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Massive ice loss from the Mauna Loa Icecave, Hawaii

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ABSTRACT

We provide the first detailed documentation of a lava tube cave with permanent ice on the Hawaiian Islands. "Mauna Loa Icecave" had been surveyed in 1978; we periodically visited the cave and monitored temperature, humidity, and ice levels from 2011 to 2014. Perennial ice still blocks the lava tube at the terminal end, but a previously present large ice floor (estimated 260 m^2) has disappeared. A secondary mineral deposited on the cave walls is interpreted as the result of past sustained ice levels. Airflow measurements, scallop patterns in the ice, strong temperature and humidity variations, and ice volume fluctuations indicate ventilation of the cave, which suggests that additional ice loss could occur rapidly. The scientific potential of the ice record remains to be explored, before it is lost.

Introduction

Less impressive than the huge polar caps and glaciers and less visible than the vast ice masses above ground, the more concealed subsurface ice can be an archive for past climate conditions. Cave ice can contain well-conserved air and sediments with plant and animal matter, so it holds information on past environmental conditions. It is well known from the analysis of ice cores and pollen (Feurdean et al., 2011), that the ice in some caves is several thousand years old, has outlasted several climate optima, and is not a remnant of the Little Ice Age (Silvestru, 1999). Besides the visible biomass (e.g., leaf, pollen) inside the ice, the geochemistry and the water isotopes provide information about precipitation, meltwater, and karst water composition for each year that formed ice in the cave (Kern et al., 2010, 2011). Recently, many cave ice bodies worldwide have experienced significant mass loss (Kern and Perşoiu, 2013).

The Mauna Loa shield volcano (19°N, 156°W), one of two summits over 4000 m a.s.l. on the Island of Hawaii, has a high density of lava tubes. The Hawaiian chain, the most isolated islands on earth with the highest summits in the North Pacific, is located in the northern tropics, and air temperatures inside lava tubes near sea level are well above 20 °C. At high elevations, the climate is alpine in character and snowfall and freezing temperature are possible any time of the year. Heavy storms occasionally bring snow to the tallest summits of Hawaii, but at elevations below 3350 m any snow vanishes quickly (Blumenstock and Price, 1994). Mean annual temperatures are well above freezing, even on the summit (Da Silva, 2006). At the Mauna Loa Observatory (3397 m), which is close to our study site, the average annual mean and diurnal max/min are +7, +11, and +4 °C, respectively (Da Silva, 2012). Many of the high altitude lava tubes on Mauna Loa have icy floors during winter months or seasonal icicles (Jack Lockwood, personal communication), but perennial ice has rarely ever been reported in Hawaii (Pflitsch et al., 2012). Patches of buried permafrost were once documented near the summit of the other tall volcano on the island, Mauna Kea (Woodcock et al., 1970; Woodcock, 1974).

In a comprehensive literature survey, Turri et al. (2009) have evaluated historical sources, including English, Italian, and Russian literature, and compiled the geographic distribution of ice caves in Europe and Asia. For the United States, ice cave locations have been compiled by Merriam (1950) and Halliday (1954). There are also theoretical approaches on the geographic distribution of ice caves (Mavlyudov, 2008) and studies based on historical data (Mavlyudov, 2010). In none of this literature do we find any mention of ice caves on the Hawaiian Islands. For many parts of the world, the publications of caving clubs and associations as well as of speleology meetings and conferences hold additional information on ice cave locations. In these, Kempe (1979) and Kempe and Ketz-Kempe (1979a, 1979b) briefly describe a lava tube cave on Mauna Loa with perennial ice.

We have visited and surveyed the "Mauna Loa Icecave" on the north flank of Mauna Loa from 2011 to 2014, and here we present our first results, emphasizing changes in the ice volume. The cave is located at ~3600 m elevation, still ~600 m below the summit. The lava flow that contains the ice is 750–1500 yr old (U.S. Geological Survey, 1996), which places a maximum age on the ice.

The Ice Deposits of Mauna Loa Icecave: Then and Now

Mauna Loa Icecave has been known since at least 1978 (Kempe and Ketz-Kempe, 1979a). A map was published by Kempe (1979), and reprinted in Halliday (1991), based on a visit in August 1978. The lava tube is over 200 m long and slopes downhill. The map shows large areas of ground ice from the middle of the cave to its end. Based on the map, the contiguous ice-covered area was about 260 m^2, as determined by drawing the mapped area onto gridded paper. The known end of the cave was blocked by an ice plug (Fig. 1). The Kempe team found a contiguous, walkable ice floor, which they called "Skating Rink." Figure 2, part a, shows a photograph from 1978 with the ice floor.

We located and visited this cave in November 2011 and semiannually thereafter, until April 2014, and found that ice is still present year-round. But a comparison with the 33-year-old cave map reveals that a significant volume of ice has been lost (Figs. 1 and 2). Except the ice plug, all of the former known ice blocks are gone. The "Skating Rink" segment has entirely disappeared, leaving only sporadic spots of ice, a few centimeters thick, on the ground. Figure 2 compares the photograph from 1978, of an area of the cave once covered by ice, with one from 2014 from nearly the same point of view. Today the floor of the lava cave is exposed, with a few small wet or icy spots in cracks in the middle of the room. More ice (patches up to 0.3 m in diameter and up to 0.1 m thick) appears seasonally along the walls.

Two alcoves, respectively 0.7 and 1.1 m high and 4.5 and 5.5 m deep, which were previously submerged in the ice, have appeared in the "Party Hall" (Fig. 1). Both still have ice-covered floors. In summer, the lower alcove has meltwater, up to 0.1 m deep, over a thin ice layer. The upper alcove never had any meltwater on the ice and the ice is at some parts at least 0.5 m thick (Fig. 3), based on the penetration depth of the laser distometer. In the small room between the Party Hall and the ice-filled siphon (pit) are a few spots as well, which are between 0.1 and 1.0 m in diameter and filled with water (summer) or ice (winter) up to 0.2 m deep.

