**THERMAL DIFFUSIVITY EXPERIMENT AT THE GRAND FALLS DUNE FIELD.** T. N. Titus[1] and G. E. Cushing[1], [1]U.S.G.S. Astrogeology Science Center, 2255 North Gemini Dr., Flagstaff, AZ 86001

**Introduction:** Thermal inertia is a commonly derived surface property for many terrestrial solar system bodies (e.g. Mars [1,2], Vesta [3], the Moon [4]). Thermal inertia is defined as $I = \sqrt{k\rho c}$, where $k$ is thermal conductivity, ρ is the density and $c$ is the heat capacity. Thermal inertia, unlike surface temperature, is treated as a surface invariant and can therefore be mapped. High thermal inertia indicates exposed rock while low thermal inertia indicates fine grain material, such as dust or sand. Complicated numerical models are needed to convert observed surface temperatures into thermal inertia; these models include several other input parameters – such as albedo, slopes, and surface roughness. Most models assume that the surface properties are vertically homogeneous. A few models allow for compositional gradients or 2 layers (e.g. [5]). These compositionally multilayered models are usually only used where large differences are expected – such as a layer of ice covered by a thin layer of dust (e.g. [6]). This study will focus on testing the assumption of vertical homogeneity in the top 20 cm of sand in a local dune field.

This study focuses on *in situ* temperature observations of one location on a dune field located in northern Arizona. Because temperatures are measured at the surface and at several depths, the usual complex numerical models that require knowledge of albedo and slope are unnecessary. A simple analytical solution to the thermal diffusion equation is all that is required to test the homogeneity of the top layer of the sand.

**Thermal Physical Properties:** Temperature as a function of depth can be determined by solving:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$, where $\alpha = \frac{k}{\rho c}$, α is the coefficient of thermal diffusion (thermal diffusivity), $T$ is temperature and $z$ is depth.

*Thermal Skin Depth:* The thermal skin depth is a measure of how far either a diurnal or annual surface temperature cycle penetrates the regolith. The exact definition is the depth at which the amplitude of the thermal wave is attenuated by a factor 1/e.

$$D = \sqrt{\frac{kP}{\pi\rho c}} = \sqrt{\alpha \frac{P}{\pi}}$$, where $D$ the skin depth, and $P$ is the period of the cycle (86,400 sec for the terrestrial diurnal cycle).

*Diffusion Equation Solution:* Since the surface temperature is cyclic, one convenient and useful solution is:

$$T(t,z) = T_0(z) + \sum_i e^{-z/D_i} \left(A_i \cos\theta_i(t,z) + B_i \sin\theta_i(t,z)\right)$$

where

$$\theta_i(t,z) = \frac{2\pi i}{P} t - \frac{z}{D_i} \text{ and } A_i^2 + B_i^2 = 1.$$

For the diurnal thermal wave, the temperature profiles can usually be described using as few as 3 harmonics (i=1,2,3) using linear regression of sines and cosines. The attenuation of the amplitude between sensors allows the calculation of skin depth as a function of depth.

**Data Collection:** Temperature data was collected for nearly a week at a single location at the Grand Falls dune field, near Leupp, AZ. A series of temperature probes were attached to a pole. The sensors were separated by 4 cm and the pole was placed in the sand so that the top sensor was at the surface (Fig. 1). The sand in this region was observed to be loose and dry. To allow the temperature probes to reach equilibrium with the sand, we excluded the first50 minutes of data.After about 20 hours of data collection, a sand storm altered the placement of the temperature probes. Therefore, only 19 hours of temperature data were available.

**Table 1: Physical Properties of Sand (Source: http://www.engineringtoolbox.com)**

| | Density (Kg m$^{-3}$) | Heat Capacity | Conductivity (W m$^{-1}$ K$^{-1}$) | Diurnal Skin Depth (cm) |
|---|---|---|---|---|
| Dry Sand | 1281 | 830 | 0.15 – 0.25 | 6.2-8.0 |
| Wet Sand | 1922 | | 0.25 – 2 | 6.6-18.6 |
| Saturated | 2082 | | 2 - 4 | 18-25 |

**Analysis:** While most thermal inertia studies are expressed in either units of thermal inertia or thermal conductivity, this study presents the results as units of skin depth in centimeters. Neither the density nor the heat capacity of the sand at the Grand Falls dune field was measured. The results from comparing the amplitude attenuation with depth are thermal diffusivity, α. However, α can be converted to effective skin depths

**Figure 1: Equipment layout used to collect temperatures.**

which are independent of assumptions about density and heat capacity, but retain results that can easily be compared to Table 1. The results of this analysis is shown in Table 2. A decrease in the thermal diffusivity as a function of depth is quite apparent. There are three possible causes for this effect: (1) an increase in moisture with depth, a decrease in particle size (related to *k*) with depth, or (3) a decrease in density (or heat capacity). Because the sand was observed to be dry, it is unlikely that the sand has a moisture gradient. Particle size variations were not observed either. Therefore the vertical layering of the sand must have a density gradient, which could be caused by compaction at the lower layers. Based on the change in skin depths, the change in density would need to be a factor of 2.

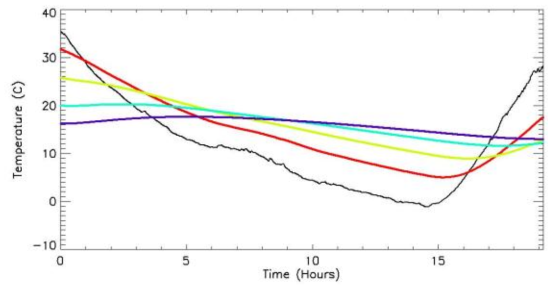


**Figure 2: Temperature data collected from Grand Falls dune field over a period of 19 hours. The temperatures were collected at the surface, and at depths 4cm, 8cm, 12cm, and 16cm (black, yellow, cyan, and purple, respectively).**

**Summary:** The top 16 cm of the dune field was not homogeneous with depth, but varied in at least one of the thermal physical parameters: density, heat capacity, and thermal conductivity. The most likely cause is an increase in density with depth, suggesting that the top 8 cm may be a less-dense active layer and the lower layer (depth greater than 8 cm) is a denser, less active layer.

**Table 2: Estimated Skin Depth Results for the 1st three harmonics.**

| | Effective Skin Depth (cm) | | |
|---|---|---|---|
| Depth (cm) | P=24 hours | P=12 Hours | P=8 Hours |
| 0-4 | 9.14 | 9.38 | 11.5 |
| 4-8 | 8.39 | 9.21 | 15.5 |
| 8-12 | 6.90 | 7.18 | 11.1 |
| 12-16 | 6.37 | 5.34 | 7.24 |

**Future work:** This study was conducted at one location for a short period of time. The authors of this study intend to expand the thermal measurements to multiple locations, at greater depth, over a period of several diurnal cycles.

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