POTENTIAL CAPTURE OF TRANSIENT ATMOSPHERE VOLATILES IN SUBSURFACE COLD TRAPS.

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Introduction: Past research indicates the Moon may have had transient collisional atmospheres in its geologic history [1–6]. The Moon currently has a surface boundary exosphere with a near vacuum pressure of ~10^{-12} mbar [1]. Large impacts of comets, asteroids, and volcanic eruptions are proposed mechanisms that could generate transient atmospheres for geologically short intervals until the transient atmosphere is lost to space [1–3]. The peak volcanic activity period was 4–2 Ga [1, 2], and a typical erupted transient atmosphere had a mass of ~1.2×10^{12} kg, ~5×10^{-4} mbar surface pressure, and a lifetime of ~2500 years [2]. Thousands of transient atmosphere events were modeled [2]. Each event shows a sharp rise in total atmospheric and water vapor mass. The transient atmospheres remain collisional until the total mass falls below 10^7 kg [2]. The water from a typical eruption may be removed within 50 years by deposition on the surface of polar cold traps and by loss to space from Jeans escape, photodissociation, and sputtering [2].

Cold traps are sometimes defined as the temperature at which a volatile sublimates at a rate less than the amount deposited [7]. Water ice has a vacuum sublimation stability temperature ~110 K at the surface [8]. Ice may be adsorbed on grain surfaces, deposited on the surface of cold traps as an optically visible frost, or as individual layers that are a few millimeters to a few centimeters thick, depending on the size of the eruption event [2]. Without accounting for loss processes and assuming cold traps were present at 4 Ga or earlier, there is potential for meters to hundreds of meters of ice cumulatively in the coldest surficial cold traps [2, 9, 10].

Subsurface cold traps for water ice may exist where temperatures are below ~145 K [7, 11]. The higher sublimation rate threshold temperature in the subsurface is due to the diffusion barrier of the regolith in exospheric conditions and the need for volatile molecules to make short hops from grain to grain to escape a subsurface cold trap [7].

Past research on subsurface volatiles generally used current exospheric conditions [7, 12]. Current published research on transient atmospheres does not account for the deposition of volatiles in the subsurface pore space of regolith and megaregolith at cold trapping temperatures [1, 2, 4, 6].

Methods: This work presents the conceptual setup for a quantitative model of the infiltration of volatile molecules into regolith pore space and the potential for deposition in the subsurface (Figs. 1, 2). After an impact or volcanic eruption, a transient collisional atmosphere develops as the exobase rises above the lunar surface [2]. Ice will deposit on cold trap surfaces as frost and may reduce the cold trap's surface porosity and permeability. The pressure front will diffuse into the regolith pores and will slowly attempt to equilibrate connected subsurface void space (Fig. 1).

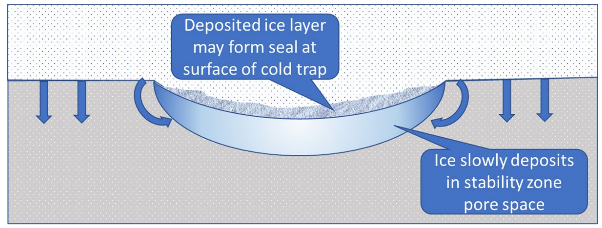

Fig. 1. As the pressure increases above the regolith surface, the transient atmosphere molecules will diffuse into the lower pressure (near vacuum) regolith pore space.

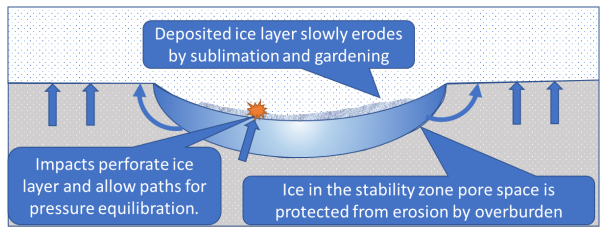

Fig. 2. The pressure gradient reverses as a transient atmosphere is stripped away over a few thousand years. As a result, gaseous molecules stripped of higher sublimation temperature volatiles will diffuse from the pore space to the remaining atmosphere or exosphere.

Ice deposited on the surface will experience gardening by primary and secondary impacts [13, 14]. Thus, ice in surficial cold traps is likely mixed with regolith by impact processes, and surficial layers of ice are likely to be perforated and eroded (Fig. 2). However, gardening efficiency decreases with depth [13, 14]. Therefore, volatiles buried or deposited below the shallow zone of intense gardening are more likely to be protected from various erosive surface processes.

Results: A 2D thermal model over real lunar polar topography shows that the potential zone of stability is 10s to hundreds of meters deep [15]. Thus the corresponding grain surface area available for volatile deposition is large (Fig. 3).

