

ONGOING GENESIS OF A NOVEL GLACIOVOLCANIC CAVE SYSTEM IN THE CRATER OF MOUNT ST. HELENS, WASHINGTON, USA

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Abstract

Mount St. Helens, one of the highest-risk volcanoes in the Cascade Volcanic Arc, hosts a novel system of glaciovolcanic caves that has formed around the 2004–2008 lava dome. From 2014 to 2021 a multidisciplinary research team systematically explored and mapped these new caves to ascertain their characteristics. Air and fumarole temperatures, volume flow rates, and wind regimes were also monitored. More than 3.0 km of cave passages have formed in a semicircular pattern in the volcanic crater and provide an opportunity to (1) observe cave development over time, (2) identify low temperature fumaroles as the main driving force for cave formation, (3) verify the impact of seasonal snow accumulation on cave climate, and (4) assess heat distribution in subglacial and subaerial portions of the new lava dome. Glaciovolcanic cave systems on Mount St. Helens are comparatively young (<10 years) and the most dynamic in the Pacific Northwest. Observed cave expansion during the study suggests ongoing genesis and future formation of interconnected systems. However, further expansion may also be limited by increasing fumarole temperatures towards the upper parts of the lava dome, cave instability due to snow overload, or variable subglacial volcanic heat output. New glaciovolcanic cave system development provides a unique barometer of volcanic activity on glacier-mantled volcanoes and to study the subglacial environment. We present the results of eight years of initial study within this dynamic cave system, and discuss a pathway towards future longitudinal analyses.

INTRODUCTION

The term glaciovolcanism describes all processes in which heat from the Earth's interior interacts with ice masses (Smellie and Edwards, 2016). Edwards et al. (2020) identified 245 Holocene volcanoes that potentially impact or can be impacted by surrounding ice. However, volcanically-influenced subglacial voids are rarely studied. Volcanoes that currently host glaciovolcanic cave systems include Mount Erebus (Antarctica) (Giggenbach, 1976; Curtis, 2016); Mutnovsky (Kamchatka Peninsula, Russia) and Hrafninnusker and the Kverkfjöll mountain range (Iceland) (M. Szeglat, personal communication, 2021). Mount Rainier in the Cascade Volcanic Arc (USA) hosts the world's largest glaciovolcanic cave system, with more than 3.5 km of surveyed passages in the summit East Crater (Florea et al., 2021). The first mapping efforts on Mount Rainier date back to the 1970s (Kiver and Mumma, 1971) and comparison to recent studies by Florea et al. (2021) reveal that main passages have remained static for half a century.

The elements of volcano-ice interactions and their related hazards are known from literature (Curtis and Kyle, 2017 and references therein). However, glaciovolcanic caves have often been overlooked. Recent approaches to describe these systems are those of Zimbelman et al. (2000), Curtis (2016), and Pflitsch et al. (2017). These and previous studies examined preexisting glaciovolcanic cave systems, while Mount St. Helens presents an exceptional opportunity to observe system evolution and examine factors involved in the genesis of glaciovolcanic caves.

A brief summary of Mount St. Helens' recent eruptive history and environmental setting identifies exceptional conditions for glaciovolcanic cave formation. Mount St. Helens is an active andesite-dacite volcano (Anderson and Vining, 1999) located in the State of Washington near the Portland and Seattle Metropolitan areas (Fig. 1). It is part of the Cascade Range and the subduction of the oceanic Juan de Fuca Plate beneath the continental North American Plate (Miller and Cowan, 2017). During the past four decades Mount St. Helens has undergone dramatic morphological changes. The cataclysmic eruption in May 1980 mobilized a huge debris avalanche, removing ~400 m of the volcano's conical summit and leaving a horseshoe-shaped 2 × 3.5 km diameter north-facing crater. Two subsequent periods of activity from 1980–1986 and 2004–2008 generated lava domes. A new glacier formed in response to the morphological changes (Harris, 2005). Despite the relatively low elevation of the crater floor (<2,200 m), deep shade and insulating dust layers allow snow, rime, and avalanche deposits to accumulate (Schilling et al., 2004). The glacier, since 2006 officially called Crater Glacier (Scott et al., 2008), is impacted by rockfall from the surrounding crater walls and has an average rock content of 15 % (Walder et al., 2008); Schilling et al. (2004) estimated one-third of the glacier to be rock debris in some areas.

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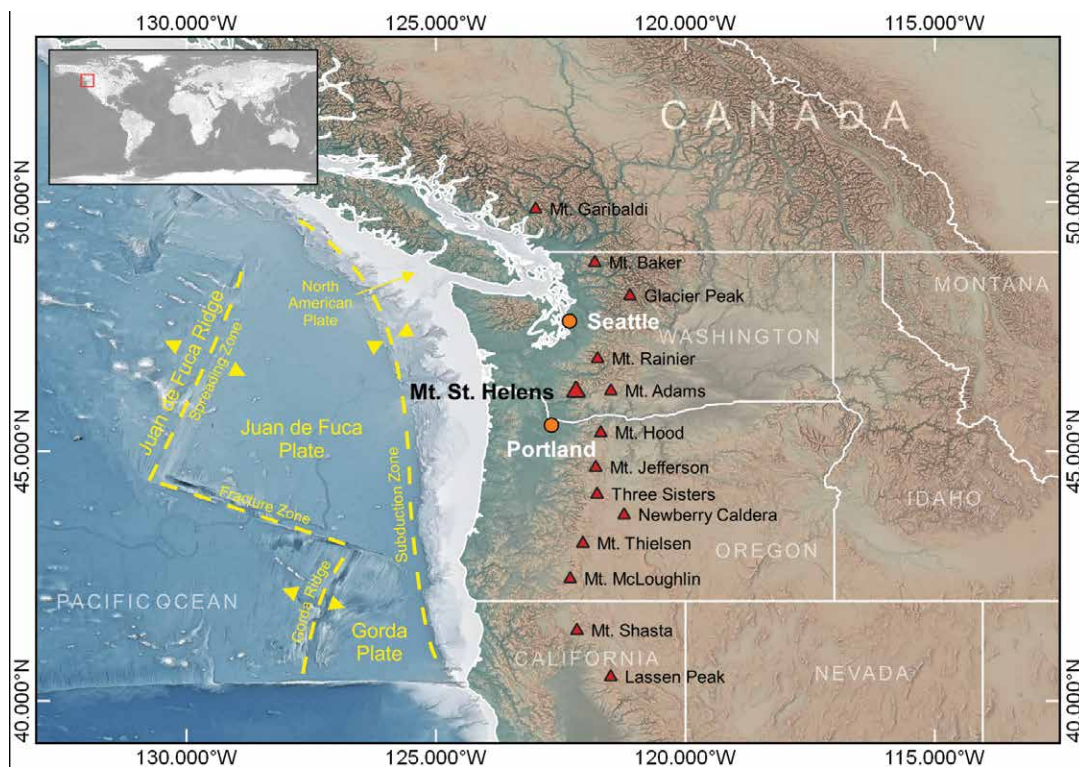


Figure 1. The Cascade Volcanic Arc with selected geological structures and major cities. Volcanism results from subduction of the oceanic Juan de Fuca Plate beneath the continental North American Plate. Basic map: General Bathymetric Chart of the Oceans (GEBCO). Inset: Natural Earth.

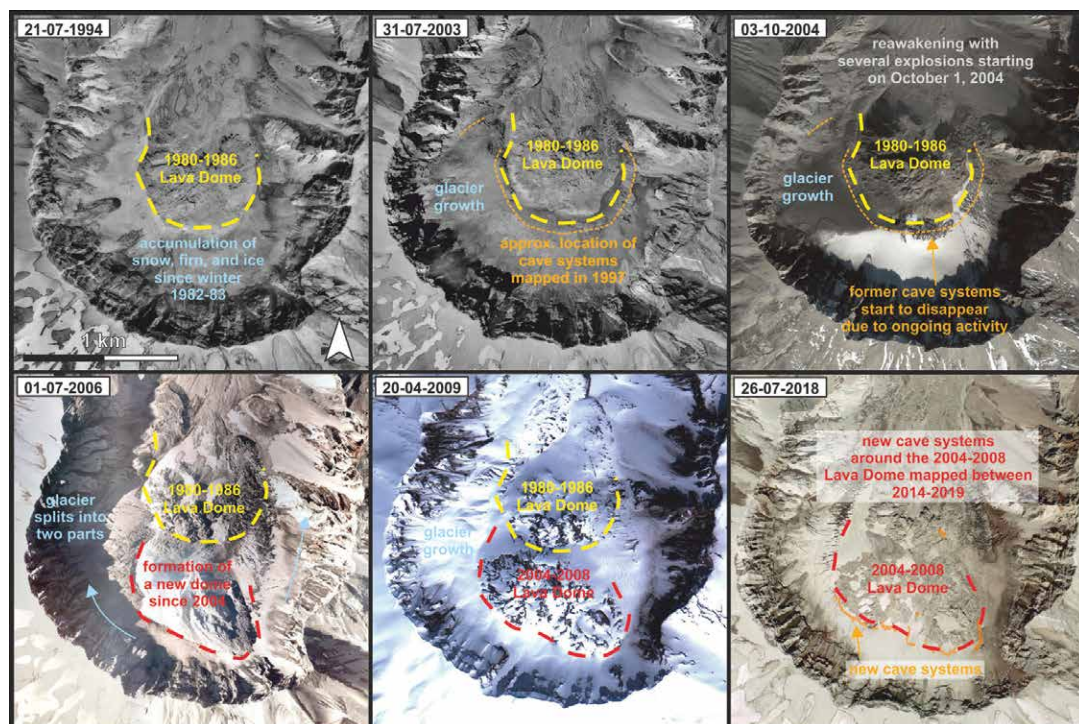


Figure 2. Development of Mount St. Helens crater and Crater Glacier. Images derived from Google Earth and document the main morphological changes from 1994 to 2018. Today, the crater is characterized by two lava domes, the 1980–1986 lava dome and the 2004–2008 lava dome; a newly formed glacier; and more than 3.0 km of glaciovolcanic cave systems which circumnavigate the new dome. Former cave systems were obliterated by renewed eruptions between 2004 and 2008. © Google Earth.

