Geochemistry of the lunar highlands as revealed by measurements of thermal neutrons

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Abstract Thermal neutron emissions from the lunar surface provide a direct measure of bulk elemental composition that can be used to constrain the chemical properties of near-surface (depth < 1 m) lunar materials. We present a new calibration of the Lunar Prospector thermal neutron map, providing a direct link between measured count rates and bulk elemental composition. The data are used to examine the chemical and mineralogical composition of the lunar surface, with an emphasis on constraining the plagioclase concentration across the highlands. We observe that the regions of lowest neutron absorption, which correspond to estimated plagioclase concentrations of >85%, are generally associated with large impact basins and are colocated with clusters of nearly pure plagioclase identified with spectral reflectance data.

1. Introduction

Thermal neutron emissions provide a sensitive indicator of the bulk concentration of neutron-absorbing elements, which for the Moon includes Fe, Ti, and the rare earth elements (REEs) Gd and Sm [Elphic et al., 1998, 2000, 2002]. These elements are diagnostic indicators for basaltic volcanism (Fe- and Ti-rich materials), fractional crystallization (REE-depleted/enriched materials), and cumulate floatation (Fe- and REE-poor materials) during the cooling of a global magma ocean (GMO). As a consequence, neutron measurements provide a useful data set for constraining the igneous processes that formed the Moon’s present-day crust [e.g., Feldman et al., 2000].

The Lunar Prospector (LP) Neutron Spectrometer (NS) acquired measurements of lunar thermal neutron emissions from lunar orbit. To date, these data have been used to examine global distribution of Fe, Ti, and REEs [Elphic et al., 1998, 2000, 2002], with particular emphasis on high-absorption regions. We present a new calibration of the LP/NS thermal neutron map, providing the first map of absolute values of neutron absorption across the Moon. The data clearly delineate between the major geochemical terranes of the lunar surface—the Procellarum KREEP (potassium, rare earth element, and phosphorus) terrane (PKT), the South Pole-Aitken basin (SPA) terrane, and the feldspathic highlands terrane (FHT) [Jolliff et al., 2000]—and reveal compositional variability within these regions. Within the FHT, we identify numerous, large regions of low neutron absorption whose properties are consistent with presence of high (>85 wt %) concentrations of plagioclase. This hypothesis is supported by comparisons of absorption data to albedo and spectral reflectance measurements.

2. Thermal Neutron Measurements

2.1. Neutron Production

Neutron emission from the lunar surface is the result of a complex series of nuclear interactions initiated by surface-incident galactic cosmic rays (GCRs). GCRs penetrate the surface to depths of several meters, along the way inducing spallation reactions with the constituent nuclei of the lunar surface. Spallation liberates neutrons from nuclei at initial energies of ~1–10 MeV. As these neutrons traverse lunar materials, some are downscattered to lower (epithermal, thermal) energies through nuclear elastic and inelastic scattering. Modeling of neutron production and transport (section 3.3) indicates that the thermal neutrons that escape the surface were created at an average depth of ~60 cm.

Thermal neutrons, defined here as neutrons having energies <0.4 eV, are readily absorbed by elements with high neutron absorption cross sections. On the Moon, absorption is dominated by four elements—Fe, Ti, and the REEs Gd and Sm [Elphic et al., 1998, 2000, 2002]. The thermal neutron flux takes the form of a temperature-dependent Maxwellian distribution whose magnitude increases until it reaches equilibrium with the rate of...
Thermal neutron count rates are derived from LP/NS measurements. The NS consisted of two $^3$He gas proportional counters, which detected neutrons with energies below $\sim 1$ MeV via the $^3$He + n $\rightarrow ^{3}$H + p reaction [Feldman et al., 2004], which converts neutrons (n) into charged particles ($^3$H, p) whose energies sum to the characteristic Q value for the reaction (0.764 MeV). One of the two sensors was covered in Cd foil, which effectively absorbs thermal neutrons and prevents them from reaching the sensor. The Cd-covered sensor is therefore an epithermal ($>$0.4 eV) only neutron detector. The other detector was covered in a Sn foil, which is transparent to neutrons and has response to $>$0.4 eV neutrons that is the same as that of the Cd-covered sensor. The Sn-covered detector is therefore sensitive to thermal + epithermal neutrons, and the difference in count rates between the Cd- and Sn-covered sensors is defined as the thermal neutron count rate.

Thermal neutron emissions from the lunar surface during its 19 month orbital mission (6 January 1998 to 31 July 1999). Our analysis focuses on data acquired during the 30 km altitude orbits (19 December 1998 to end of mission), which provided the highest spatial resolution (~45 km full width at half maximum; Maurice et al. [2004]) measurements. Derivation of neutron count rates from NS-measured spectra, including all corrections applied to the data (e.g., to remove altitude- and attitude-dependent systematic variability, corrections for lunar topography) are presented in Maurice et al. [2004].

2.2. Lunar Prospector Neutron Spectrometer

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The LP/NS measured neutron emissions from the lunar surface during its 19 month orbital mission (6 January 1998 to 31 July 1999). Our analysis focuses on data acquired during the 30 km altitude orbits (19 December 1998 to end of mission), which provided the highest spatial resolution (~45 km full width at half maximum; Maurice et al. [2004]) measurements. Derivation of neutron count rates from NS-measured spectra, including all corrections applied to the data (e.g., to remove altitude- and attitude-dependent systematic variability, corrections for lunar topography) are presented in Maurice et al. [2004].

2.3. Thermal Neutron Map

The LP/NS thermal neutron map (Figure 1) exhibits large variability both globally (222 to 764 counts per 32 s; cp 32 s) and within the highlands (550 to 764 cp 32 s). Thermal neutron count rates ($C_T$) clearly delineate between the Moon’s major geochemical terranes, as first noted by Feldman et al. [1998] and Elphic et al. [1998]. The high-absorption PKT manifests as the lowest $C_T$ regions on the surface ($< ~300$ cp 32 s), whereas the moderate absorption SPA terrane has $C_T$ values between ~300 and 550 cp 32 s, and the low-absorption FHT has $C_T$ values $>$550 cp 32 s.

