DESCRIPTIVE AND GENETIC MODELS FOR LUNAR ICE DEPOSITS CONSISTENT WITH CURRENT REMOTE SENSING DATA. K. M. Cannon[1], [1]Colorado School of Mines, 1500 Illinois St., Golden, CO 80401. Email: cannon@mines.edu.

Introduction: It has been challenging to reconcile the limited data we have on where and how much ice is present at the lunar poles, to say the least. There are no clear surface expressions of ice deposits as geomorphologic features [1] or as clearly distinct albedo anomalies [2], but patchy–perhaps ephemeral [3]–spectral signatures are present at the optical surface (i.e., nanometers to micrometers) [4–6]. Radar data were previously interpreted as thick subsurface deposits [7] but are probably better explained by buried rocks [8,9]. Crater morphometry could indicate tens of meters of icy infill in smaller craters [10], but newer work [11] challenged those findings. The reliability of neutron spectroscopy datasets has been vigorously debated [12].

On the other hand, these data have both a positive and negative component: what do they suggest, but also what do they rule out because if it was there it would show up in the data? For example, thick surface deposits would be clearly visible in ShadowCam imagery. The epithermal neutron suppression would be stronger if there were more hydrogen in the upper ~100 cm. In addition, ice was deposited and then modified at the poles by geologic processes that are well understood, for example impact cratering.

This work will present up to date models for lunar polar ices based on new computer simulations coupled to constraints from all existing remote sensing datasets. There are significant implications for ice mining architectures and exploration strategies going forward.

Descriptive Model: Many types of "models" exist to describe a mineral deposit (Fig. 1). A *descriptive model* is an empirical description of a grouping of deposits, in this case lunar polar ice located in cold traps, each of which is an individual deposit. A potential criticism is that we do not have enough data to make a descriptive model in the same way we would for Earth. But Fig. 1 shows the process is iterative. Models feed into each other and eventually into a final model that connects back to the beginning: as we get more information the models continually improve over and over. What I am suggesting is that even though current data are limited, we can develop both descriptive and genetic models that may be crude but will be improved repeatedly as more information becomes available. The best current descriptive model is as follows:

At the *optical surface* (nm to µm) there is a patchy "frost" [4–6], although frost is a generous term because this ice does not show up in initial ShadowCam imagery [2]. The results from [6] "some ice-bearing pixels may contain ~30 wt % ice" have been taken too literally in the space resources community, not appreciating that the M^3 instrument only senses to microns beneath the surface and that there cannot be this much ice at cm to m depths over any large area because neutron spectroscopy rules this out.

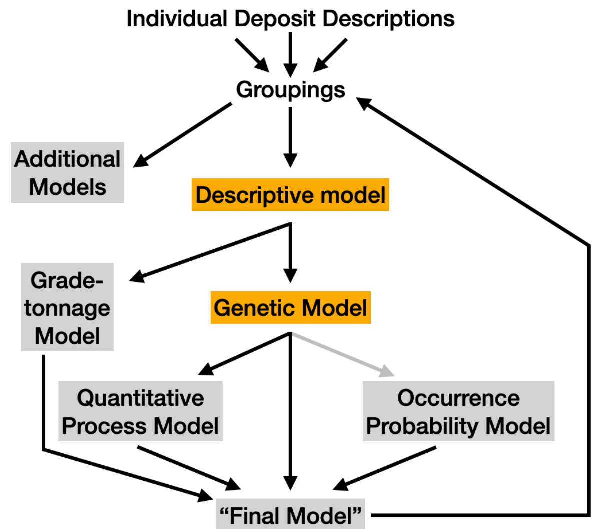

Fig. 1. Mineral deposit model types.

Strong, independent lines of evidence suggest the upper 5–15 cm of polar cold traps is desiccated with essentially no ice. This comes from 2-layer inversions of neutron spectroscopy data [13], the size of meteoroids responsible for LADEE detections of exospheric H_2O [14], and a time-lag linked to SELENE/Kaguya Spectral Profiler detections of possibly sublimated H_2O [15]. If this desiccated layer is ubiquitous, it more or less rules out mining ice by shining light or microwaves directly into the ground.

The same 2-layer models of neutron spectroscopy data suggest 0.2–2.0 wt.% water-equivalent hydrogen below the desiccated layer down to ~80–100 cm [13]. There is degeneracy in whether there is more ice in small horizontal exposures, or a smaller amount everywhere. Probably the simplest model is that all the signal is coming from cold traps [16] with an even distribution within them, in which case ~0.4 wt.% ice is a middle ground estimate [16,17].