Anderson et al. (1998) described the formation of firn caves around the 1980–1986 lava dome (Fig. 2). More than 2.4 km of cave passages were mapped at that time. Volcanic activity from 2004 to 2008 and the formation of a second lava dome disrupted and obliterated these caves. In 2012, aerial observations suggested the existence of new glaciovolcanic caves, as indicated by a large chasm south of the 2004–2008 lava dome. Our study commenced with this discovery and from 2014 to 2021 we identified numerous glaciovolcanic caves which surround the new lava dome. In 2020 the crater hosted 10 individual caves with 2.3 km of mapped passages, arranged in a semicircular pattern around the 2004–2008 lava dome (Fig. 3). By June, 2021, 13 caves were described with a combined length of 3.0 km.

This paper presents a detailed description of the Mount St. Helens caves in order to illustrate different stages of glaciovolcanic cave development and their dynamics, and forecast further evolution. Climatic data include air temperatures and wind regimes and are supplemented by fumarole temperatures and flow rates. These data, supplemented by snow accumulation from nearby climate stations, help to understand season-

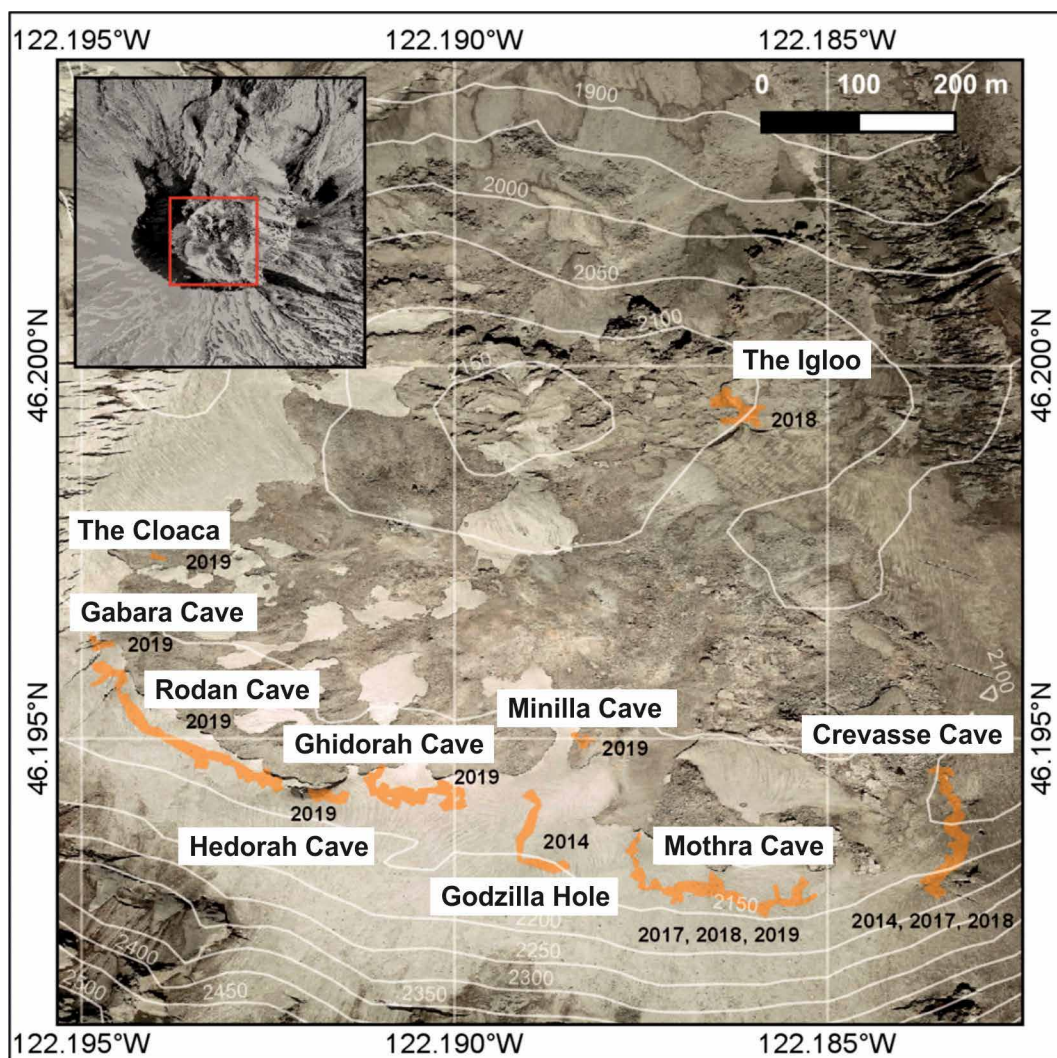


Figure 3. Location of glaciovolcanic cave systems around the 2004–2008 lava dome in the crater of Mount St. Helens (survey results to 2019 only). Black numbers indicate the year(s) the cave was surveyed. Image taken in 2018, © Google Earth (the latest available version). The Igloo, Cloaca, and Minilla caves were firn caves in 2019, although this 2018 image indicates a location on bedrock. The inset illustrates the dimensions of the crater. Image: High Resolution Orthoimagery (2006) from USGS Earth Explorer.

time series are attributable to loss of instrumentation or technical problems. Short-term studies investigated wind regimes and velocity profiles of individual fumaroles. The location of instrumentation is illustrated in Figures 4 and 5. Fumarole temperatures were recorded inside the caves and outside on various locations on the 2004–2008 lava dome.

Typical tacheometric cave survey methods were used to record cave morphology and to record the location of fumaroles and temperature loggers inside Mothra Cave and Crevasse Cave. Georeferenced stations were recorded at each cave entrance using GPS. Cave survey data were collected using calibrated DistoX and DistoX2 to generate distance, azimuth, and inclination measurements and to compute passage volumes via splay measurements at each station (Heeb, 2009). The DistoX2 communicated with a Dell Axim X51 PDA and PocketTopo cave survey software or Samsung Galaxy Note 4 or similar Android OS devices and TopoDroid software. The 2014 survey data generated with the DistoX were manually recorded, with passage cross sections hand drawn at key stations. The International Union of Speleology (UIS) grading standard was used. Precision of the majority of surveys meets standards for Grade 5 survey as per Häuselmann (2012) which gives a minimum precision for measurements of 0.05 m and a 2 % error ratio.

We dealt with several challenges during the fieldwork. The DistoX laser depends on a clear line of sight with no interference from water spray, fog, mist, or other obstructions. Conditions in the caves often include thick steam depending on location in the cave or time of day. During periods of limited visibility detailed splay measurements were not possible. In such cases, basic passage measurements were estimated in four directions from the fixed stations. Other challenges included glacier movement and rockfall which made it impossible to relocate some marked stations from previous surveys.

al changes, identify driving forces, and predict a possible transition from several individual caves to an interconnected passage system. This work focuses on this initial cave genesis and also provides a pathway towards future analyses. As this is a developing cave system requiring longitudinal study, this paper also discusses limitations and challenges.

METHODS AND DATA PROCESSING

Fieldwork in the Mount St. Helens crater was conducted from 2014 to 2021. To mitigate risks such as severe weather, rockslides, and cave collapses, most of the expeditions were confined to May and June when glacial ablation is moderate but cave entrances are no longer sealed with snow. The exploration in 2020 was limited to data logger download. Surveying efforts were conducted in 2014, 2017–2019, and 2021; long-term air and fumarole temperature data were collected from 2017–2020. Missing

Table 1. Summary of glaciovolcanic caves and cave statistics. Cave statistics were generated with COMPASS and indicate the most recent survey results.

Cave (most recent survey date)	Included Length, m	Cave Depth, m	Cave Volume, m ³
Rodan (2021)	775	82	43,265
Mothra (2021)	594	65	38,340
Ghidorah (2019)	434	30	21,025
Crevasse Cave (2018)	276	56	27,307
Lower Crevasse (2021)	197	30	1,859
The Igloo (2018)	191	8	4,323
Godzilla Hole (2014)	176	41	10,662
Hedorah (2019)	99	13	6,543
Dogora (2021)	71	9	1,026
Gigan (2021)	47	113	1,043
Gabara (2019)	62	119	728
Minilla (2019)	54	8	614
The Cloaca (2019)	34	10	286
Total	3010	...	157,021

Notes
Included Length: This is the included slope length of all the surveys processed. Slope length is the sum of all the tape lengths in the cave. It is the distance that you move through the cave, both horizontally and vertically.
Cave Depth: This is the absolute vertical distance between the highest and lowest points in the survey. It includes no horizontal movement.
Cave Volume: This statistic gives the volume of the cave surveys processed. It is based on the passage Left, Right, Up and Down dimensions. Surveys that are missing LRUD's for part or all of the data will give inaccurate volume calculations.

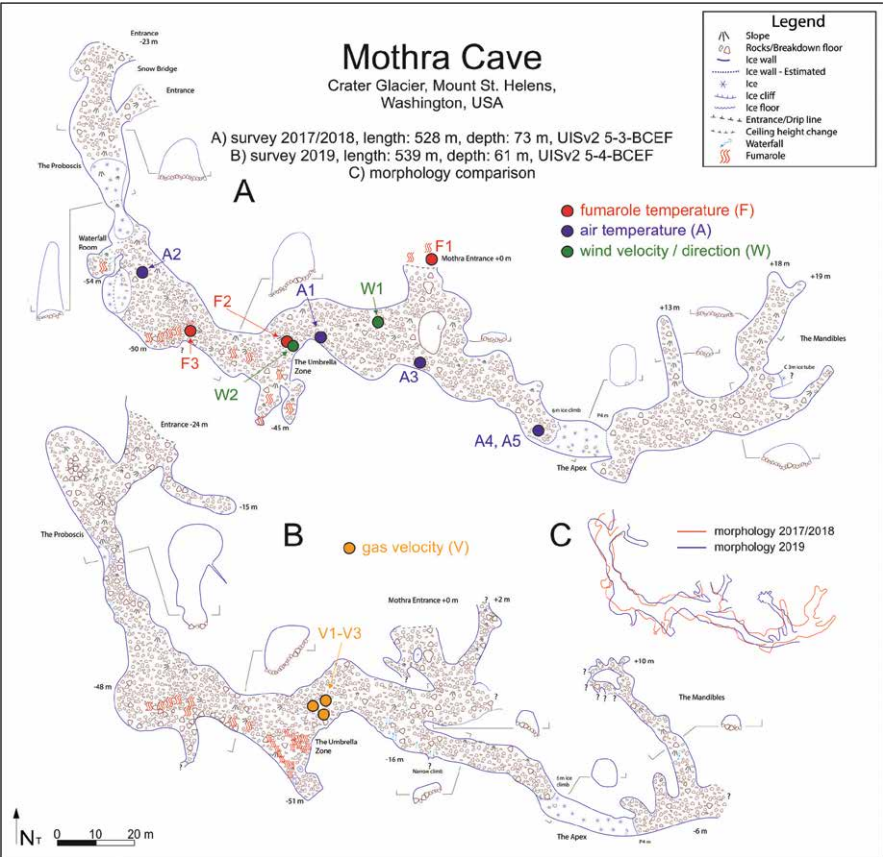


Figure 4. Map of Mothra Cave. A) Results of surveys in 2017 and 2018 and location of climatic instrumentation. Fumarole and air temperature measurements are illustrated in red and blue; wind velocity and direction measurements are shown in green. B) Results of surveys in 2019. C) Morphology changes between 2017–2019.