The ice that blocks the lava tube is at about the same level as on the map from 1978. Debris particles are seen on the ice surface (Fig. 4), and dust-sized evaporite deposits (probably cryogenic) are often uniformly scattered over the ice surface. Embedded in the ice are millimeter-sized air bubbles. The length of the ice block from the beginning to where it narrowed to the ceiling until we could no longer pass was 5.4 m. From there to the next wall reached with the laser distometer, it was 4.2 m. During the last visit in April 2014, the passage was open for the first time and we could crawl through and confirmed the previously measured length of 9.6 m. The maximum width in the passage is 2.25 m. The depth of the ice is unknown, but is at least 0.5 m, based on the penetration depth of the laser distometer. During the first visit in November 2011, the ice near the walls at the beginning of the block had a few scallops, which is often a sign of ablation by air flow or melting (Benn and Gulley, 2006). They changed in depth, width, and shape at each following visit. At the second visit in April 2012, the scallops on the right side had

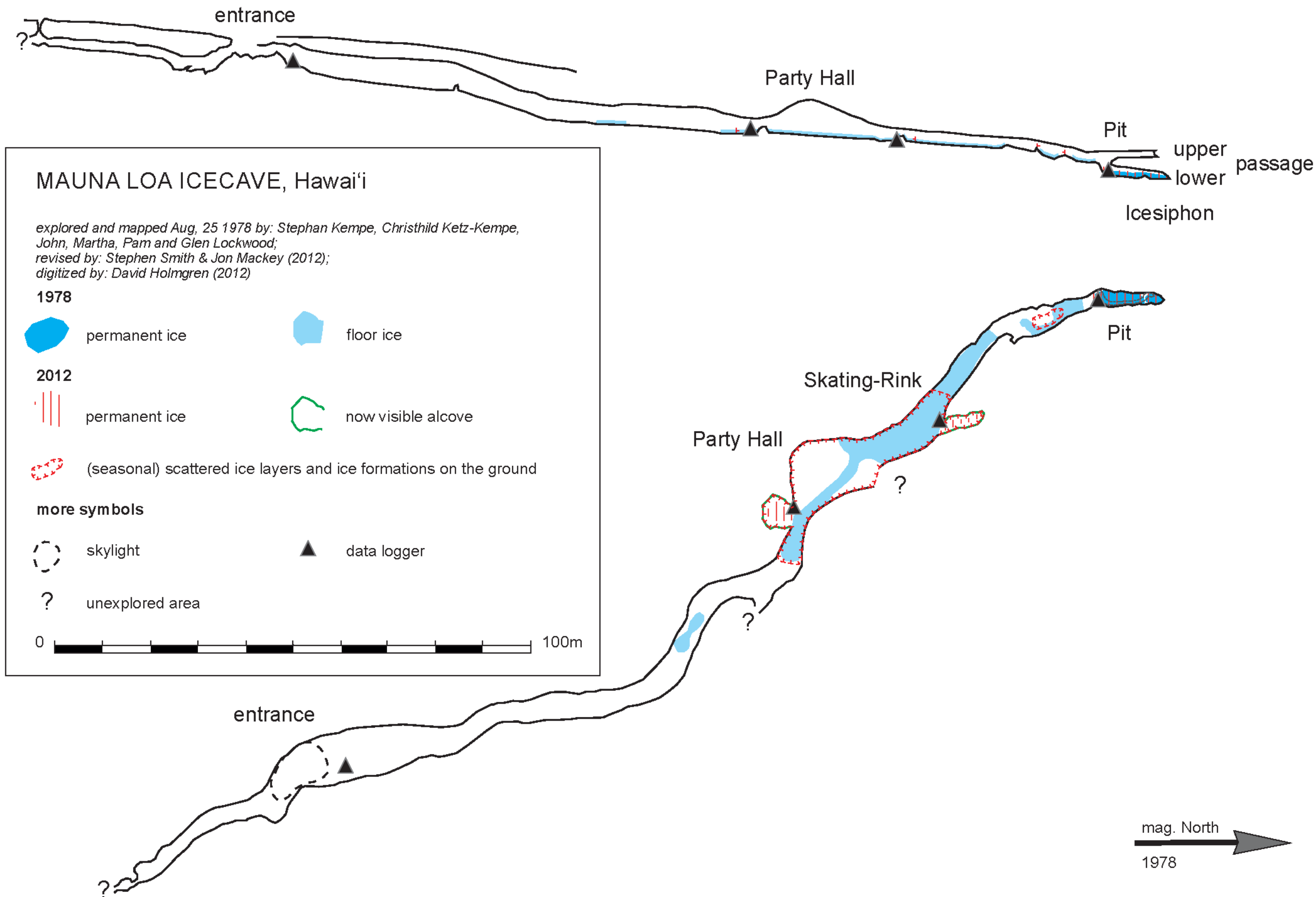

Figure 1. Map of Mauna Loa Icecave based on a survey by Kempe and his colleagues in August 1978 (Kempe, 1979) and on observations from 2012 to 2014. The map emphasizes the ice inside the cave; other information is omitted. Two new alcoves have emerged. The locations of our data loggers are also indicated (triangles). Results from two data loggers at the ice siphon are used in the present study.