The LCROSS experiment detected around 5 wt.% ice at Cabeus crater, with this number sensitive to the total mass of the ejected plume that was indirectly assessed [18]. Newer analyses of the data [19] suggest an increasing concentration of ice with depth, and a fair interpretation is little to no ice in the upper meter with the 5 wt.% coming from beneath that depth.

Genetic Model: A *genetic model* is more general than a descriptive model and includes a genetic component: what processes led to the deposit type having the properties in the descriptive model? In other words, how did the ice get there? The genetic model here builds on earlier work [20] and includes new ideas from recent theoretic models. Ice is initially deposited at the top of cold traps and possibly within regolith pores as gas-solid deposition from transient collisional atmospheres created by impacts of mostly large, hydrated asteroids. Based on recent models of obliquity evolution [21], this process began ~3.5 Ga with about 50% of present cold trap area present by ~2.1 Ga. This post-dates most mare volcanism, so volcanic outgassing probably did not supply much ice to the poles.

Once deposited, ice is subject to strong erosion at the upper few mm from micrometeoroids [3]. Impact gardening continually brings fresh ice up in contact with this "broiler" at the surface and desiccates regolith over time. Ice can be protected at depth via dry lag deposits formed by impact ejecta, landslides, levitated dust deposition, and/or anhydrous meteoritic infall.

Monte Carlo Methods: The processes in the genetic model can be parameterized in Monte Carlo computer simulations. In previous work [20,22] the relevant dynamics were not captured properly because of the scale of the grid and size of impact craters, or because starting models at ~4 Ga leads to orders of magnitude too much ice [21].

New simulations reported for the first time here use a 12×12 km grid with craters between D=60–1500 m modeled explicitly with excavation from depth and surface ejecta. Ice is deposited at the surface stochastically from 2.1 Ga to present based on globally distributed impacts that lead to transient atmospheres. Surface erosion of ice, and gardening, are parameterized on a sub-grid scale allowing 5 cm vertical resolution.

The simulation outputs are tested against a set of strict constraints: (1) no contiguous, high-purity ice at the very surface; (2) small patches of low-purity ice present at the surface; (3) a desiccated layer in the upper 10 cm over most of the grid; (4) low-purity ice present beneath the desiccated layer; (5) widespread moderate-purity ice present below 1 m depth.

Results: Fig. 2 shows a successful simulation output that satisfies all 5 constraints. In general, most failed model runs either had too much ice (contiguous surface exposures and no desiccated layer) or too little (no patchy surface ice and not enough ice below desiccated layer), with other rarer combinations. The successful simulation results are the first to reproduce all known features of lunar ice deposits as captured by the descriptive model and demonstrate that the genetic model provides a process-based explanation for the deposits as currently understood.

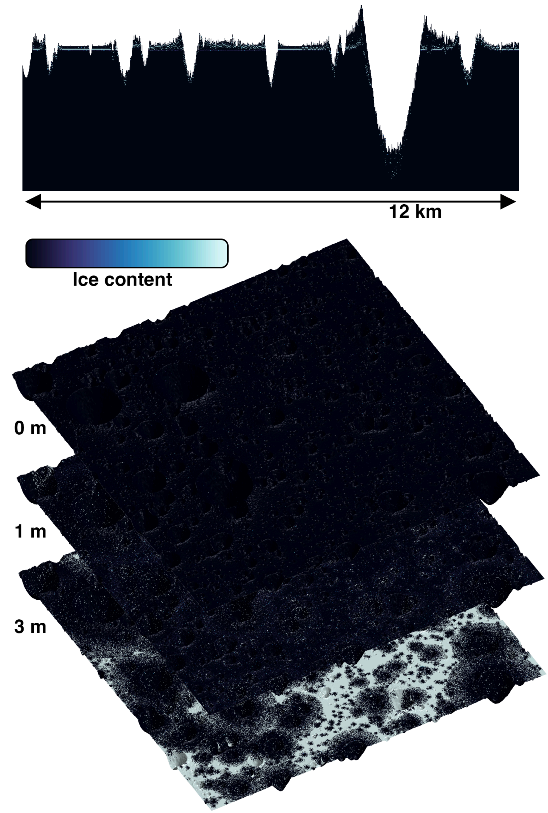

Fig. 2. Cross section (top) and slices at different depths (bottom) through a successful model run.

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