

Permafrost Survey on the Maunakea Summit Plateau: Final Report

Study Period: 2013 – 2017

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Executive Summary

The summit plateau of Maunakea is an alpine periglacial stone desert. A small, ice-rich body of permafrost was documented in the early 1970's. The role, extent, and fate of this permafrost in the 21st century was unknown. We have investigated the state of the permafrost with methods that involve minimal disturbance to the environment: temperature data loggers, electrical resistivity tomography (ERT), ground penetrating radar (GPR), and infrared imaging, supplemented with satellite observations, model calculations, and the survey of rare literature. The study resulted in the characterization of four bodies of perennial water or ice in the Maunakea summit region: permafrost in Pu'uwēkiu and Pu'uhaukea, the vicinity of Lake Waiau, and Pu'upōhaku Pond.

Nearly half a century after their discovery in 1969, two ice-rich bodies are still present, but the one in Pu'uwēkiu has retreated all around; its volume has shrunk by an order of magnitude and the remaining ice body is expected to disappear soon. The other, in Pu'uhaukea, is still at least 50 m wide and about 10 m thick. We also prospected the summit region for additional permafrost bodies, based on solar radiation modelling, two additional ERT surveys, temperature probing, and geomorphological indicators, but none was found. Permafrost occurs preferentially in the interiors of craters with a closed basin, even though there are exterior slopes that receive less solar energy annually.

Basaltic lava is generally porous and cannot hold water to form lakes. Nevertheless, Pu'upōhaku hosts a previously unrecognized perennial body of water, at an elevation that exceeds that of Lake Waiau. Perched groundwater resides in its crater to a depth of 2.5-3m below the surface. At Pu'uwaiau, we discovered a layer of high electrical conductivity that may constitute a water reservoir outside of the lake. At both water bodies, ground temperatures are too high and specific electrical resistivity too low to be consistent with ice-rich permafrost.

The microclimates of cinder cone craters was characterized. Nocturnal cold air pools are common in closed crater basins, and are responsible for the coldest temperature ever reported from the Hawaiian Islands (-20°C). These cold air pools are not frequent enough to substantially affect the annual heat budget of the ground, but cold air is frequently trapped between boulders and contributes to freezing conditions in this way.

1. Results by Site

Pu‘uwēkiu (Summit Cone Crater)

Woodcock (1974) documented permafrost in Pu‘uwēkiu; the ice body extended horizontally for several decameters, in north-south as well as east-west direction (Figure 1), and it was at one place 10m thick. He measured the temperature of the ice and the annual mean temperature near the surface to be only a few tenths of degree Celsius below melting. At the time, Woodcock drilled three (or more) holes, excavated one trench, and sampled the ice in a partially successful attempt to determine its age.

Based on Woodcock’s documentation, we were able to relocate the area inside Pu‘uwēkiu that once had permafrost. Four of his boreholes are still in place; we refer to them as pipe 1, borehole 2, pipe 3, and borehole 5 (Figure 2). We cleaned two pre-existing boreholes (2 & 5) and emplaced temperature sensors in them to depths of up to 6m (Borehole 2) and 4m (Borehole 5). Elsewhere, we emplaced data loggers with temperature sensors at various shallow depths, and recorded several years of continuous ground temperature data.

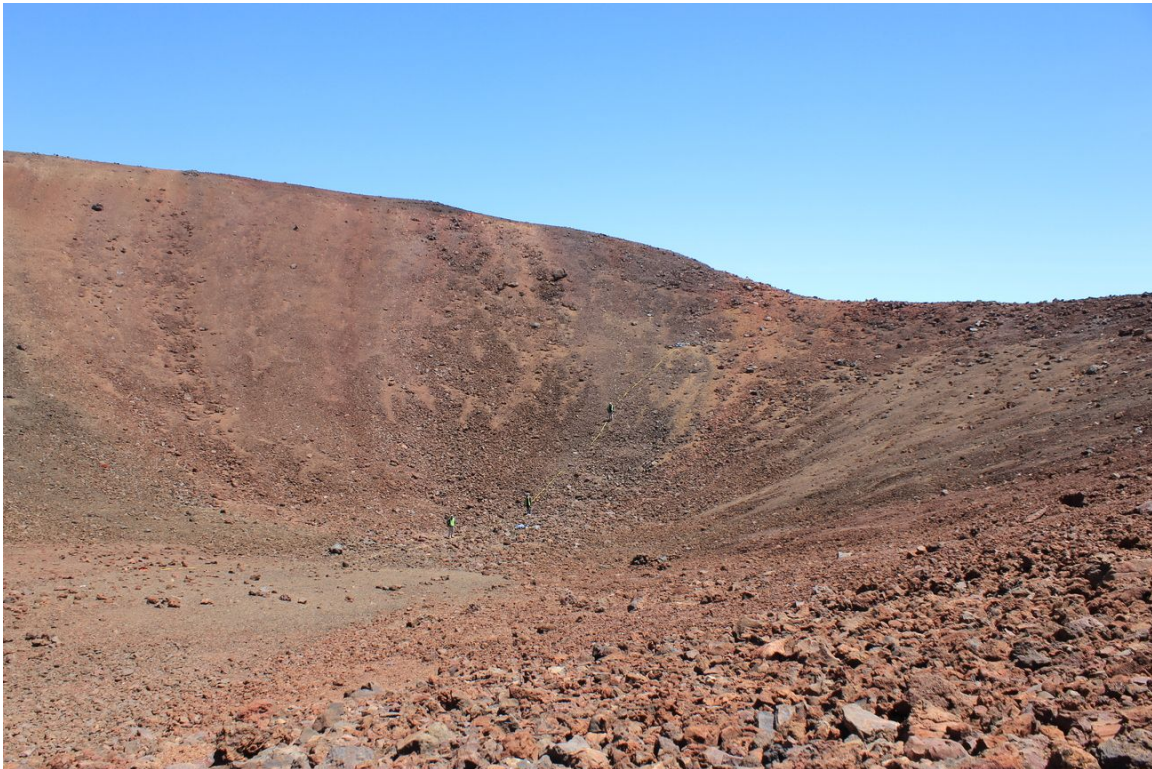


Figure 1. Extent of permafrost in 1973 along an approximately north-south oriented line. Persons stand at the top and bottom end of the former permafrost body, and at “Pipe 3”. Distances from this reference point were measured according to Woodcock (1974).



Figure 2. “Pipe 3” is a leftover from Woodcock’s fieldwork and served as a reference point.

Electrical Resistivity Tomography (ERT) surveys were attempted in Pu‘uwēkiu in June 2013, October 2014, June 2015, and September 2016 to probe for a buried ice body. The first two attempts suffered from bad contact between the electrodes and the ground under the dry conditions. The third study was carried out after a tropical storm passed the island; wet conditions improved the contact of the electrodes with the ground, and revealed the first evidence of an ice body (a body of high electrical resistivity) centered at the same location as documented in Woodcock (1974). A GPR survey was also conducted in June 2016. The fourth and final ERT survey the following summer provided the most conclusive data. Inversion of these data generates cross-sections of electrical resistivity, e.g. as in Figure 3.

The ice body identified in the ERT survey is centered exactly where Woodcock’s was, but is smaller in size in all directions. Along the NNE transect, which is document the best, the ice has shrunk from about 25m to about 11m lateral extent. In the perpendicular direction it has retreated from what was described as “decameters” to 14m (Figure 4). It also has retreated considerably at the bottom, from about 11 to 5m depth. The permafrost table retreated from depths of ~0.4m to ~1.4m. In total, the ice volume has shrunk dramatically, and complete disappearance may be imminent.

