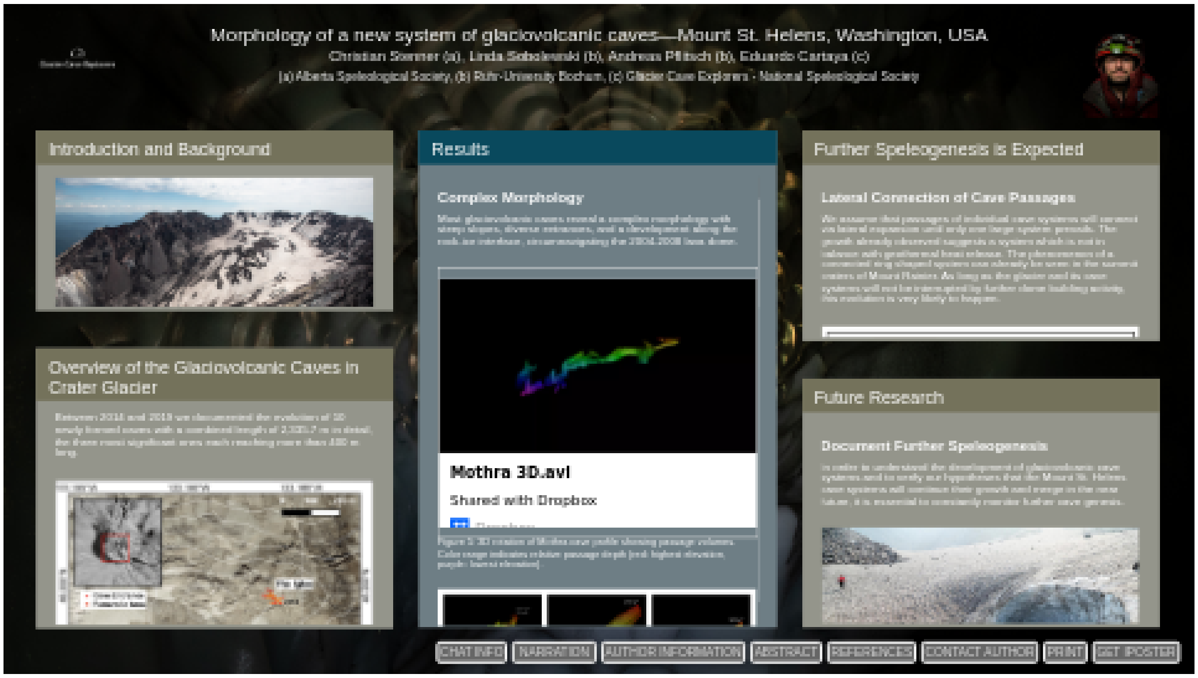
Morphology of a new system of glaciovolcanic caves—Mount St. Helens, Washington, USA



Christian Stenner (a), Linda Sobolewski (b), Andreas Pflitsch (b), Eduardo Cartaya (c)

(a) Alberta Speleological Society, (b) Ruhr-University Bochum, (c) Glacier Cave Explorers - National Speleological Society

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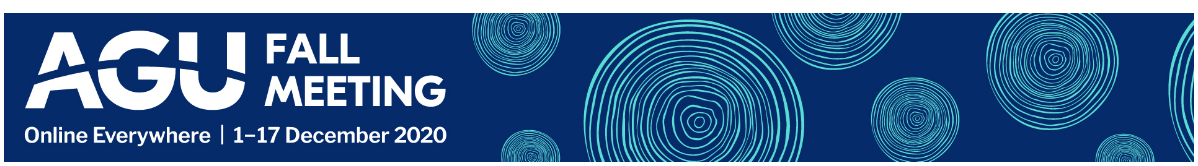

INTRODUCTION AND BACKGROUND

Figure 1: Mount St. Helens' Crater Glacier; viewing direction: south-east. The volcano hosts one of the last expanding glaciers in the Cascade Volcanic Arc, accompanied by a new and extensive system of glaciovolcanic caves which has developed around the 2004-2008 Lava Dome. Image: Eric Guth, 2018.

Definition of Glaciovolcanic Caves

Glacier caves are characterized as caves which exist purely in glacier ice, therefore bound to the appearance of glaciers or ice plugs. They form due to several mechanisms such as meltwater runoff, air convection, sublimation, glacier movement, venturi effects, or a combination thereof (1).

A rarely studied glaciovolcanic phenomenon similar to glacier cave systems are **glaciovolcanic caves** which form proximal to volcanic edifices under the influence of geothermal heat. Based on this, their distribution area is very limited and only include glaciated regions which are characterized through persistent volcanic activity. These caves provide the chance to better understand the interaction of glaciers and active volcanoes. Furthermore, speleogenesis of glaciovolcanic caves may be useful indicators of subnivean volcanic activity and volcanic unrest.

