Detecting Subsurface Lunar Lava Tubes Using Thermal Inertia. J. A. Meyer[1] and J. M. Hurtado, Jr.[2], [1,2]University of Texas at El Paso, Department of Geological Sciences and UTEP Center for Space Exploration Technology Research, 500 West University Avenue, El Paso, Texas 79968-05555, [1]jameyer@miners.utep.edu, [2]jhurtado@utep.edu.

Introduction: Lava tubes have the potential to serve as a sustainable solution to long-term lunar habitation by providing protection from radiation and micrometeorite bombardment while potentially providing resources in the form of trapped water ice [1,2]. They also pose compelling science targets in their own right [3]. While the potential benefits of utilizing lunar lava tubes is clear, their discovery is less straightforward. Formation processes for lava tubes do not always result in a surface expression, making their discovery using remotely sensed imagery difficult. Furthermore, there is the potential for lava tubes to be covered by secondary lava flows, impact ejecta, or other deposits, masking their surface expression.

It may be possible to detect subsurface lunar lava tubes using thermal inertia measurements derived from Lunar Reconnaissance Orbiter (LRO) data. In this study we create a thermal inertia map over a known lunar lava tube candidate in northern Oceanus Procellarum. Using the thermal inertia map we are able to detect a thermal inertia low over the trend of the lava tube candidate, which we believe may be a direct result of the subsurface lava tube void space.

The thermal inertia map results are supported by a periodic heating and cooling semi-infinite half space model we developed to determine the influence a subsurface cavity would have on surface temperatures. The model surface temperatures along the trend of the lava tube agree with surface temperatures observed by the Diviner Lunar Radiometer Experiment (DLRE). In addition to showing the influence of a subsurface cavity on surface temperatures, further modeling may allow us to predict characteristics such as roof thickness and cavity dimensions.

Study Location: For this study we use a well-known lava tube candidate ("C") in northern Oceanus Procellarum first studied by Coombs and Hawke [2]. Exceptional Lunar Reconnaissance Orbiter data coverage and both collapsed and uncollapsed lava tube sections make lava tube C an ideal location for this study. Lava tube C is approximately 20-km long, sinuously trending northwest to southeast for the majority of its length, becoming more north-south trending at its southernmost extent (Fig. 1). Lava tube C contains numerous roofed-over sections ranging in length from 0.5 to 1.2 km [2]. Roof widths range from 450 to 970 m, with roof thickness ranging from 30 to 136 m [2].

Remote Sensing Methods: We hypothesize that surface temperatures over the trend of a subsurface tube will be anomalously warmer than the surroundings during local day and anomalously colder than the surroundings during local night. This diurnal temperature difference is due to the presence of the subsurface void and the lower effective thermal inertia of the relatively thin roof of the tube as compared with the surrounding terrain. Studies of Martian lava tubes have also demonstrated this diurnal variation in surface temperature [5].

Apparent thermal inertia (*ATI*) was calculated using the relationship [4]:

$$ATI = \frac{(1 - ABE)}{\Delta T} \quad (1),$$

where *ABE* is albedo and ΔT is the diurnal temperature difference. *ABE* was determined from Lunar Reconnaissance Orbiter Camera (LROC) narrow angle camera (NAC) imagery. To compute ΔT, we use DLRE reduced data record (RDR) surface brightness temperatures from channel A6 (13-23 μm). This wavelength range was chosen because of its sensitivity to temperatures >178 K, which most closely encapsulate mean equatorial day and night surface temperatures [8]. By subtracting day and night temperatures, we created the ΔT map used in Eq. (1) (Fig. 1a).

Since the NAC and DLRE data have different spatial extents and resolutions, the DLRE data was resampled from its 608-m/pixel resolution to the NAC 0.5-m/pixel resolution, and the two datasets were precisely coregistered using *ENVI* software. Eq. (1) was also implemented in *ENVI*, and the resampled and coregistered data were used to compute the *ATI* map over lava tube C (Fig. 1b).

Thermal Model: We also used a periodic heating and cooling semi-infinite half space model [6] developed to determine the influence a subsurface cavity would have on surface temperatures. Surface temperature (*T*) was calculated using [6]:

$$T = T_0 + \Delta T \exp\left(-y\sqrt{\frac{\omega}{2k}}\right)\cos\left(\omega t - y\sqrt{\frac{\omega}{2k}}\right) + \frac{D}{2}\left[erf\left(\frac{y-D}{10\sqrt{t}}\right) - erf\left(\frac{y+d}{10\sqrt{t}}\right)\right] \quad (2),$$

where T_0 is the average surface temperature, ΔT is the temperature range over a lunar day, *y* is depth, ω is frequency, κ is thermal diffusivity, D is tube depth, and t is time.