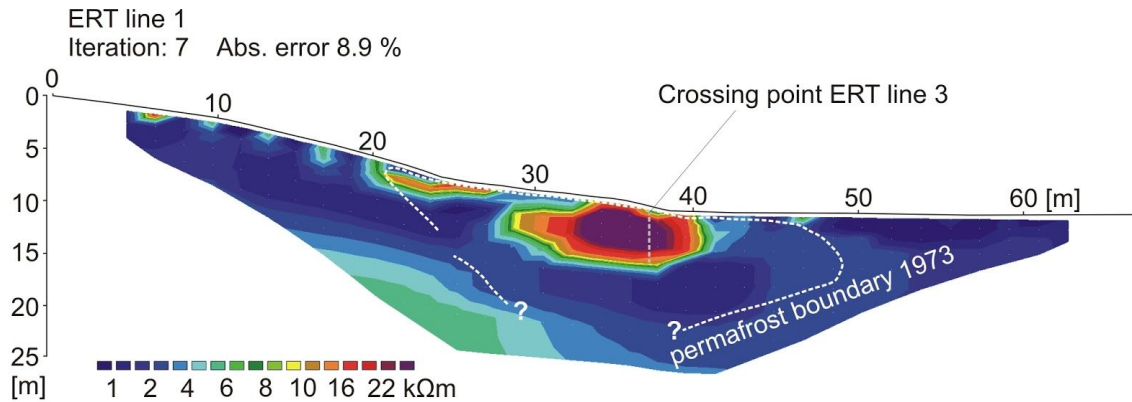


Figure 3. 2D section of the specific electrical resistivity distribution in Pu'uwēkiu Crater. The line along the north slope of the interior cinder cone follows the same slope as displayed in Woodcock (1974). The dashed white line shows the approximate permafrost distribution in 1973. The high-resistivity zone between 30 and 40 m is interpreted as the remnants of the permafrost described in 1974.



Figure 4. Extent of current permafrost along an approximately east-west oriented ERT survey line. A person to the east (32m along the survey line) and a red backpack to the west (16m along the survey line) mark the boundaries of the permafrost body. "Pipe 3" is visible in the foreground.

Temperature measurements in borehole 2, which was once immersed in permafrost, also show the loss of permafrost condition (Figure 5), consistent with the extent determined from the ERT survey. Borehole 5, which is not documented in Woodcock's publications, is now also outside the permafrost body.

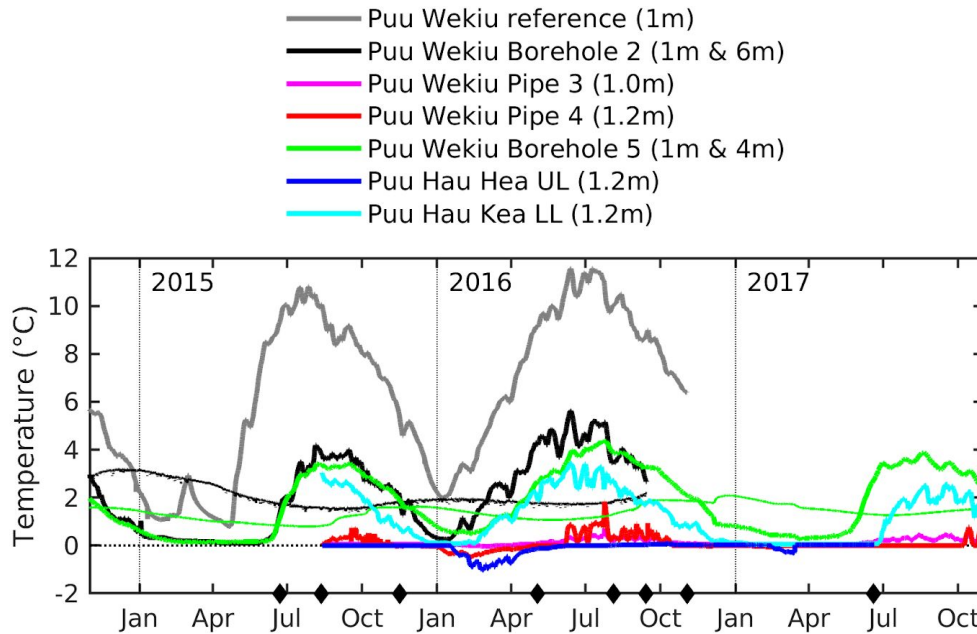


Figure 5. Temperature record from sensors at depths of 1m or more over a span of three years. The reference probe is located in the outer, flatter part of the crater interior. According to Woodcock's documentation Borehole 2 was once immersed in permafrost, which is no longer the case. Three of the temperature probes are frozen most of the year, but none fully reaches into the permafrost. (Black dots mark the dates of field visits.)

Prior to our study period, a weather station was present on the crater floor from 2007 to 2011 (Eaton and Businger, 2014). Our analysis of these meteorological data revealed record low air temperature (-20°C), the lowest temperature ever reported from Maunakea, and Hawaii altogether. These data also contain clear evidence for the formation of nocturnal cold air pools (CAPs). At this station, air temperature fell below -8°C only when the air in the crater was stagnant (Figure 6). These CAPs are responsible for temperature minima far lower than on the summit. However, CAPs are not frequent enough to significantly change the annual mean temperature inside the crater.

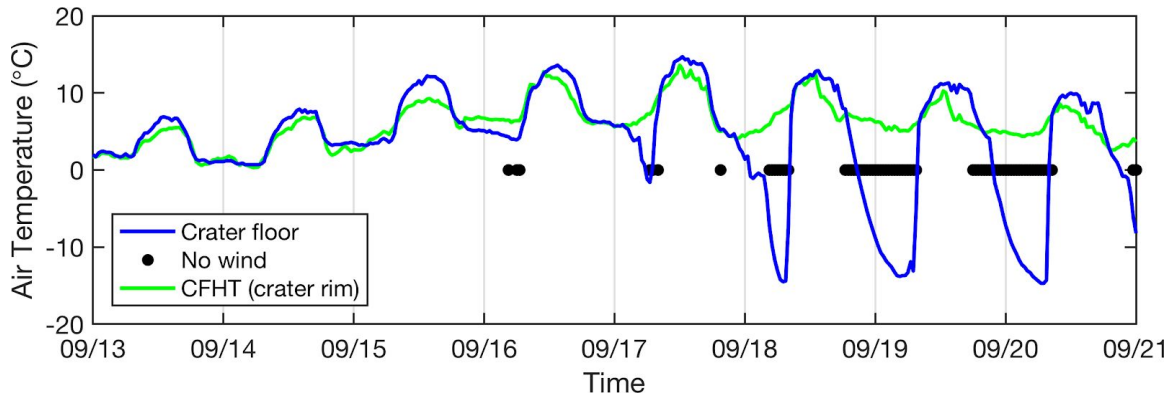


Figure 6. Air temperature at Pu‘uwēkiu crater floor and rim over eight consecutive days in September 2008. Black dots indicate periods when no wind ($< 0.2 \text{ m/s}$) was detected on the crater floor.

Pu‘uhaukea (Goodrich Cone)

Woodcock et al. (1970) mentioned permafrost in Pu‘uhaukea, near the base of the south wall, without any detailed description of its location, extent, or of other observations. We found a additional hints about the location in his unpublished field notebooks. We also emplaced several soil temperature data loggers in Pu‘uhaukea, and three air temperature sensors at the crater floor, at intermediate height, and near the crater rim for a microclimate study. The minimum nighttime air temperatures on the floor of Pu‘uhaukea crater are comparable to those in Pu‘uwēkiu and also associated with calm nights.

Three lines in the crater interior were surveyed with GPR: two parallel in approximately north-south direction in June 2015 and one in approximately east-west direction in September 2016. They revealed an ice-rich body on the lower north-facing interior slope of Pu‘uhaukea (Figure 7). It is about 35m long in N-S direction, when measured along the surface, and in E-W direction the entire 50m long survey line was underlain by ice. If the ice body is symmetric in E-W direction it may be twice as long. The thickness of the ice body, inferred from radar velocities, is about 10m, and its depth $\sim 1\text{m}$. Hence, this ice body is far larger than the one in Pu‘uwēkiu.

The ground temperature sensors turned out to be barely deep enough to reach into the permafrost. Figure 5 shows multi-year temperature records from all sensors at 1m depth or deeper, at Pu‘uwēkiu and Pu‘uhaukea.