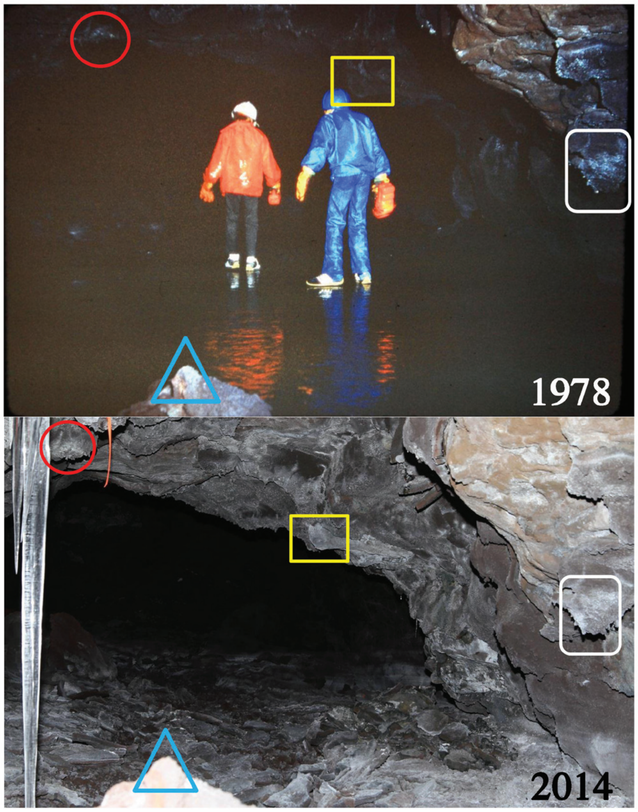

Figure 2. View of the Skating Rink in 1978 (credit: Stephan Kempe), when the ground was entirely covered with ice, and in April 2014 from almost the same position. One can see the rocky ground without any ice. The symbols are put in for easy comparison between the two photographs.

almost completely disappeared, while the ones on the left side had deepened (Fig. 4). In November 2012 and April 2013, the right side showed them again, and in November 2013, they were filled with ice or with water covered by a thin ice layer, which was frozen completely in April 2014. Because the scallops were completely dry first and were completely filled with water later on, they must have formed by air flow and invaded by meltwater later in the warm season. Due to the topography, the development of the scallops by flowing water is not possible. The meltwater during the summer melting fills the scallops and refreezes in early winter. Moreover, this small passage is the only place in the cave where we detected an airflow during all visits (as described at the end of the next section).

The surface temperature of the ice ranges from –0.6 to –0.0 °C over time and surface location, which demonstrates that the ice is only marginally frozen. (Surface temperature was measured with a precision ribbon surface probe from ThermoWorks, THS-103-030, nominal accuracy ±0.5 °C; the temperature of liquid water above ice was measured as +0.1 °C, which serves as validation of the measurements, as this water must have been very near the freezing point.)

Precipitation in this exceptionally dry region on Mauna Loa (45 cm yr^{-1}) is primarily by rain and secondarily by snowfall (9 cm yr^{-1}) (Western Regional Climate Center, 2015). Water percolates through the cave ceiling and forms small seasonal ice stalactites and stalagmites. These melt after winter, at the latest, or during short warming periods. This trickle supplies a slow intermittent flow along the cave floor; the occasional icefall at the terminal pit is evidence of this episodic supply of water to the terminal ice plug. The ice level changes at the ice plug are small even compared to the 1978 map, so that this ice may be a fossil relic. In some years, a coat of fresh ice may cover the ice plug.

Mauna Loa Icecave Is a Dynamic Cave

In November 2011, it appeared the ice cave was of "ice cellar" type, because the lava tube led downward from a single entrance and was blocked by ice. But in April 2012, we noticed an airflow at the distal end of the cave. The airflow, combined with the scallop patterns in the ground ice, suggest the air continues through cracks and spaces impenetrable to humans. In April 2014, the scallops were deep enough for us to crawl to the end of the cave, where large cracks are visible on the wall and a strong airflow came through the cracks.

The air passage may be larger now than in the past. The cave ice may have blocked the cave passage in the past and during our first visit, but not during the second, so that the cave climate might be changing either seasonally or secularly. Long-time observations are needed to distinguish between these two possibilities. In any case, the remaining ice block is very dynamic and changing.

These conclusions are consistent with measurements of the air temperature and humidity in front of the ice block. Figure 5 shows large fluctuations of the air temperature over short periods and at all seasons, which are not typical for a stable situation in an ice cellar–type cave. There is no strong cool-

Figure 3. (a) View into the upper alcove, with an ~1.8-m-wide and 0.6-m-high entrance. Inside is ice on the ground and there are seasonal icicles, but there is no ice in front of the alcove. (b) View into the lower alcove, with an ~2-m-wide and 0.7-m-high entrance and an ice floor.

ing-down season with invasion of cold air and no stable season with a slow warming without strong temperature fluctuations, which are typical for stable ice cellar–type caves (Meyer et al., 2014). Although a yearly cycle is clearly discernible in the air temperature evolution, with warmer summer and cooler winter temperatures near the ice block, the air temperature can rise above freezing any time of the year and it can fall below freezing even in summer.

Two air temperature sensors (GeoPrecision M-Log5W, PT1000 and HOBO U23-002) were placed ~10 cm above the ice; they provided consistent measurements. The temperature average was 0.16 °C (median: 0.11 °C, min: −1.7 °C, max: 2.6 °C) for the two-year period 20 November 2011 to 20 November 2013, and only 37% of the time was below freezing (Fig. 5). This explains the repeated melting of the ice.

The relative humidity also shows large fluctuations throughout the year, which again is typical for a dynamic cave climate (Fig. 6). In closed limestone caves, the relative humidity near free water surfaces is usually nearly constant and close to the saturation point (Badino, 2010). But the relative humidity at the end of Mauna Loa Icecave shows only short intervals above 90% and dry extremes down to 20%. The annual mean for 2012 was 65%. Altogether, this is a clear hallmark for a dynamic cave system with significant air exchange.