Post processing of survey data was conducted in COMPASS cave survey project management software. Data were corrected for annual magnetic declination. The software was used to generate statistics including length, depth, and volume (Table 1). Due to magnetic interference from volcanic rock it was expected that some survey measurements generated by DistoX2 could be erroneous. Error mitigation relied on using multiple georeferenced entrance stations and loop closure correction in the software. COMPASS makes this correction via the least square method (Schmidt and Schelleng, 1970). Final outputs included shapefiles for ArcGIS, 3D visualizations generated in CaveXO software, and the corrected line plots used in Adobe Illustrator to complete final cartographic plans of each cave.

Fumarole temperatures describe the temperature of steam or gas emitted from an opening in the ground. Four fumaroles on the crater floor of two caves were equipped with GeoPrecision M-Log5W-CABLE temperature sensors (accuracy: ± 0.1 °C at 0 °C), configured for a measurement interval of 5 minutes. These were monitored between 2017

and 2020. Supplementing the fumarole temperatures are short-term gas velocity data collected from June 22–24, 2019. Single fumarole openings were equipped with a plastic tube with a given diameter of 40 mm combined with a hot-wire anemometer (Testo 425; accuracy: ± 0.03 m/s) (Fig. 6L). The surrounding area was completely sealed to prevent gas escape. Gas velocity was measured every second at three different sites inside Mothra Cave and flux data were calculated afterwards. Discrete fumarole temperature measurements were also made with a thermocouple (TE Typ K; measurement range: -60 °C to $+1,400$ °C).

Cave air temperatures were recorded using the same instrumentation at a measurement interval of 5 minutes. Four sites inside Mothra Cave were monitored for air temperature between 2017 and 2020. Data sets from A4 and A5 represent the same site. As one of the sensors (A4) was not detectable during the expedition in 2018 and downloaded data indicated that the sensor froze, a second sensor (A5) was deployed. Freezing of sensors, and thus a probable shift of their original location, was observed at investigation sites A2 and A4, as indicated by constant temperatures of 0 °C. It is likely that sensors fell to the cave floor, where they were affected by freeze-thaw cycles. It was not possible to visually locate these sensors during freeze cycles, but wireless data download was successful.

An assessment of wind regimes inside the caves was performed for the first time using smoke tracers (Fig. 6J) to visualize major pathways and to locate appropriate sites for ultrasonic anemometers (USA-1, METEK; accuracy (max. dev.) wind speed / wind direction: 0.1 m/s or 2% / 2° at 5 m/s). Data were collected from June 17–18 and 15–18, 2018 (Fig. 6K). Vertical and horizontal wind velocities were measured at 10 Hz at a 1 second average. Simultaneously, air temperatures were recorded. Horizontal wind velocities are supplemented by information about wind direction.

As no climate station exists in the crater of Mount St. Helens, supplementary data on air temperatures and snow depths come from nearby climate stations operated by the U.S. Department of Agriculture, National Resource Conservation Service (<https://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home/>). Snow Telemetry (SNOTEL) sites are Sheep Canyon ($\sim 1,216$ m), Swift Creek ($\sim 1,353$ m), and June Lake ($\sim 1,048$ m), located on the western and southern flank of the volcano at radii of 3 to 5 km. The SNOTEL snow depths are a proxy for conditions in the crater of Mount St. Helens, although absolute values differ. These surrounding climate stations also serve to reveal the onset of snowfall and the end of snow accumulation.

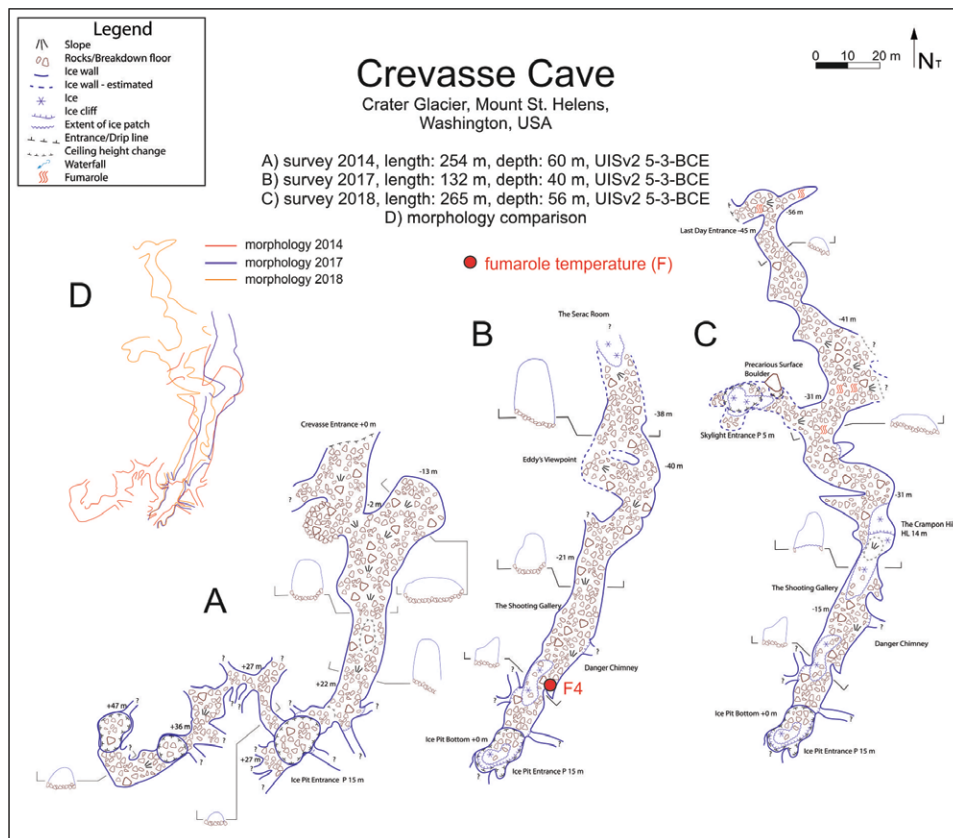


Figure 5. Map of Crevasse Cave. A) Results of survey in 2014. B) Results of survey in 2017 and location of climatic instrumentation. Fumarole temperature measurements are illustrated in red. C) Results of survey in 2018. D) Morphology changes between 2014 and 2019.

Data analysis was performed in OriginPro using the signal processing tool “smooth” after Savitzky and Golay (1964) and the fitting tool “linear fit”. A simplified illustration of data sets was created using options such as multiple y-axes, line and bar diagrams, windrose graphs, and reference lines. The final editing was done with CorelDRAW.

RESULTS

Cave Survey

Between 2014 and 2021 a total of 13 newly-formed caves with a combined length of more than 3.0 km were surveyed. The longest, Rodan Cave, comprised a surveyed length of 775 m, followed by Mothra Cave with ~ 593 m, and Ghidorah Cave with ~ 433 m. The smallest cave, the Cloaca, was just over 30 m long. Cave depths ranged from less than 10 m up to ~ 81 m. Table 1 summarizes the main survey results and statistical analyses generated using COMPASS software. See Supplemental Figures S1–S3 for additional cave survey results.