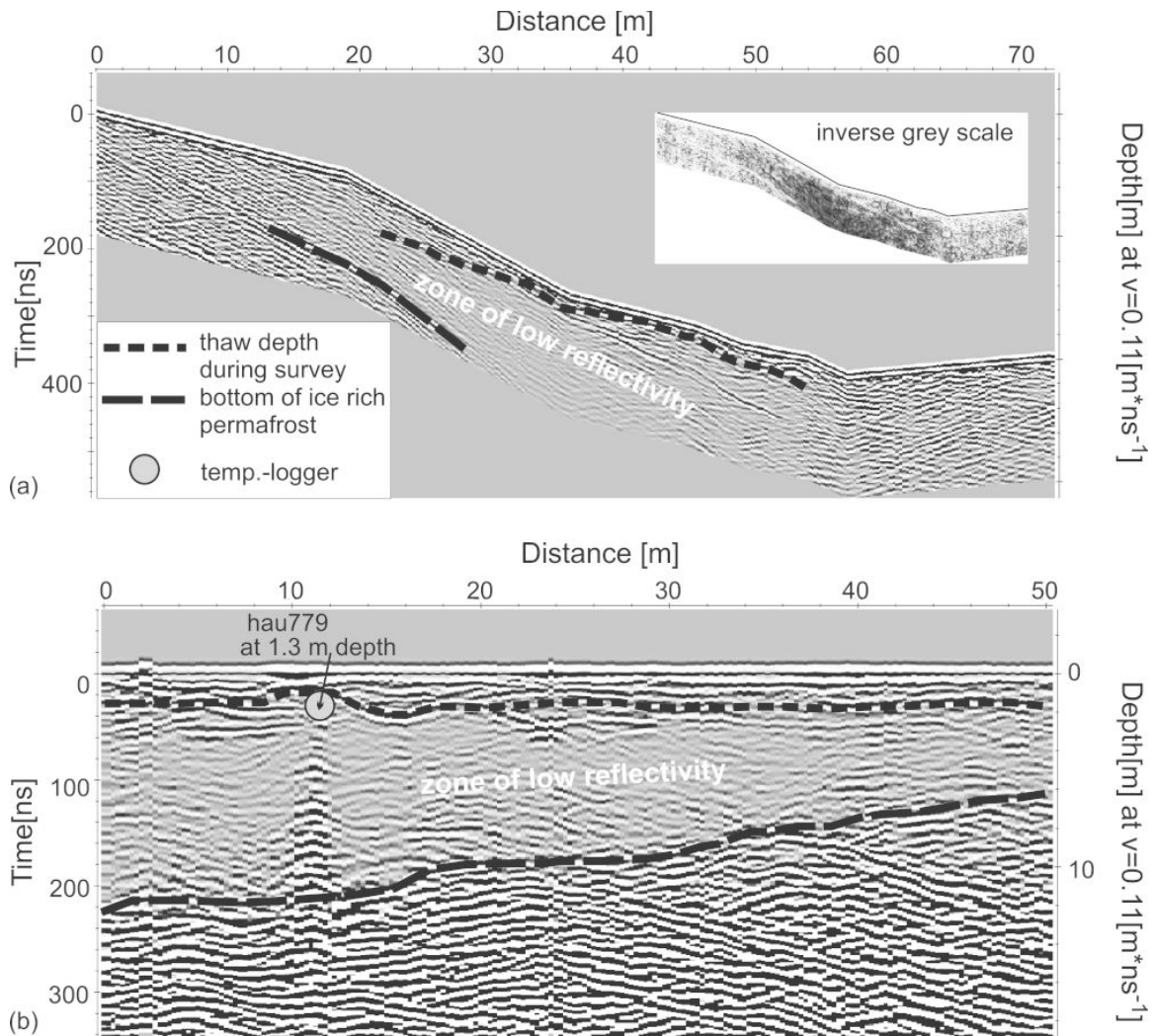


Figure 7. Results of the GPR survey at Pu'u'uhaukea. (a) GPR-line 1 runs down the steep north-facing slope of the cinder cone. The 100 MHz reflection pattern shows multiple strong reflections caused by layers of cinder sediments. Between 20 and 50 m along the line a zone of low reflectivity corresponds to homogeneous dielectric properties. The inset displays this low-reflection zone as a dark gray/black area in an inverse grayscale, which is interpreted as ice-rich permafrost. (b) GPR line 3 runs approximately from west to east. The same low-reflection zone is observed but at a lower basal depth towards the east.

Pu'uwaiau

Pu'uwaiau (Figure 8) refers to the cinder cone that holds Lake Waiau. The reason for the impermeability of this crater has long been a subject of speculation. Gregory & Wentworth (1937) had hypothesized permafrost as one of several potential reasons for the impermeability of the lake basin. The temperature measured by Woodcock & Groves (1969) in the lake sediment, 6.3°C at 7m depth, is inconsistent with this hypothesis.

(Temperatures slowly decreased with depth, contrary to the gradient beneath most lakes, but this may be due to the geometry of the heat flow). Later, Woodcock (1980) argued that during the drought of 1977/78, the tritium concentration of the Waihu Spring followed that of the lake and not that of groundwater, and lake seepage, due to melting of relic permafrost, is the source of spring flow.

A data logger recorded temperature at ~40cm depth from 2013 to 2016 on the south slope where model calculations indicate a minimum of insolation. Even at this relatively shadowed location, the mean annual ground temperature was well above freezing.

We conducted an ERT survey in areas surrounding Lake Waiau, which revealed no resistivity values as high as expected for permafrost, but it led to the surprise discovery of a *low* resistivity layer east of the lake. Low electrical resistivity suggests the presence of liquid water (Figure 9). This layer reaches essentially to the surface (Figure 10), slopes downhill toward the lake, and enters *under* the lake (which is only ~3m deep). The physical nature of this layer has not been unambiguously determined, but it is consistent with the presence of water.



Figure 8. Frost stripes at Pu'uwaiau on May 3, 2016.

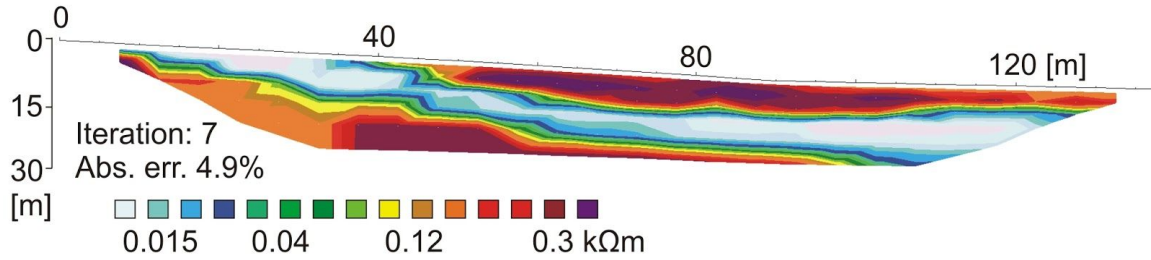


Figure 9. ERT inversion results for survey line to the east of the lake.

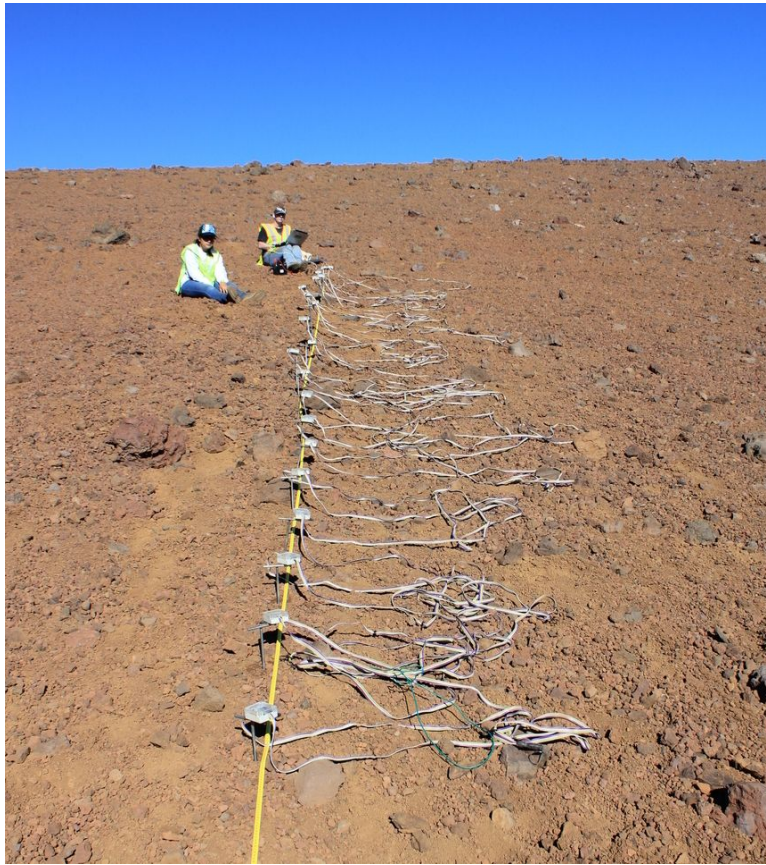


Figure 10. Top part of an ERT survey line at Pu'uwaiau, where the low resistivity layer reaches almost to the surface (Figure 9).

