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ICE CAVE RESEARCH OF THE UNITED STATES

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Abstract

Natural and anthropogenic ice caves are spread out on the North American continent, especially in the United States. Many of these climate archives are already forgotten, no longer contain ice due to climatic changes, or are expected to lose their ice soon. However, sources from the nineteenth and twentieth centuries suggest the former density of ice caves in this nation. A synopsis of the American ice cave research from its beginnings in the early nineteenth century to the present is the focus of this article. A priori, basic terms and problems of ice cave research are addressed and elucidated. Subsequently, climatic conditions that facilitate or counteract the buildup of cave ice over the course of a year are presented. On the basis of an ice cave classification, different ice cave types are outlined and analyzed in their distribution in the United States. The accompanying map illustrating the geographic locations of caves in the mainland United States represents the first version of an American ice cave distribution.

Introduction

Ice caves have always drawn the attention of mankind. Native Americans, like the Zuni in Arizona, regarded ice caves as religious places (Balch, 1900). During the colonization of the country by European settlers, ice caves were used to cool and store perishable goods, extending their shelf life. At a later time, cave ice was chipped off and transported into the basements of townspeople to enable in-house cooling of groceries. With the invention of the electric refrigerator, ice caves lost their importance, and over decades, vital knowledge about them from previous generations was lost (Balch, 1900).

Today, information about many ice caves is only available from older literature. Still, ice caves represent hidden archives that provide information about the climate decades to centuries past. Ice caves can help to assess current climate shifts, giving important information about regional changes. The changes in ice mass over the course of a year during the phases of ice formation and melting are meaningful climate indicators for short- and long-term changes of regional climate (Saar, 1956). For this reason, scientific ice cave research in northern America has great untapped potential.

American and European literature from the nineteenth and twentieth centuries (e.g. Balch, 1900; Halliday, 1954) was reviewed, and oral evidence from local cavers was gathered and combined with findings and results from our own cave visits and research beginning in 2007. In addition to this information, measurements undertaken since 2007 were compiled to establish an ice cave distribution for North America.

This first overview includes information about the spatial distribution and changes in American ice caves in the last 110 years, as well as the variability of ice thickness of individual ice caves. A main goal of the ice cave distribution data is a future expansion to a method of climate monitoring that may provide usable information of past and present climate changes.

Definition of Terms Relating to Ice Cave

The term *ice cave* and its distinction from *glacial caves* have been discussed in the literature for centuries. The problem and the historical development of a clear nomenclature are summarized in the master's thesis by Grebe (2010), which deals with the global ice cave research since the sixteenth century. There have been different attempts to define the term *ice cave* since the eighteenth century. The first definitions solely related to a particular characteristic of ice caves. Such a characteristic could be air currents (Thury, 1861), the shape of the cave (Schwalbe, 1886), the presence of ice, the location and morphology of the cave, the air temperature inside the cave in comparison to the air temperature outside of the cave, or the formation and position in the rock (Balch, 1897). Nearly sixty years later, Saar (1956) was the first to summarize more than one characteristic element in his definition, defining the cave type by combining the influence of the outdoor climate with the specific soil temperature. Despite these efforts, a much-needed international, globally uniform definition of the term *ice cave* is still missing.

The authors of this paper define ice caves as chambers that contain or are composed of ice. The specific rock, its structure, or the position of the cave are not relevant. Any underground cavities where ice is present for more than six months a year are considered as ice caves, while short, seasonal snow and ice are not considered. As Halliday (1954)

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stated, the ice itself is the curiosity and not the cave. Cave ice is defined as moisture that freezes in the inside of the cave. Snow masses that are blown into the cave during winter and subsequently accumulated in the cave are not considered cave ice (Halliday, 1954).

Factors for the Formation of Cave Ice

Percolating water from the surface and temperatures below the freezing point are the two elementary factors that are mandatory for the formation of cave ice. Without these low temperatures and a simultaneous supply of moisture, ice cannot form in caves (Balch, 1897; Fugger, 1888; Fugger, 1893). In addition to these two elementary factors, each cave has features that impact the climate of the cave. These factors can be the morphology of the cave or the orientation and size of the entrances, which impact the formation of ice in caves in various ways. As these factors often favor the formation of ice in caves, ice caves are much more common than generally believed and even occur in regions with hot summer climates, such as New Mexico or Hawaiʻi (Balch, 1900; Fugger, 1888; Fugger, 1893; Kraus, 1894; Schwalbe, 1886).

Factors that vary with season like regional snowfall during winter also impact the occurrence of ice in a cave. Strong snowfalls in late winter have a particularly positive impact on the growth of ice. Snow masses that block openings can preserve cave ice from direct solar radiation or prevent warm air masses from entering the cave, so that the melting of cave ice may be delayed until late spring or summer by limiting the time that defrosting processes affect the ice. In contrast, the penetration of cold and dry air masses during winter can lead to degradation of ice masses by sublimation, while dripping water during snow melt supplies the necessary moisture for ice formation (e.g., Fugger, 1888; Fugger, 1893; Kraus, 1894). A comparative consideration of the various impact factors is given in Table 1.