To quantify the airflow at the known end of the cave and to corroborate the theory of a dynamic cave, we measured the air velocity over a period of several days at the beginning of the ice block. We carried two motorcycle batteries to power the ultrasonic anemometer (three-axis, Vaisala, Wettertransmitter WXT 510), which lasted 3.5 days. The raw data with a sampling interval of 10 s were smoothed by averaging over 1-min intervals. The measurements shown in Figure 7 reveal an outflow from the passage over the ice block out of the cave. The flow velocity in the 1 min average was up to 2.08 m s^{-1}. The unsmoothed data showed a maximum of 2.5 m s^{-1}, an average of 0.99 m s^{-1} and a standard deviation of 0.56 m s^{-1}. These very high fluctuations of the air velocity are apparent in Figure 7. These measurements, although short, clearly demonstrate that air enters the cave mostly through the cracks inside the walls of the last chamber at the end of the ice block. The relatively strong air flow and the variability of the air current at the last few meters of the cave are clear evidence for its dynamic character.

Mineral Deposits

A few almost continuous white lineations go along both sides of the Party Hall, approximately around where the Skating Rink used to be. The white mineral deposit shows a strong contrast with the darker background of the lava tube, especially at the lower end of the Party Hall (Fig. 8, parts a–d). We counted up to seven clearly identifiable levels and additional ambiguous levels, although most of them cannot be traced over long distances. The highest weakly visible line is about 1.2 m and the highest clearly visible one is 0.87 m above the ground. These almost continuous white linings may indicate a previous sustained ice level. The white lineations are tilted with the lava tube, which in-

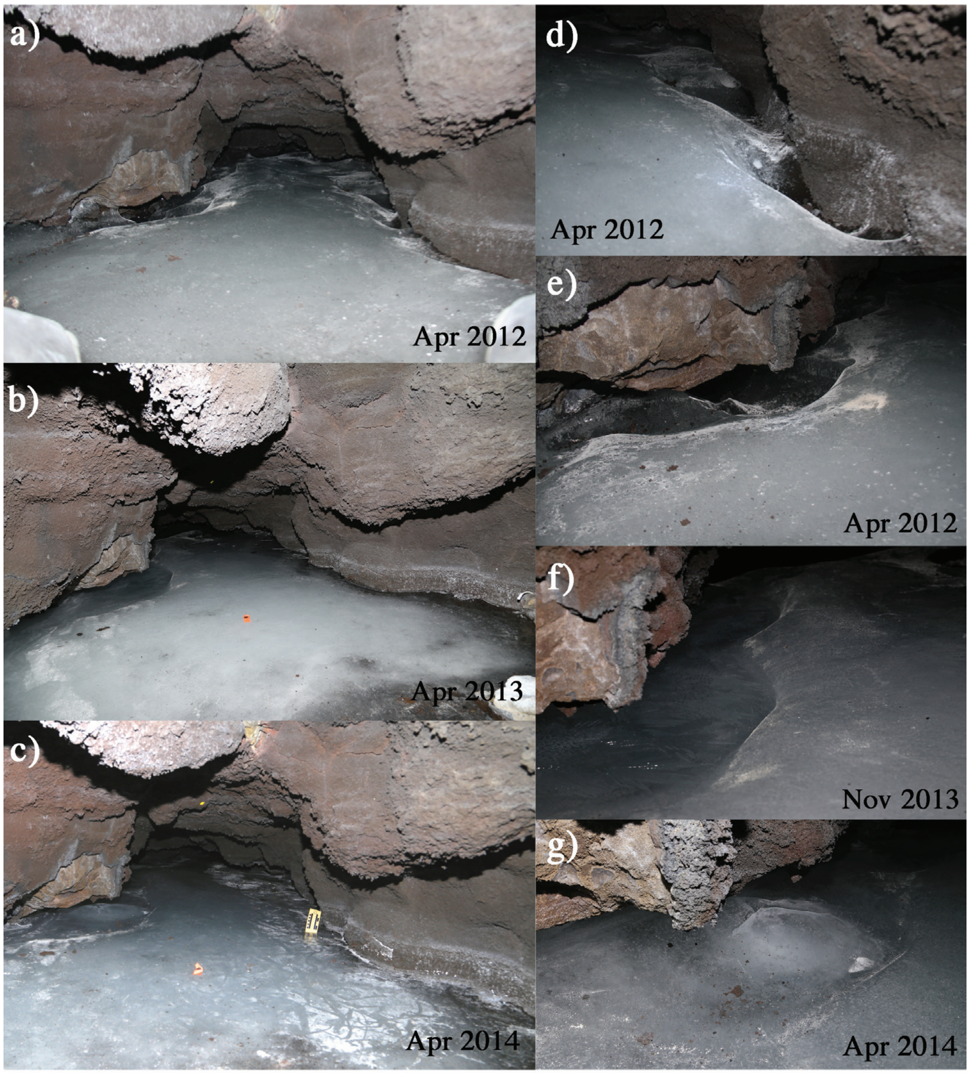

Figure 4. (a–c) View of the ice block at the terminal end of the cave at various times. (d–g) Close-up view of the scallops on the sides of the ice block. (a and e) Deep scallops on the left side in April 2012; (b) scallops deepened on the right side between November 2011 (not shown) and April 2012; (f) water filled and slightly over frozen scallops on the left in November 2013; (c and g) refilled and fully frozen scallops in April 2014.