We studied the newly formed cave systems around the 2004-2008 Lava Dome in the crater of Mount St. Helens and found that the cave systems are highly dynamic, trending to expand in the near future, with fumarolic activity as the driving force.

Glacier Cave Explorers

Fieldwork for this project began in 2014 after the initial aerial observation of a new glaciovolcanic chimney in the Crater Glacier in 2012. This chimney was descended and named *The Godzilla Hole*. This work preceeded the remaining field studies, which integrate cave morphology studies with climatology, geochemistry and astrobiology research, as aspects of each have complex interrelated associations. Glacier Cave Explorers is part of the Oregon High Desert Grotto (OHDG), a non-profit chapter of the National Speleological Society (NSS).

Figure 2: The first descent into the chimney entrance of the Godzilla Hole, 2014. The cave system was found to be comprised of a sloping shaft which continued to a depth of 38 m underneath the glacier, where the void space then continued upwards along the rock/ice margin to another entrance at the interface of the 2004-2008 lava dome and glacier. Image: Brent McGregor, 2014.

Figure 3: Fieldwork in the crater of Mount St. Helens and team members in summer 2018. Image: Eric Guth, 2018.

OVERVIEW OF THE GLACIOVOLCANIC CAVES IN CRATER GLACIER

Between 2014 and 2019 we documented the evolution of 10 newly formed caves with a combined length of 2,335.7 m in detail, the three most significant ones each reaching more than 400 m long.