The calculation of $\Sigma_a$, the characteristic macroscopic neutron absorption cross section, is expressed in units of $10^{-4}$ cm$^2$/g (alternatively denoted an "elphic"), and when multiplied by the regolith density (g/cm$^3$) it is proportional to the probability per unit pathlength that a thermal neutron will be absorbed.

The calculation of $\Sigma_a$ is made under the assumption that $\sigma_i$ values for all elements have an identical energy dependence that is inversely proportional to particle velocity at low energies. This is true for most elements, and in those cases $\sigma_i$ values are taken at a reference energy of 0.0253 eV from the Evaluated Nuclear Data File [Chadwick et al., 2011]. This assumption ignores the presence of resonances in the neutron absorption cross sections, which are important for Sm, Eu, and Gd. For these elements, we adopt $\sigma_i$ values of Prettyman et al. [2013], who explicitly included all resonances to derive an effective $\sigma_i$ value at 0.0253 eV. All $\sigma_i$ values used in this analysis are listed in Table 1.

Thermal neutron fluxes can also be altered by variations in hydrogen concentrations. Lawrence et al. [2015] used LP/NS epithermal neutron data to map variations in hydrogen across the highlands, reporting an average value of 65 ppm and a 99th percentile upper limit of 121 ppm. The most highlands-like Apollo landing site was that of Apollo 16 (A16), and “soils and regolith breccias” collected during that mission have hydrogen concentrations of 3.9 to 146 ppm [Haskin and Warren, 1991], comparable to the neutron-derived values. Radiation transport modeling (see section 3.3) of thermal neutron fluxes for A16-like samples predict a 7% increase in the thermal neutron flux as the hydrogen content is increased from 0 to 121 ppm. This compares to the 32% variability observed across the highlands (555 counts per 32 s (cp 32 s) to 765 cp 32 s; Figure 1). This observation, combined with the poor correlation (Pearson correlation $r = -0.2$) between the thermal neutron map and Lawrence et al. hydrogen distribution, led us to conclude that hydrogen variability is not an important contributor to thermal neutron variability in the lunar highlands.

The relationship between measured thermal neutron count rates ($C_T$) and $\Sigma_a$ takes the form $C_T = \Sigma_a^{-1}$. $\Sigma_a$ is calculated as the abundance-weighted sum of the individual (microscopic) neutron absorption cross sections ($\sigma_i$) for the elemental constituents (i) as

$$\Sigma_a = N_A \sum_i \left( \frac{w_i}{A_i} \right) \sigma_i$$

where $N_A$ is Avogadro’s number (6.022 x 10$^{23}$ atoms/mole) and $w_i$ is the weight fraction for each element i. $\Sigma_a$ is expressed in units of $10^{-4}$ cm$^2$/g (alternatively denoted an “elphic”), and when multiplied by the regolith density (g/cm$^3$) it is proportional to the probability per unit pathlength that a thermal neutron will be absorbed.
### Table 1. Elemental Composition and Σ values for the Apollo and Luna Soils and Regolith Breccias (SRBs), Along With an Apollo 16 Clast of Ferroan Anorthosite (FAN)

| Element | Apollo | Luna | Apollo 16 FAN |
|---------|--------|------|---------------|
| O       | 1.90 × 10⁻⁴ | 0.4254 | 0.4322 | 0.4437 | 0.4333 | 0.4596 | 0.4433 |
| Na      | 0.028  | 0.0035 | 0.0030 | 0.0035 | 0.0035 | 0.0035 | 0.0032 |
| Mg      | 0.063  | 0.0478 | 0.0628 | 0.0568 | 0.0660 | 0.0362 | 0.0561 |
| Al      | 0.233  | 0.0666 | 0.0642 | 0.0923 | 0.0758 | 0.1414 | 0.1003 |
| Si      | 0.2160 | 0.2160 | 0.2254 | 0.2206 | 0.2098 | 0.2081 | 0.3180 |
| S       | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| K       | 2.1    | 0.0014 | 0.0021 | 0.0046 | 0.0013 | 0.0008 | 0.0001 |
| Ca      | 0.438  | 0.0839 | 0.0704 | 0.0767 | 0.0748 | 0.1041 | 0.0879 |
| Ti      | 0.067  | 0.0476 | 0.0156 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| Fe      | 3.04   | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Mn      | 13.4   | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Sm      | 2.56   | 0.0125 | 0.0136 | 0.0081 | 0.0116 | 0.0387 | 0.0801 |
| Eu      | 1.67   | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Gd      | 22000  | 1.70   | 1.80   | 1.70   | 1.70   | 1.80   | 1.70   |
| Th      | 0.57   | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| U       | 3.38   | 5.20   | 1.20   | 1.20   | 1.20   | 1.20   | 1.20   |
| Σ (x10⁻⁴ cm⁻³/g) | 110.73 | 87.78 | 106.52 | 74.08 | 47.82 | 66.99 |

### 3.1. Creation of the Σ Map

First principle dictate that the relationship between thermal neutron count rates (C) and Σ takes the form C ∝ Σ⁻¹, however, Σ has not been reported for the Apollo and Luna sample suites. For lunar sample compositions, we use the relationship derived from the Apollo 16 FAN composition. To examine the relationship in detail, we present the relationship in Figure 1. The neutron map for the Apollo and Luna landing sites, which includes the high-absorption (low Σ) regions (see Figure 1), the thermal neutron map for Apollo 16 FAN, the high-absorption (low Σ) regions (see Figure 1), and the high-absorption (low Σ) regions (see Figure 1), shows the range of values represented in the high-absorption (low Σ) regions (see Figure 1), which are included in the high-absorption (low Σ) regions (see Figure 1), for the Apollo and Luna sample suites.
landing sites under the assumption that they are most representative of the mean composition of surface materials to depths of tens of centimeters. Out of necessity, we also assume that the samples are representative of broader areas of the surface whose size is comparable to the LP/NS spatial resolution (~45 km), which is considerably larger than the regions sampled by the Apollo and Luna missions (< ~1 km). The \( C_T \) values at each sample site were derived by adopting the mean and standard deviation thermal neutron count rates measured within 1° × 1° pixels centered on the landing sites. The results are listed in Table 2.