Table 1. Climatological impact factors for the formation and degradation of cave ice.

Positive Impact	Negative Impact
Early-onset and/or prolonged winter	Early-onset and/or prolonged summer
Autochthonous radiation weather conditions	Long-lasting summer heat waves
Long-lasting cold periods, especially with extreme cold	Warm and/or short winter
winter storms (air temperature ≤ 0°C)	Storms with air temperatures > 0 °C
Snow fall that blocks cave openings during late winter or early spring	Early snow fall that blocks cave opening
Entering humidity in spring facilitate ice formation (e.g. snow melting, precipitation)	Large amounts of precipitation and prolonged rainfall in the months with air temperatures > 0 °C
Summer months with low amounts of precipitation	
Early onset of winter in autumn	

Classification of Ice Caves by Halliday

Based on the classification of ice caves by Halliday (1954), different ice cave types are listed below. Halliday classified ice caves by their cave type and not by the properties of the ice. We expand Halliday's classification by the category of the glacier caves. Additionally, the term *glacières* is replaced by the term *ice caves* to prevent misunderstandings because most cave ice has nothing to do with glaciers. Figure 1a shows the location of all ice caves in mainland US that have been reported in the literature.

Limestone Solution Ice Caves

The group limestone solution ice cave includes a large number of ice caves. This type comprises ice caves that have formed by dissolution of limestone. While this type of cave is spread all over the country, the special climatic conditions in mountain areas favor this type of ice cave, leading to a cluster of limestone solution ice caves in the Rocky Mountains (compare Fig. 1b). The cave size and ice volume in these caves vary greatly. One of the most well known limestone solution ice caves in the US is the Decorah Ice Cave in Iowa. Here, meteorological measurements were already conducted before 1900 (Kovarick, 1898).

Lava Tube Ice Caves

Lava tubes are frequently found on the slopes of volcanoes, and ice formed in them may persist for large parts of the year. The necessary moisture and cold air masses penetrate through cracks, skylights, and collapsed parts of the lava tube caves (Halliday, 1954). These ice caves are primarily located in western parts of the US, from Washington to New Mexico (Fig. 1c), like the ice caves in the Craters of the Moon National Monument, Idaho. Publications on these ice caves by Stearns (1924) and Limbert (1924) are among the first reports about this ice cave type in America. Lava-tube ice caves are also found on Hawaiʻi (e.g., at the Mauna Loa volcano above elevations of 3,000 m) (Kempe, 1979; Halliday, 1991) (Fig. 2).

Figure 1. a, Top, distribution of ice caves in the contiguous United States. b. Lower left, ice in solution caves. c. Distribution of lava tube ice caves.