At times when the lake was not fully filled (Patrick & Delparte, 2014; Patrick & Kauahikaua, 2015), e.g. in the fall of 2013, there are spots with water seepage in the lake basin, on the southeast side and along the north side of the lake. These areas are discernible on visible images, and particularly apparent on daytime infrared images, where they appear as cold spots. Ranger photos also documented small localized springs on the north side of the lake bed. These areas remained wet many months after the lake level had receded, and are evidence for a small subsurface water supply from the slopes north and southeast of the lake, within the Lake's drainage basin. Ehlmann et al. (2005) compared the isotopic composition of the lake water with that of the snow and identified

winter storms as the primary source of water for the lake. In other words, they found no evidence of a groundwater input. However, they made only infrequent isotope measurements and their data do not exclude a short-term delay in water recharge.

Overall, the investigation of Pu'uwaiiau provided no evidence for permafrost, and excludes it at many places, but suggests the presence of at least temporary water reservoirs outside the lake. These reservoirs are still within the Waiau crater, and are expected to be recharged by the same snowmelt that would end up in the lake in any case, but they will cause the water to arrive in the lake with a delay.

Pu'upōhaku (Douglas Cone)

Pu'upōhaku has a shallow crater that can hold water (Figure 11). Woodcock & Groves (1969) reported perched groundwater about 0.4 m below the rocky surface of the crater of the cone; rangers have photographed a sporadic puddle of water, and we visited Pu'upōhaku during times with and without a puddle. The area where the water accumulates is darker than the rest of the surface, a discoloration due to standing water. The water level is limited by the outlet that leads into a sharply incised and easily visible gully on the northeast side of the cone. At its widest, the discolored area is 50m and it stretches about 40m in the perpendicular direction. From oblique photos with scales, we estimated the discolored area to be 1,360 m². The drainage area, derived from 4.5m topography data, is 13,000 m², about ten times less than that of Lake Waiau. The drainage area of the ephemeral water pond is small, yet perched water lasts well beyond the duration of a snow cover, so that the ground must be impermeable. Hence, Pu'uwaiiau is not the only impermeable cinder cone in the summit region.

Woodcock's notebooks provided significant, new, and previously unpublished information about Pu'upōhaku. He had installed vertical pipes and recorded temperatures in them over several years. We digitized and averaged these numbers to determine that the annual means were well above freezing. Woodcock also made notes of the pond over several years. Figure 13 shows a sketch from one of his notebooks, and Figure 14 is from his photo archive.

The ERT survey at Pu'upōhaku revealed a layer of very low electrical resistivity (as expected for water), about 2.5m deep. We emplaced ground temperature data loggers at the west rim of the discolored area and on the exterior north slope. There annual means were well above freezing.

For Pu'upōhaku, the major conclusions are: 1) There is 2.5-3m deep standing water in the crater, part of which can be expected to last throughout the year. Hence, in addition to Lake Waiau, there is a second perennial body of standing water on the summit plateau. 2) Temperature as well as electrical resistivity values beneath these depths are inconsistent with permafrost or an ice-rich body, and consistent with an impermeable layer of fine-grained material.



Figure 11. Pu'upōhaku from the distance, with a sharply incised gully on the northeast side of the cinder cone.

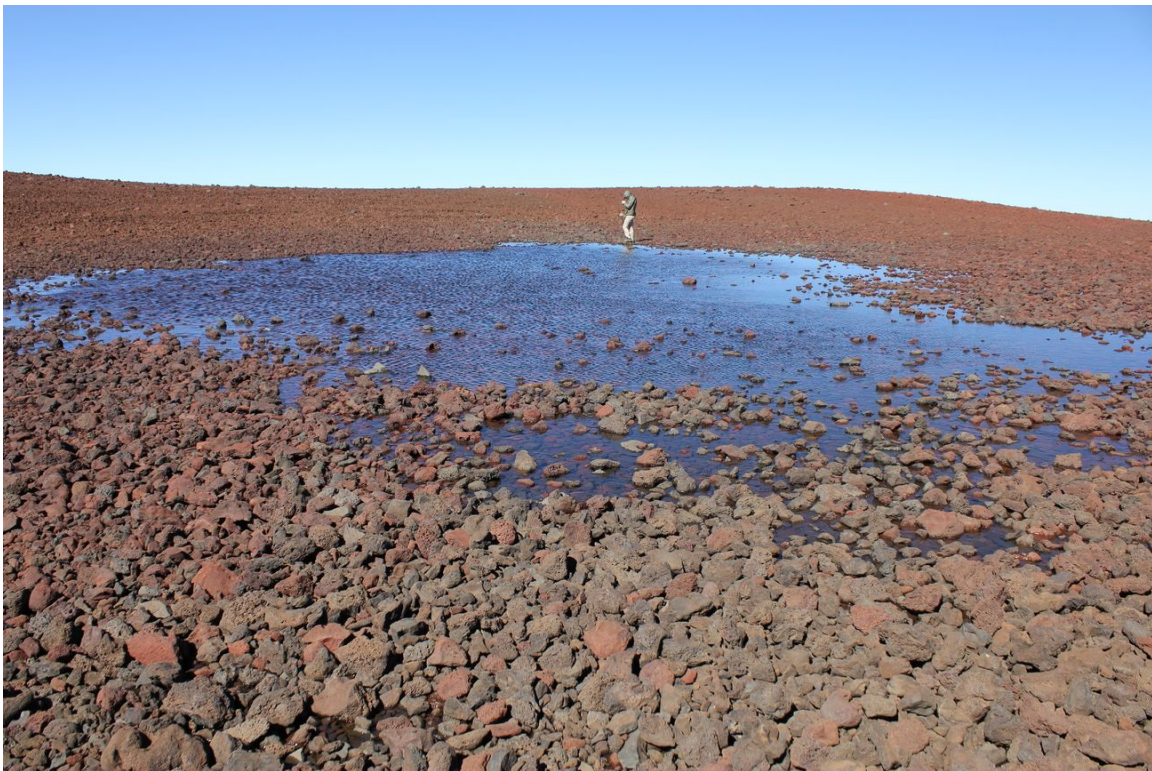


Figure 12. A puddle at Pu'upōhaku on Nov. 21, 2014, with wind-caused ripples.

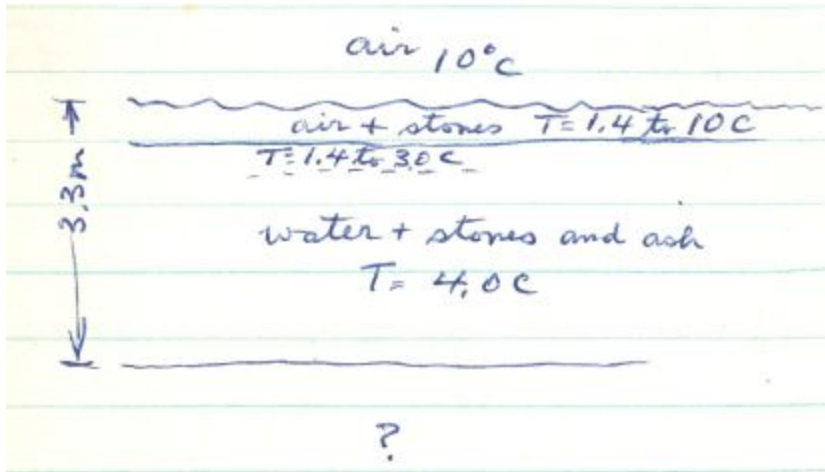


Figure 13. Sketch in Woodcock's unpublished field notes from Nov. 10, 1968, documenting groundwater at Douglas Cone (Record Book No. 6, p20, Woodcock Archives, 2007).