The errors reported for the landing site measurements represent the standard deviation of all individual measurements falling within the 1° × 1° pixels. Smaller errors can be achieved with larger pixel sizes but at the expense of further reducing the spatial correspondence between the sample sites and the LP measurements.

Figure 1. Map of LP/NS-measured thermal neutron count rates, in units of counts per 32 s (cp 32 s), across the lunar surface as measured during the 30 km altitude orbit phase of the LP mission. The map was generated from thermal neutron count rates, corrected as described in Maurice et al. [2004], binned into 0.5° × 0.5° quasi-equal-area pixels and smoothed over the spatial resolution of the NS (~45 km full width at half maximum). “A#” denotes an Apollo landing site (e.g., Apollo 11 = A11), and “L#” denotes a Luna landing site (e.g., Luna 16 = L16). The map is centered on the lunar farside.

### Table 2. \( \Sigma_a \) and Thermal Neutron Data (Measured and Modeled) for the Reference Soils and Regolith Breccia (SRB) Samples Returned During the Apollo (A) and Luna (L) Programs

| SRB | \( \Sigma_a \) (10^{-4} cm^{2}/g) | Measured \( b \) | Raw | Normalized \( c \) |
|-----|--------------------------------|-----------------|-----|-----------------|
| L20 | 45.8                           | 481 ± 40        | 506 | 567             |
| A16 | 47.8                           | 554 ± 23        | 498 | 557             |
| A17 | 67.0                           | 376 ± 33        | 373 | 417             |
| L24 | 67.4                           | 443 ± 38        | 354 | 396             |
| A15 | 74.1                           | 375 ± 11        | 342 | 382             |
| L16 | 82.6                           | 376 ± 33        | 299 | 334             |
| A12 | 87.8                           | 280 ± 10        | 294 | 329             |
| A14 | 106.5                          | 277 ± 6         | 278 | 311             |
| A11 | 110.7                          | 309 ± 22        | 228 | 255             |

\( a \) Derived from the elemental compositions of Haskin and Warren [1991]; see Table 1.

\( b \) Mean thermal neutron count rate (and standard deviation) as observed by LP while the subspacecraft point was within ±0.5° of the respective landing sites.

\( c \) Modeled (raw) count rates were iteratively normalized to obtain an optimal match to the measured thermal neutron count rate (see section 3.3). Normalization is 1.12. See text for details.

Figure 2 (inset) plots LP/NS-measured thermal neutron count rates over each Apollo and Luna landing site versus the \( \Sigma_a \) values derived from those sample’s bulk geochemistry. The data confirm the inverse relationship and suggest that it is linear. However, the SRBs cover just a fraction (~250 to ~550 cp 32 s) of the full dynamic range (222 to 764 cp 32 s) of \( C_T \) values mapped by LP, which complicates attempts to derive the relationship between \( C_T \) and \( \Sigma_a \) at it is unconstrained for \( C_T > 570 \) cp 32 s, a range that includes the entirety of the FHT.

### 3.2. Feldspathic Lunar Meteorites

Lunar meteorites, particularly feldspathic types that are thought to originate from the FHT, provide a means to supplement the Apollo and Luna sample suites and fill in the missing portion of the \( \Sigma_a \) range of interest. Unfortunately,
the lack of knowledge regarding the source regions of the feldspathic lunar meteorites (FLMs) means that the $\Sigma_a$ values for these meteorites cannot be directly compared to LP measurements as was done for the SRBs. In order to leverage the feldspathic lunar meteorites (FLMs) in our analysis, we first calculate their $\Sigma_a$ values using knowledge of their elemental concentrations and equation (1). A meteorite bulk chemistry data set for FLMs was constructed following many of the same guidelines described in Beck et al. [2015], who constructed a similar data set to constrain neutron behavior on asteroid 4 Vesta using the extensive collection of Vesta-originating howardite-eucrite-diogenite meteorites. First, compositional averages were computed from multiple analyses of the same lunar meteorite to mitigate sampling size issues. Then, to ensure that our meteorites had valid $\Sigma_a$ values, we dismissed compositional averages from the data set that (1) did not have concentrations of at least 8 of the top 10 neutron absorbers in basaltic/silicate materials [Prettyman et al., 2013] and/or (2) had “MissElemweight” values of $\geq$0.6 wt % [see Beck et al., 2015]. The later of these two criteria omits bulk chemistries that would likely produce inaccurate O concentrations (calculated as a remainder), a critical consideration given that O concentrations are important in $\Sigma_a$ calculations [Beck et al., 2015].

The FLM meteorite data compiled to construct this data set largely come from two sources. Fe, Ti, and Th were taken directly from Calzada-Diaz et al. [2015], and other major elements were taken from references therein. Minor/trace element averages were computed using data available on the Lunar Meteorite Compendium (available at http://curator.jsc.nasa.gov/antmet/lmc/). Our FLM $\Sigma_a$ values, listed in Table 3, range from $\sim33 \times 10^{-4}$ to $44.5 \times 10^{-4}$ cm$^2$/g—below the Apollo and Luna SRBs ($\Sigma_a > 46 \times 10^{-4}$ cm$^2$/g—Table 1) and are consistent with expectations for materials from the neutron-absorber-depleted lunar highlands.