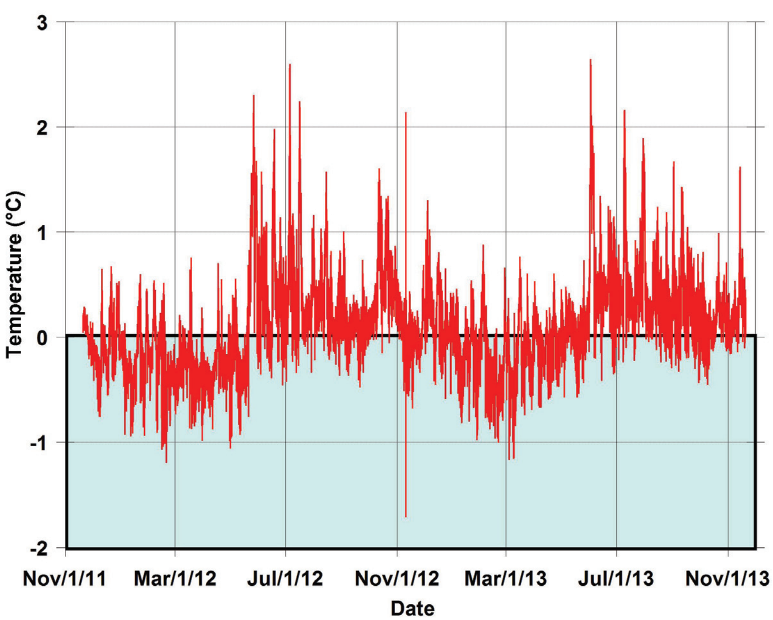

Figure 5. Air temperature above the ice block from 21 November 2011 to 24 November 2013 measured with a data logger (GeoPrecision M-Log5W, sensor type PT1000, accuracy of ±0.1 °C at 0 °C), and with data stored every 10 min.

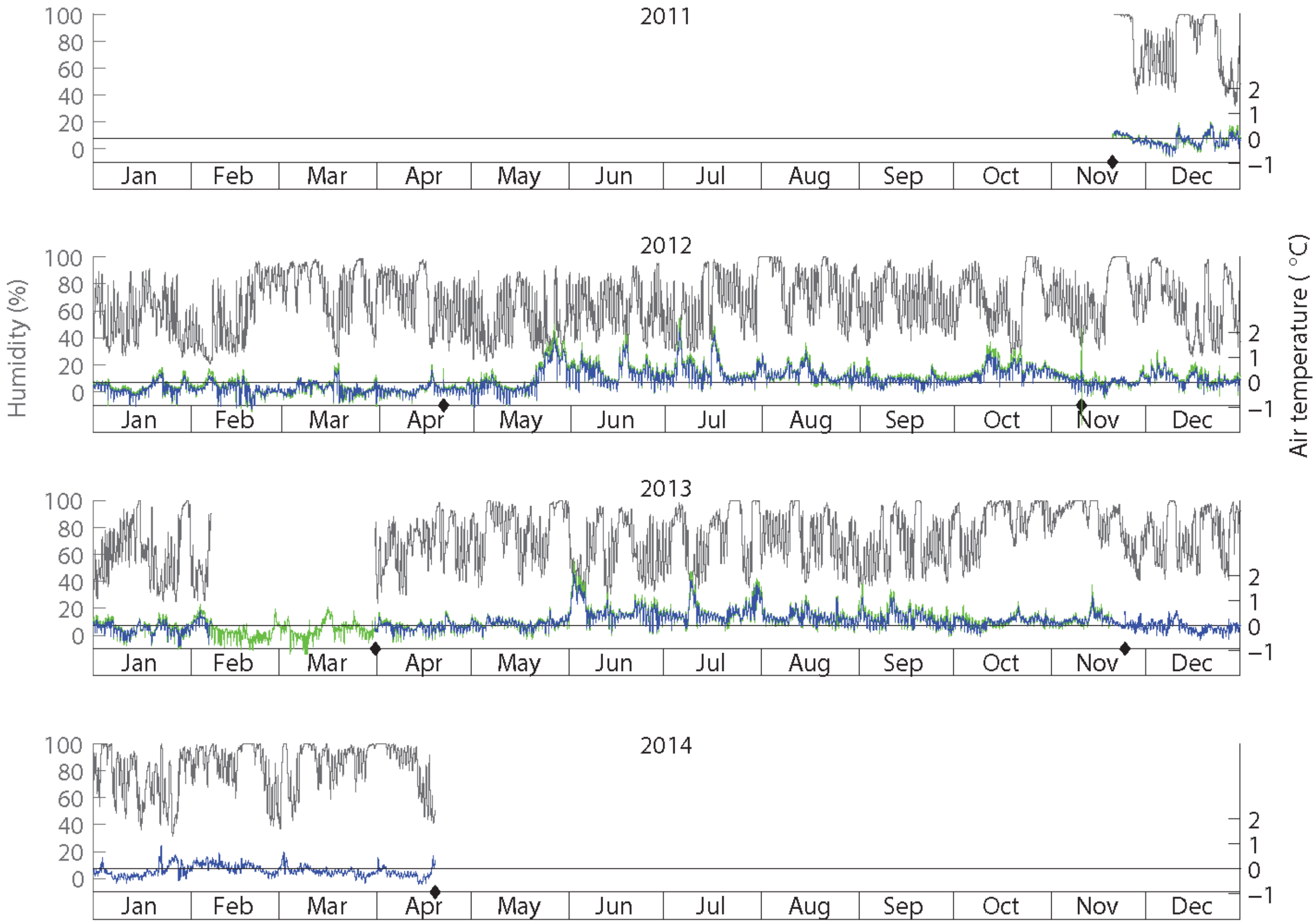

Figure 6. Relative humidity (gray) and air temperature (blue) above the ice block from 21 November 2011 to 20 April 2014. Diamond symbols indicate the days of cave visits (20 November 2011; 21 April and 10 November 2012; 31 March and 24 November 2013; and 19 April 2014). Variables were measured with a HOBO U23-002 data logger with a nominal accuracy of 0.2 °C; average values were stored in 30 min intervals. The air temperature was also measured with another data logger from GeoPrecision (M-Log5W), with sensor type PT1000 (green line).

dicates that these levels correspond to a tilted ice surface rather than ponded water. We interpret the white material as a secondary mineral deposit (White, 2010). The water may contain dissolved ions extracted from the lava, and when it freezes, the ions precipitate.

The volume of the ice that once reached to the most pronounced of these levels is estimated using depth measurements along six transects. The average depth is ~0.50 m; combined with the aforementioned area of the ice floor, this corresponds to an estimated volume of 130 m^3. The map (Fig. 1) and the photograph of 1978 (Fig. 2) provide a constraint on the depth of the ice at the time. Based on the photo, the ice level in 1978 was slightly lower than the main white line, and the extent of the ice in the map was slightly smaller than indicated by the main white line. Hence, most but not all of the 130 m^3 of ice was lost since 1978.