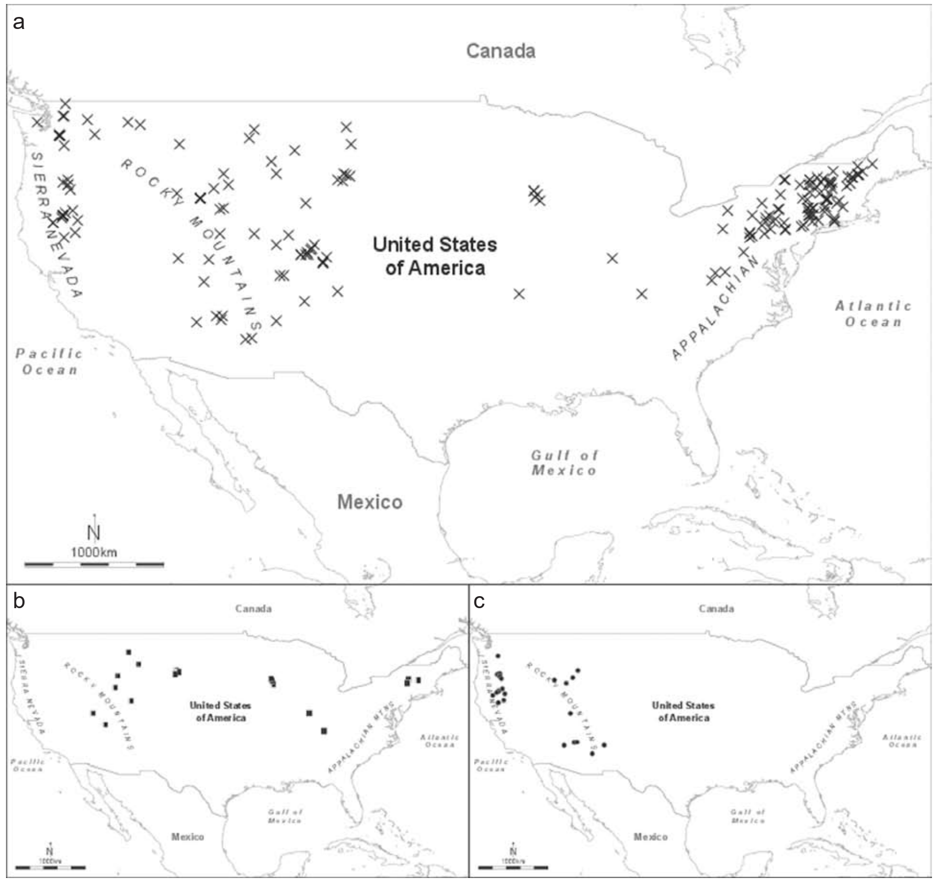

Figure 2. Frozen lake in a lava tube ice cave on Hawai‘i.

Fissure-and-Sink Ice Caves

Fissure-and-sink ice caves are ice caves that feature smaller cave volumes. Ice deposits in cracks and sinks, mainly in higher latitudes, fall into this category. These ice caves can be found in the northeastern United States and in high elevation areas from North Dakota and Wyoming to New Mexico (Halliday, 1954) (Fig. 3a).

Talus-and-Gorge Ice Caves

An ice cave type that is further discussed in another study (Holmgren et al., 2017) is termed talus-and-gorge ice caves. This type is typified by ice deposits in debris and ravines, and the actual caves are relatively limited. The smallest ice caves of the world can probably be classified as this type. The occurrence of these caves is limited to only a few

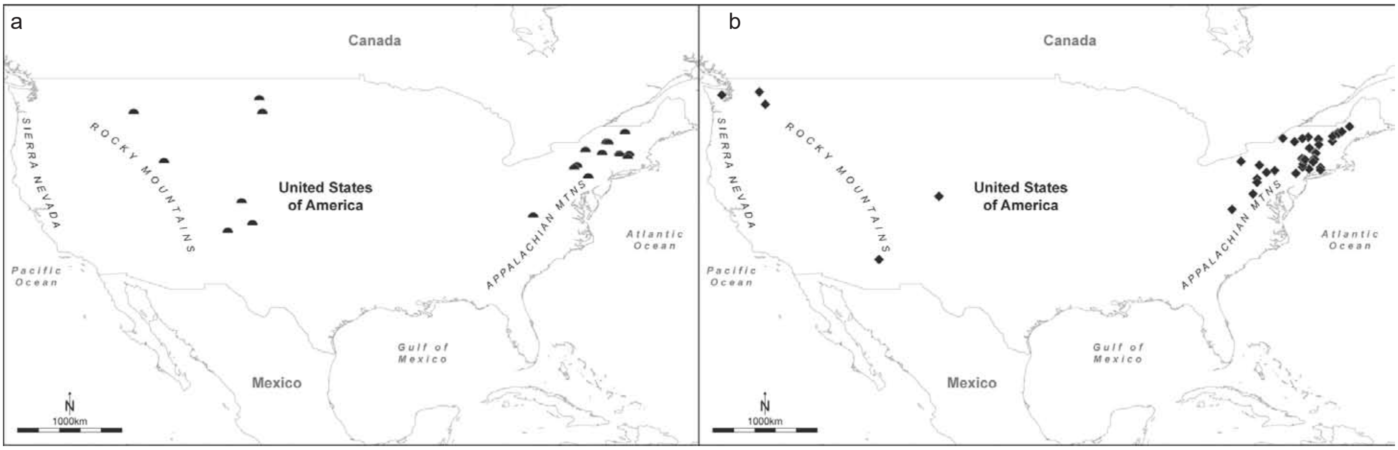

Figure 3. a. Locations of fissure-and-sink ice caves in the contiguous United States. b. Talus-and-sink ice caves.

regions in the US (Fig. 3b). On the west coast, observations of this cave type have been limited to the state of Washington. There are some documented caves in the Rocky Mountains such as Palmer Lake Ice Cave in Colorado, but most of these caves have been documented in the northeastern US (Holmgren and Pflitsch, 2012). An example is the Randolph Hill Ice Gulch in New Hampshire (Halliday, 1954).

Artificial Ice Caves

Mine Ice Caves

One of two ice cave types that can be classified as anthropogenic or artificial is mine ice caves. These are ice deposits in mines and tunnels in cold climates (Halliday, 1954). The cave size is dependent on human activity (Fig. 4). These caves can be found in New Hampshire, New York, Vermont, Alaska, and especially in Colorado (Fig. 5a). Preliminary investigations and explorations by Andrews (1913) in Sweden Valley Ice Mine, Pennsylvania, are among the most important early American ice cave studies.