**Table 3.** $\Sigma_a$ Values for the 22 Felspathic Lunar Meteorites (FLMs) Used in This Study

| Meteorite(s) | $\Sigma_a$ ($\times 10^{-4}$ cm$^2$/g) |
|-------------|----------------------------------|
| Y791197     | 41.6                             |
| PCA 02007   | 41.8                             |
| Dag400      | 36.2                             |
| SaU 300     | 44.2                             |
| Dag262      | 37.4                             |
| MAC88104    | 35.8                             |
| Yamamoto 86032 | 36.4                          |
| QUE 93069   | 38.7                             |
| ALHA 81005  | 39.0                             |
| Dhofar 025  | 37.5                             |
| Dhofar 733  | 34.5                             |
| SaU 449     | 43.3                             |
| Dhofar 301  | 37.0                             |
| Dhofar 302  | 33.8                             |
| NWA 4932    | 44.1                             |
| Dhofar 303  | 33.3                             |
| Dhofar 081, 280, 910 | 33.1                          |
| Dhofar 081  | 33.0                             |
| Shisr 161   | 38.4                             |
| Dhofar 026  | 36.3                             |
| NWA 3163    | 38.8                             |
| NWA 482     | 34.0                             |

3.3. Modeling Thermal Neutron Count Rates

As noted in section 3.1, the characterization of $\Sigma_a$ versus $C_T$ derived solely from the Apollo and Luna sample compositions and LP measurements of the landing sites (Figure 2, inset) does not cover the range of $C_T$ values of interest for the lunar highlands. The FLMs can fill the gap in sample composition space; however, the lack of known source locations for the FLMs means that we do not have LP-measured $C_T$ measurements to directly compare to FLM $\Sigma_a$ values. This prohibits empirically deriving a relationship between $\Sigma_a$ and $C_T$ in the highlands. Instead, we adopt a methodology whereby modeled thermal neutron emissions for materials with FLM-derived compositions are used to

![Figure 2](https://example.com/figure2.png)

*Figure 2.* Modeled and (inset) measured relationship between thermal neutron count rates observed by LP/NS and the macroscopic thermal neutron absorption cross section for near-surface materials ($\Sigma_a$; equation (1)). "A#" denotes an Apollo SRB composition (e.g., Apollo 11 = A11), "L#" denotes a Luna SRB composition (e.g., Luna 16 = L16), and A16-FAN denotes the Apollo 16 FAN clast. SRB and FAN compositions are listed in Table 1. Felspathic meteorites used in this study are listed in Table 3. Dashed lines denote fits to the data, which are linear in the inset and a third-order polynomial in the main panel (equation (2)).
characterize $\Sigma_a$ versus $C_T$. These modeled thermal neutron count rates—denoted $C_T$(model)—allow us to derive the relationship between LP/NS-measured $C_T$ values (Figure 1) and $\Sigma_a$ over the entire compositional range of lunar materials observed at the 45 km spatial scale of the LP measurements.

The process of deriving $C_T$(model) values begins with full-planet simulations of GCR-induced neutron production on the Moon. We use the radiation transport code MCNPX [Pelowitz, 2005], which has a long history of successful application to planetary neutron spectroscopy [e.g., McKinney et al., 2006; Lawrence et al., 2010; Prettyman et al., 2013]. Our inputs to MCNPX include the elemental compositions of the lunar surface (SRBs, FLMs, and Apollo 16 FAN), and the output is the energy dependent lunar neutron flux at the surface in units of neutrons cm$^{-2}$ s$^{-1}$ per incident GCR proton. Lawrence et al. [2006] reported a solar modulation parameter ($\phi$) value of 360 MV and GCR particle flux of 5.54 protons cm$^{-2}$ s$^{-1}$ for the LP mission.

Usokin et al. [2011] reported monthly $\phi$ values from 1936 to 2010, a time period that includes the entire LP mission. LP neutron data were normalized to the count rates measured from 16 to 19 January 1998, and Usokin et al. [2011] reported a $\phi$ value of 427 MV for January 1998. We adopt this $\phi$ value, and following McKinney et al. [2006], we calculate GCR particle flux as a function of $\phi$ and obtain a value of 4 protons cm$^{-2}$ s$^{-1}$. Following Lawrence et al. [2006, 2010], we further normalize the flux by a factor of 4 (MCNPX output geometry correction), the NS sensor area (114 cm$^2$), a sensor orientation correction (0.9) [Maurice et al., 2004], the NS integration time (32 s), and a geometric correction for the difference in the flux at an altitude of 30 km, relative to the MCNPX surface flux (0.967). Finally, we multiply by the energy dependent efficiency for detecting thermal neutrons, derived from the response of the Sn-covered sensor minus the response of the Cd-covered sensor [Feldman et al., 2004]. These corrections provide the "raw" modeled count rates for the SRBs (listed as "raw" in Table 2).

Comparison of the "raw" $C_T$(model) values to measured neutron count rates at the Apollo and Luna sample sites (Table 2) revealed the need for an additional normalization. We iteratively apply a correction factor to the models to search for the optimal normalization using a least squares optimization, and find that multiplying the "raw" modeled values by a normalization factor of 1.12 provides a best match between the models and the measurements. This normalization is comparable to those required for prior analyses of LP data [Lawrence et al., 2010] and is likely due to uncertainties in the GCR particle flux. For reference, adopting the Lawrence et al. [2006] GCR flux of 5.54 protons cm$^{-2}$ s$^{-1}$ yields a normalization of 0.78, highlighting the sensitivity of the neutron models to this parameter. The (1.12) normalized modeled count rates for the sample sites are adopted as the final $C_T$(model) values and are listed in Table 2.