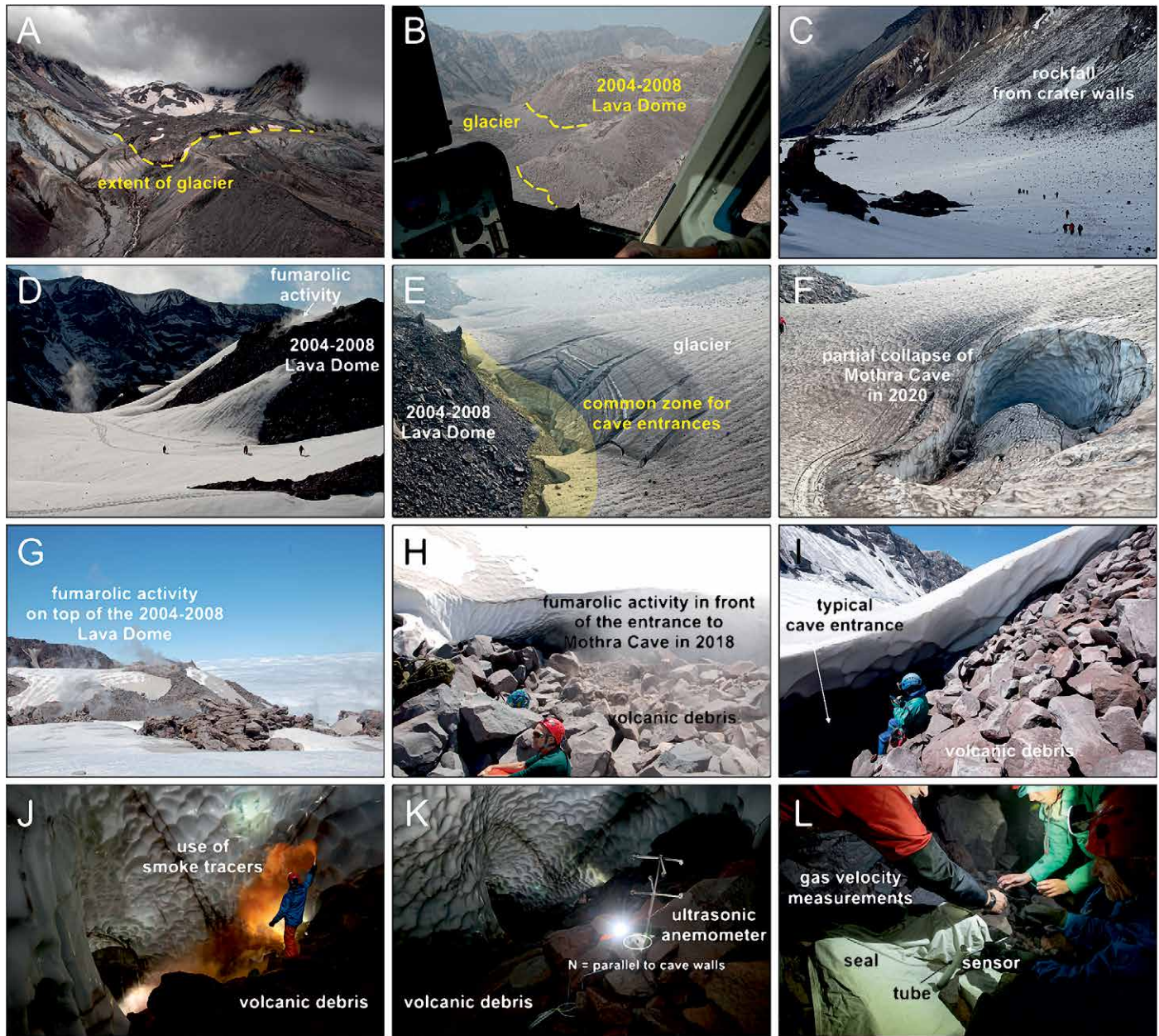


Figure 6. Mount St. Helens' crater and Crater Glacier. A) Southward view towards the crater from a helicopter. Yellow dashed line indicates the extent of Crater Glacier in 2019. B) Westward view inside the crater from the helicopter. Yellow dashed line indicates the area where the newly formed glacier (Crater Glacier) encircles the 2004–2008 lava dome. (2020). C) Rockfall in the crater which derives from the surrounding crater walls. D) 2004–2008 lava dome with fumarolic activity. E) Close-up view of where lava dome and glacier interact. Yellow area is where cave entrances form. F) Partial collapse of Mothra Cave in September 2020 and creation of a new chimney entrance. (2020). G) Fumarolic activity on the 2004–2008 lava dome. H) Entrance to Mothra Cave. Cave entrances and cave floors usually exist of volcanic debris. Fumarolic activity leads to the formation of cave systems and controls the location of entrances. I) Another typical and traversable cave entrance. (2019). J) Use of smoke traces inside Mothra Cave. K) Ultrasonic anemometers inside Mothra Cave measure wind velocity (horizontal and vertical) and indicate wind direction. The north arrow is orientated parallel to cave walls and indicates the nearest cave entrance. L) Gas velocity measurements inside Mothra Cave.

Cave systems on Mount St. Helens share many characteristics. Most have formed in proximity to the 2004–2008 lava dome with passages trending parallel to the dome perimeter. Most have developed near the lateral contact between ice and rock. Thus, they can be categorized as marginal caves. Cave passages do not extend towards the crater rim. Entrances usually occur along the interface of the ice and the lava dome with passages descending at angles of ± 30 – 40 degrees. Vertical entrances also exist as chimneys and through moulins or crevasses. Most caves feature more than one entrance. Entrance elevations ranged from $\sim 2,100$ m (Igloo) to $\sim 2,260$ m (Mothra). Other common characteristics include vertical walls and convex ceilings, prominent scalloping, and rock debris embedded in glacial walls and ceilings. Embedded rock debris varies in size from a few centimeters to a few meters. The cave floors are subglacial portions of the lava dome,

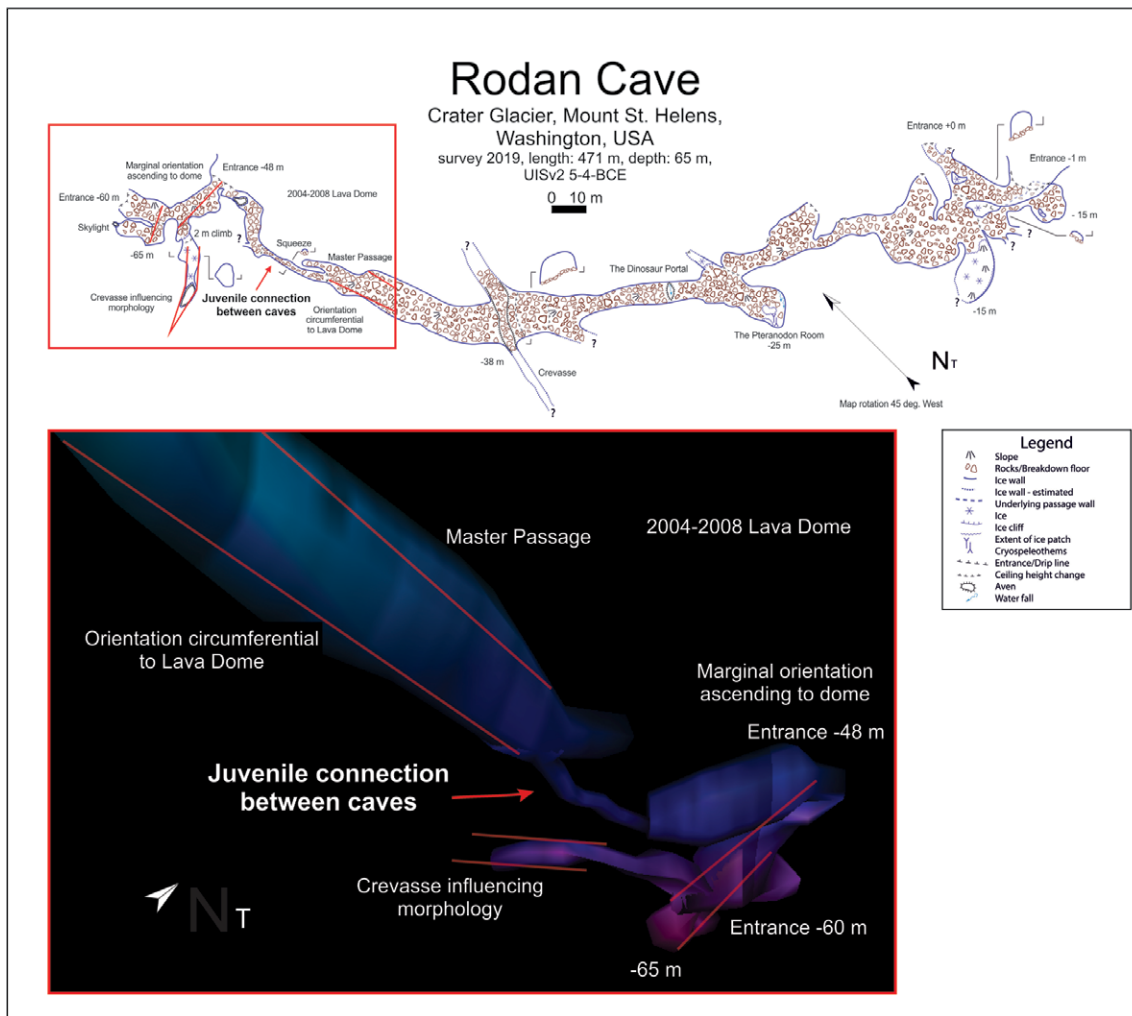


Figure 7. Map of Rodan Cave, survey 2019. Red boxes = west entrances and profile view; a laterally-orientated central passage connects a section with upward trending morphology. The west section of Rodan Cave is a juvenile cave system where formation of connecting cave passages began recently. Further expansion will likely occur.

ed of volcanic debris with a slope following the rock-ice interface. From 2017 to 2020 a closed depression at the former location of this entrance made further exploration impossible.

Crevasse Cave, formed beneath the east arm of Crater Glacier, was also discovered and surveyed in 2014. Resurveys in 2017 and 2018, and a brief exploration in 2019, revealed distinct morphology changes (Fig. 5). In 2014, the main chimney entrance and the southwest cave passage was explored to a dendritic series of chambers with three skylights which no longer existed in 2017. Other changes from 2014 to 2018 include expansion further north and a shift of the main passage to the west. In addition, a sloping, scalloped ice floor section had formed. Fumarole activity was not surveyed during initial explorations but is indicated in the 2018 map in the northern cave passage. In 2017, fumarole activity had been verified in the southern section.

Mothra Cave was discovered in 2017, with an initial survey in 2017–2018 and a resurvey in 2019 and 2021. Exceptional features include two large rooms (20 m × 20 m × 13 m; 14 m × 21 m × 16 m) observed in 2018 and an elliptical passage in ice 6 m above the volcanic debris floor and about 15 m in length. The resurvey indicated that the main passages remained but documented small changes along the east branch and south wall. Persistent fumarolic activity was observed in the southwest section of the cave and likely formed the two largest rooms. A detailed survey of subglacial fumarole locations within Mothra Cave was conducted and is indicated on Figure 4. Isolated fumarole activity was also present (see temperature sensors). In 2020, a brief exploration without any formal survey revealed distinct morphology changes in the form of a partial collapse of the southwestern cave passage, forming a new chimney (Fig. 6F).

The Igloo was discovered in 2014 and first surveyed in 2018. This cave is contained completely in firn and has a depth of 8 m. Although its dynamic passages appear to reform every season, a distinctive and central hemispherical chamber located around a fumarole vent seems to be persistent.

comprising volcanic debris, tephra, and occasional sediment. Melt-water runoff from the walls and ceilings was present, however this runoff did not result in bodies of standing water as the porous debris floor does not allow water to accumulate. Within each cave occasional cryopeleothems were observed, including ice stalactites and stalagmites. Figure 6 illustrates examples of the cave environment.