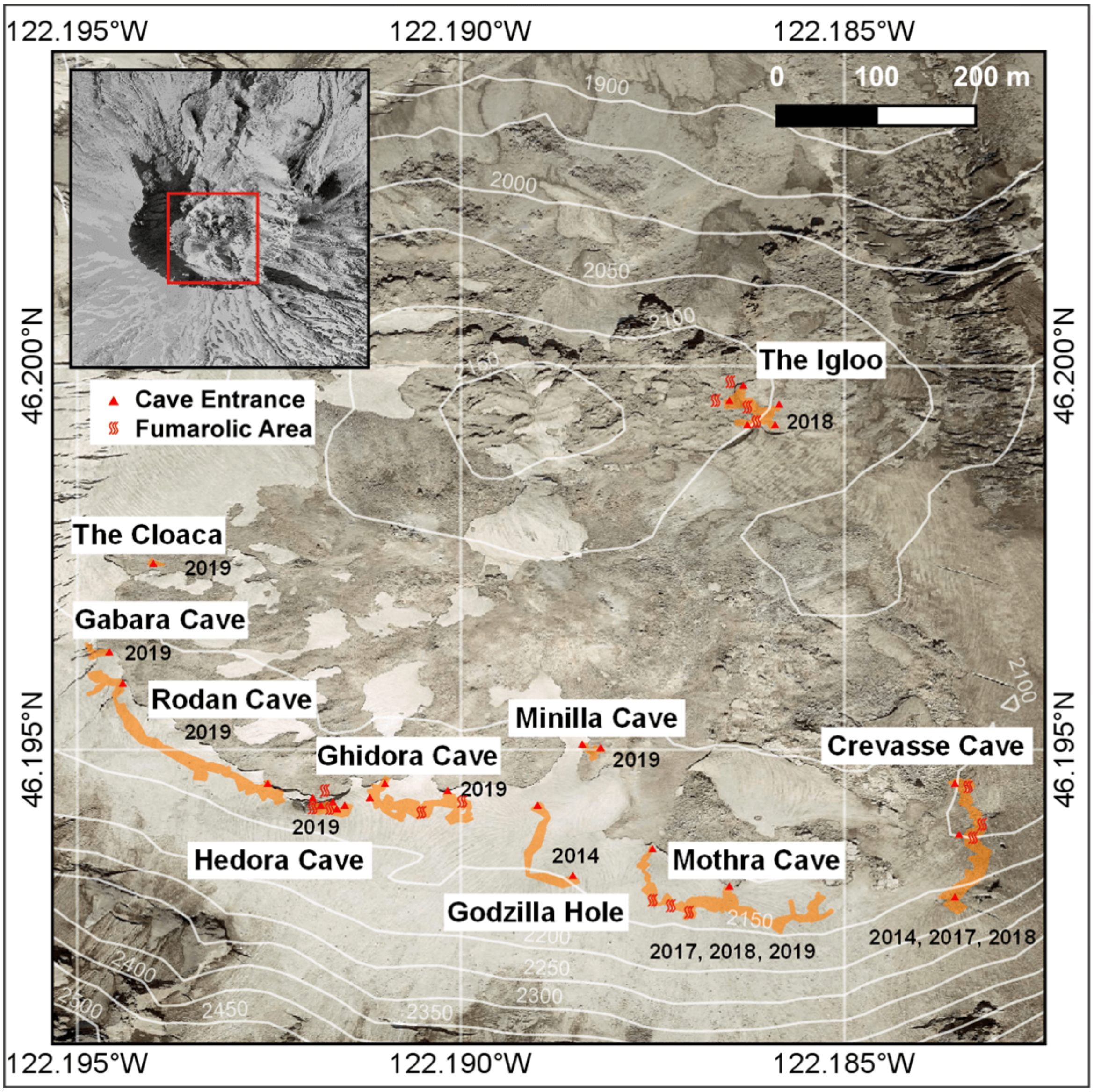

Figure 4: Location of glaciovolcanic cave systems around the 2004-2008 Lava Dome in the crater of Mount St. Helens with main entrances. Black numbers indicate the year of survey. Locations of concentrated fumarolic activity are indicated when clearly identified for individual cave systems. Image taken in 2018, © Google Earth. The inset illustrates the dimension of the crater. Image: High Resolution Orthoimagery 60 (2006) from USGS Earth Explorer (2).

Table 1: Summary of caves and cave statistics showing the results from surveys done between 2014 and 2019. Cave statistics were generated with COMPASS (2).

Cave	Included Length (m)	Horizontal Length (m)	Cave Depth (m)	Cave Volume (m³)
Crevasse Cave	275.7	261.8	56.4	27 307.4
Gabara	62.4	55.9	18.5	727.5
Ghidora	433.9	394.0	29.3	21 025.0
Godzilla Hole	176.4	163.3	41.3	10 662.2
Hedorah	98.6	87.4	13.4	6 542.8
Minilla	54.0	50.3	8.4	614.2
Mothra	539.3	502.8	60.7	40 903.5
Rodan	470.6	446.7	65.2	33 961.2
The Cloaca	33.5	25.2	10.3	285.9
The Igloo	191.3	187.2	7.7	4 323.4
Total	**2 335.7**	**2 174.6**	-	**146 353.1**

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.

Horizontal Length: This is the included horizontal length of all the surveys processed. Horizontal length is the length of the cave when it is flattened into a horizontal plane. Horizontal length includes no vertical component.

Cave Characteristics

- passages trend parallel to the lava dome periphery
- development near the lateral contact between ice and rock, circumnavigating the 2004-2008 lava dome
- hemispherical rooms due to fumarolic activity
- tephra & debris layers present throughout cave interiors from recent eruptive history and crater wall debris

RESULTS

Complex Morphology

Most glaciovolcanic caves reveal a complex morphology with steep slopes, diverse entrances, and a development along the rock-ice interface, circumnavigating the 2004-2008 lava dome.

Figure 5: 3D rotation of Mothra cave profile showing passage volumes. Color range indicates relative passage depth (red: highest elevation, purple: lowest elevation).

