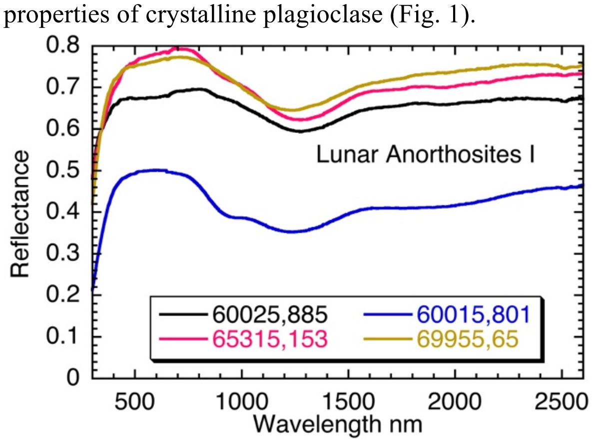

Fig. 1. Laboratory reflectance spectra of lunar anorthosite samples (RELAB BDR). All exhibit the diagnostic absorption near 1250 nm due to ferrous iron in plagioclase. 60015 also exhibits a weak feature (near 900 nm) mainly due to the presence of trace amounts of low-Ca pyroxene.

Crystalline plagioclase with a 1.25 µm feature was eventually detected using modern spectroscopic instruments orbiting the Moon [9, 10] and was found to be widespread across the highlands [9, 11]. At high spatial resolution crystalline plagioclase was usually found with the more common 'featureless plagioclase' (shown in Fig. 2.). The challenge for remote compositional analyses is that ***no*** 'featureless plagioclase' has been identified in lunar samples to validate interpretations of the remote data. In addition, *no* outcrops or mountains exhibiting pure maskelynite properties (Fig. 2) have been identified in remote spectra of the surface.

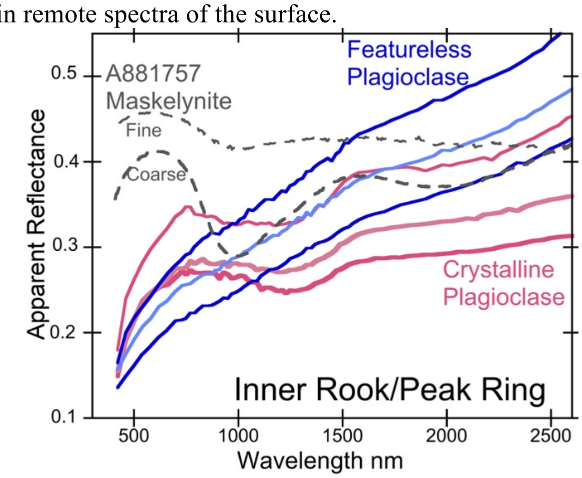

Fig. 2. M^3 spectra of crystalline and 'featureless' plagioclase found along the Orientale Inner Rook mountains [10,12]. Shown for comparison are offset laboratory spectra of clean maskelynite from the gabbroic lunar meteorite A881757.

The origin and distribution of featureless plagioclase: Evaluating the character and scope of the primary anorthositic lunar crust relies on establishing a valid link between the pervasive observations of crystalline plagioclase and those of featureless plagioclase.

Option I: Abundance of iron. Due to crystallographic properties of the site accommodating small amounts of iron in plagioclase, the strength of the 1.25 µm ferrous absorption varies linearly with the abundance of iron [13]. This relation has been confirmed with reflectance spectra of synthetic plagioclase over the range of iron found in lunar samples [14]. Theoretically, featureless plagioclase could represent a plagioclase composition with $\ll 0.1\%$ FeO.

Geologic relations between crystalline plagioclase and featureless plagioclase mapped by M^3 argue against a separate and exceptionally low value of FeO for featureless plagioclase. As illustrated in a traverse across the plagioclase-rich inner ring of the Orientale Basin illustrated in Fig. 3 [12], there is no measurable distinction between the two types of material – both are part of the same ridge that is believed to be crustal material uplifted during the basin forming event. Crystalline plagioclase is observed throughout the entire inner ring [12].

Option 2: Space weathering. Although mafic-poor well-developed highland soils exhibit an almost featureless spectrum, mature soils are also darker than the craters or steep slopes that host featureless plagioclase. Nevertheless, the rate of space weathering for crystalline plagioclase is unknown and all featureless plagioclase areas exhibit the classic red-sloped continuum of lunar space weathered materials (see Fig. 2). This option was reviewed by [15] who note similarities in the distribution of crystalline and featureless plagioclase from Kaguya data and propose a space weathering mechanism. The distributions were also examined using M^3 data by [11] and, although the patterns were similar, the featureless plagioclase regions appear more wide-spread than those seen in Kaguya data. One example that argues against space weathering is the prominent outcrop of featureless plagioclase along a cliff in Theophilus central peaks [16].

