FORMATION AND EVOLUTION OF THE MOON’S UPPER REGOLITH: CONSTRAINTS FROM DIVINER THERMAL MEASUREMENTS. P. O. Hayne[^1], R. Ghent[^2], J. L. Bandfield[^3], A. R. Vasavada[^4], M. A. Siegler[^5], B. T. Greenhagen[^6], J.-P. Williams[^7], and D. A. Paige[^8], ^1Jet Propulsion Laboratory, California Institute of Technology (Paul.O.Hayne@jpl.nasa.gov), ^2University of Toronto, ^3Planetary Science Institute, ^4University of Washington, ^5University of California, Los Angeles.

**Introduction:** On airless planetary bodies regolith forms through the comminution of bedrock by infrequent large impacts and the degradation of rocks by a relatively continuous flux of smaller impactors [1]. Observed regolith thicknesses of ~5–10 m are consistent with theoretical models describing these processes [2], and show an abrupt decrease in accumulation rates after ~3.5 Ga [3]. After this time, spatial variations in overall regolith thickness are strongly influenced by local factors such as composition, mass wasting, and recent impacts [2]. During the most recent billion years the uppermost ~10 cm of regolith have experienced substantial processing globally, with overturn rates increasing exponentially toward the surface [4].

Nighttime lunar surface temperatures are strongly influenced by the structure of this upper ~10 cm of material, and therefore provide constraints on the distribution and rate of geologically recent regolith accumulation. We used multiband thermal infrared data acquired by the Diviner Lunar Radiometer to constrain a model of upper regolith structure, thereby deriving a “thickness” parameter that correlates with published ages for recent (<1 Ga) craters [5]. Here we investigate the relationship between regolith accumulation derived from Diviner data and the relative ages of some of the Moon’s major geologic units.

**Instrument and Methods:** Diviner [6] is a nine-channel push-broom radiometer onboard the Lunar Reconnaissance Orbiter (LRO). Using Diviner’s radiance measurements at multiple wavelengths, Bandfield et al. (2011) [7] separated nighttime thermal emission by rocks from that of the regolith surface. We used the resulting nighttime regolith temperatures to constrain a model for the subsurface density profile, which is found to follow an exponential density profile [8]:

$$\rho(z) = \rho_D - (\rho_D - \rho_S) e^{-z/H}$$

where $z$ is the depth below the surface, $\rho_S$ is the density at the free surface, and $\rho_D$ is the density at depths $z >> H$. Regolith density profiles can be affected by soil grain size and morphology, composition, and buried rocks. Ejecta surrounding fresh impact craters have strongly enhanced subsurface densities even where surface rocks are absent, suggesting the influence of buried rocks [5].

Based on results from the Apollo drill cores [9] and Diviner eclipse cooling measurements [10], we fixed $\rho_D = 1900 \text{ kg m}^{-3}$ and $\rho_S = 900 \text{ kg m}^{-3}$. The parameter $H$ can be thought of as a density scale height for the upper regolith, which we fit using a least-squares minimization procedure using all available local times during the night for each sample at a resolution of 128/degree. Examples of the modeled density profiles are shown in Fig. 1.

Our thermal model employs a standard finite-difference method for solving the one-dimensional heat equation, including temperature- and density-dependent thermal conductivity [8,11]. We found that

![Fig. 1: Example regolith density profiles for $H = 0.5, 1, 2, 3, 4, 5, 6$ cm. The red curve is an approximate fit to Apollo 15 core data [9].](image1)

![Fig. 2: Map of the upper regolith thickness parameter $H$ in northern Oceanus Procellarum, with mare basalt units from [13] outlined in white. Distinct differences among these units are observed, though the regolith pattern is heterogeneous within each unit.](image2)
a higher than expected [cf. 8] radiative conduction factor $\chi = 4$ was needed in order to minimize latitudinal gradients in $H$.

**Results:** Nighttime regolith temperatures are accurately matched by the exponential density model, with typical values of the parameter $H$ lying in the range 0–10 cm (Fig. 2). In general, fresh craters show the smallest $H$ values (highest thermal inertia), while older craters and their ejecta have degraded to values closer to the background ~6 cm. While this background is relatively constant within individual geologic units, it is variable over the lunar surface. Mode values of $H$ for sufficiently large regions (>10,000 km$^2$) of maria and highlands units are indistinguishable within uncertainties, though the highlands show a narrower distribution of values.

![Figure 3: Histograms of upper regolith thickness $H$ show a progression from low to high values for the three mare basalt units outlined in Fig. 2. The small peak at ~4.5 cm is due to recent impact craters with buried blocky ejecta.](image)

To assess the evolution of $H$ during the most recent epoch, we compared values among three mare basalt units mapped by Hiesinger et al. (2010) [12]. Figure 2 shows the boundaries of these units on a map of $H$. Based on crater counts [12], the three numbered units have ages of ~1.0, 2.0, and 3.5 Ga. The histograms in Fig. 3 show a clear progression in the distribution of $H$ from low to high values with age, corresponding to a rate ~1 mm Gyr$^{-1}$, or about 1 kg m$^{-2}$ Gyr$^{-1}$, significantly slower than for regolith accumulation within individual craters’ ejecta during their first billion years [5] (Fig. 4).

**Discussion and Conclusions:** Regolith temperatures from Diviner are consistent with an upper layer with an exponential density profile down to ~10 cm. This type of profile is consistent with the exponential increase in regolith gardening rates toward the surface predicted by models [4]. Thermal model fits to the Diviner temperature curves show geographic variabil-

![Figure 4: Evolution of upper regolith thickness through a time sequence of craters with established ages: Giordano Bruno (upper left), Byrgius-A (upper right), Jackson (lower left), and Vavilov (lower right). Ages are taken from [5].](image)