We apply the landing-site-benchmarked corrections (including the normalization) to the modeled count rates for the FLMs to complete the set of $C_T$(model) values. Figure 2 plots the $C_T$(model) values as a function of $\Sigma_a$ for the Apollo and Luna samples, the FLMs, and the Apollo 16 FAN clast. These data justify the motivation for including the FLMs and the FAN sample, as they reveal that $\Sigma_a$ is a nonlinear function of $C_T$ over the entire range of interest for lunar $C_T$ values. We fit the $C_T$(model) values versus $\Sigma_a$ with a third-order polynomial to derive a conversion between the $C_T$ and $\Sigma_a$ of

$$
\Sigma_a(C_T) = (-6.17043 \times 10^{-7})C_T^3 + (1.26601 \times 10^{-3})C_T^2 + (-0.934086)C_T + (280.8),
$$

which appears as a dashed line in Figure 2 and was applied to the LP/NS measurements (Figure 1) to produce the $\Sigma_a$ map shown in Figure 3.

### 4. Overview of the $\Sigma_a$ Map

Our $\Sigma_a$ map (Figure 3) provides a view of the lunar surface that is compatible with established views of lunar geochemistry and prior interpretations of LP/NS thermal neutron measurements [Elphic et al., 1998, 2000, 2002; Feldman et al., 2000]. The highest $\Sigma_a$ regions (>100 × 10$^{-4}$ cm$^{-2}$/g) correspond to the PKT, whose high Fe, Ti, and REE concentrations result in the lowest thermal neutron fluxes observed on the surface. The high $\Sigma_a$ values in western Oceanus Procellarum are a close match to the $\Sigma_a$ values for the KREEP-rich A14 SRBs (106.5 × 10$^{-4}$ cm$^{-2}$/g). Mare Tranquillitatis has a local high in $\Sigma_a$ values (~90–115 × 10$^{-4}$ cm$^{-2}$/g) relative to neighboring Mare Serenitatis, Fecunditatis, and Crisium ($\Sigma_a < 85 \times 10^{-4}$). This difference is understood as being due to the Ti-enriched mare basalts found within Tranquillitatis. The Tranquillitatis $\Sigma_a$ values match the A11 SRBs (110.7 × 10$^{-4}$ cm$^{-2}$/g), which sampled the southern end of Mare Tranquillitatis.

On the lunar farside, the SPA terrane as well as Mare Orientale, Moscoviense, and Australe appear as local highs in $\Sigma_a$, reflecting the locally high Fe concentrations observed in these regions. SPA is also higher in Th
than the majority of highlands, and Th is a tracer for neutron-absorbing REEs Gd and Sm [Elphic et al., 2002]. Other local highs in $\Sigma_a$ within the highlands include the Fe-rich cryptomare around crater Dewar [Lawrence et al., 2008] and the Compton-Belkovich Th anomaly [Lawrence et al., 2000].

The lowest $\Sigma_a$ values are found within the lunar highlands, in particular within the FHT. A histogram of $\Sigma_a$ values in the highlands (Figure 4) shows a multimodal distribution with prominent peaks located at $\sim 40 \times 10^{-4}$ and $\sim 44 \times 10^{-4}$ cm$^2$/g (Figure 4). The $\Sigma_a$ values of the FLMs, also shown in Figure 4, overlap almost the entire range of measured highlands $\Sigma_a$ values and support the hypothesis that the source region of the FLMs is the highlands.

5. $\Sigma_a$ Constraints on the Geochemical Properties of the Highlands

5.1. Elemental Composition of the Lowest $\Sigma_a$ Regions

There is considerable variability in $\Sigma_a$ within the lunar highlands (Figure 3b), a region that is known for its low concentrations of
Fe, Ti, K, and Th (and by inference Gd and Sm) but high concentrations of Ca and Al. The overlap in $\Sigma_a$ values for the FLMs and the highlands justifies the use of the FLMs to assess the elemental and mineralogical composition of the highlands. Figure 5 plots the abundances of Ca, Fe, Mg, and Al as a function of $\Sigma_a$ for each FLM. In each case the elemental concentrations are highly correlated with $\Sigma_a$. For Fe, this relationship is straightforward given Fe’s significant influence on $\Sigma_a$. For Ca, Al, and Mg the correlations result from the relatively simple mineralogy of the lunar surface (see section 5.2), which results in correlations between elemental concentrations (i.e., Mg and Fe) that result in secondary (noncausal) correlations with $\Sigma_a$. The conclusions inferred from Figure 5—that the low-$\Sigma_a$ regions are high in Ca and Al but low in Fe and Mg—are both expected and well supported by remote sensing data for the highlands [e.g., Lucey et al., 1998; Lawrence et al., 2002; Prettyman et al., 2006; Yamashita et al., 2012].

Although the $\Sigma_a$ values of the FLMs fall within the range of $\Sigma_a$ values mapped across the lunar highlands (Figure 3), we note that the $\Sigma_a$ map includes regions with values as low as $30.6 \times 10^{-4} \text{ cm}^2/\text{g}$, 8% less than the lowest $\Sigma_a$ value for an FLM ($33.1 \times 10^{-4} \text{ cm}^2/\text{g}$). This indicates that the lowest $\Sigma_a$ regions on the Moon are not entirely represented by the bulk compositions of the feldspathic lunar meteorites currently in the collection. Figure 5 can be used to infer the chemical compositions of these low $\Sigma_a$ regions, and we conclude that they are likely composed of materials with approximately 12.5 to 13.3 wt % Ca, 1 to 2 wt % Fe, 1.5 to 2.2 wt % Mg, and 16.4 to 17.7 wt % Al. The inferred Al/Ca weight ratios (1.2-1.4) are similar to that of Ca-rich plagioclase (1.3), suggesting a possible mineralogy for the lowest $\Sigma_a$ regions that we explore in the next section.