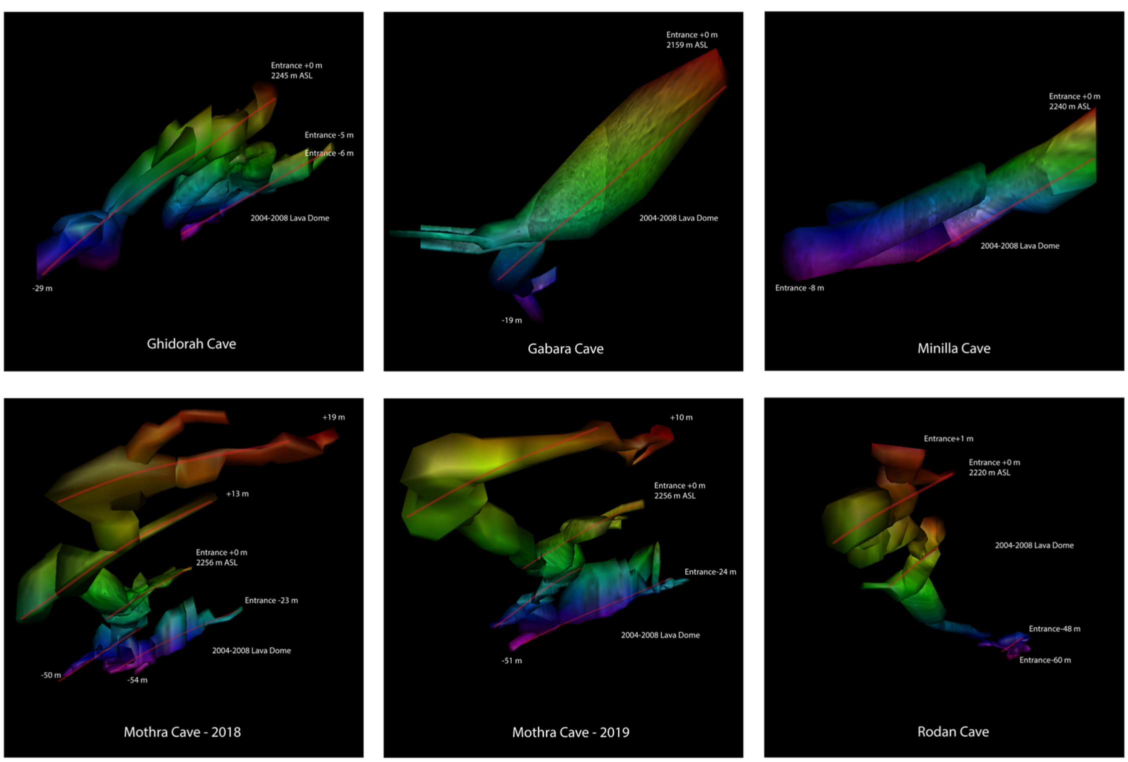

Figure 6: Profile views of selected Mount St. Helens caves. Profiles are rotated so that entrances along the 2004-2008 lava dome are to the right of the images. These caves show the prevailing complex morphology but also a pattern of higher elevation entrances along the rock-ice interface against the dome. Color range indicates relative passage depth (red: highest elevation,

purple: lowest elevation) (2).

Extremely Dynamic

Cave systems are extremely dynamic. Structures, dimensions, and certain characteristics can change annually. One of the caves has become inaccessible whereas others have shown static and dynamic zonation in passage morphology. Major passages have remained static while others exhibit varying amounts of growth. Overall, the cave passages trend towards growth based on repeated measurements.

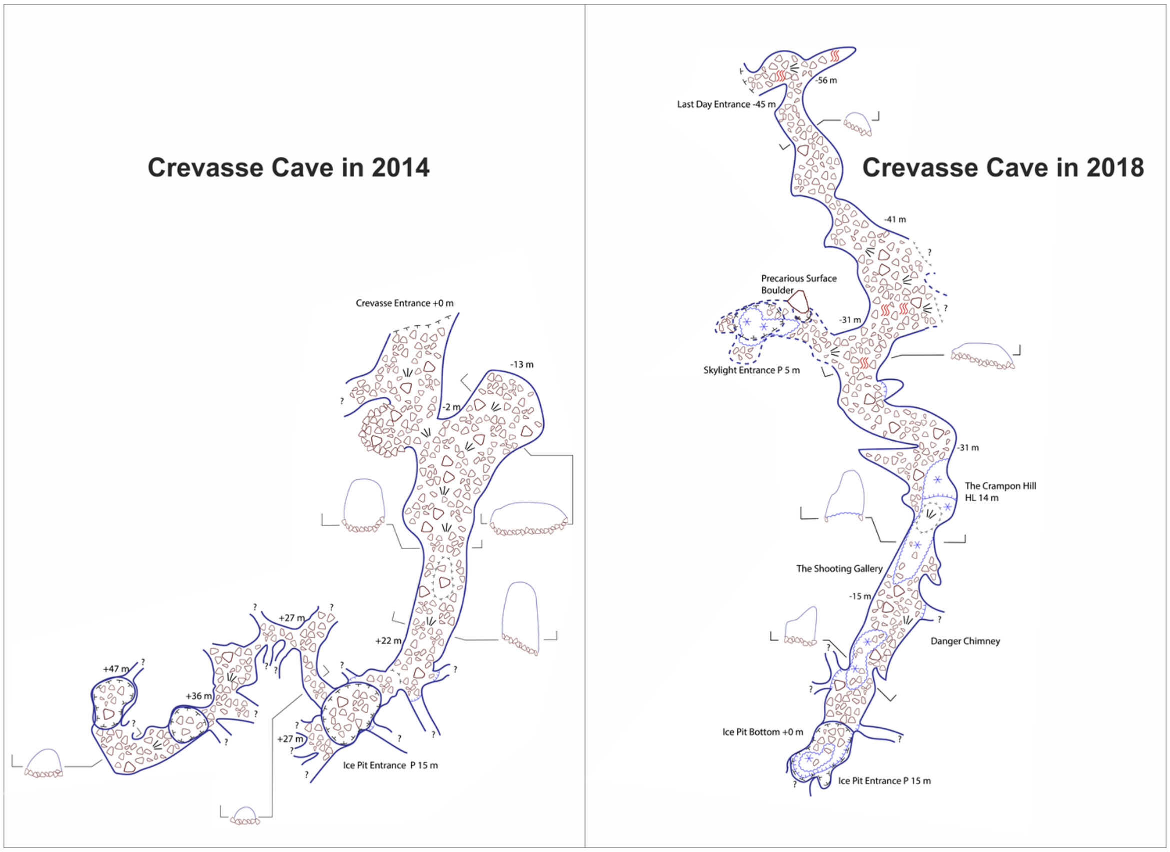

Figure 7: Map of Crevasse Cave in 2014 and 2018. Morphology changes and the growth of the system are clearly visible. Surveyed by: Glacier Cave Explorers, Oregon High Desert Grotto, National Speleological Society (2).