Results: Compared to areas away from a lava tube, the thermal model predicts a ~10 K larger diurnal surface temperature swing over a subsurface void with a similar roof thickness to lava tube C (~100 m). This is in agreement with the ~10-15 K larger difference in diurnal temperature change measured on the tube vs. away from the tube in Fig. 1b.

The *ATI* map reveals thermal inertia lows over the uncollapsed segments of the lava tube (Fig. 1b). The largest of these lows is outlined in Fig. 2 by a dashed rectangle. This thermal inertia low trends northwest to southeast following the trend and spatial extent of a likely uncollapsed portion of lava tube C. Thermal inertia lows can also be seen over the smaller uncollapsed segments further north along the trend of the tube (Fig. 1b). These smaller sections approach the 608-m/pixel spatial resolution of the DLRE data, and, in some places, the thermal inertia low is indicated by a single pixel. However, the consistency of the thermal inertia low precisely over these small segments is too coincidental to ignore.

To further test the association between the thermal inertia lows and uncollapsed lava tube segments, we conducted a statistical analysis that compared the *ATI* of uncollapsed lava tube segments to that of the surrounding areas. The large uncollapsed section (Fig 1) has a mean *ATI* value of 0.0056 ± 0.0043. This is similar to the mean *ATI* value for smaller uncollapsed segments to the north (0.0056 ± 0.001). Both uncollapsed regions have lower thermal inertia values than the surrounding area (0.006 ± 0.0049). While the *ATI* values overlap somewhat within uncertainty (due in part to the limited resolution of the DLRE data), we believe that these values are consistent with the observed (15 K) temperature difference between the uncollapsed lava tube segments and their surroundings.

Discussion & Conclusions: We demonstrate that the uncollapsed portions of a lava tube produce thermal inertia lows and that small temperature anomaly resulting from the presence of a subsurface cavity like a lava tube is detectable in DLRE data. We believe that this signature can be used to detect lava tubes in the subsurface. The thermal inertia detection method is currently being applied to five more known lava tube candidates with varying degrees of surface expression, including the area around Marius Hills Hole [7]. Testing this method on lava tubes with varying morphologies and roof thicknesses will allow us to determine the effective limits of this method, and build confidence in the ability of this method to detect subsurface lava tubes.

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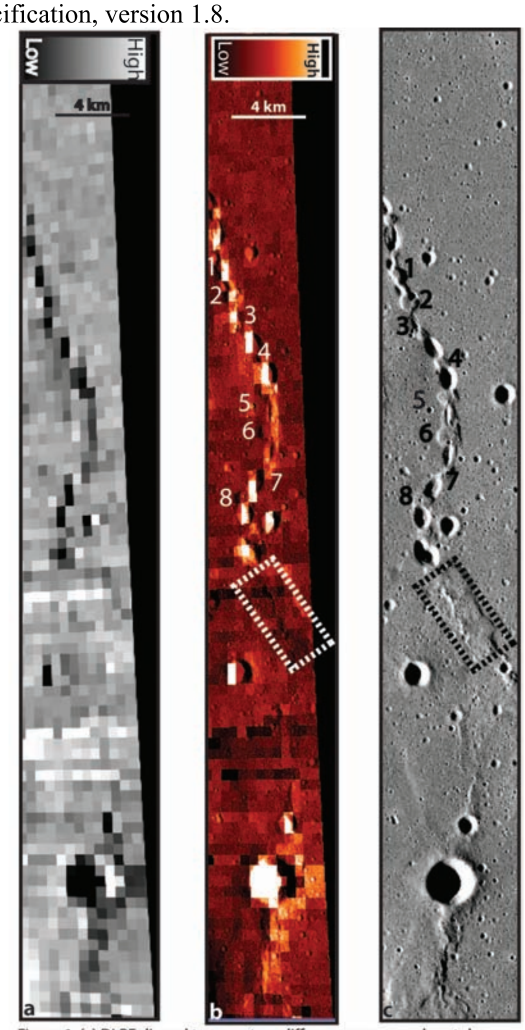

Figure 1. (a) DLRE diurnal temperature difference map over lava tube candidate C. (b) Thermal inertia map for lava tube C. Dotted rectangle denotes the thermal inertia low discussed in the text. Numbers 1-8 indicate the locations of thermal inertia lows over uncollapsed segments. Bright north trending portions are created by shadows in the NAC image and do not indicate high thermal inertia. The east-west trending lows south of dotted rectangle are an artifact of the DLRE data and do not indicate low thermal inertia. (c) LROC NAC Image m102443238rc.