PREDICTING VOLATILE PRESERVATION IN THE LUNAR REGOLITH THROUGH HEAT TRANSFER MODELING. M. E. Rumpf[1], S. A. Fagents[1], I. A. Crawford[2], and K. H. Joy[2], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, 1680 East-West Road, Honolulu, HI 96822, USA, [2]Birkbeck/UCL Research School of Earth Sciences, Gower Street, London, WC1E 6BT, UK.

Introduction: The Moon, lacking both an atmosphere and a magnetic field, potentially makes an excellent laboratory for studying particles originating in the solar wind, solar flares, galactic cosmic rays, and even material ejected from the Earth and other bodies in the solar system during very large impacts [1-4]. Impacting material may become embedded in the lunar regolith. However, if regolith is exposed to the space environment for too long, the particle concentrations become saturated and difficult to interpret [5]. Subsequent burial by impact ejecta or an overlying lava flow is required to preserve an adequate record. If found, a region of layered lava flows with intercalated paleoregolith deposits could give an excellent account of past solar activity. However, a cooling lava flow will heat the underlying regolith, releasing some of the embedded volatiles. The goal of this study is to determine the depths at which a significant proportion of implanted volatiles will remain unaffected by heating due to an overlying lava flow.

Background: The lunar surface is constantly bombarded with micrometeorites and occasionally disrupted on a regional to global scale by larger impacts. These impacts both excavate and deposit material. Over time this process mixes, fragments, and fines the surface material forming a poorly sorted regolith. Large impacts often deposit material far from source, thus most regolith samples are typically composed of a portion of every type of material found on the Moon [5].

The majority of particles that impact the lunar surface are protons emitted by the sun. The major elements from the sun include hydrogen, carbon, nitrogen, and helium. Because of their relatively low energies, these are usually implanted near the surface of rocks and grains [6]. High-energy particles from more distant sources tend to make particle tracks as record of their paths as they pass through a rock. Molecules of CO, CO_2, H_2O, N_2 are often created when the high kinetic energy of the incoming particles is greater than the energy of reaction [6].

Of the impacting elements, H_2, He, and H_2O are lightly absorbed on rock surfaces and might be released at temperatures as low as 300°C. Reaction products, including CH_4, ^{20}Ne, and ^{36}Ar, will be released when heated above 500°C. Many entrapped species (C, N, S, CO, and N_2) will remain in the regolith until a temperature range of 750–1150°C is reached [7]. Such molecules would survive burial by impact debris or lava flows under moderate temperatures.

Model: In a previous contribution [8], we explored regolith heating by thin (1-meter thick) lava flows. Here we investigate in more detail the thermal consequences of emplacement of a 10-meter thick lava flow and the survivability of the underlying solar wind volatiles. Using the PHOENICS computational fluid dynamics software program (http://cham.co.uk), a model was created to simulate the heat transfer between an in situ lava flow and an underlying regolith. The geometry replicated a 10-meter thick lava flow emplaced over a 5-meter thick regolith and consisted of 600 vertical cells. The cell size decreased near the interfaces (regolith to lava contact and lava to free surface contact) to increase the precision at these areas of interest. Heat loss in the lava flow was attributed to radiative cooling to space and conductive heating of the regolith.

The regolith was assigned a density of 1660 kg/m^3 [9], a specific heat of 760 J/kg*K [10], and a thermal conductivity of 0.011 W/m*K [11]. Lava density was set at 2980 kg/m^3 [11]. The current model does not include latent heat released during crystallization of the lava [12]. To account for this, two lavas with end-member values of specific heat (1500 and 3200 J/kg*K) and thermal conductivity (1.5 and 0.75 W/m*K) were modeled [8]. The initial temperatures of the lava and regolith were set at 1500 K [12-14] and 200 K, respectively. The lava flow was not allowed to cool below 200 K, the average ambient temperature on the lunar surface [15]. The model was run for intervals of 100 days to determine the maximum depth that pertinent isotherms would descend into the regolith.

Results: To determine the maximum depths to which principle volatiles are released, the 750°C (1023 K), 500°C (773 K), and 300°C (573 K) isotherms were examined in detail. These isotherms represent the minimum temperatures required to release different volatile species. When the specific heat of the lava is taken as 1500 J/kg*K, maximum depths reached 32.0 centimeters after 500 days for 750°C and 69.4 centimeters after 900 days for 500°C (Figure 1). The maximum depth of the 300°C isotherm was not reached within the 1000 day interval of this model.

The effects of the lava retaining heat for a longer period of time are clearly seen when using a specific heat of 3200 J/kg*K (Figure 2). Here, the maximum depth of the 750°C isotherm reaches 66.1 centimeters after 2100 days of cooling. At 3700 days the 500°C isotherm reached a maximum depth of 143 centimeters. The 300°C isotherm reached a maximum depth of 288.7 centimeters after 8900 days.