Trending to Expand

With the use of historical imagery of the crater to identify the previous dimension of the crater and the location of the rock-ice-interface, it was possible to estimate growth rates and the evolution of certain caves over the years prior to tachometric surveys. Two examples, Mothra Cave and Crevasse Cave, revealed an immense growth during the last few years.

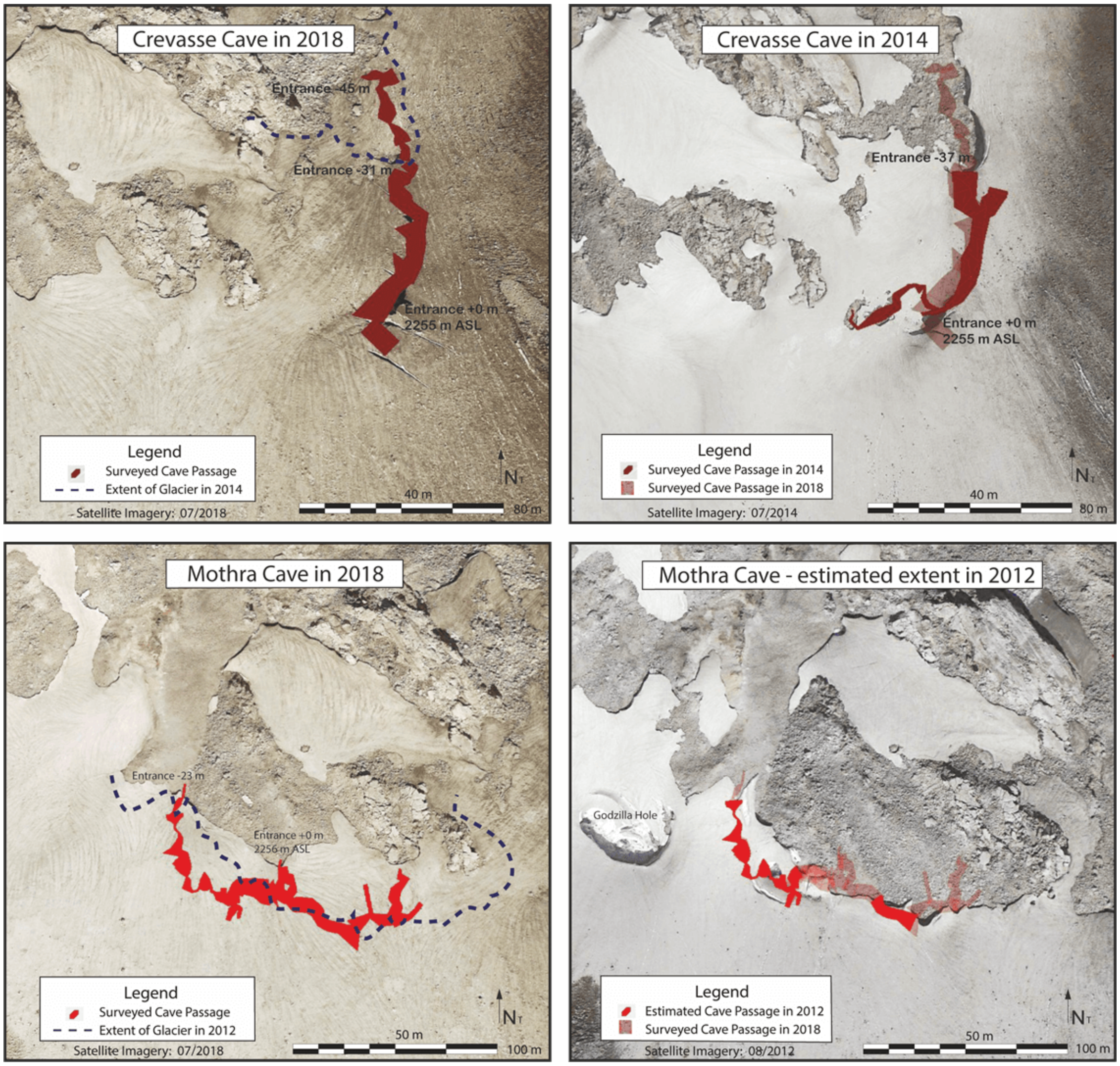

Figure 8: Location and extension of Crevasse Cave in 2018 compared to cave passages surveyed in 2014 (top). Comparison of Mothra Cave as of 2018 and projection of the cave passages onto 2012 imagery indicating the movement of the rock-ice interface to higher elevations along the 2004-2008 lava dome and the increase in cave passages that would have formed since 2012 (bottom). Both, Crevasse Cave and Mothra Cave, demonstrate the rapid rate of cave genesis. The approximate extension of Crater Glacier in 2014 for Crevasse Cave and 2012 for Mothra Cave is illustrated onto 2018 imagery. Satellite imagery originate from Google Earth. © Google Earth (2).