Figure 14. This photo of Pu'upōhaku dated May 19, 1969 shows a small puddle and a vertical pipe that was used for temperature monitoring (Woodcock Archives, 2007).

Pu‘umākanaka

Cinder cone Pu‘umākanaka has the deepest crater on Maunakea, and hence potentially the strongest microclimate effects. A six month long cold-air pool (CAP) study was conducted with air temperature sensors located near the rim, at the crater floor, and an intermediate elevation in the crater, respectively. These measurements reveal that nocturnal cold air pools form more frequently in Pu‘umākanaka crater than in Pu‘uwēkiu and Pu‘uhāukea, but the floor-rim temperature difference (the strength of the CAP) is no larger than in these two craters. Due to its lower elevation and the limited influence of CAPs on annual mean conditions, Pu‘umākanaka is not expected to have any permafrost.

More detailed and technical descriptions of the results are available in journal articles (Leopold et al., 2016; Schorghofer et al. 2017, 2018).

2. Methods and Data

The methods are described in the abovementioned journal articles. Here, we merely summarize the methods involved and elaborate only on those topics not already described in publications.

HOBO data loggers with external temperature sensors, and a few with humidity or light intensity sensors, were deployed for this field study: Models Nrs. U12-008, U23-002, U23-003, and UA-002. A number of them were tested in an ice bath after years in the field. All of the logger data are archived at Zenodo, along with their GPS coordinates (Schorghofer & Yoshikawa, 2017). In this archive, the file `loggers_summary_mk.csv` lists the data loggers, with dates of deployment and sensor depths. The map in Figure 16 shows data logger locations.

The geophysical methods, Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR), are described in Leopold et al. (2016) for Pu‘uwaiau and Pu‘upōhaku and in Schorghofer et al. (2017) for Pu‘uwēkiu and Pu‘uhāukea. Figure 15 shows the geophysical survey lines at all four study sites. The raw data from the geophysical surveys are also archived on Zenodo (Leopold & Schorghofer, 2017).

To validate that electrical resistivity values measured at Pu‘uwēkiu are indeed representative of ice-rich permafrost, lab measurements were conducted with borrowed cinder material (Figure 16). The first measurement series used a very moist to saturated rock with four electrodes in the same rock. The resistivity jumps at 0°C, but only to about 2 kΩm. A second measurement series used several rocks with gaps in between and two electrodes in one and two electrodes in another rock, all saturated with water. The resistivity increases even more at 0°C and resistivity values are close to what we have determined in the field (Figure 3).

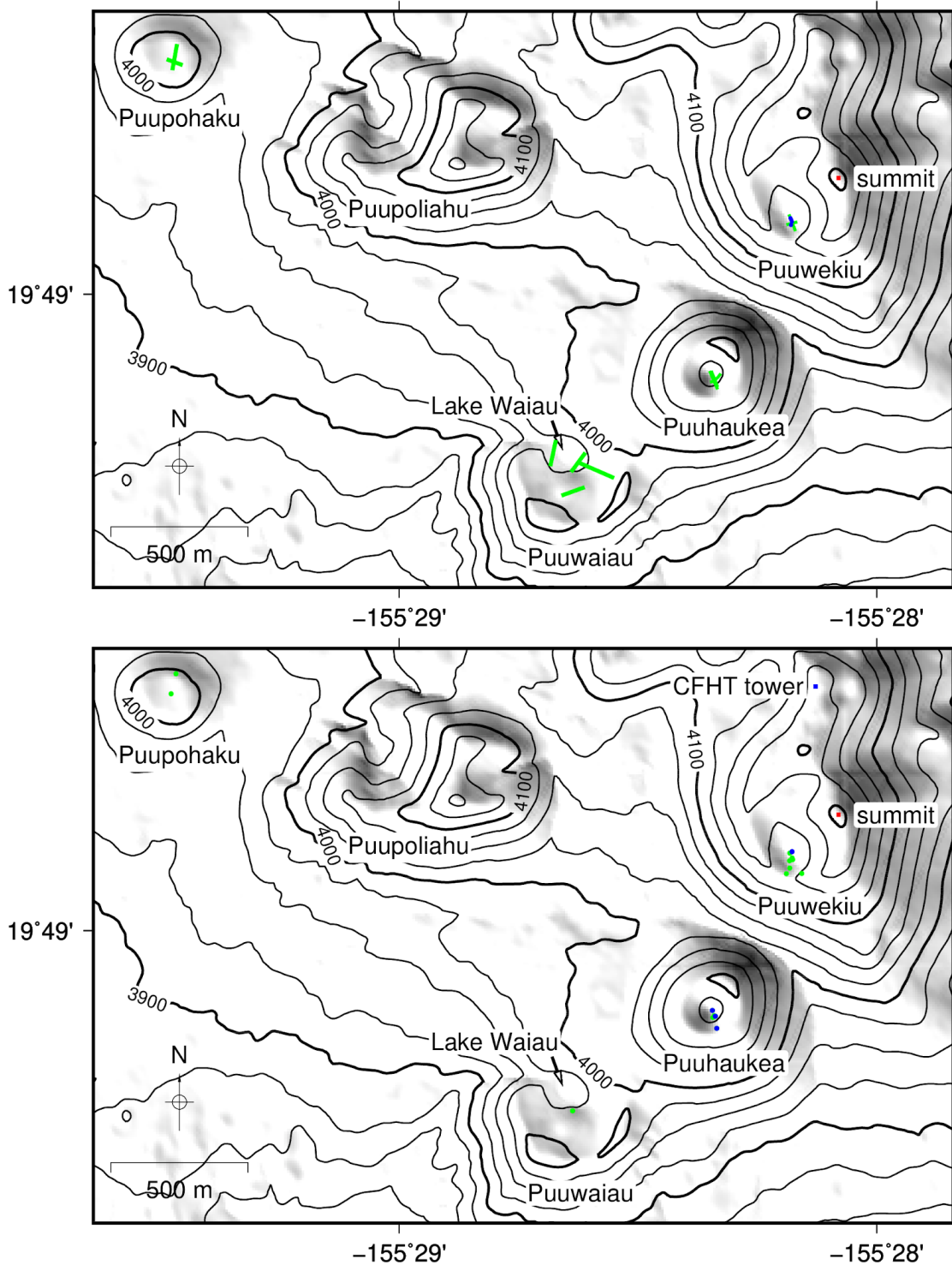


Figure 15. The upper map shows all geophysical survey lines (ERT and GPR, green) and the boreholes left by Woodcock (blue dots). The lower map indicates the location of multi-year temperature measurements, for ground temperature (green dots) and air temperature (blue dots). The latter includes the CFHT/Gemini weather tower and a temporary weather station on the floor of Pu'uwēkiu.

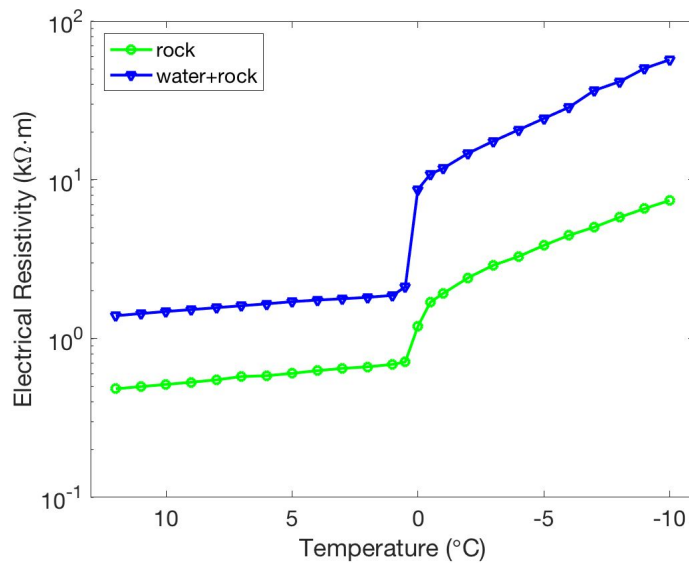


Figure 16. Laboratory measurements of electrical resistivity with cinder from Maunakea.