There are also differences among caves. The Godzilla Hole was the first cave discovered in 2014. It was accessible by single-rope techniques through an opening in the glacial surface 10 m long × 20 m wide. The floor consist-

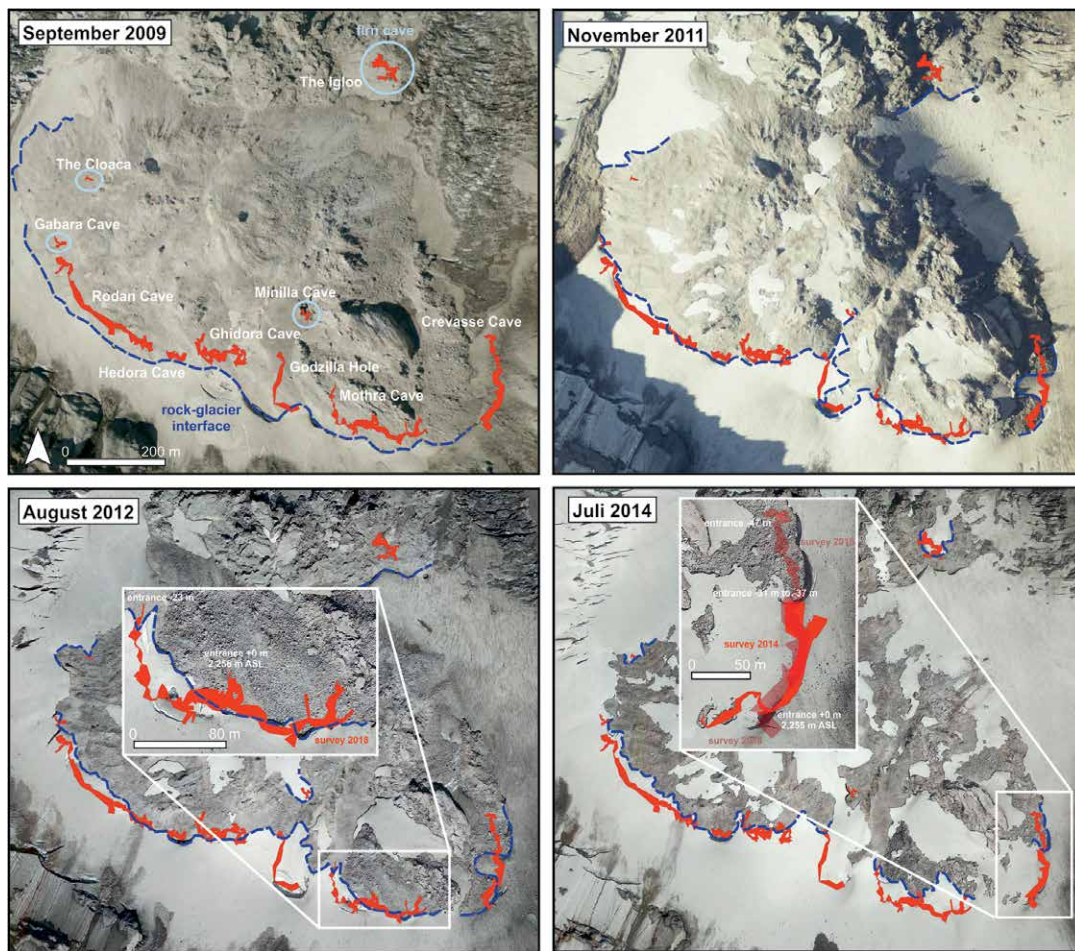


Figure 8. Glacial expansion from September 2009 to July 2014 compared to the latest known location of glaciovolcanic cave systems. Blue dashed line indicates the rock-glacier interface where relevant. Bright blue circles indicate firn caves. Detailed views of Mothra Cave in 2012 and Crevasse Cave in 2014 illustrate that passages surveyed in 2018 were bedrock in 2012 and 2014, respectively. Simplified calculations for both caves were made to estimate possible growth rates. ©Google Earth

Minilla, Ghidora, Hedorah, Rodan, Gabara Cave, and the Cloaca were discovered and surveyed in 2019. Minilla, Gabara, and the Cloaca formed in firn, similar to the Igloo. Hedorah Cave was found near a group of fumaroles, and featured five closely-spaced entrances orientated towards the fumarole field. Ghidora, the third largest cave in the crater, had a remarkable dendritic passage network, comparable to karstic caves. Rodan Cave is the longest and deepest of the caves. Its central passage is intersected by large crevasses and hemispherical rooms. In the western cave section the laterally orientated passage interconnects via a narrow tunnel to a zone with slope-orientated morphology (Fig. 7). Caves located and surveyed in 2021 include Dogora, Gigan, and a cave north

of Crevasse Cave with passage morphology trending towards a connection with Crevasse Cave, but too tight to confirm with human exploration.

Survey results from the past years illustrate to what extent cave systems must have grown and which ones could not have existed at earlier times (Fig. 8). Images from 2009 and 2011, along with current cave survey data, indicate that most caves could not exist prior to 2011 due to absence of ice.

Cave Climatology

Fumarole temperatures fluctuate and show sudden changes (Fig. 9). The highest temperatures were observed at site F1 (60.1 °C), followed by F3 (57.4 °C), F4 (57.1 °C), and F2 (46.6 °C). Minimum temperatures were −11.7 °C (F3), −10.0 °C (F1), 0.9 °C (F4), and 1.4 °C (F2). Data smoothing indicates that some fumaroles follow similar patterns as clearly shown by F1, F3, and F4. Only F2 does not reveal the same trend. Distinct seasonality is absent. Gas velocity measurements revealed average values from 0.3 m/s to 1.3 m/s. Calculated volume flows range from about 1 m³/h to 5.5 m³/h at fumarole (gas) temperatures of up to 33 °C (Fig. 10).

Maximum air temperatures inside Mothra Cave measured 10.7 °C at A1; minimum temperatures −9.2 °C at A2. Mean air temperatures at all sites varied between 0 °C and 2.3 °C. Data smoothing clearly illustrates similarity of all five temperature profiles. All sites are subjected to seasonal air temperature changes, with the highest temperatures in spring of each year (April–May), falling temperatures during the summer months, and absolute minima in winter (November–December) (Fig. 11A). Constant temperatures around the freezing point usually indicate that the sensor has fallen to the ground and been influenced by meltwater or ice, and do not represent air temperatures.

Cave air temperatures seem to be strongly correlated to snow accumulation (Fig. 11B) and fumarole activity. Monthly mean temperatures at three different locations inside Mothra Cave reveal increasing values with the onset of snow

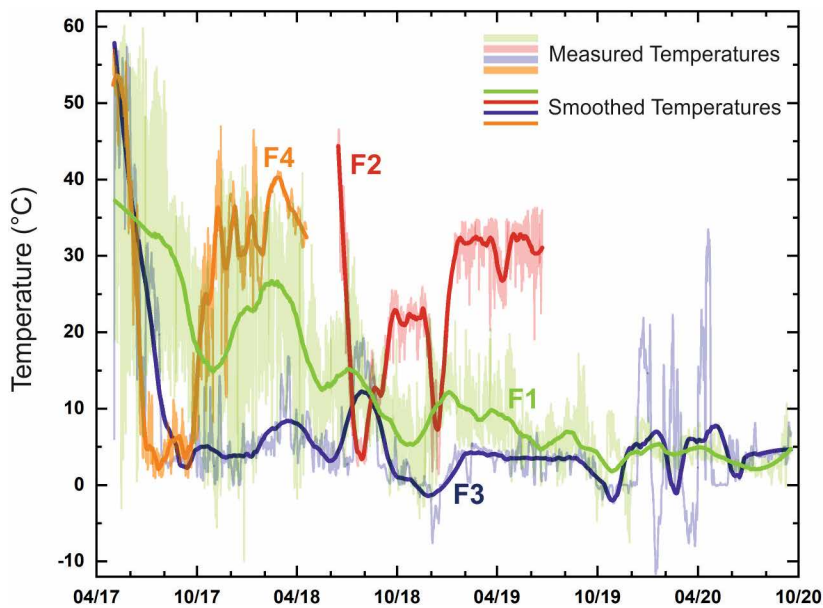


Figure 9. Fumarole temperatures (°C) at four different locations (F1–F4) inside Mothra and Crevasse Cave from April 2017 to September 2020; measurement interval 5 minutes. Transparent colors show measured temperatures. The data were smoothed for better visualization (non-transparent colors) by the method of Savitzky and Golay (1964). According to the number of measurements the Points of Window in OriginPro 2021 were set to 10 % of each individual data set.

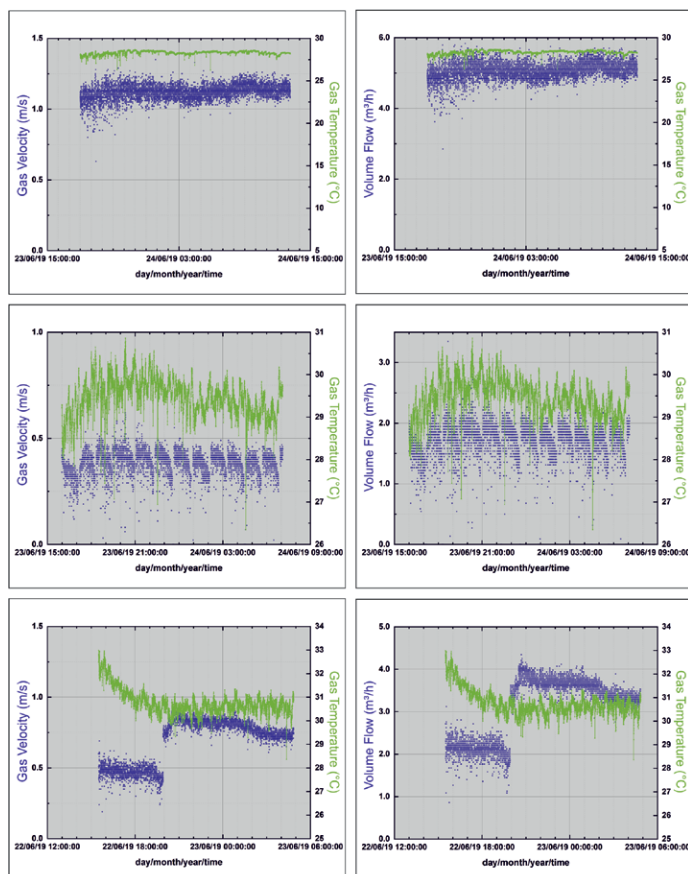


Figure 10. Gas velocity (m/s) and gas temperature measurements (°C) at three different locations (V1–V3) inside Mothra Cave from June 22–24, 2019. The term gas is used to describe the fumarolic output. Volume flow calculations (m³/h) were performed by using gas velocity values and the known diameter of a plastic tube.

