

**IN SEARCH OF IMPACT-INDUCED H<sub>2</sub>O-ALTERATION SIGNATURES: INITIAL THERMAL CONSTRAINTS.** J. D. Stopar<sup>1</sup>, M. S. Robinson<sup>1</sup>, E. Asphaug<sup>1</sup>, B. L. Jolliff<sup>2</sup>, E. J. Speyerer<sup>1</sup>, P. R. Christensen<sup>1</sup>  
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**Introduction:** Reservoirs of volatiles, including water (H<sub>2</sub>O), may persist within the lunar polar regions, where burial and cold-trapping prevent rapid loss to space [e.g., 1-9]. Water-ice, along with other volatiles, potentially exists as masses, an intimate regolith mixture, or adsorbed on grains [e.g., 3,10]. At very low temperatures (e.g., <110 K), which are typical of many polar regions, water-ice may even be geologically stable at the surface [e.g., 11].

The nature and extent of lunar polar volatiles are not yet well-constrained, and volatiles possibly exist as a variety of species or in various forms. The LCROSS impact-generated plume supports ~6 wt% water-ice within a small permanently shaded region (PSR) of Cabeus crater [5-8]. Surface temperatures suggest that as much as two-thirds of the surface pole-ward of 85°S may be an effective cold-trap, if not necessarily a PSR [12]; even small shaded regions may harbor volatiles [11]. Over time, these modest volatile resources may affect near-surface chemistry and its evolution, if conditions permit.

To further constrain the distribution of water-ice, which is a key driver of future exploration, as well as methods of its detection and determination, we investigate the probability of near-surface, water-mineral reactions that might result in detectable signatures (e.g., via in-situ and/or stand-off sensing techniques).

**Background:** To enable water-mineral reactions in cold polar regions, a heat source is needed. One plausible environment where reactions between water and minerals may occur is in the near-surface adjoining an impact event. Impacts generate a large amount of thermal energy, affecting a radius of target rock that scales with impactor parameters and target properties [e.g., 13-15]. Impact-generated heat can provide the energy needed to melt and vaporize target rocks, as well as water-ice. However, it is unclear if, or what quantity of, volatiles delivered, melted, and/or vaporized during impact can be retained; though a few vol% of cometary and meteoritic volatiles may be imparted to the surface [e.g., 16]. Moderate impact heating of already buried volatiles, however, could allow for localized oxidation or hydration reactions when subsurface materials are heated.

The length of time and extent of heating depend on thermal conductivity as well as rates of thermal radiation and volatile diffusion, which vary with compaction, fractures, and pore-interconnectivity [e.g., 17-18]. The duration and radius of heating directly affect the

amount of chemical alteration reactions that can occur. As a point of reference, the terrain around two small terrestrial craters (4-km Kardla and 1.5-km Lonar) are thought to have cooled over several thousand years, even with enhanced convective cooling resulting from hydrothermal circulation [e.g., 19-20]. Apollo materials contain evidence for long-duration (e.g., thousands of years) and shorter-lived, high-temperature (600-1000°C) vapor-phase reactions during large (i.e., basin-forming) impact events [e.g., 21-24]. These temperatures and timescales are generally favorable for mineral alteration reactions [e.g., 25].

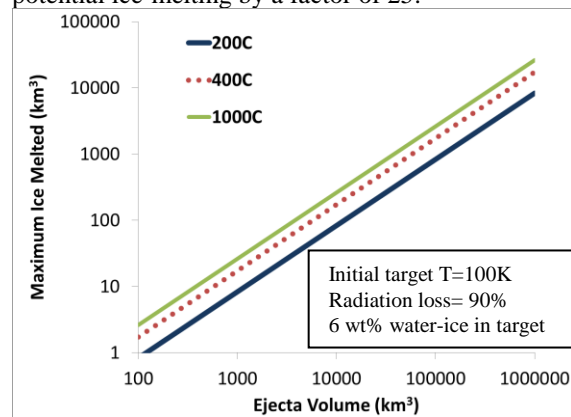
**Methods:** Heat-transfer modeling [e.g., 2,8,18,26-27] provides a straightforward approach to assessing the potential for water-mineral reactions in the lunar polar regions. For our preliminary model, we employ a simple, uniformly distributed, two-layer model of hot crater materials overlying a porous, non-mare regolith with 6 wt% pore-bound water-ice. While the bulk of impact-generated heat is expected adjacent to the crater cavity, we adopt a flat-lying model volume for ease of calculation (and refer to this model as ejecta overlying regolith), but the general principle of heat transfer also applies to the areas adjacent to the crater cavity. We allow for large thermal losses through radiation, and we employ published values of heat capacities, latent heats, and densities for the lunar regolith and H<sub>2</sub>O [e.g., 9,18,28]. We also assume constant pressure, minimal diffusion, effective heat transport, no pore connectivity, pore-pressures can exceed the triple point of water, and H<sub>2</sub>O and regolith warm on similar time-scales. These simplifications provide an estimate of the maximum amount of water-ice that can be liberated during various impact events. Future work will refine these preliminary models.