5.2. Mineralogy of the Lowest $\Sigma_a$ Regions
The mineralogy of the lunar surface is dominated by just four minerals: plagioclase [(Ca,Na)(AlSi)$_4$O$_8$], pyroxene [(Mg,Fe,$\pm$Ca)$_2$Si$_2$O$_6$], olivine [(MgFe)$_2$SiO$_4$], and ilmenite (FeTiO$_3$) [Papike et al., 1991]. As a consequence, mineral concentrations can be estimated from elemental composition data in some scenarios. One such case is plagioclase, which is composed of elements (Ca, Al, Si, Na) with moderate to low $\sigma_i$ values and a correspondingly low $\Sigma_a$ that contrasts sharply with the second most common lunar mineral, Fe-rich pyroxene.

The Ca-rich plagioclase end-member, anorthite (An: CaAl$_2$Si$_2$O$_8$), dominates plagioclase compositions in the lunar highlands. For example, ferroan anorthosites contain An$_{88-98}$ plagioclase, with the remaining 2–12 molecular percent being composed of albite (Ab: NaAlSi$_3$O$_8$) [Papike et al., 1991]. The presence of high concentrations of anorthitic plagioclase in the FHT is supported by the observation of high (11–14 wt %) Ca and low ($<6$ wt %) Fe concentrations in the lunar highlands by orbiting gamma-ray spectrometers [Prettyman et al., 2006; Yamashita et al., 2012] as well as the high An concentrations in lunar plagioclase [Papike et al., 1991].

We adopt a methodology for estimating the plagioclase content of the FLMs from their measured Al concentrations. The purpose of this calculation is to identify and characterize the relationship between $\Sigma_a$ and plagioclase content in order to use the thermal neutron map to estimate plagioclase concentrations in the highlands. Estimating plagioclase content from Al concentrations is possible because plagioclase is the only major lunar mineral that contains Al. Al can also be found in pyroxene as a minor cation [Papike et al., 1991], which we ignore in our plagioclase estimates but include as an error later. Note that applying a normative calculation to derive plagioclase abundance is not applicable here because FLMs are breccias of cumulate rocks.

![Figure 5.](image-url)
The limited number of lunar FAN samples, along with the fact that the FLMs are breccias of cumulate rocks, led us to adopt a terrestrial plagioclase (An95) as our standard. Specifically, we use samples from Monte Somma and Velle di Fassa, Italy (see http://webmineral.com/data/Anorthite.shtml#.VfG4QaYXq60 for details). These samples have an Al weight fraction of 0.1897, a value that compares favorably to the mean Al content of nine lunar FAN samples (0.1888), taken from Papike et al., 1998, Jolliff et al., 1991, and Gross et al., 2014. Assuming that (1) all Al measured in the FLMs occurs in plagioclase and (2) all Ca-rich plagioclase (≥ An90) in FLMs has approximately the same weight fraction of Al as An95 plagioclase, we can estimate the plagioclase abundance ($P_{est}$) from bulk Al content ($w_{Al}$) of the FLMs using the following equation:

$$P_{est}(w_{Al}) = \frac{w_{Al}}{18.97}$$  (3)

where $P_{est}$ and $w_{Al}$ are in units of weight percent.

For the FLMs, $\Sigma_a$ decreases with increasing Al content (Figure 5). We convert Al concentrations in the FLMs to plagioclase concentrations using equation (3) and subsequently derive a relationship between $\Sigma_a$ and plagioclase content. The relationship, plotted in Figure 6, is

$$P_{est}(\Sigma_a) = -2.004\Sigma_a + 152.482.$$  (4)

The deviations of the FLM $P_{est}$ values from the linear fit to those data (Figure 6) suggest that the errors in our $\Sigma_a$-derived $P_{est}$ values are approximately 4 wt%; however, there are additional uncertainties to consider that originate from our assumptions regarding the mineralogy.

The validity of equations (3) and (4) is limited by the previously listed assumptions #1 and #2. As discussed, ferroan anorthosite plagioclase ranges from An88-98 [Papike et al., 1991] (i.e., is not necessarily An95). Testing the sensitivity of equation (4) to varying An# values suggests that an error of ~1% can be assigned due to uncertainties and/or variability in An# content across the highlands. We consider this to be an additional error on top of the previously noted 4%. Additionally, note that equation (4) was derived from meteorites with $\Sigma_a < 45 \times 10^{-4} \text{ cm}^2/\text{g}$ only, here assumed to be plagioclase-rich and pyroxene-poor material. Applying equation (4) to high $\Sigma_a$ values (> $65 \times 10^{-4} \text{ cm}^2/\text{g}$) typical of Fe-bearing materials results in clearly erroneous values of $P_{est}$. This may be due to the presence of Al cations in pyroxene, although Papike et al., [1991] report small contributions of Al cations of <0.12 wt % Al. The limited data set used to derive equation (4) leads us to suggest that equation (4) only applies to FHT-like compositions ($\Sigma_a < 48 \times 10^{-4} \text{ cm}^2/\text{g}$; value of the A16 SRBs).

6. Plagioclase Distribution Within the Lunar Highlands

6.1. Comparison to Mineralogy and Albedo

Crites and Lucey [2015] used gamma-ray and neutron data to improve global mineral maps derived from Clementine Ultra-Violet/Visible Camera measurements. Their results reveal high concentrations of plagioclase within the highlands, generally exceeding ~60% (by volume) and significantly higher (~75 vol %) in the FHT. The ~5% uncertainties in our estimated plagioclase concentrations (section 5.2) and the limitation of equation (4) to low $\Sigma_a$ (<$48 \times 10^{-4} \text{ cm}^2/\text{g}$) regions only complicate a direct comparison of the two plagioclase maps. Instead, we compared the Clementine plagioclase values to the $\Sigma_a$ map of Figure 3. We observe a general correlation between the highest plagioclase regions and our lowest $\Sigma_a$ regions, for example, within the Orientale and Freundlich-Sharonov basins and south of Fowler crater. Regional differences are observed in locations west of Orientale toward Hertzsprung basin, where Crites and Lucey report regional decreases in plagioclase content that are not correlated with increased $\Sigma_a$.

