

MODELING THE THICKNESS OF LUNAR POLAR VOLATILE STABILITY ZONES AND SCENARIOS FOR WATER ICE REMOBILIZATION. H. A. Danque¹ and K. M. Cannon¹, ¹Colorado School of Mines, Golden, CO, USA. (hdanque@mines.edu).

Introduction: The quantity and distribution of lunar volatiles in polar cold traps may offer clues to the Moon's thermal history, orbital variations, and changes in volatile supply and loss rates over time. It is also of interest for volatile In Situ Resource Utilization (ISRU) cases. Current research focuses on lunar volatiles' presence and spatial extent in cold traps [1, 2]. In addition, a body of work examines the depth to the top of volatile stability zones [3, 4]. However, the depth to the base of volatile stability zones, changes of stability zone shape with crater infill, and potential remobilization of volatiles in regolith are topics needing dedicated research.

The water ice stability zone exists where regolith surface temperatures are below $\sim 110\text{K}$ [5], or regolith subsurface temperatures are below $\sim 145\text{K}$ [4, 6]. Volatiles may exist in lunar regolith as discrete grains of ice mixed with the regolith, adsorbed onto regolith grains, or as discrete layers of ice [7]. Large impacts or volcanic events may have formed relatively ice-rich layers similar to those observed in cold traps near Mercury's poles [8]. Over time, gardening processes will mix, bury, and expose the ice and icy regolith mixtures. Erosional processes will remove volatiles at the surface [9]. Icy regolith mixtures may also be buried and protected from gardening by blanketing impact ejecta layers [10].

This work explores the hypothesis that volatiles may experience subsurface temperatures that could sublimate ice from the base of cold traps. The temperature conditions may exist to redeposit volatiles in other parts of subsurface cold traps. We also explore a potential positive feedback in which increased ice content improves the thermal conductivity of icy regolith mixtures, thickening volatile stability zones [4]. The remobilization and positive feedback in thermal conductivity may result in more ice at shallower depths and closer to the edges of cold traps than simple volatile and regolith depositional models would imply.

Methods: Here, we calculate two-dimensional (2D) thermal models of regolith and icy regolith mixtures to define modified shapes of volatile stability zones around cold traps. We use the finite element solver in the Python Library for Inversion and Modelling in Geophysics (pyGIMLi) [11]; thermophysical properties of lunar regolith, megaregolith, and water ice along with a range of boundary conditions. We develop synthetic crater profiles, modify them based on topographic diffusion rates, and examine the thermal effects of infill [12]. The heat equation describes temperature variations of mediums and

depends on bulk density, thermal conductivity, and specific heat [13]. The thermal conductivity varies with composition, density, and temperature. Upper boundary conditions for the model depend on solar energy input and infrared emission to space. We choose an upper boundary condition for the model outside the cold trap of 160K , which is the average temperature at 1 m deep for latitudes of ~ 75 degrees [14]. The upper boundary condition inside the cold trap is 110K [5]. The lower boundary condition is dependent on the subsurface heat flux from the mantle and crustal radioactive sources [13, 15] and the blanketing effects of megaregolith [16]. We choose a lower boundary condition of 250K at the 1 km depth of the model's base [17]. The regolith thermal conductivity is $0.023\text{ W m}^{-1}\text{ K}^{-1}$ [18], and megaregolith thermal conductivity is $0.2\text{ W m}^{-1}\text{ K}^{-1}$ [16]. The low-temperature regolith heat capacity function is from [19]. The regolith density with depth function is from [13, 20]. Water ice's thermal conductivity is $5.5\text{ W m}^{-1}\text{ K}^{-1}$ at 110K , and the density is 932 kg m^{-3} [21].

Results: We model a lunar crater with a 1 km diameter and calculate 2D temperature profiles (Figures 1-3). Most of the model space has properties consistent with a megaregolith layer that extends from the base of surficial regolith at 10-20 meters to 2-3 km below the surface [17]. For clarity, the surficial regolith of $\sim 10\text{m}$ thick is removed from Figures 1-3.

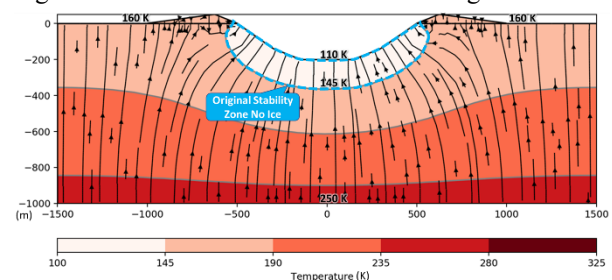


Figure 1. A 2D thermal model of a 1 km diameter crater containing a cold trap. The ice trapping zone is between the 110K and 145K temperature isotherms (dashed blue line).