accumulation. Because sensors at locations A4 and A5 were probably influenced by melt-water and internal morphology changes, only A1–A3 were chosen for further analysis. Data from these locations indicate that highest temperatures within the course of one year (June 2018–June 2019) were measured in June 2018 (A2, A3) and February 2019 (A1). Temperatures decreased from June 2018 to minima in December 2018. This period mirrors the time of missing or minor snow accumulation. Cave air temperatures and ambient air temperatures around Mount St. Helens both decrease from the middle of 2018 until November 2018 but, as soon as snow accumulation begins, cave air temperatures increase whereas outside air temperatures decrease (Fig. 11B). Correlation coefficients for snow depth and cave air temperatures approach 0.9 (Fig. 11C), whereas correlation coefficients for cave air temperatures and outside air temperatures approach –0.4 (Fig. 11D).

Smoke tracers demonstrated turbulent air flow inside the caves (Fig. 6J). This turbulence was observed during every expedition. Anemometer data verified these observations and revealed strongly varying air currents (Fig. 12). Air velocity of up to 10 m/s was observed. Velocities of 1–2 m/s or more appeared infrequently and mostly on a steep slope connecting two main cave levels. Air flow was recorded parallel to cave passages and either indicated inflow of outside air or outflow of cave air. Chimney effects were identified. Data from both investigation sites illustrate that cycles of inflow and outflow are not subject to a strong diurnal rhythm.

DISCUSSION

Mount St. Helens is not the only volcanic edifice where the interaction of glaciers and volcanic activity forms sub-glacial cave systems, but it is unique in many ways. First, the crater is characterized by a recently formed glacier which is still advancing. Second, cave systems are comparatively young (<10 years) and rapidly evolving. Glacio-volcanic caves are dynamic systems, sensitive to climate fluctuations and changes in heat flux. However, we are not aware of any other glaciovolcanic cave system that is more dynamic at this time. On Mount Rainier, host to the largest known glaciovolcanic cave system worldwide, the caves are largely static, with apparent dynamic equilibrium having been achieved throughout the majority of passages (Florea et al., 2021).

During studies over the last eight years, a goal was to understand the evolution, formation, and dynamic nature of cave systems in the crater of Mount St. Helens. A simplified schematic (Fig. 13) illustrates the processes responsible for cave evolution and expansion. Fumaroles are the main driving force. Further evolution strongly de-

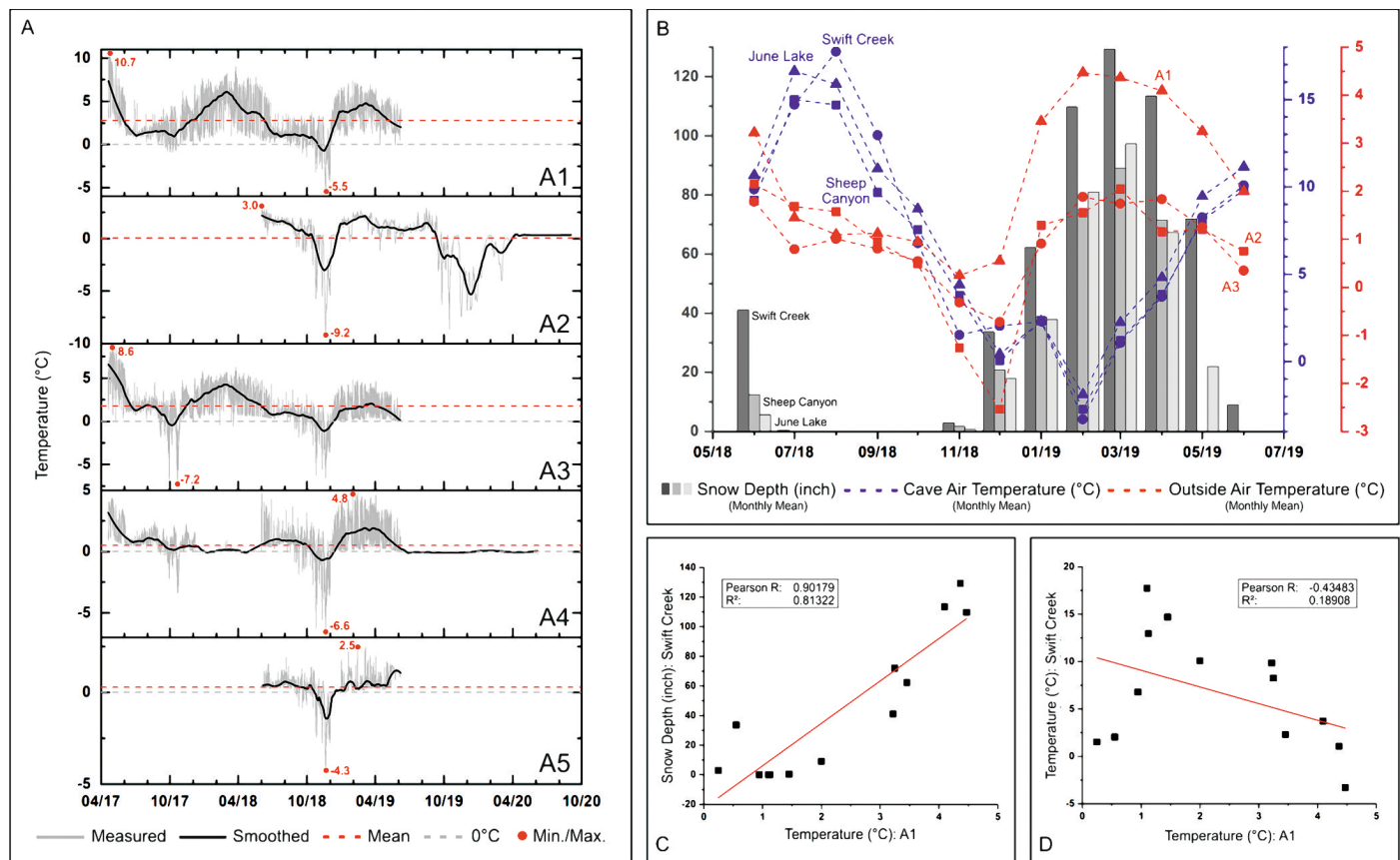


Figure 11. Comparison of cave air temperatures (°C), outside air temperatures (°C), and snow depth (inches). A) Cave air temperatures from four different locations (A1–A5) inside Mothra Cave from April 2017 to September 2020. Grey lines reveal the measured temperature; measurement interval 5 minutes. The data were smoothed for better visualization (black line) by the method of Savitzky and Golay (1964). The Points of Window in OriginPro 2021 were set to 10% of each individual data set. Red dots: maximum and minimum temperatures; red dashed line: mean; grey dashed line: 0 °C. B) Comparison between snow depths and air temperatures from three different SNOTEL sites (Sheep Canyon, Swift Creek, June Lake) and cave air temperatures at A1, A2, and A3 from Mothra Cave; May 2018 to July 2019. Data represent monthly means. Red lines: cave air temperatures; blue lines: outside air temperatures; grey bars: snow depth. C) Results of linear correlation between snow depth and cave air temperature. Snow depth at Swift Creek and cave air temperature at A1 were chosen as a representative example. D) Results of linear correlation between air temperature at Swift Creek and cave air temperature at location A1.

depends on snow and ice accumulation and the exchange of cave air and outside air. Outside air temperatures also affect the cave microclimate, but on a comparatively small scale (Fig. 11D). Glacier movement probably has an effect on caves located towards the east and west arm of the glacier, but contributes less to changes in the southern area of the crater. We assume that there is a linkage between glacier movement and distinct morphology changes (shift to the west) of Crevasse Cave from 2014 to 2018 (Fig. 5).

Cave formation can begin subsequent to snow and ice accumulation. Depending on the rate of snow accumulation in comparison to available heat flux, there are different avenues of formation. If there is enough heat flux to entirely melt accumulating snow, vertical chimneys breaching the surface form, rather than subglacial and dendritic passages (Figs. 14A–C). If the heat flux is moderate, subglacial cave systems can form and evolve (Figs. 14D–E). Unnsteinsson et al. (2021) similarly distinguished between glaciovolcanic caves and chimneys. Evolving passages are subject to seasonal meteorological changes, with snowfall as an influential parameter. Expansion occurs laterally and vertically towards higher elevations of the dome. Passages are subject to ceiling collapses induced by snow overload, ablation of the above glacial surface, or increasing heat output. Collapses can also result from sealed entrances and resultant rising cave air temperatures (Fig. 14F), as happened to the western section of Mothra Cave after winter 2019–2020, when the glacier surface was breached (Fig. 6F). Further understanding of the mechanisms of glaciovolcanic cave formation need examination. Heat flux calculations to assess cave systems were not possible in the scope of this work but would be a noteworthy tool for future assessment. Ice calorimetry may also be a useful approach in the future, once considerable data on the dynamic cave temperatures, air/gas compositions, and ventilation effects are known. Further measurements of the factors identified here as essential for cave formation and their interrelationships need to be considered.