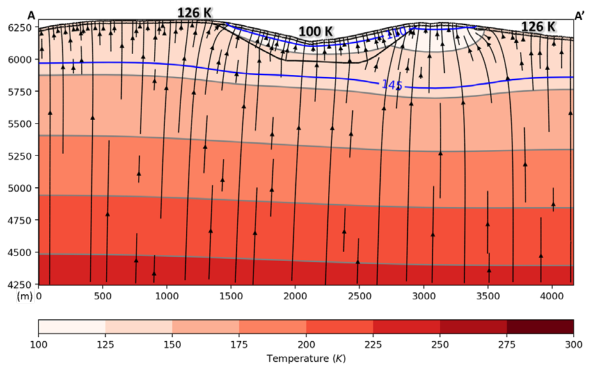

Fig. 3. A 2D thermal model of a cold trap near the VIPER mission area. The arrows indicate heat flow direction. The upper boundary conditions are the mean of the measured DIVINER temperatures inside and outside the cold trap.

Discussion: If volatiles are deposited in the subsurface it may change the timing of ice deposition, the quantity, and the ratio of deposition relative to loss mechanisms. The second implication is that volatiles deposited below the zone of intense gardening would be better protected for geologic time spans.

There is research that identifies the aerial extent of potential cold trapping temperatures in the subsurface [11, 12]. The potential thermal base of water ice stability across the south polar region was modeled and found to be 10s to hundreds of meters thick [12]. These results are consistent with the depths to the 145 K contour observed in the 2D thermal model (Fig. 3). Observations of crater morphology do not indicate extensive layers of pure or dirty ice in the shallow subsurface or even tens of weight percent ice filling pore space [12].

Some factors may limit the deposition of volatiles in the subsurface. Transient atmospheres from volcanic sources are likely to have a high CO content. CO has a very low sublimation threshold temperature of 18 K [8]. This means that CO and other low sublimation threshold temperature molecules will be concentrated in the subsurface pore space as higher stability temperature volatiles deposit on grain surfaces. Pressures should roughly equilibrate with CO or other low-stability temperature molecules filling the pore space. Gas composition gradients may lead to slow ongoing diffusion, but it is unlikely to be as efficient as pressure changes of several orders of magnitude (~10^{-12} mbar to ~10^{-4} mbar). The filling of pores with residual very low sublimation temperature gases would tend to limit the quantity of volatiles deposited during a given eruption or impact event. However, the transient nature of an atmosphere would lead to lower pressures above the surface as the atmosphere is lost, and the CO and other low sublimation temperature molecular species would slowly leak into the exosphere. Depending on the relative mass and pressure of the exosphere to the pore space gases, this slow 'exhalation" could extend the tail of atmospheric loss during an individual transient atmospheric event. If there is enough time between eruptions diffusion would leave the pore space with exospheric pressures so that when the next transient atmosphere event occurred, it would allow the process to repeat.

The ebb and flow of pressures from early transient lunar atmospheres to the regolith pore space or rock fractures could lead to the layering of volatiles that would potentially record volatile isotopic composition. An isotopic record from layered volatiles on a grain surface or a fractured rock could provide evidence in the ongoing debate on the internal or external origin of lunar volatiles and the relative abundance of different sources. If the pore space has more than a few weight percent filled by volatiles, it could be a resource for ISRU exploration. There is some information from neutron spectrometer and imaging radar data to about a meter deep. However, the depth interval from a few meters to tens of meters, where the process of volatile deposition in pore space is most likely to occur, has a shortage of data and should be a target of future missions and instruments.

Conclusion: This work explores the implications of transient atmospheres in the lunar subsurface. Thermal conditions appear to exist in regolith and megaregolith that would allow volatiles to deposit on cold grains adjacent to open pores in lunar polar regolith. A limiting factor is the time for an atmosphere to diffuse into the subsurface and the depth of the pressure front compared to the depth of volatile thermal stability.

Ongoing modeling will compare thermal models with models of diffusive flow from transient atmospheric conditions into regolith and megaregolith to determine where volatiles may be deposited in subsurface pore space.

References: [1] Head, J. W., et al., (2020), *GRL*, 47. [2] Wilcoski, A. X., et al., (2022), *Planet. Sci. J.*, 3, p. 99. [3] Ong, L., et al., (2010), *Icarus*, 207, pp. 578–589. [4] Needham, D. H., and Kring, D. A., (2017), *EPSL*, 478, pp. 175–178. [5] Tucker, O. J., et al., (2021), *Icarus*, 359, p. 114304. [6] Aleinov, I., et al., (2019), *GRL*, 46, pp. 5107–5116. [7] Schorghofer, N., (2022), *LPV Conf.* Boulder CO. [8] Zhang, J. A., and Paige, D. A., (2009), *GRL*, 36, p. 5. [9] Rubanenko, et al., (2019), *Nat. Geosci*., 12, pp. 597–601. [10] Cannon, K. et al., (2020), *GRL*, 47. [11] Siegler, M. A., et al., (2016), *Nature*, 531, pp. 480–484. [12] Siegler, M. A., et al., (2018), *LPSC*, Abstract 2087, p. 5038. [13] Costello, E. S., et al., (2020), *JGR Planets*, 125. [14] Costello, E. S., et al., (2021), *JGR Planets*, 126. [15] Danque, H. A., and Cannon, K. M., (2022), *LPSC*, Abstract 1635.