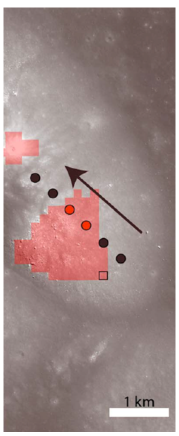

Fig. 3. Example distribution of crystalline plagioclase (red) measured by M^3 within the inner ring of the Orientale Basin [from 12]. Variations along a traverse path change from 'featureless plagioclase' (black) to crystalline plagioclase and back. Since no compositionally related properties distinguishing the featureless and crystalline plagioclase regions are recognized anywhere along the inner ring, it appears unlikely that the 'featureless plagioclase' is due to a distinct plagioclase-rich unit with a very much lower iron content.

Option 3: Impact or shock effects. In initial investigations of featureless plagioclase using spectroscopic techniques, it was assumed that the featureless signature found at bright fresh craters or mountains was due to the impact process and mineral physics. When shocked, plagioclase loses its crystal structure becoming diaplectic glass, or maskelynite. That could certainly account for the loss of a 1.25 µm band. However, spectra of pure maskelynite exhibit a weak ferrous glass absorption near 1 µm (see Fig. 2). Furthermore, in controlled shock experiments [17], the 1.25 µm band of plagioclase was indeed lost with increasing shock pressure but was replaced with the ferrous glass feature of maskelynite.

Option 4: Internal scattering. Shock produces internal fractures and micro-interfaces. If abundant at a fine scale, such scattering interfaces will reduce the optical path length in a transparent medium. Whether glass or crystalline, transparent heavily shocked plagioclase with multiple internal reflection interfaces cannot host a sufficiently large optical path length for detection of the plagioclase (or glass) diagnostic ferrous feature.

Option 5: None or some of the above. To be determined, of course.

New lunar sample measurements. This issue and the overall assessment of crustal anorthosite can best be resolved if a lunar plagioclase sample that exhibits featureless spectra can be identified for analysis. Three additional Apollo 16 anorthosite samples were identified from literature descriptions as being particularly shocked or rich with maskelynite: 61016, 60055, and 60215. All are believed to represent ancient 'pristine' anorthosite. Fines of each (200 mg) were allocated for measurement in RELAB and initial results are shown in Fig. 4. Measurements were made at ambient conditions across the visible with the bidirectional reflectance (BDR) spectrometer to maintain photometrically accurate brightness measurements. These were spliced to FTIR data obtained across the NIR region in dry-air purged environment to allow hydration features near 3 µm to be assessed.

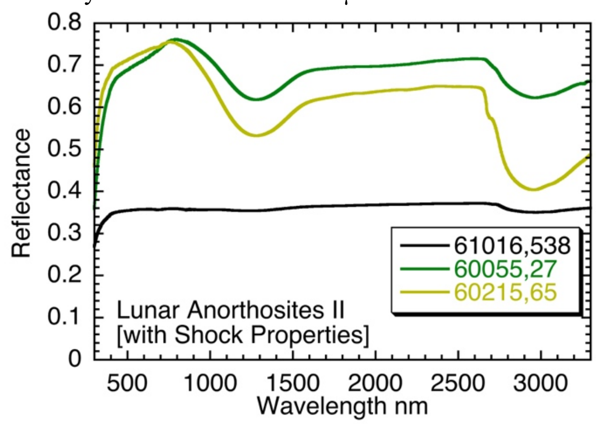

Fig. 4. Recent reflectance spectra of additional Apollo 16 anorthosite samples selected because they are described as exhibiting prominent shock features. RELAB ambient BDR spectra spliced with FT-NIR spectra (dry-air purged).

Conclusions: Although two of the newly allocated anorthosite samples clearly exhibit a crystalline 1.25 µm absorption band of plagioclase, 61016 does not. The anorthosite of 61016 occurs as a 'cap' of shocked anorthosite overlying an aluminous impact melt rock. This large rock ("Big Muley") is believed to be derived from South Ray Crater. Unfortunately, our 61016,538 sample contains trace amounts of 'saw fines' metallic contamination, requiring further investigation. Nevertheless, we are encouraged to have one solid lead for analyses that may resolve the origin of lunar 'featureless plagioclase'.

References: 1] Adams & McCord 1972, *PLPSC 3d;* McCord et al., 1981, *JGR* 86, B11 [2] Pieters C.M. 1986, *Rev Geophy* 24, 557 [3] Burns R.G. 1993, *Crystal Field Theory*, Cambridge Univ. Press [4] Hawke et al., 2003, *JGR* 108, E6 [5] Adler & Trombka 1977. *Phys. Chem. Earth*, 10, 17 [6] Adams J. B. & Goullaud, 1978, *PLPSC 9th,* 2901 [7] McGee J. J. 1993, *JGR, 98,* 9089 [8] Cheek et al. 2013, *LPS44* #2387 [9] Ohtake et al. 2009, *Nature*, 461, 236 [10] Pieters et al. 2009, *LPS40* #2052 [11] Donaldson Hanna et al., 2014, *JGR* 119, 1516 [12] Cheek et al., 2013, *JGR* 118, 1805 [13] Bell P. M. and Mao H. K. (1973) GCA, *37 755.* [14] Cheek et al. 2011, *LPS42* #1617 [15] Yamamoto et al., 2015, *JGR*, 120, 2190 [16] Dhingra et al., 2011, *GRL* 38, L11201 [17] Johnson and Hörz 2003, *JGR* 108 (E11) 5120.