Figure 6. Al-derived plagioclase content ($P_{est}$; equation (3)) of the feldspathic lunar meteorites used in this study, plotted as a function of the $\Sigma_a$ values for those meteorites. $R$ is the Pearson correlation coefficient, which measures the linear correlation between $P_{est}$ and $\Sigma_a$. $R = 1$ is a total positive correlation, and $R = -1$ is a total positive correlation.

The deviations of the FLM $P_{est}$ values from the linear fit to those data (Figure 6) suggest that the errors in our $\Sigma_a$-derived $P_{est}$ values are approximately 4 wt%; however, there are additional uncertainties to consider that originate from our assumptions regarding the mineralogy.
The spatial resolution of the Crites and Lucey mineral maps are limited by the $2^\circ \times 2^\circ$ spatial resolution of the gamma ray oxide maps (adopted from Prettyman et al. [2006]), and the precision of the maps are likewise limited by the gamma-ray data. Our formalism lacks these constraints, and the high counting rates for the thermal neutron measurements facilitated reporting results as a $0.5^\circ \times 0.5^\circ$ map. This suggests that the $\Sigma_a$ map can provide higher-resolution identification of potentially plagioclase-rich regions, with the drawback being the uncertainty associated with plagioclase concentrations derived from $\Sigma_a$ data ($\sim 5\%$, see section 5.2).

We also observe a correlation between $\Sigma_a$ and the albedo of the lunar surface. Our measure of albedo is the global map of lunar reflectance derived from Lunar Reconnaissance Orbiter/Lunar Orbiter Laser Altimeter (LRO/LOLA) 1064 nm laser returns (denoted as normal albedo following Lucey et al. [2014]). LOLA reflectance values were smoothed over the spatial response of the LP/NS prior to plotting. Despite the fact that LOLA samples surficial reflectance (depth $< 1$ mm) whereas $\Sigma_a$ samples composition to depths of $< \sim 1$ m, the two values are correlated (Figure 7). In particular, note that the highest albedo ($> 0.35$) regions of the surface are exclusively associated with low-$\Sigma_a$ materials. This observation is consistent with an absence of Fe-rich pyroxene and ilmenite (FeTiO$_3$)—opaque minerals with high concentrations of neutron-absorbing elements. Pyroxene and plagioclase concentrations are inversely correlated on the Moon, so the absence of Fe-pyroxenes and ilmenite in low-$\Sigma_a$ materials supports our hypothesis that low-$\Sigma_a$ materials are plagioclase rich.

### 6.2. Correspondence With Nearly Pure Anorthosite Deposits

The anorthositic nature of the FHT was first postulated on the basis of ferroan anorthosites (FAN) found in the Apollo samples suite [e.g., Dowty et al., 1974]. The geochemical properties of FAN, including its high An-rich plagioclase content, depletion in incompatible elements, and low Fe concentrations, led to the formation of the global magma ocean (GMO) hypothesis for lunar crustal formation [Wood, 1975; Warren, 1985]. This scenario assumes that the Moon was once mostly or completely molten and that the primary lunar crust formed from floatation of cumulates as the melt cooled. GMO models indicate that a low-density crust of plagioclase-rich material formed the Moon’s primary crust. Impact mixing diluted the upper layers of this crust through the addition of mafic materials, and within the mare the crust was completely displaced by extrusive magmatism. The GMO paradigm is supported by a large body of evidence, including the REE concentrations found in lunar samples, the relatively high reflectance of the FHT (see section 6.2), its low Fe [e.g., Lawrence et al., 2002] and FeO [e.g., Hawke et al., 2003] concentrations observed via remote sensing, and analyses of lunar meteorites believed to have originated from the FHT [e.g., Korotev et al., 2003; Gross et al., 2014].

Recently, spectral reflectance measurements have identified signatures of nearly pure anorthosite (PAN) across the lunar surface but primarily in the FHT [Hawke et al., 2003; Ohtake et al., 2009; Yamamoto et al., 2012; Cheek et al., 2013; Donaldson Hanna et al., 2014]. The association between PAN and material within and excavated by impact basins has led to the hypothesis that a subsurface layer of nearly pure plagioclase exists tens of kilometers beneath the lunar surface. This layer is thought to represent remnants of the primary crust that are relatively unaltered as compared to FAN, and as a result its presence and characteristics have important consequences for our understanding of the GMO and its evolution.

Yamamoto et al. [2012] and Donaldson Hanna et al. [2014] document occurrences of PAN across the lunar surface, and we leverage their databases for comparison to the $\Sigma_a$ map. Despite the vastly different spatial scales of the LP/NS measurements ($\sim 45$ km spatial resolution) and the PAN detections ($\sim 100$ m), we find that
clusters of PAN typically correspond to regions with low \( \Sigma_a \) (Figure 8). A histogram of the \( \Sigma_a \) values of pixels containing PAN deposits reveals a population whose \( \Sigma_a \) values are lower than the highlands (Figure 9), clustering about a mean value of \( \Sigma_a = 35 \times 10^{-4} \text{ cm}^2/\text{g} \), which corresponds to estimated plagioclase concentrations of \( > 80 \text{ wt} \% \) (\( \pm 5\% \)).