The same kind of lines, but thinner, is visible in the terminal pit and indicates a stepwise retreat of the ice there as well. Based on these deposits, the entire pit and most of the upper tube parallel to the lower ice block (Fig. 9) were once filled with ice. We could identify that the first line directly above the ice block in the siphon represents a previous level of the meltwater above the ice between two visits (Fig. 10).

Discussion

The retreat of ice observed in Mauna Loa Icecave is consistent with the trend reported by Kern

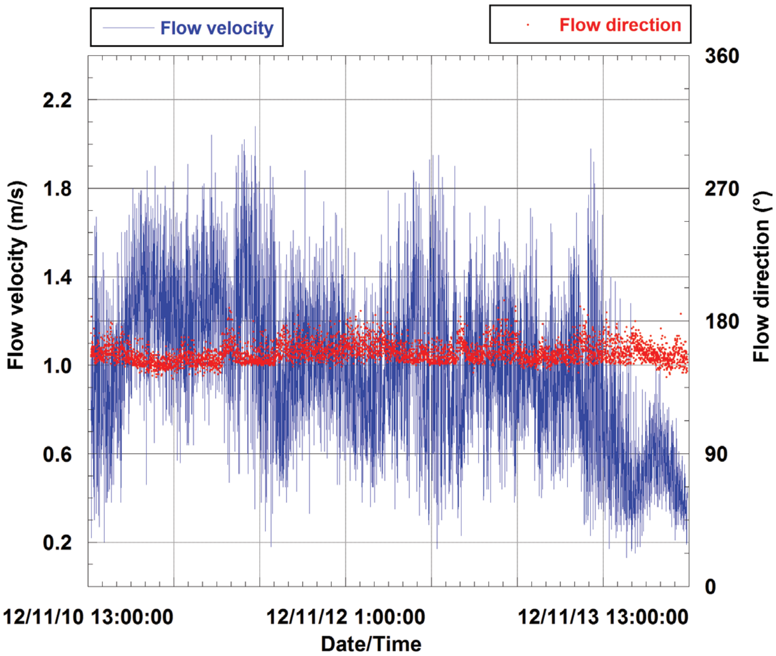

Figure 7. Wind speed and wind direction at the terminal end of the cave. The air flow (along the tunnel) at the front of the ice block from 10 November, 13:25, to 14 November, 0:46, 2012, averaged over 1 min intervals. The wind direction, from about 180°, shows a constant outflow out of the chamber of the ice block.