FURTHER SPELEOGENESIS IS EXPECTED

Lateral Connection of Cave Passages

We assume that passages of individual cave systems will connect via lateral expansion until only one large system prevails. The growth already observed suggests a system which is not in balance with geothermal heat release. The phenomenon of a connected ring shaped system can already be seen in the summit craters of Mount Rainier. As long as the glacier and its cave systems will not be interrupted by further dome building activity, this evolution is very likely to happen.

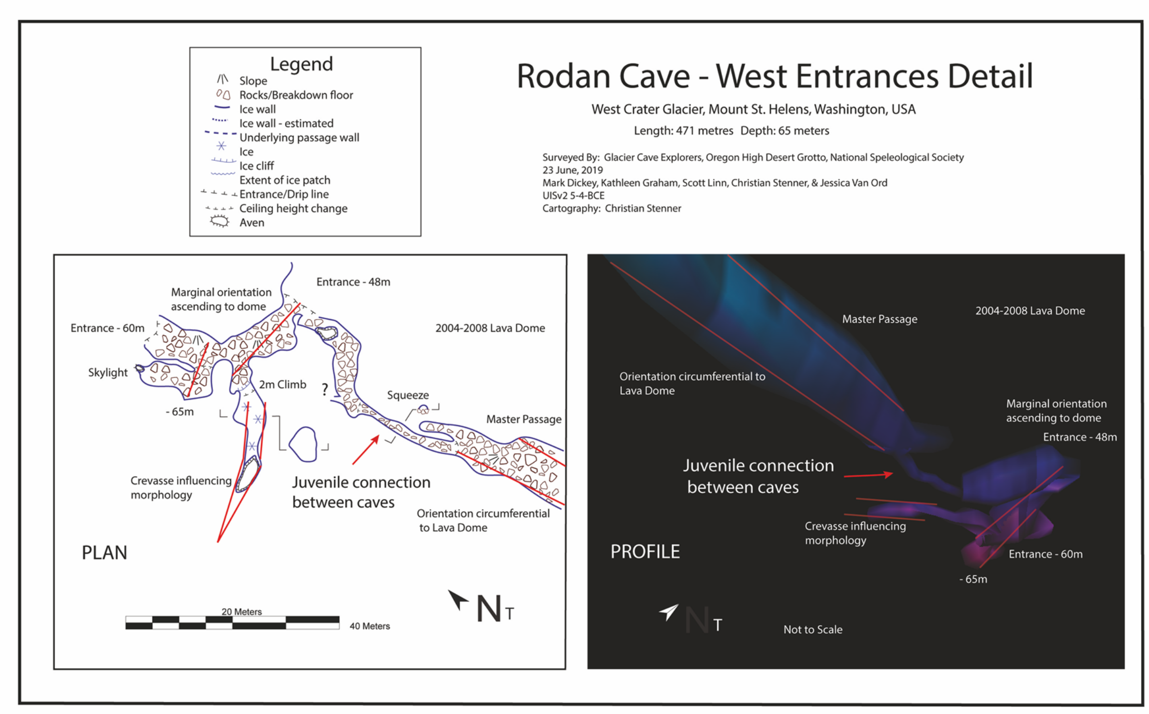

Figure 9: Map of Rodan Cave (west entrances) and profile view. A laterally orientated master passage connects a section with upward trending morphology. Rodan Cave is supposed to be a juvenile cave system where the formation of connecting cave passages has started recently. Continuing heat output will probably lead to further expanding (2).

Expansion Towards the Lava Dome

Subglacial cavern enlargement and the expansion of entrance passages towards the lava dome are expected to continue as long as snow accumulation continues and until Crater Glacier stops expansion.

