PERMAFROST ENABLING MICROCLIMATES IN CRATERS ON MAUNA KEA, HAWAII.
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Introduction: *Permafrost and seasonal frost in the tropics of Mars.* Near-surface ice, abundant in the high latitudes of Mars, becomes increasingly rare with lower latitudes. Models predict that ice remains in the subsurface indefinitely when temperatures are sufficiently cold [1]. Incident sunlight is reduced at pole-facing slopes. Planar slopes allow ground ice to be stable to latitudes of about 24° in both hemispheres [2]. On Mars the relevant temperature is the frost point temperature (~200K), while on earth permafrost is limited by the melting point of water.

Seasonal frost on pole-facing slopes has been documented at latitudes as near to the equator as 33°S in images and at 13°S spectroscopically [3–5]. Surface temperatures on pole-facing slopes reach the condensation temperature of not only H_2O but CO_2 as well (~150K). For several months, temperatures on pole-facing crater walls are so low that even carbon dioxide condenses on them. Tropical frost is observed not only on pole-facing slopes, but also on crater floors. North of Hellas in winter, frost and low ground-hugging fogs are observed at latitudes as low as 24°S [3].

These and other studies demonstrate that topographic slopes are an important factor for the presence of water ice and seasonal frost. Three-dimensional effects, particularly in the interior of craters, should allow ice to be stable at even lower latitudes, in the tropics. We will present computational and analog field studies designed to explain the prevalence of tropical ice deposits on Mars.

Sporadic permafrost on Mauna Kea, Hawaii. The summit of Mauna Kea, Hawaii, located in the tropics (19°N) approximately 4,200 m above sea level, is exceptionally dry and has only a seasonal snow cover. Its climate is classified as an Alpine desert. The ice cap from the last Pleistocene glaciation disappeared from the summit before 9 kyr ago [6]. There are numerous cinder cones in the summit region. These craters have depth to diameter ratios of about 1:10 to 1:5, typical for (impact) craters on Mars as well. For example, the crater of Puu Wekiu is about 300 m in diameter and 30 m deep.

In 1969, permafrost was discovered in two cinder cones near the summit [7]. At one of the locations the permafrost extended from the north-facing inside wall to the floor, the ice table was 0.4 m below the surface, and the ice layer was ~10m thick [8]. The mean annual air temperature at the summit, however, is well above freezing. The survival of the ice is associated with shadowing by the crater rim and local trapping of radiatively cooled air (nocturnal cold air lakes) [8].

Irrespective of the origin of the ice, it is the microclimate in the craters that is responsible for the cold temperatures necessary for the permafrost to persist. We study this cooling effect with temperature measurements in the field and modeling. These microclimates, and the arid unvegetated summit region of Mauna Kea in general, may serve as analog for Mars.

Results: *Temperature data loggers.* We placed data loggers inside two of the cinder cones (Puu Wekiu and Puu Hau Kea) in January 2012. The first ten months of temperature data reveal strong night-day differences, and some of the lowest temperatures ever measured on the Hawaiian Islands (-16°C on the crater floor). At locations with permafrost, we expect the annual mean temperature to be below freezing.

Infrared imaging. We developed an autonomous time-lapse camera system to acquire infrared temperature series for 24-hour periods (Figure 1). It was deployed in Puu Wekiu to image the north-facing inner slopes for a day-night cycle. This camera has an uncooled microbolometer sensor with a spectral range of 7.5–13μm. The time lapse system draws heritage from experience with previous visual camera implementations in Antarctic field work.

After setting up the system and calibrating, the camera was left to image the crater every five minutes. Figure 2 shows the temperature distribution late at night and around sunrise on November 27, 2012.

Modeling of crater microclimates. We have developed a three-dimensional surface energy balance model that numerically calculates the incidence angle and intensity of incoming sunlight and the shadows cast by the crater rims. The direct flux of sunlight is determined from local time, date, and latitude. The topography is represented with triangular grid cells, based on Digital Elevation Models (DEMs) with a horizontal resolution of 10 m.

The numerical model is divided into two parts. The first part determines the height of the horizons as a function of azimuth for each surface element. Numerically, shadowing for each surface element is accomplished with azimuth rays [9]. The second part simulates the time evolution of illumination and surface temperature, using the horizon information as input.

Reflection and infrared emission still need to be implemented. Figure 3 shows model results for Puu Wekiu.

In addition to slopes and shadowing, other major factors may contribute to the thermal balance. The radiative cooling of a cold air pool and the phenomenon of "mountain breathing" are relevant micrometeorological processes [10–13]. We will be able to identify any major contributions to the surface energy balance.

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Figure 1. Time-lapse infrared camera in the field. The camera looks to the right (south).

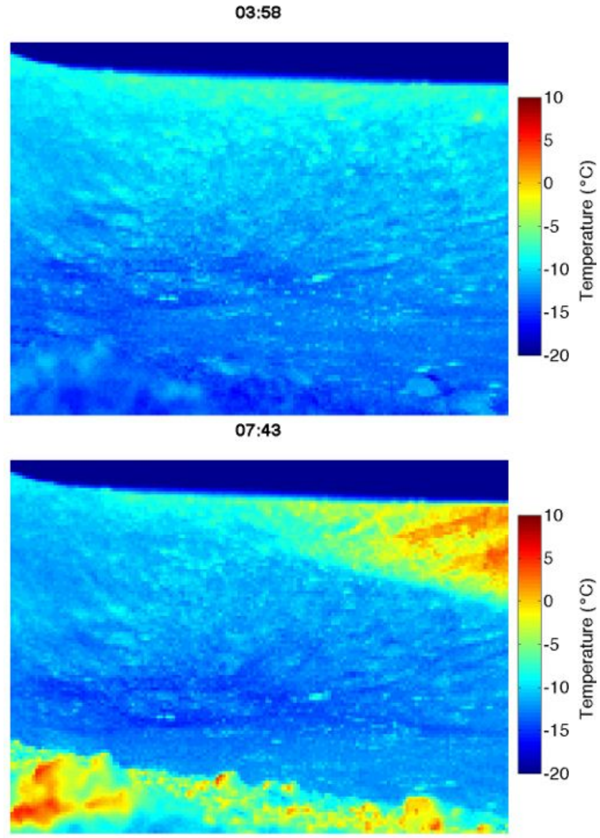

Figure 2. a) Infrared-derived temperatures at ~4am reveal the temperature difference between crater rim and crater floor at night. The crater floor is near the center of the image, and the cold sky is at the top of the image. b) At sunrise, the surface heats up quickly, while the shadowed part of the crater remains cold.

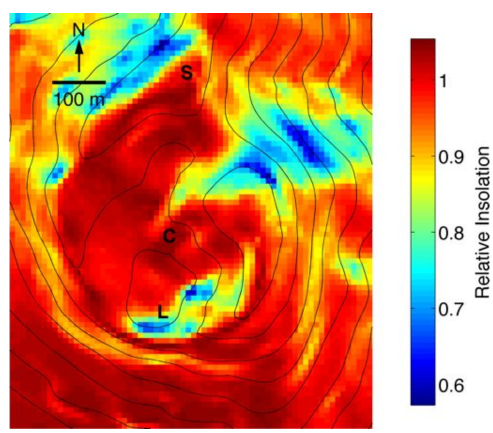

Figure 3. Annual mean of direct sunlight at Puu Wekiu (Summit Cone Crater) relative to a flat surface at the same latitude. Contours are elevation. The locations of the summit (S), IR camera (C), and data loggers (L) are also indicated.