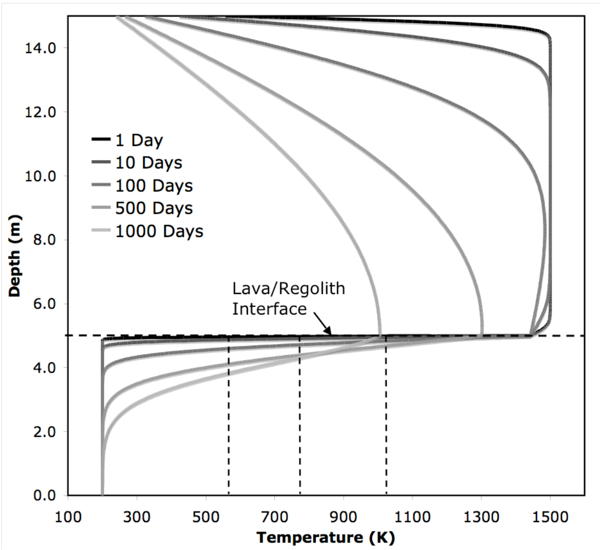

Figure 1. Temperature gradients at several time intervals. Geometry represents a 10-meter thick cooling lava flow with a heat capacity of 1500 J/kg*K overlying a 5-meter thick regolith. Vertical lines represent pertinent isotherms within regolith at 300, 500, and 750°C.

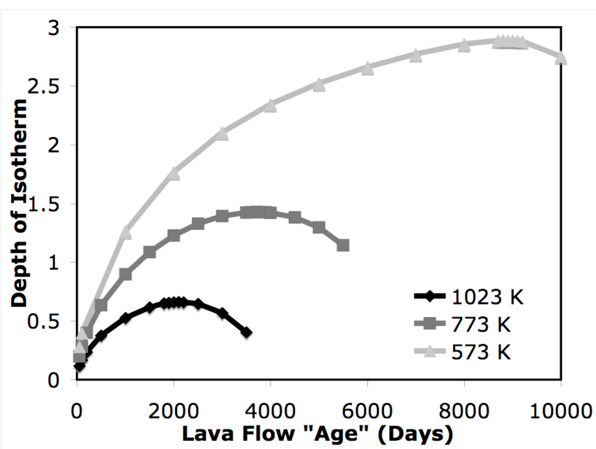

Figure 2. Depth of pertinent isotherms within regolith with time. Overlying lava had a heat capacity of 3200 J/kg*K. Maximum depth of 1023 K (750°C) isotherm: 66.1 cm at 2100 days. Max depth of 773 K (500°C) isotherm: 143 cm at 3700 days. Max depth of 573 K (300°C) isotherm: 288.7 cm at 8900 days.

Discussion: This model shows that many particles, namely C, N, S, CO, and N_2, would be sheltered from heating if they were buried below 32 to 66.1 centimeters of regolith. Reaction-derived species and molecules such as CH_4, ^{20}Ne, and ^{36}Ar will survive this heating to a depth between 69.4 and 143 centimeters. However, weakly implanted particles (H_2, He, H_2O) may be baked out of the regolith at depths greater than 115 centimeters and possibly up to 288.7 centimeters. Repeated burial and constant mixing of regolith deposits make it plausible that solar and extrasolar particles would be found at these depths.

The model described above represents an instantaneously emplaced lava flow. In the future, the model will be modified to include an active flow that changes in depth and velocity with time. Inclusion of temperature and compositional dependences of viscosity, thermal conductivity, and heat capacity will also enhance the model. After the initial modeling stage, the major scope of this project will turn toward surveying preferred landing and exploration sites that likely contain buried paleoregolith deposits. Extraction of such deposits and studies of the implanted volatiles may yield insight into ancient solar and extrasolar activity as well as expose samples ejected from the crust or atmosphere of the early Earth.

References:

[1] Spudis, P.D. (1996) *The Once and Future Moon,* Smith. Inst. Press. [2] Wieler, R., et al. (1996) *Nature*, 384, 46-49. [3] Ozima, M., et al. (2005) *Nature*, 436, 655-659. [4] Armstrong, J.C., et al. (2002) *Icarus*, 160, 183-196. [5] McKay, D.S., et al. (1991) in: *The Lunar Source Book*, 285-356. [6] Haskin, L. & Warren, P. (1991) in: *The Lunar Source Book,* 357-474.[7] Simoneit, B.R., et al. (1973), *Proc. LSC* II, 1635-1650. [8] Crawford, I.A. et al., (2007), *LPSC XXXVIII,* abs. #1323. [9] Carrier, W., et al. (1991) in: *The Lunar Sourcebook*, p 475-594. [10] Hemingway, B.S. & Robie, R.A. (1973) *LPSC* IV 355-356. [11] Langseth, M.G., et al. (1976) *LPSC* VII, 3143-3171. [12] Turcotte, D. & Schubert, G. (2001) *Geodynamics*, CUP. [13] Williams, D.A., et al. (2000) *JGR,* 105, 20,205. [14] Murase, T. & McBirney, A.R. (1973) *GSA Bull.,* 84, 3563-3592. [15] Vaniman, D., et al. (1991) in: *The Lunar Sourcebook*, 27-60.