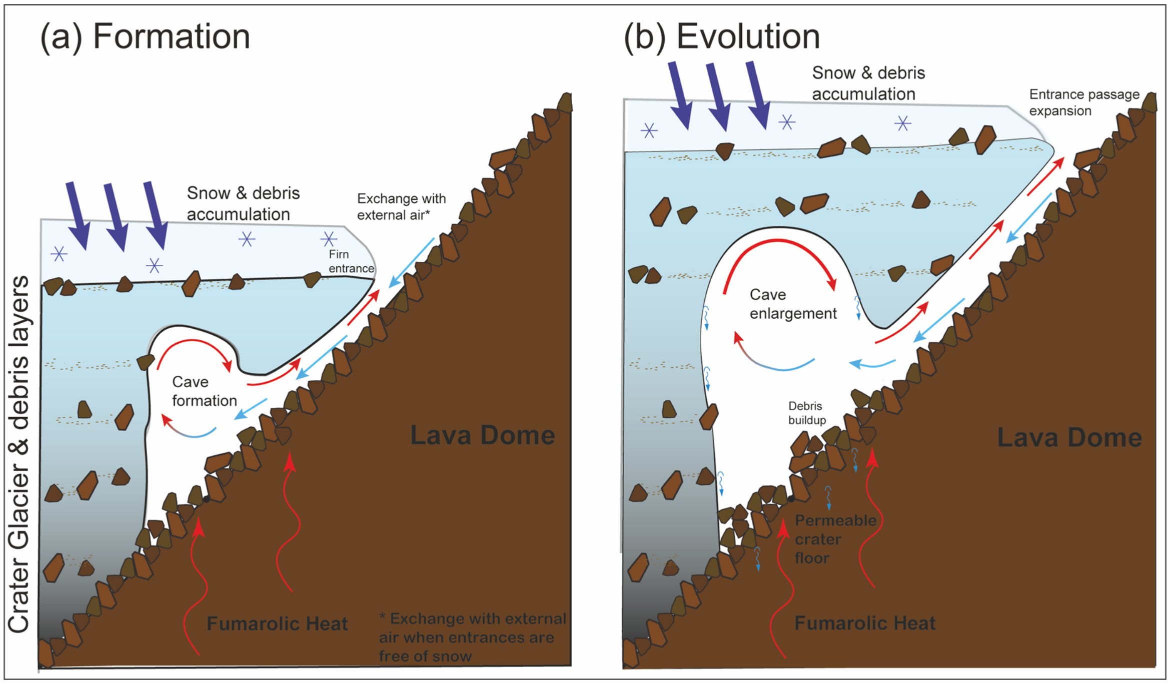

Figure 10: Future evolution of caves viewed in profile, using Mothra Cave as an example. Subglacial cavern enlargement continues laterally, and vertically by way of passage enlargement and passage lengthening towards the lava dome with further glacial accumulation. (a) Onset of formation due to fumarolic heat. (b) Further evolution and cave enlargement. Exchange with external air arises as long as cave entrances are not sealed with snow. The high content of debris and the permeable crater floor are exceptional features of Crater Glacier (2).

FUTURE RESEARCH

Document Further Speleogenesis

In order to understand the development of glaciovolcanic cave systems and to verify our hypotheses that the Mount St. Helens cave systems will continue their growth and merge in the near future, it is essential to constantly monitor further cave genesis.

Figure 11: A new chimney entrance to Mothra cave which formed in 2020. This photo from September 2020 shows a new stage in cave development as fumarolic heat from glaciovolcanic caves on Mount St. Helens typically creates passages upwards trending along the rock/ice margin rather than breaching the glacier surface. Further study is needed to understand glaciovolcanic cave genesis and the mechanism for chimney development versus lateral development. Image: Andreas Pflitsch, 2020.

Petrologic Studies of Tephra Layers

Cave systems on Mount St. Helens are unique archives of the recent eruptive history and contain several tephra layers which represent material from several ash eruptions and debris from the crater walls which deposit onto the glacier surface annually. These layers provide the chance to study the coexistence of Crater Glacier and Mount St. Helens as one of the most dangerous volcanoes in the Cascade Range.