At Pu‘uwaiau, the low resistivity layer east of the lake reaches the surface. At this location, we conducted two types of in-situ electrical conductivity measurements. First, an Extech EC100 handheld conductivity meter was used, which had been calibrated earlier the same day with a KCl solution ($1345\mu\text{S}/\text{cm}$ at 22°C). A half-half mixture of deionized water and soil from about 14cm depth had a conductivity of $12\mu\text{S}/\text{cm}$ (21°C). With mostly soil and little deionized water, it increased to $75\mu\text{S}/\text{cm}$ ($=133\Omega\text{m}$), and an even lower resistivity can be expected without dilution. Second, using the ERT survey equipment, electrodes in the near-surface layer in a 4-point Wenner configuration measured $64\Omega\text{m}$ ($=156\mu\text{S}/\text{cm}$). Hence, the low resistivity values seen in Figure 9 are plausible, although the nature of the ions that lead to such high conductivity remains puzzling.

A model of insolation (incoming solar radiation) with terrain shadowing is archived at <https://github.com/nschorgh/Planetary-Code-Collection/> and further described in the accompanying User Guide. A clear-sky atmospheric model has been developed and validated specifically for the atmosphere above Maunakea, and is also part of the archive. Drainage areas were calculated from 4.5m topographic models based on steepest descent among eight neighbor cells. Topography at a resolution of $4.5\times 4.5\text{m}$ is based on Interferometric Synthetic Aperture Radar (InSAR) data from Intermap Technologies.

Time-lapse infrared imagery was acquired and the results of the ongoing analysis will be described in future. Pyranometer (solar flux) data accompany these infrared measurements.

Two literature survey projects were undertaken. Narratives from 1778 to 1870 were surveyed to constrain the duration of snow cover on Maunakea, Maunaloa, and Hualalai. Until about the mid-19th century snow cover was longer than in the present-day climate,

but contiguous cover was not perennial (Schorghofer et al., 2014). All of Woodcock's handwritten unpublished notebooks for 1966-1977 were examined (Woodcock Archives, 2007), while the archive was on loan to the OMKM library.

3. Permafrost on Maunakea: Past, Present, and Future

Insolation patterns; permafrost elsewhere?

In addition to the geophysical surveys and temperature data loggers deployed at four cinder cones, we have systematically searched for potential permafrost sites in the entire summit region with the aid of insolation modeling, geomorphological indicators, and, spot-wise needle probe measurements. Previously, Ehses (2007) had explored the use of climate-geographic modeling to assess permafrost occurrence on Maunakea.

Although there is no rigorous connection between insolation quantities and permafrost occurrence, insolation is the primary source of heat, especially under the frequent clear-sky conditions on Maunakea. Figure 17 shows results from the insolation modeling, which takes into account solar incidence angles on sloped surfaces and terrain shadowing. At a few meters depth, where seasonal variations are smoothed, the annual mean insolation is expected to be the governing parameter for ground temperature. At shallower depth, summer insolation may determine whether the ice can last through the year, but in the tropics, June insolation is higher on north-facing slopes than on south-facing slopes, a pattern opposite that of the annual mean. Based on mean annual insolation (MAI), the north-facing interior slopes of Pu'uwēkiu and Pu'uhauea receive considerably less sunlight than a flat unobstructed surface. At the permafrost site in Pu'uwēkiu, the insolation is higher than at Pu'uhauea, and there are exterior slopes with lower MAI values. Both identified permafrost bodies lie in the interior of craters with closed basins. This preference may be related to reduced wind speed rather than insolation.

Guided by the insolation map and geomorphological evidence, such as patterned ground, solifluction lobes, or ridges of loose unconsolidated material, we used a 1ft temperature probe, long enough to penetrate the diurnal thermal skin depth, for comparative temperature measurements on north-facing slopes. At areas above permafrost, the probe measured 0°C in September. No similarly low temperatures were measured at any other site. In the absence of such evidence, we did not carry out additional geophysical surveys. This approach does not rigorously exclude the presence of permafrost elsewhere on the summit plateau, but reduces the likelihood that any could be found.

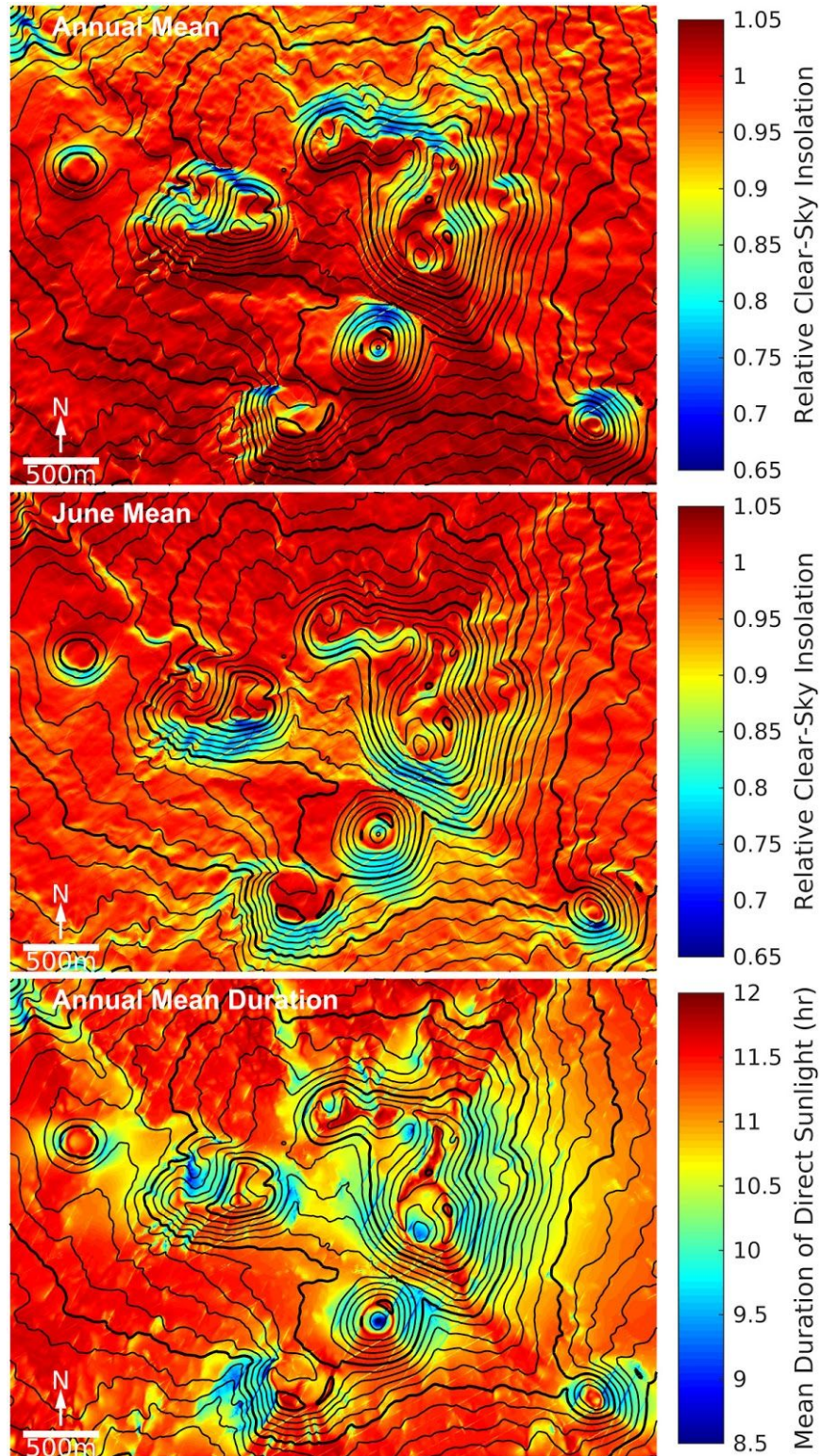


Figure 17. Maps of clear-sky short-wavelength insolation in the summit region: annual mean insolation, June mean insolation, and annual mean daily duration of direct sunlight according to model calculations.