PAN is identified from orbit via the detection of a characteristic 1.25 \( \mu \text{m} \) absorption band in measurements of the spectral reflectance of the lunar surface, a signature that is only apparent in nearly pure plagioclase \(( > 95 \text{ vol} \%) \) within fresh (not space weathered) materials. Many PAN deposits are surrounded by spectrally bright materials that do not exhibit the absorption feature but that otherwise may be plagioclase rich [Cheek et al., 2013]. Figure 9 supports the hypothesis that the PAN deposits are located within regions of plagioclase-rich material of comparable spatial extent as the LP/NS resolution but with plagioclase concentrations below the threshold required for identification of the 1.25 \( \mu \text{m} \) absorption band. This suggests that the association of PAN with basin peak rings [e.g., Cheek et al., 2013] may be an artifact of the requirement for fresh material for PAN detection and not intrinsic to the excavation of PAN, as the \( \Sigma_a \) map provides strong evidence for widespread plagioclase that is not limited to basin peak rings.

### 6.3. Geological Context for the Low \( \Sigma_a \) Regions

The lowest \( \Sigma_a \) regions (LSRs) are defined as areas with \( \Sigma_a \) values less \( < 34 \times 10^{-4} \text{ cm}^2/\text{g} \), roughly the lower limit of \( \Sigma_a \) values observed in FLMs. The LSRs are, at least in terms of neutron absorption, a compositional end-member for the lunar surface. We suggest that they correspond to material that is composed almost entirely \(( > 85 \text{ wt} \%) \) of plagioclase. LSRs are found exclusively within the farside highlands, at equatorial latitudes \(( > 45\text{S} \) and \(< 45\text{N} \)) and longitudes of \( 135\text{E} \) to \( 270\text{E} \). This region overlaps the FHT, which Jolliff et al. [2000] proposed to be an anorthositic “craton”—a modified but intact remnant of the primordial lunar crust.
Figure 10 plots the outlines of the LSRs against a LRO/LOLA topographic map [Smith et al., 2010] and highlights a general (but not universal) association between LSRs and impact features. LSRs are found in the western portion of the ~570 km diameter Hertzsprung (Hz) basin, the southern and northeastern portions of the ~600 km diameter Freundlich-Sharonov (F-S) basin, the western portions of the ~930 km diameter Orientale (O) basin, and the eastern portion of the ~220 km diameter Korolev (K) basin. Crater basin abbreviations correspond to labels in Figure 10.

Not all LSRs are found within impact basins or craters. There is a large LSR whose northern boundary includes the ~140 km diameter Fowler (Fo) crater but whose spatial extent extends significantly southward of the crater. There are notable LSRs west and northwest of the ~470 km diameter Dirichlet-Jackson (D-J) basin, northeast of Freundlich-Sharonov, and southeast of Hertzsprung. Although these LSRs are not obviously correlated with impact features, the heavily cratered terrain in the FHT may mask an association with impact features (e.g., degraded basins) or impact ejecta. Alternatively, these LSRs may be signatures of alternative mechanisms for concentrating anorthositic-rich material on the surface. For example, they may represent remnants of anorthositic rockbergs [e.g., Longhi and Ashwal, 1985].

The general association between LSRs and impact features suggests that the majority of LSRs represent material excavated from depth. The $\Sigma_a$ map provides a number of constraints on the subsurface distribution in this source region. Within the FHT, craters with diameters less than approximately 300 km are generally not associated with LSR deposits. For example, the 207 km diameter Galois, ~160 km diameter Tsander, ~175 km diameter Mach, ~128 km diameter Poynting, and ~148 km diameter Fersman craters are not collocated with LSR. Baker and Head [2015] calculated the maximum depth of excavation ($d_e$) for 10 peak-ring basins with final rim-crest diameters ($d_r$) of 207 to 492 km and found a relationship of

$$d_e = 8.03 \times 10^{-2} d_r - 0.6903$$

for their data. This indicates that <300 km diameter craters sample depths of <23 km, suggesting that the LSR source region lies at least that far below the surface. The spatial extent of the LSR region can be inferred from the spatial extent of the LSRs, which outline a region that is comparable to the FHT [Jolliff et al., 2000]. The neutron data alone suggest that the LSR source region is either absent outside of the FHT or that it exists further beneath the surface, making it inaccessible. Note, however, that there are some PAN detections outside of the FHT, including some within or bordering the PKT, which argue against this hypothesis [Yamamoto et al., 2012; Donaldson Hanna et al., 2014]. If PAN and LSRs are indeed sampling the same source region, then it is possible that plagioclase outside of the FHT is too contaminated with Fe-, Ti-, or REE-bearing material to reliably identify in the PKT and SPA terrane at the spatial resolution of the LP/NS.
7. Discussion and Summary

Our $\Sigma_a$ map of the lunar surface, derived from LP/NS thermal neutron data, provides a unique view into the geochemical composition of the lunar surface. This is particularly true in the lunar highlands, where low Fe, FeO, and radioactive element concentrations often result in low statistical significance data that hinders efforts to characterize elemental and mineralogical composition using remote sensing data. We interpret the lowest $\Sigma_a$ values in the FHT as being due to materials having high >85 wt % (±5%) concentrations of Ca-rich plagioclase. This interpretation is consistent with other remote sensing data sets, including detections of PAN within lunar basins. The uneven distribution of plagioclase within and around these basins suggests a heterogeneous distribution for the source region of this plagioclase-rich material.

The nonuniform composition of the lunar highlands as revealed by the $\Sigma_a$ map supports chemically heterogeneous highlands crustal formation. This conclusion is unsurprising, as the composition of the farside and nearside highlands are known to differ [e.g., Ohtake et al. (2012); Gross et al. (2014)], and the existence of the magnesian suite and magnesian anorthosites in the FLMs argues for significant contributions from non-GMO crustal formation processes. Alternatively, the heterogeneous distribution may be the result of the South Pole-Aitken basin, whose ejecta is predicted to have fallen in our LSR-rich region [Kendall et al., 2015] and which may have resulted in a nonuniform depth for the layer of overlying material that obscures LSR source region, which is now exposed by the post-SPA impact basins.

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