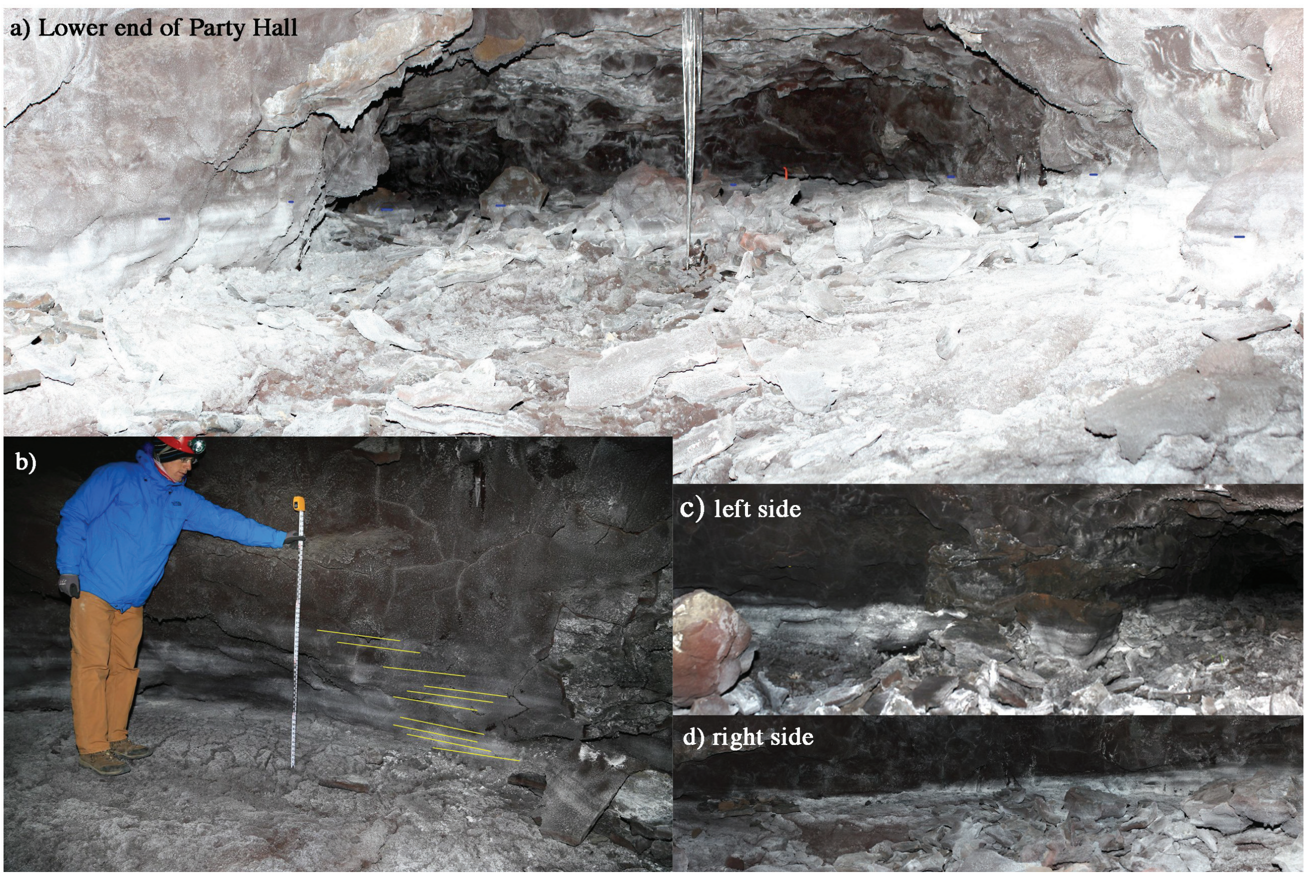

Figure 8. (a) Lower end of Party Hall, where the cave is about 7 m wide. A white mineral deposit covers the lower walls on both sides of the cave, and most of the floor. Blue markers are added to the image to highlight its boundary. The seasonal icicle at the center is 2 m high and was only seen during our visit in April 2014. The red tape is a temporary survey marker. (b) Mineral deposits on the wall of the Party Hall. Various levels are marked yellow. (c) The white deposit forms a stark contrast with the dark lava tube at the lower left (west) end of the Party Hall and continues beyond the Party Hall farther into the cave. (d) A mosaic of images of the mineral deposit on the right (east) side of the lower end of the Party Hall.

Figure 9. Upper and lower passage at the distal end of the cave. The lower passage is filled with old ice. The upper passage has a mineral deposit with discrete levels, evidence of a past ice level.

and Perşoiu (2013). They have evaluated the literature and data for caves in the northern hemisphere and found a trend of decreasing ice levels.

The temperature at the nearby Mauna Loa Observatory shows a trend of increasing temperature between 1977 and 2006 (Malamud et al., 2011). The rising temperatures suggest the ice retreat in the Mauna Loa Icecave may be due to climate warming. On the other hand, there has also been a trend of decreasing rainfall since the cave was described in 1978 (Diaz and Giambelluca, 2012). And beginning in 2008, the island experienced a drought. Less precipitation may mean not all of the ice that was lost was replenished; dynamic cave weather could have caused a significant ice loss by sublimation alone.

A question of concern is whether Mauna Loa Icecave will continue to lose ice. Climate warming at high elevations in Hawaii is estimated at 0.27 K decade^{-1} since the mid-1970s (Giambelluca et al., 2008) and at the nearby Mauna Loa Observatory it was 0.21 K decade^{-1} (Malamud et al., 2011). At this point we cannot determine whether the fluctuations in the ice level at the terminal end of the cave and the frequent melting represent short-term variations or whether they indicate the beginning of a systematic retreat. However, ventilation of the cave means that ice loss can potentially occur rapidly. Ice could be lost from the cave in three ways: melting and subsequent evaporation, melting and subsequent run-off, or by sublimation alone. Any of these modes would be accelerated by the dynamic character of the cave climate. On the other hand, growing ice could stop the ventilation by blocking the ventilation channel and would change the cave climate back to a more static environment. This can accelerate the growth of ice at least in some parts. We have also observed these processes of rapid changes in the climatology of a cave with a strong

Figure 10. A faint straight line of mineral deposit (arrow) is discernible on a scale that was placed in a scallop on the right wall at the ice block in November 2013. The photo was taken in April 2014, and the white line must have formed at a water level from the intervening time period. The bottom 0.5 cm of the scale is frozen in ice, and the faint white line is about 1 cm above that.

effect on the cave ice by opening or closing of passages in the Fossil Mountain Cave (Wyoming) and in the Schellenberger Eishöhle (Germany). In both cases, a strong positive feedback exists.

There are numerous differences between basalt caves and carbonate caves, and some potentially have an impact on ice formation. Intact open lava caves often have only a thin ceiling and do not reach to great depth, while karst caves often reach deep underground. The incline of long lava tubes is small overall, and deep ducts as well as large halls are rare. Karst caves have more vertical ducts and larger rooms. These factors affect the inversion between cold air in the cave and warmer air outside. The thin ceiling of lava tubes is often very porous and thus extremely permeable to water, so that rainwater enters the cave neither delayed nor damped. In any case, there exist mighty ice bodies even in lava caves, whose conditions have been insufficiently investigated and there is a significant need for additional studies.

Ice-filled lava tubes on Mauna Loa illustrate that cave ice can be found in extreme geographic isolation, and in geologic environments similar to those of Mars, where many lava tubes have been observed (Cushing et al., 2007; Leveille and Datta, 2010; Williams et al., 2010). Moreover, the high altitude lava tubes on Mauna Loa are situated in a stone desert, an environment poor in organic carbon (the food source of heterotrophs), and they are potentially interesting for the microbial communities that colonize and inhabit these dark biospheres (Northup and Lavoie, 2001).

Conclusions

We provide the first detailed documentation and monitoring of a lava tube cave with permanent ice on the Hawaiian Islands. Mauna Loa Icecave still contains a perennial ice deposit at its distal end, but a comparison with a map based on a visit in the summer of 1978 reveals that a massive ice floor (~260 m^2) at the middle of the cave has disappeared.

Several almost continuous white linings are discernible around where the massive ice floor used to be. This secondary mineral deposited on the cave walls may indicate previous sustained ice levels and is further evidence for significant ice loss.

Airflow measurements, scallop patterns in the ice, and relatively strong temperature and humidity variations indicate that air flows through the cracks at the reachable end of the lava tube. The cave ice may intermittently block the air passage, so that the microclimate is changing stochastically, seasonally, or gradually. In any case, ventilation of the cave implies that additional ice loss can potentially occur rapidly.

Acknowledgments

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References Cited

Badino, G., 2010: Underground meteorology—"What's the Weather Underground?" *Acta Carsologica,* 39(3): 427–448.

Benn, D., and Gulley, J., 2006: Under thin air: The 2005 Ngozumpa Glacier Cave research project. *National Speleological Society News*, 64(10): 16.