Climate warming

The last glaciation of Maunakea culminated about 20,000 years ago, and the last eruption occurred 4,500 year ago (Porter et al., 1977; Pigati et al., 2008). Further climate variations occurred during the Holocene (such as the “Little Ice Age”), but no proxy records are available on how these may have affected the high summits of Hawaii. Based on measurements from 1964 to 1974, the mean July freezing isotherm, a proxy for snowline altitude, lies at 4,715m altitude, over 500m above the current summit (Porter, 2005).

Over four decades have past since the last documented observations by Woodcock (1974), who already suggested that this permafrost is “in part a product of the past”. At Pu‘uwēkiu, the measured annual mean at the surface was -0.3°C and the bottom of the permafrost layer was at 0°C . Even a small persistent warming will melt the entire permafrost layer, the remaining question being how fast.

Giambellucca et al. (2008) have evaluated long-term air temperature measurements from four high-elevation meteorological stations on the Hawaiian Islands, the nearest in elevation the Mauna Loa Slope Observatory (MLO, 3,400m). Annual mean air temperature had increased at a rate of $0.268^{\circ}\text{C}/\text{decade}$ from 1975 to 2006. At MLO, the mean warming trend was $0.21^{\circ}\text{C}/\text{decade}$ in the period 1977-2006 (Malamund et al., 2011). Climate warming usually proceeds faster at higher elevation (Pepin et al., 2015). The overall increase in air temperature since the early 1970’s can be expected to be about 1°C , and possibly more.

In addition to the increase in air temperature (climate warming), permafrost health is potentially also affected by snow cover, rainfall, and by the phenomenon of “mountain breathing” (Woodcock & Friedman, 1979; Woodcock, 1987).

Snow cover

Fresh snow has an albedo of 0.80-0.90 that quickly decreases every passing day, while basalt has an albedo of about 0.05. The difference amounts to a significant decrease in absorbed energy, due to the sunlight reflected by the snow. In addition, the latent heat of melting snow draws heat from the ground. But snow can also disfavor permafrost. Dry snow has low thermal conductivity, and hence prevents the ground from cooling when the outside air temperature is low (Zhang, 2005). On Maunakea, where the seasonal and diurnal temperature amplitude is small, the thermal insulation effect should play a diminished role. Due to the clear-sky conditions, the albedo effect should play an enhanced role compared to other mountain permafrost environments.

Our survey of historical accounts, mostly writings by eyewitnesses, suggests that in the first half of the 19th century, snow covered Maunakea typically many months of the year, often even in summer (Schorghofer et al., 2014). Brigham (1909) noted that the summit

of Mauna Kea “is covered with cinder cones, most of them with deep craters filled all the year with snow...”, based on observations over the preceding decades. In contrast to the present-day climate, snow once filled these craters far more often, and reflected sunlight from the crater interiors, which may have created stable permafrost conditions. Regional climate model calculations by Zhang et al. (2017) suggest snowfall will be increasingly rare on Maunakea in future.

As part of our snow cover study, we also a) compiled snow cover history from monthly Weather Bureau reports beginning in 1893 (Martin & Schorghofer, 2018), b) used MODIS satellite observations to quantify snow cover from 2001 to 2017 and snow albedo as a function of age, and c) determined the relation between measured ground temperature and snow cover. Figure 18 shows three years of simultaneous ground temperature and snow cover data. The results of this ongoing analysis will be published in a dedicated journal article.

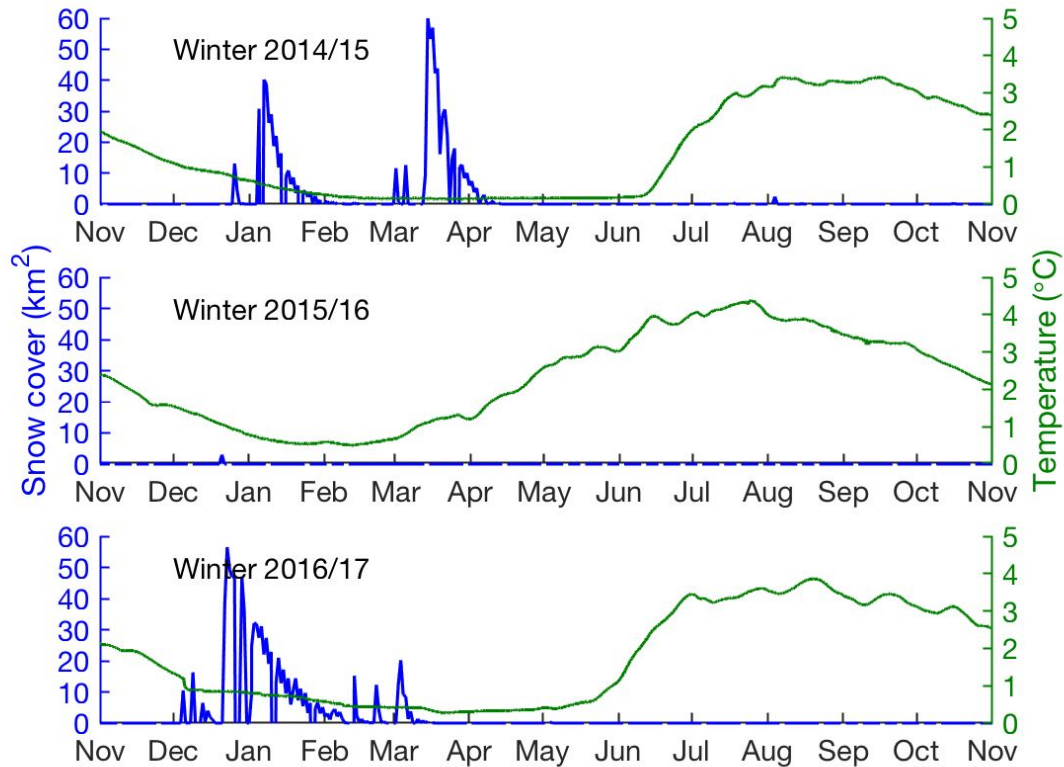


Figure 18: Snow cover and ground temperature at 1 m depth over 3 years. Following the winter without significant snow, the ground warmed faster and reached a higher temperature than in years with significant snow cover.

Discussion of broader implications

Due to climate warming and changes in snow cover over the last few centuries, it is likely that permafrost once was more abundant on Maunakea than it is now, and at this point very little is left. Studies of the ice-rich bodies also suggest ice is being lost. If retreat of ice-cemented permafrost causes erosion, most of that erosion has already occurred.

Our findings, combined with previous studies, suggest that localized subsurface layers impermeable to water are not uncommon in the summit region. Hence, there may be additional perched water at unknown locations in this stone desert. The four known perennial water/ice reservoirs could potentially serve as water source for insect and plant species (e.g. Ashlock & Gagne, 1983; Eiben & Rubinoff, 2014). Whether such a relation exists is currently unknown, but based on sparse data about the time-varying distribution of these species, no such relation is apparent (Stephenson et al., 2017; Kirkpatrick 2018).

The permafrost may store a record of the past. This potential proxy record may contain information about the natural history of Hawai‘i that cannot be found anywhere else, and would warrant further study.

Four long-lasting water/ice reservoirs are known in the Maunakea summit region. The smaller of the two permafrost bodies is expected to disappear soon. Lake Waiiau vanished almost completely during the last extended drought (and refilled afterwards). The resilience of (the subsurface portion of) Pu‘upōhaku Pond has never been determined. The number of continuously-lasting ice and water bodies is expected to be smaller in the future.