Fumarole temperatures inside the caves did not exceed 60 °C. Thus, all of the fumaroles can be classified as low temperature. In the literature (e.g., Balić-Žunić et al., 2016; Coradossi, 1980) thresholds of ≤100–200 °C for low

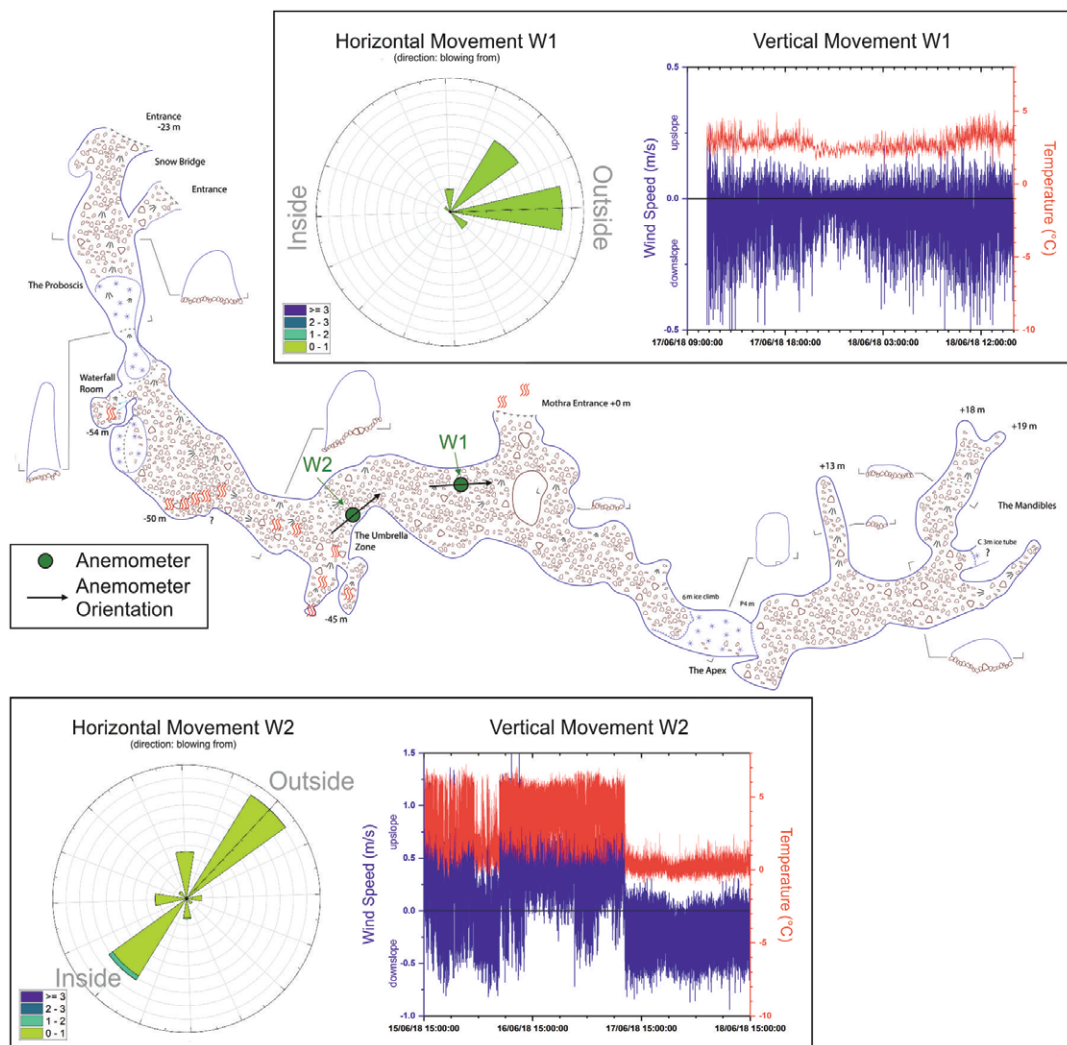


Figure 12. Ultrasonic anemometer data from two sites (W1 and W2) inside Mothra Cave. Horizontal movement (m/s) is illustrated by windrose graphs (direction: blowing from). Vertical movement (m/s) is expressed as upslope (positive) and downslope (negative) movement. Measurement interval 1 second (average; 10 Hz sampling rate). Measurements at location W1 were performed from June 17–18, 2018 and measurements at location W2 were performed from June 15–18, 2018.

Similar temperatures were confirmed during recent studies in 2021 (92 °C). We assume that cave expansion towards higher elevations on the dome may be limited by higher fumarole temperatures. Future studies should include the identification of fracture zones on the dome to also explain discrete high fumarole temperatures at lower elevations.

Fumarole temperatures showed great variability and a wide range. Data smoothing (Fig. 9) shows good correlation between F1 and F3 in Mothra Cave and F4 in Crevasse Cave. The outlier is F2, located in the Umbrella Zone of Mothra Cave. Big variances are most likely linked to rain and snow melt, as is the case for fumarole areas outside the caves higher on the lava dome (P. Kelly, personal communication, 2021). Observation of the Umbrella Zone showed F2 to be greatly influenced by nearby meltwater runoff. Thus, is it not surprising that this fumarole does not present characteristics similar to F1, F3, and F4. Long-term fumarole-temperature data also exist from Mount Rainier (see Supplemental Fig. S4) where fumarole temperatures did not exceed about 60 °C and correlations in pattern trends were also present. However, strong fluctuations are apparently absent at Mount Rainier (isolated outliers). We hypothesize that the crater floor has major influence. Whereas the summit of Mount Rainier is characterized by various clays that result from strong hydrothermal alteration (Zimbelman, 1996), we observed permeable debris floors within Mount St. Helens caves and water that drains into the hydrothermal system. The way the fumaroles behave and the temperatures they show over the year is largely influenced by water and the crater floor. Future analyses need to focus on the volcano's hydrogeology. Geochemical data from fumaroles are necessary to determine the origin of gas (magmatic or recycled water) and to compare these data with hotter fumaroles higher on the dome.

temperature fumaroles can be found, although another common classification is based on the type of minerals deposited. Fumaroles in the caves around the 2004–2008 lava dome do reveal that the dome is still hot at depth. Subglacial fumarole temperatures are lower compared to subaerial counterparts on higher elevations of the dome as confirmed by a permanent monitoring station (<https://www.usgs.gov/volcanoes/mount-st-helens>) and recent measurements in June 2021, where maximum fumarole temperatures of 94 °C on the dome summit were recorded. Monitoring data from 2014–2015 showed temperatures of up to 380 °C (Crankshaw et al., 2018), indicating that the dome is cooling. Although summit fumaroles are usually hotter, we also located a subaerial fumarole north of Hedorah Cave of nearly 90 °C during the expedition in 2019.

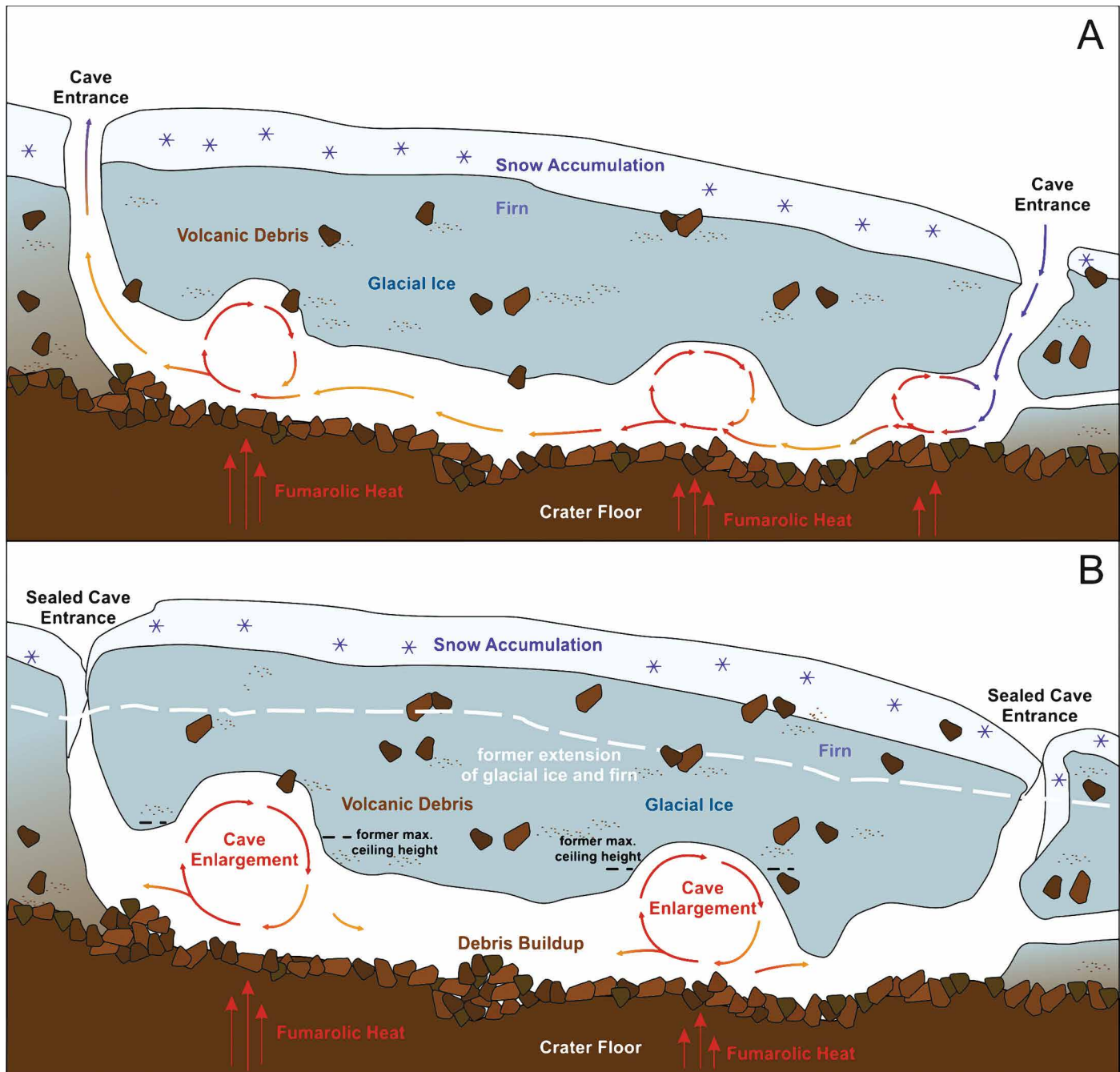


Figure 13. Transformation of cave systems over time. A) Early stage of development. Fumarolic heat from the recent lava dome interacts with the glacier and promotes formation of cave systems. Hemispherical rooms develop where fumarolic heat is concentrated. Ventilation effects occur as colder ambient air flows in and warmer cave air escapes. B) Further evolution of a cave system. Sealed cave entrances inhibit the exchange of ambient air and cave air. Cave enlargement and debris buildup take place. Continued snow accumulation leads to glacier growth above the caves. Fumarolic activity often undergoes minor changes.