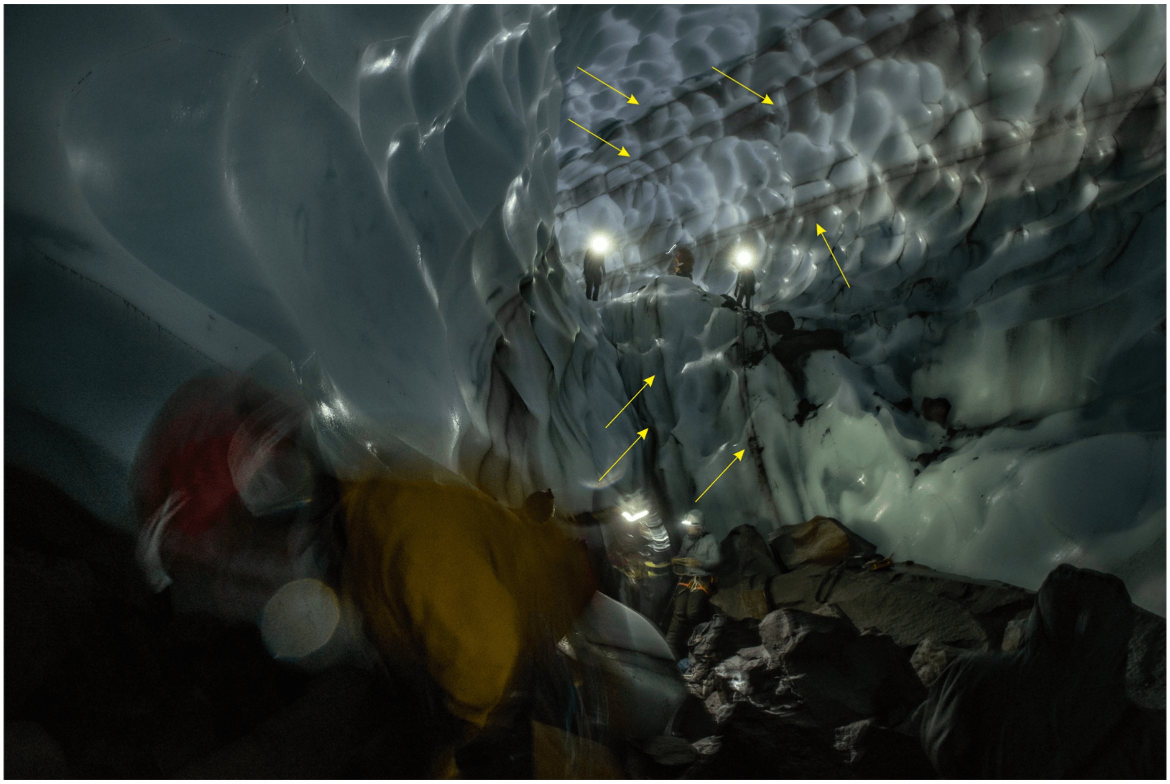

Figure 12: View inside Mothra Cave and its several tephra layers which derive from the recent eruptive history of Mount St. Helens. Image: Eric Guth, 2018.

Fumarole Sampling

Fumaroles are an essential part of the cave systems and contribute much to cave formation and further evolution. To find out more about the volcano's magmatic and hydrothermal system it is planned to sample fumarole output on and around the newly formed lava dome and subglacially within the cave systems.

Figure 13: Fumaroles in the entrance area of Mothra Cave. Image: Eric Guth, 2018.

AUTHOR INFORMATION

Christian Stenner: Explorer at the Alberta Speleological Society, survey and exploration lead for the Mt. St. Helens glaciovolcanic cave projects of Glacier Cave Explorers.

Linda Sobolewski: PhD student at the Ruhr-University Bochum with research interest on volcanology and glaciology; currently researching the glaciovolcanic cave systems in the crater of Mount St. Helens.

Andreas Pflitsch: Scientist at the Ruhr-University Bochum; head of the working group *Climatology of Extreme Environments*.

Eduardo Cartaya: Coordinator of the Glacier Cave Explorers group of the National Speleological Society, & United States Forest Service Officer.

ABSTRACT

Mount St. Helens, Washington State, USA, is characterized by a 2 x 3.5 km horseshoe-shaped and north-facing crater and hosts one of the last expanding glaciers in the Cascade Volcanic Arc, Crater Glacier. First observed in 2012, a new and extensive system of glaciovolcanic caves has developed around the 2004-2008 Lava Dome inside the Crater Glacier. Field studies have documented the cave characteristics via photography and tacheometric survey methods repeated from 2014-2019. Climatologic measurements reveal that sub-glacial fumarole activity leads to large-scale cave complexes, sometimes several hundred meters long. These allowed comparisons of passage extent and volume to be made and gave us a unique opportunity to observe their genesis over time.

Ten distinct caves have been discovered in a circumferential pattern surrounding the 2004-2008 Lava Dome. The caves comprise a combined length of 2,232.3 m, the three most significant ones reaching more than 400 m each. Changes in the output of individual fumaroles which have melted the passages have also contributed to the appearance and disappearance of subglacial rooms and marginal dendritic passages which typically orient to entrances along the rock/ice interface. Over time the caves have demonstrated significant morphological changes. Multiple caves demonstrated increases in length and volume over the study period, along with changes to internal morphology. Caves located on the east and west arm of the glacier are additionally influenced by glacier movement and a fast flow rate which contribute much to morphology changes.

Resurveys of cave passages over multiple years have revealed the dynamic nature of the systems, which are not necessarily in balance with the geothermal heat release. We expect that the overall growth of the cave systems will continue as long as an equilibrium of snow accumulation and ablation is reached or changes in volcanic activity occur. The newly formed glaciovolcanic cave systems on Mount St. Helens offer a rare view into the internal workings of a glacier and can lead to a better understanding of how glaciers and active volcanoes interact.

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(1) Badino, G., Vivo, A. de and Piccini, L.: Caves of Sky. A journey in the heart of glaciers, 2007.

(2) Sobolewski, L., Stenner, C., Hüser, C., Berghaus, T., Cartaya, E., and Pflitsch, A.: Formation and evolution of newly formed glaciovolcanic caves in the crater of Mount St. Helens, Washington, USA, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-279, in review, 2020.