4. Outcomes

Publications

The project resulted in the publication of the following peer-reviewed journal articles:

- i) Schorghofer, N., E. Kantar*, P.M. Nogelmeier (2014). Snow on the summits of Hawai‘i Island: Historical Sources from 1778 to 1870. *Hawaiian Journal of History* 48, 89-113.
- ii) Leopold, M., A. Morelli*, N. Schorghofer (2016). Subsurface architecture of two tropical alpine desert cinder cones that hold water. *Journal of Geophysical Research* 121, 1148-1160. This article describes study results for Pu‘uwaiau and Pu‘upōhaku that both hold perennial water bodies.
- iii) Schorghofer, N., M. Leopold, K. Yoshikawa (2017). State of high-altitude permafrost on tropical Maunakea volcano, Hawaii. *Permafrost and Periglacial*

Processes 28, 685-697. This article contains the study results for the two cinder cones with permafrost: Pu‘uwēkiu and Pu‘uhaukea.

- iv) Schorghofer, N., S. Businger, M. Leopold (2018). The coldest places in Hawaii: The ice-preserving microclimates of high-altitude craters and caves on tropical island volcanoes. *Bulletin of the American Meteorological Society*, in press, <https://doi.org/10.1175/BAMS-D-17-0238.1>. This article includes the microclimate investigations at Pu‘uwēkiu, Pu‘uhaukea, and Pu‘umākanaka.
- v) Martin, J.*, N. Schorghofer, K. Yoshikawa, F.L. Klasner. Snow cover in Hawaii since 1893 at its effect on permafrost. In review (2018).

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Three data archives were created:

- vi) Schorghofer, N., & Yoshikawa, K. (2017). Multi-year temperature time series from five cinder cones on the Mauna Kea summit plateau, Hawaii [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.1296049>
- vii) Leopold, M., & Schorghofer, N. (2017). Mauna Kea permafrost survey, Geophysical Data [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.896963>
- viii) Martin, J.* & Schorghofer, N. (2018). Historical snow cover data for Hawaii [Data set]. Zendo. <https://doi.org/10.5281/zenodo.1307476>

Transcripts of portions of Woodcock’s handwritten field notebooks have been created and are on file at the OMKM Library.

We have presented the results of the study at several academic conferences, including three in Hawai‘i: GSA Cordilleran Section 113th Annual Meeting, Honolulu, May 23-25, 2017, AAAS Pacific Division 98th Annual Meeting, Waimea, Big Island, June 19-23, 2017, and AOGS 15th Annual Meeting, June 3-8, 2018, Honolulu.

Education & Public Outreach

Undergraduate Student Training and Support

The following undergraduate students have carried out dedicated research projects:

- i) Eliana Kantar (UH Manoa & U. Minnesota) surveyed 19th century narratives to identify and evaluate information about snow on the summits of Hawaii Island. To accomplish this work, she enrolled in a two-credit course at UH Manoa (GEOG 399 Independent Study in Geography) in fall 2012.
- ii) Jessica Lee (UH Manoa) has improved a prototype infrared time-lapse camera system and processed data from it. Her two-semester fellowship, for fall 2013 and spring 2014, was sponsored by NASA Space Grant. Her final fellowship report ‘Time-Lapse Infrared Imaging of Craters on Maunakea’ is published at www.spacegrant.hawaii.edu/reports/23_SUM13-SP14/JLee_S14.pdf

- iii) Brian Chan (UH Manoa) participated in the infrared data processing and a project study to measure infrared emissivity in the field. He spent two semesters (spring and fall 2014) as a trainee of NASA Space Grant.
- iv) Amanda Morelli, a summer intern at UH Manoa from Indiana University and the University Sao Paulo, systematically examined the unpublished field notes of Alfred Woodcock. Her summer internship in 2015 was supported by the Brazil Mobility Program.
- v) Jake Martin, a Farrington High School graduate, spent two summers to compile and analyze snow cover data, while attending Princeton University. His two summer internships, in 2016 and 2017, were directly or indirectly supported by OMKM.

In total, four undergraduate students have participated through paid internships, over 4 semesters and 3 summers, and one through for-credit coursework. Several have become co-authors of peer-reviewed publications. Additional UH students have been involved in a peripheral manner and gained research experience in this way, and several OMKM interns and employees participated in the field work.

School Visits

Kenji Yoshikawa visited Hilo Intermediate School on November 22, 2013 to install a temperature monitoring borehole, and presented 4 outreach lectures at Hilo Intermediate School on Oct 24, 2014. Matthias Leopold gave a demonstration of geophysical methods at UH Hilo in September 2016.

Public Lectures

Kenji Yoshikawa presented a public lecture about permafrost at UH Hilo on October 24, 2014. Norbert Schorghofer presented a talk about the 'History of snow and ice on the summit of Hawaii' on November 20, 2014 in the same speaker series. Both presentations were recorded and posted on YouTube by the OMKM.

Recommendations

R1. Sampling of permafrost

Certain scientific questions can only be answered by analyzing samples of the permafrost.

- a) The emplacement age of the ice could be determined by Carbon-14 dating of organic inclusions in the ice (in the form of insect fragments, pollen, or other particulate organic carbon). C-14 dating has been unsuccessfully attempted by Woodcock (1974) with insects he found in the ice, but with modern technology, specifically Accelerator Mass Spectroscopy (AMS), the detection limit for C-14 is about a thousandfold lower, so dating of the permafrost should now be feasible, if sufficient organic material can be found.
- b) Organic and inorganic inclusions (e.g., ash deposits) or sections of increased acidity may reveal pre-historic volcanic or climatic events.

As the ice retreats to greater depth, sampling will become increasingly difficult, and ultimately the opportunity to study this unique natural historical record will be lost entirely.

R2. Long-term permafrost monitoring

The extent of the ice-rich permafrost bodies can be monitored by repeating the geophysical survey along defined transects at time intervals of about once a decade, but the most direct way to assess permafrost health is through long-term in-situ temperature measurements. These temperature sensors have to be inserted into the interior of the permafrost bodies, at depths of 2-10 m. Emplacement of such sensors could be accomplished simultaneously with permafrost sampling.

R3. Continuous and reliable meteorological data

There is a lack of high-quality climate data for the summit area. Currently, meteorological data are available from weather sensors associated with the astronomical observatories, but these were not designed for the purpose of climatological characterization, and they often lack continuity, calibration, and curation. Specifically we recommend to collect:

- a) A long-term air temperature record to reliably assess the climate and climate warming on Maunakea. In the short-term, these would provide a better characterization of the prevailing climate, and in the long-term they could be used to determine the rate of climate warming on Maunakea. Climate warming is usually amplified with elevation (Pepin et al., 2015; Mountain Research Initiative EDW Working Group, 2015).
- b) A long-term continuous precipitation record. Better precipitation data would be helpful to properly identify drought conditions on the summit plateau, understand changes to the water level of Lake Waiau and Pu‘upōhaku Pond, and reliably quantify snowfall.
- c) A precipitation record that distinguishes between snowfall and rainfall over a baseline of at least several years. Snow and rain have different effects on permafrost.

Some of these objectives could be accomplished by upgrading instruments and maintenance of existing weather stations.

R4. Solar radiation

- a) The solar radiation budget, which is affected by cloud cover, is an important component of the surface energy balance and ultimately for evaporation, freezing, and melting.
- b) UV exposure on Maunakea is expected to be exceptionally high, due to the tropical location, high altitude, and sparse cloud cover, but has not been measured for the duration of a year.

R5. Perched groundwater

The presence of perched groundwater in Pu‘upōhaku crater came as a surprise and demonstrates that the physical environment of the summit plateau has not yet been fully explored. The groundwater at Pu‘upōhaku could be easily monitored with a water level gauge to assess its resilience to drought conditions.

R6. Archiving and validation of collected data

Environmental and climatological data collected in the summit region are, in most cases, already publicly archived. This data archiving and sharing policy benefits ongoing and future research, and it should be continued and extended. We recommend that, in addition, environmental data archives be reviewed to ensure they are of maximum potential benefit to future investigators. Archived data ought to include basic information, such as units for all measured variables, references to publications that describe the data and methods, and the names of people who have collected and archived the data; they might also benefit from a review for completeness. Not all archived data currently meet these standards.

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