The initial model is a 3 Ga old impact crater shortly after reaching thermal equilibrium. It has a relatively thick volatile stability zone (Figure 1). The crater model is filled with regolith to a thickness consistent with topographic diffusion for three billion years. The filled crater is 52% of its original depth [12]. The low thermal conductivity regolith infill acts as a blanket to elevate temperatures below the crater. The model shows the new base of volatile stability will move up to equilibrate with the new surface and infill thermal

properties. The new base of stability is above the original surface of the crater (Figure 2).

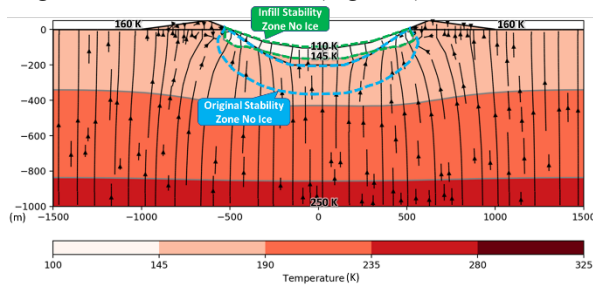


Figure 2. Shows a model with regolith infill that is ice-free or has a low weight percent ice to 52% of the crater depth [12]. The shape of the stability zone changes with fill and shows thinning in the middle and thickening at the edges of the cold trap (dashed green line).

If low-weight percent ice exists in the regolith fill, it could be sublimated from the base of the fill zone. The cold trapping temperature conditions exist to redeposit the volatile molecules at shallower depths or closer to the edges of the cold trap. With the given model parameters, there appears to be remobilization potential for crater fill with less than a few weight percent ice mixed with regolith.

If the crater model contains a layer of relatively pure ice, the base of stability is deeper (Figure 3). The modeled ice layer could represent a Mercury-like layer of ice that formed relatively quickly following a large volatile-rich impact [7, 8, 22]. This scenario requires an ejecta cover following ice layer deposition to reduce gardening and erosion. The modeled base of stability also stays below the original crater floor if there are 10s of weight percent high thermal conductivity ice mixed with the regolith fill.

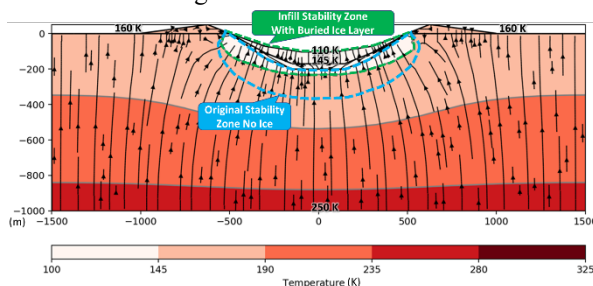


Figure 3. A model with a buried layer of old (~3 Ga) relatively pure ice deposited on the original crater floor.

The ice layer has a high thermal conductivity compared to regolith. This partially compensates for the blanketing effect of regolith infill. In addition, there are areas near the edges of the crater that have a thickened stability zone. This model run indicates a thick layer of ice would enhance its thermal stability by keeping the 145K isotherm below the original crater floor and the base of the ice layer.

Discussion: The model results support the hypothesis that a low-weight percent icy regolith mixture may sublimate at the base of the stability zone in craters that are old enough and small enough to have a significant percentage of infill. The models indicate that the base of the volatile stability zone may become shallower than the original crater surface.

Icy regolith mixtures have a higher thermal conductivity than dry regolith but lower than pure ice. Linking the potential remobilization of volatiles from the base of a stability zone with the observation that icy mixtures have a higher thermal conductivity creates scenarios where icy regolith will wick away internal heat more quickly to the surface of cold traps where it will radiate to space. This will depress the depth to the base of the volatile stability zone. This positive feedback may create a reverse "accommodation space" in porous regolith as ice content increases. This could allow pore-filling ice to build down to the limits of regolith porosity and the intergranular volatile migration paths. However, there will be a functional limit to the stability zone thickening feedback where lunar heat flux balances the improved thermal conductivity of icy regolith mixtures.

Conclusion: This work examines a hypothesis for subsurface volatile remobilization and a potential positive feedback with ice concentration that may decrease the depth and increase the thickness of ice stability zones around lunar cold traps. More accurate measurements of both regolith and megaregolith thermophysical properties are critical for understanding and accurately modeling the location and concentration of volatiles in the lunar subsurface.

References:

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