Ventilation effects exist when cave entrances are not sealed with snow. Complex cave morphologies with more than one cave opening cause chimney effects and promote invasion of cold air. Use of smoke tracers inside Mothra Cave (Fig. 6J) verified these effects. Anemometer data (Fig. 12) show that there is a permanent alternation/shift from inflow to outflow. Similar observations were made on Mount Hood (Pflitsch et al., 2017) and Mount Rainier (Florea et al., 2021). Recent studies by Florea et al. (2021) also illustrated the influence of sealed entrances on cave air temperatures, indicating that it may be a common process in glaciovolcanic caves. Similar reports are known from Mount Hood (A. Pflitsch, personal communication, 2020). Velocities in the Mount St. Helens caves are moderate and comparable to those observed in the summit caves on Mount Rainier and in Hot Imagination Cave on Mount Hood. However, higher velocities are also possible (e.g., Pure Imagination Cave, Mount Hood: >6 m/s, June 23–25, 2015).

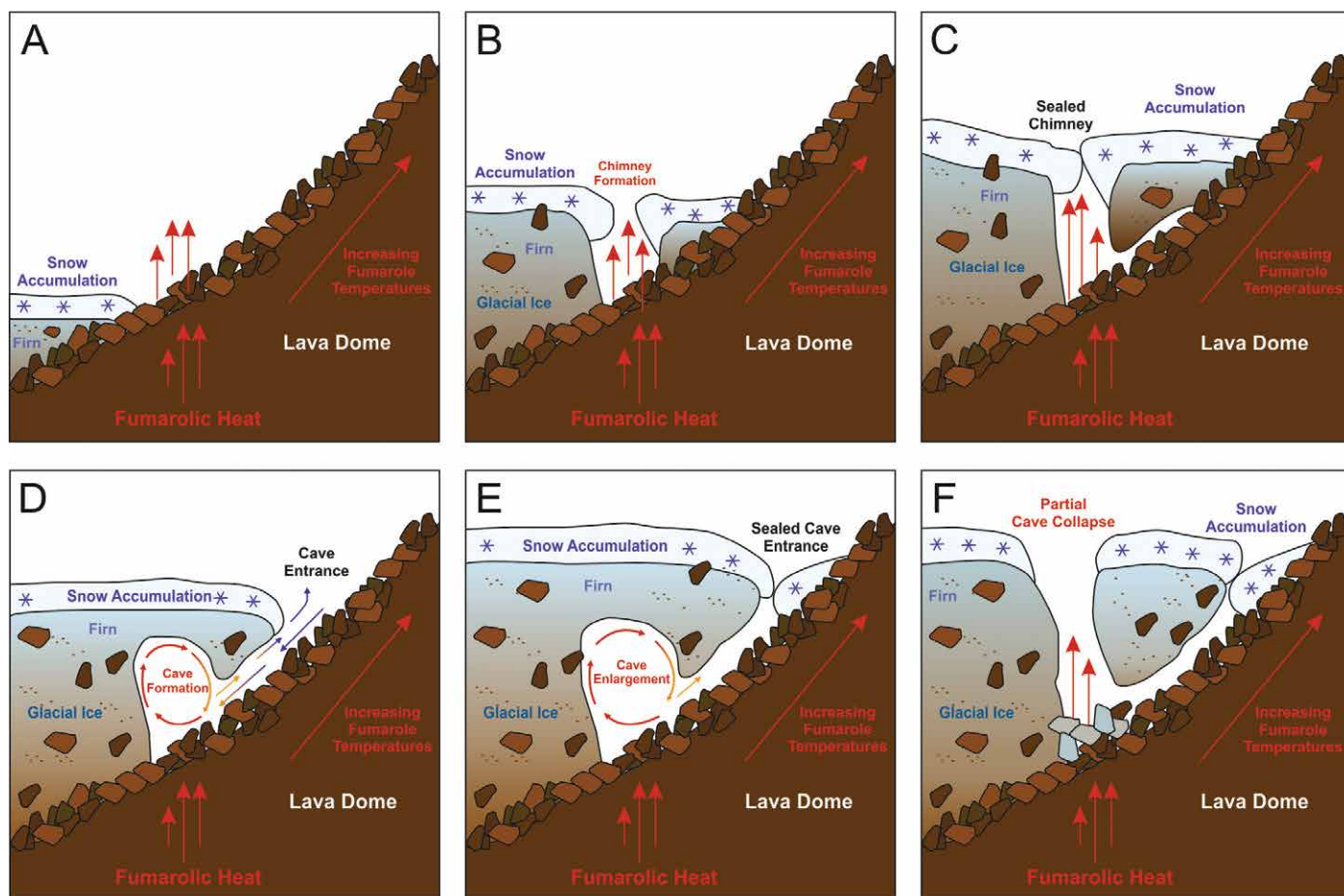


Figure 14. Transformation of cave systems over time viewed in profile. Caves are characterized by steep slopes circumnavigating the lava dome. Fumarole temperatures increase with elevation on the 2004–2008 lava dome. Glacial ice expands towards the lava dome. A) Glacial expansion begins encroaching on fumarolic areas, but is still limited to lower elevations along the lava dome and does not yet affect fumarolic activity. B) Heat output is too high to allow snow accumulation directly above fumarolic activity and leads to chimney formation. C) Where chimneys have formed, snow overload may eventually cause chimneys to seal off; then, subglacial passage volume increases and passages expand along the rock-ice interface. D) Subglacial dome shaped passages and entrance passages form along the rock-ice margin. There is interaction between outside air and cave air. New subglacial fumarolic output may cause renewed cave formation at this stage. E) Cave enlargement continues laterally (not shown in profile view) and vertically along the lava dome, with further snow accumulation and seasonal cave entrance blockages in winter. F) Snow overload, increasing heat output, or a combination thereof may lead to partial cave collapse (though this is rather uncommon). Usually, the main passages remain comparatively stable and pass through several cycles of D and E.

Gas output (Fig. 10) is much lower compared to Mount Rainier (Stenner et al., 2021). Although the Mount Rainier fumarole only presents one example of more than 100 fumaroles found in summit caves, no fumarole with a comparable flux was found in the Mount St. Helens caves. Differences in gas output and composition were also obvious during recent expeditions to both volcanoes: persistent risks in the summit of Mount Rainier due to CO_2 -traps, or O_2 deficiencies often complicated research (Stenner et al., 2021). Comparable situations were not observed on Mount St. Helens. The absence of hazardous atmospheres on Mount St. Helens facilitates fieldwork to a great extent. Other advantages include the comparatively low elevation of the crater, extensive monitoring efforts by the USGS, and accessibility (e.g., in contrast to Antarctica and Kamchatka).

Cave systems on Mount St. Helens are distributed in a semicircular pattern around the 2004–2008 lava dome. In future years we expect that (i) cave systems will continue to expand vertically and laterally, (ii) the rock-ice interface will move towards higher elevations on the dome, and (iii) individual caves may merge over time and form longer central passage systems around the southern part of the dome. Resurveys have already shown growth of individual caves. Moreover, comparison of available satellite images from 2012 and 2014 with the current location of cave systems indicates a growth during the last few years and also illustrates that some caves could not have existed at earlier times due to lack of snow and ice. As most parts of Ghidorah Cave did not exist in 2012, we can estimate that the rock-ice interface moved upward ~30 m by 2019. The rock-ice interface in August 2012 and July 2014 were compared to survey results for Mothra and Crevasse Cave in order to estimate the growth of passage length and volume (Fig. 8). For

Mothra Cave an estimated increase of ~240 % in length and 530 % in volume was calculated from 2012 to 2018; for Crevasse Cave an increase of ~100 % in length and ~250 % in volume were calculated for the north extension from 2014 to 2018. The depth of individual caves can be a proxy for glacier growth. Cave mergers and formation of a longer master passage is suggested by the western part of Rodan Cave (Fig. 7), where a connection formed recently. Further expansion of Rodan will probably connect to Ghidorah and Hedorah Cave in the east and Gabara Cave in the west. A similar situation of circular cave morphology with a central passage is known from the summit East Crater of Mount Rainier (Florea et al., 2021), albeit with orientation of entrance passages towards the crater rim.

CONCLUSIONS AND FUTURE WORK

The glaciovolcanic cave systems of Mount St. Helens exhibit rapid growth within the last decade. We were able to observe the onset of cave formation and subsequent evolution. We expect that individual caves will expand in the near future and may interconnect, forming a semicircular passage around the 2004–2008 lava dome. This circular morphology exists on nearby Mount Rainier and is supported by our observations of dynamic genesis of caves in the crater of Mount St. Helens. Vertical passage extension towards higher elevations along the dome is expected but may also be limited by increasing fumarole temperatures (see Supplemental Fig. S4 for fumarole temperature data from Mount Rainier). It is not surprising that fumarolic activity turned out to be the main driving force of cave evolution and transformation. However, seasonal meteorological patterns also emerged to be a major factor, particularly snow accumulation. Variations of cave air temperatures are related to seasonally sealed entrances, and the resulting absence of ventilation.

From 2017 to 2020 we performed long-term monitoring of fumarole temperatures inside glaciovolcanic caves, supported by temporary gas velocity measurements and volume flow calculations. Similar to observations on top of the lava dome, cave fumaroles revealed a high variability that appears to be closely related to precipitation. Subglacial gas emissions were observed to be quite weak compared to fumaroles inside the Rainier caves and also much less than on upper parts of the lava dome.

This paper summarizes the results of eight years of exploration of an expanding cave system and illustrates the factors involved in cave formation. Work inside the caves was often challenging, and the continuous, ongoing evolution of the system both hinders and necessitates further analyses. However, pathways towards future studies were discussed in this paper and may lead to a detailed understanding of glaciovolcanic caves.

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