**Results:** Materials ejected near the crater rim will be the thickest, and most volumetrically significant, though often the least shocked. However, ejecta materials experience a wide range of shock pressures and temperatures, and range from a few hundred degrees to more than 1450°C [e.g., 29]. A single, small 5-km crater with cool ejecta (200°C), is unlikely to melt significant ice, but a 30-km crater with warmer ejecta (600-1000°C) has enough heat to melt several hundred km<sup>3</sup> of ice or vaporize ~50 km<sup>3</sup> of ice (**Fig. 1**). However, small craters form much more frequently than larger craters, and may over time activate volumetrically significant water.

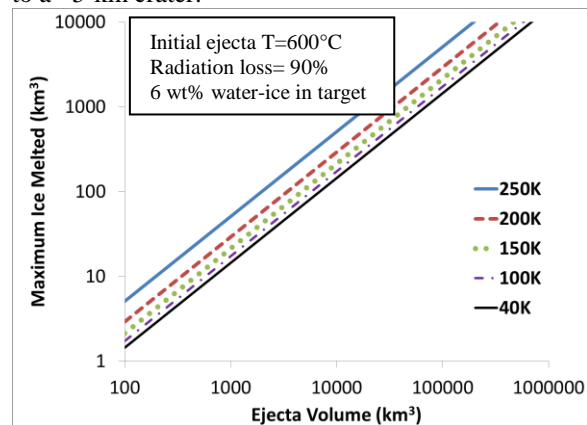
If ice is confined to a thin layer (e.g., upper meter), then, for modeled craters larger than  $\sim 1$  km in diameter, there is less ice available for melting than energy to melt it. However, low thermal conductivity of the porous upper regolith [e.g., 18], may help concentrate heat in the near-surface and increase the duration of the heating event.

Initial surface and subsurface temperatures of target materials also affect the volumes of melt/vaporized ice. Target materials with an initial temperature of 200K can significantly reduce the amount of heat required to raise regolith and ice temperatures to the melting point compared to those at 40K, thereby increasing the maximum volume of ice melting by a factor of two (Fig. 2).

The initial assumption that radiation reduces the available impact-generated heat by 90%, strongly controls the magnitude of the maximum melt volumes. Decreasing radiation losses from 98% to 50% increases potential ice-melting by a factor of 25.



**Figure 1.** Maximum volume of ice melted by heating from overlying ejecta as a function of ejecta temperature. Assuming 50% of ejected materials are within two crater radii of the transient crater (TC) rim crest, and depth/diameter of the TC is 1/3, a volume of 1,000,000 km<sup>3</sup> equates to a  $\sim 140$ -km diameter crater and 100 km<sup>3</sup> to a  $\sim 5$ -km crater.



**Figure 2.** Maximum volume of ice melted as a function of ejecta volume and initial target temperature.

**Implications:** Chemical reactions are generally enhanced by surface defects such as fractures, shocking, and disordered chemical structure [e.g., 30-31], all of which should be relatively common in the battered, near-surface lunar regolith. Our initial calculations of the maximum volumes of melted and vaporized ice suggest that the formation of detectable chemical signatures during impact-events into polar, volatile-enhanced reservoirs might be possible.

Where pore-interconnectivity is minimized (as modeled), liquid-water alteration pathways are reactant-limited, and chemical reactions are strongly controlled by local mineralogy [e.g., 25]. Under these conditions, liquid solutions tend to quickly become saturated [e.g., 30]. While saturation may slow reactions, it also can also favor the formation of secondary product.

Over time, near-surface materials, including any alteration products, will tend to be churned up through impact gardening, potentially becoming exposed at the surface, where they can be detected and studied. The pervasiveness (or dearth) of alteration signatures ultimately informs the persistence, reactivity, and evolution of volatile resources on the Moon.

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