VOLATILE COMPOSITION OF VOLCANICALLY SOURCED LUNAR ICE DEPOSITS. A. X. Wilcoski¹, C. M. Elder¹, M. E. Landis², and P. O. Hayne² ¹Jet Propulsion Laboratory, California Institute of Technology (andrew.x.wilcoski@jpl.nasa.gov), ²Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO.

Introduction: The discovery of water ice at the lunar poles over the last several decades has shed new light on the Moon’s complex history and made polar ice the target of numerous ongoing and future lunar missions [1], including the VIPER rover slated for launch at the end of 2024.

One of the primary goals of investigations into lunar ice deposits is the determination of their origins and compositions, with both having implications for the history of water in the inner solar system and the utility of lunar water as a resource. The most likely sources of lunar surface and shallow subsurface water are impacts from asteroids and comets, solar wind ion implantation, and volcanic outgassing from the lunar interior [1].

The composition of non-water volatiles within an ice deposit may be a useful indicator of the deposit’s source (e.g., [2]). For example, various sulfur species have been suggested as potential tracers of volcanically sourced ice [1]. However, it is not known if any of these volatile species would be able to condense in polar cold traps. Additionally, different volatile species may experience an unknown degree of fractionation as they migrate from their source regions to polar cold traps, resulting in ice compositions that differ from those of their sources [2]. Before ice composition can be effectively used as an indicator of ice origin, it is necessary to quantify the degree of fractionation expected as volatiles from each source migrate to and are sequestered in polar cold traps.

In this work, we estimate the volatile composition of ice sourced from volcanic outgassing after undergoing several fractionating processes, including escape to space and condensation within cold traps. We build on previous work [3] that modeled the cold trapping of water during transient atmospheric episodes induced by volcanic outgassing on the early Moon. We adapt this model to include non-water volatiles to develop testable predictions of ice composition with a volcanic origin.

Methods: We model ice accumulation onto the lunar surface during the Moon’s most volcanically active period (4-2 Ga). During this period, typical eruptions should have released enough gas to create short-lived, global, collisional atmospheres [3,4,5]. The composition of these atmospheres would have been dominated by CO, but included water and other non-water volatiles [6,7]. We model the creation of collisional atmospheres by 50,000 eruptions over this 2 Gyr period [5], the subsequent atmospheric escape to space, and the temperature-dependent accumulation of water and non-water volatiles as ice in polar cold traps.

The modeled atmospheres are composed of CO, H₂O, and several sulfur-bearing species. [6] modeled gas speciation in volcanic eruptions and determined the relative abundances of the sulfur bearing molecules SO₂, H₂S, S₂, and COS [5]. [7] performed a similar analysis using lower oxygen fugacity and determined the relative abundances of H₂S, S₂, COS, CS₂, and H₂S₂. We explore model behavior under both of these assumptions of erupted sulfur-bearing volatile content.

After an eruption occurs, the model calculates the atmospheric escape rate of each atmospheric species, considering three types of escape: Jeans escape, sputtering, and photodissociative escape [8]. Atmospheric escape occurs above the exobase altitude when molecules achieve escape trajectories and energies. The exobase altitude is defined as the altitude above which an upwardly ejected particle experiences exactly one collision and is a function of both atmospheric mass and composition.

The model uses maps of maximum annual temperature measured by the Diviner Lunar Radiometer Experiment [9,10] to

Figure 1 Supplied thickness of water ice deposits after a full 2 Gyr model run from the pole to 80° latitude for the South (left) and North (right). The model outputs similar maps for each of the volatile species considered.
calculate condensation rates onto the surface for each species. This method treats each ~300 m scale Diviner pixel as a potential cold trap that removes each volatile species from the atmosphere at a rate determined by its temperature and the saturation vapor pressure curve of that species.

**Results & Discussion:** The model produces maps of accumulated mass for each volatile species down to 60° latitude in both poles, though most mass is accumulated above 80° latitude (Fig. 1). Note that these maps show total ice supply, but do not consider processes that could destroy ice such as sublimation to space over billions of years or impact gardening. We find that significant amounts of non-water volatiles (e.g., SO₂, H₂S, OCS) accumulate in polar cold traps. These species are able to accumulate for several reasons. Water, as the lightest volatile species modeled here, strongly controls exobase altitude. Because all the non-water volatiles modeled here are heavier than water, they are concentrated below the exobase, preventing efficient escape. In addition, while all the non-water ices modeled here have lower stability temperatures than that of water ice, enough lunar cold traps achieve sufficiently cold temperatures to accumulate these volatiles on much shorter timescales (<100 yr) than the lifetimes of the CO-dominated atmospheres (~2500 yr).

An important, though not unexpected, result of this modeling is that the composition of volatiles accumulated in each cold trap depends on the cold trap’s temperature. Figure 2 shows the fraction of molecules of each species that make up ice deposits as a function of cold trap maximum temperature. Composition remains relatively stable with increasing temperature and then changes rapidly as temperatures exceed a species’ stability temperature. This causes ice composition to be an almost stepwise function of cold trap temperature.

The composition of ice deposits is fractionated with respect to the source composition for several reasons. The most obvious is the fact that only the coldest cold traps can trap all the erupted volatile species, while the warmest are only able to sequester water ice. However, even the coldest cold traps have fractionated compositions for two main reasons. First, a significant amount of water is able to escape to space, while escape of other species is less significant. Second, the accumulated ice mass of each species is spread out over a different area than that of other species. This means that the non-water volatiles are concentrated in the colder cold traps relative to water. Together, all of these effects result in ice deposit compositions that differ substantially from the volatile composition of the volcanic source and each other.


![Figure 2](image-url) **Figure 2** Number fraction of molecules in ice deposits as a function of cold trap maximum temperature using the [6] assumption of volcanic volatile speciation. Number fraction of each non-water species drops rapidly with increasing temperature once that species’ stability temperature is exceeded.