Blumenstock, D. I., and Price. S., 1994: Climates of the states: Hawaii. *In* Kay, E. A. (ed.), *A Natural History of the Hawaiian Islands: Selected Readings II.* Honolulu: University of Hawaii Press.

Cushing, G. E., Titus, T. N., Wynne, J. J., and Christensen, P. R., 2007: THEMIS observed possible cave skylights on Mars. *Geophysical Research Letters,* 34: L17201, doi http://dx.doi.org/10.1029/2007GL030709.

Da Silva, S. C., 2006: *Climatological Analysis of Meteorological Observations at the Summit of Mauna Kea.* Ph.D. thesis, University of Lisbon, 77 pp.

Da Silva, S. C., 2012. *High Altitude Climate of the Island of Hawai`i.* M.S. thesis, University of Hawaii, 110 pp.

Diaz, H. F., and Giambelluca, T. W., 2012: Changes in atmospheric circulation patterns associated with high and low rainfall regimes in the Hawaiian Islands region on multiple time scales. *Global and Planetary Change,* 98-99: 97–108.

Feurdean, A., Persoiu, A., Pazdur, A., and Onac, B. P., 2011: Evaluating the palaeoecological potential of pollen recovered from ice in caves: a case study from Scarisoara Ice Cave, Romania. *Review of Palaeobotany and Palynology,* 165: 1–10.

Giambelluca, T. W., Diaz, H. F., and Luke, M. S., 2008: Secular temperature changes in Hawaii. *Geophysical Research Letters,* 35: L12702, doi http://dx.doi.org/10.1029/2008GL034377.

Halliday, W. R., 1954: Ice caves of the United States. *Bulletin of the National Speleological Society*, 16(12): 3–28.

Halliday, W. R., 1991: *6th International Symposium on Vulcanospeleology—Field Guide*. Hilo, Hawaii, August 1991.

Kempe, S., 1979: Three caves on Mauna Loa and Kilauea, Hawaii. *Limestone Ledger* (Sierra Mojave Grotto, California), 11(6): 37–43.

Kempe, S., and Ketz-Kempe, C., 1979a: Fire and ice atop Hawaii. *National Speleological Society News,* 37: 185–188.

Kempe, S., and Ketz-Kempe, C., 1979b: Three lava tubes on Hawaii, a caving report. *Limestone Ledger,* 11(7): 47–53.

Kern, Z., and Perşoiu, A., 2013: Cave ice—the imminent loss of untapped mid-latitude cryospheric palaeoenvirnmental archives. *Quaternary Science Reviews,* 67: 1–7.

Kern, Z., Fórzizs, I., Horvatincic, N., Széles, É., and Nagy, B., 2010: Glaciochemical investigations on the subterranean ice deposit of Vukusic Ice Cave, Velebit Mountain, Croatia. *The Cryosphere*, 4: 1561–1591.

Kern, Z., Fórzizs, I., Pavuza, R., Molnár, M., and Nagy, B., 2011: Isotope hydrological studies of the perennial ice deposit of Saarhalle, Mammuthöhle, Dachstein Mts, Austria. *The Cryosphere*, 5: 291–298.

Leveille, R. J., and Datta, S., 2010: Lava tubes and basaltic caves as astrobiological targets on Earth and Mars: a review. *Planetary & Space Science*, 58: 592–598.

Malamud, B. D., Turcotte, D. L., and Grimmond, C. S., 2011: Temperature trends at the Mauna Loa observatory, Hawaii. *Climate of the Past,* 7: 975–983.

Mavlyudov, B. R., 2008: Geography of caves glaciation. *In* Proceedings, 3rd International Workshop on Ice Caves, Kungur, Russia, 38–44.

Mavlyudov, B. R., 2010: Cave glaciations in the past. *In* Proceedings, 4th International Workshop on Ice Caves, Obertraun, Austria, 21.

Merriam, P., 1950: Ice caves. *Bulletin of the National Speleological Society,* 12: 32–37.

Meyer, C., Pflitsch, A., Holmgren, D., and Maggie, V., 2014: Schellenberger Ice Cave (Germany): a conceptual model of temperature and airflow. *In* Proceedings, 6th International Workshop on Ice Caves, 17–21 August, Idaho Falls, Idaho, 82–87.

Northup, D. E., and Lavoie, K. H., 2001: Geomicrobiology of caves: a review. *Geomicrobiology Journal*, 18: 199–222.

Pflitsch, A., Schorghofer, N., and Smith, S., 2012: Exploration of ice caves on Mauna Loa, Hawaii. *In* Proceedings, 5th International Workshop on Ice Caves, Barzio, Italy, 18–19.

Silvestru, E., 1999: Perennial ice in caves in temperate climate and its significance: *Theoretical and Applied Karstology,* 11–12: 83–93.

Turri, S., Trofimova, E., Bini, A., and Maggi, V., 2009: Ice caves scientific research history: from XV to XIX centuries. *Materialy glaciologicheskikh Issledovanij,* 107: 156–162.

U.S. Geological Survey, 1996: Geologic map of the island of Hawaii. MAP I-2524-A, scale 1:100,000.

Western Regional Climate Center, 2015: Period of Record General Climate Summary—Precipitation. www.wrcc.dri.edu/cgi-bin/cliGCStP.pl?himaun (accessed 27 May 2015).

White, W. B., 2010: Secondary minerals in volcanic caves: data from Hawai'i. *Journal of Cave and Karst Studies*, 72: 75–85.

Williams, K. E., McKay, C. P., Toon, O. B., and Head, J. W., 2010: Do ice caves exist on Mars? *Icarus*, 209: 358–368.

Woodcock, A. H., 1974: Permafrost and climatology of a Hawaii volcano crater. *Arctic and Alpine Research,* 6: 49–62.

Woodcock, A. H., Furumoto, A. S., and Woollard, G. P., 1970: Fossil ice in Hawaii? *Nature*, 226: 873.

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