Figure 4. Ice in an abandoned car tunnel, Alaska.

Ice-forming Wells

The ice-forming wells type includes ice deposits in artificial wells and shafts. Reports on these vertically oriented ice caves come solely from the northeastern US (Massachusetts, New Hampshire, New York, and Vermont) (Fig. 5b). While ice-forming wells might be more common than previously thought, they are one of the least studied ice cave types (Halliday, 1954).

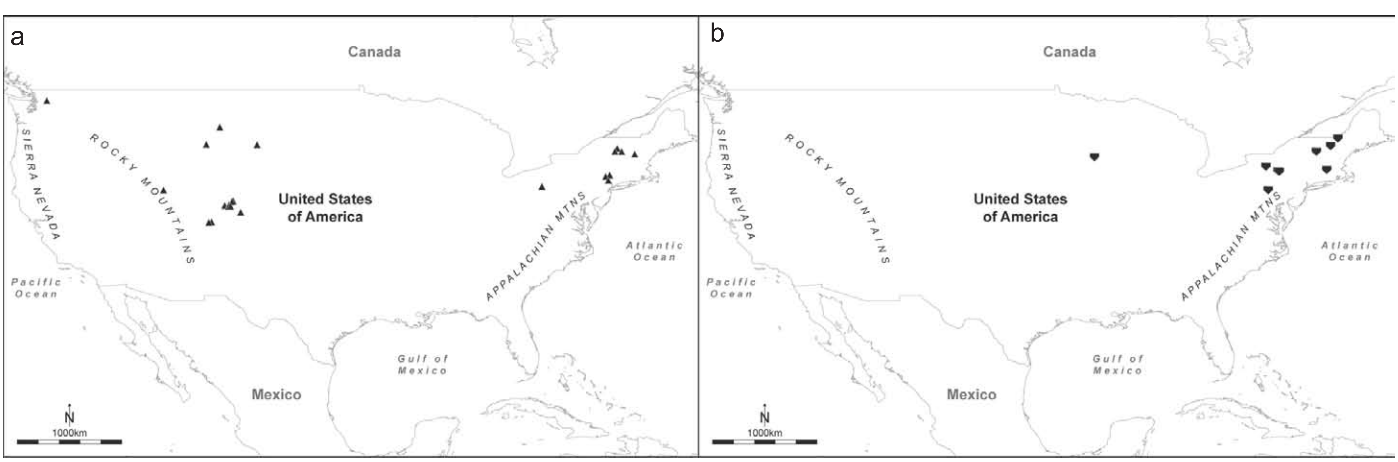

Figure 5. a. Mine ice caves in the contiguous United States. b. Ice-forming wells.

Glacier Caves

Glacier caves are the final cave type of this classification. Glacier caves consist purely of ice and are not influenced by, or dependent on, physical or chemical rock weathering. Glacial meltwater runoff creates and modifies these tunnels constantly (Fig. 6). Indeed, this is a defining feature, as the changes in the shape of the cave are much more rapid than in any other cave type. As these caves are bound to glaciers, they can mainly be found in Alaska, Washington, and Wyoming (Fig. 7). Glacier Caves are also sparsely scattered throughout California, Colorado, Montana and Oregon (Halliday, 1954). One of the most well known glacier caves in the U.S. is contained within the Matanuska Glacier in Alaska; it has been explored in multiple studies by Gulley and Benn (Gulley, 2009; Gulley et al., 2009).

Ice Cave Research of the United States

Global ice cave research is diverse. Students of a wide range of scientific disciplines, including biology, earth sciences, hydrology, and climatology consider ice caves in their research. Current ice cave research focuses mainly on European ice caves. In recent decades, studies about ice caves in the Alps are among the most essential contributions to ice cave research.

The world's first mention of an ice cave is in an Asian publication by the Indian Kalhana. In his book *Kalhaṇa's Râjataraṅgiṇî* (1148/1149), he refers to a cave that contains blocks of ice in the region of Kaschmir, according to a modern edition (Stein, 1961). It was more than 600 years later when the first accounts can be found for an ice cave in the US (Dearborn and Ives, 1822; Dewey, 1819). Starting in the year 1800, Dearborn, Ives, and Dewey visited the Snow Hole near Williamstown, New York, on multiple occasions.

In Europe, the distinct features of ice caves were recognized earlier than in North America. First written records come from a personal note by Leonardo daVinci about a cave in Italy in the late 1400s (Turri et al., 2009).

Previous Ice Cave Research in North America

Past ice cave research in North America can broadly be classified into two main eras. The first era includes extensive publications by Edwin S. Balch between 1880 and 1930. The second era began in 1930 with significant publications by William R. Halliday that extended through the late 1950s.

First Era of North American Ice Cave Research

The most important work of the first era of North American ice cave research is *Glacières or Freezing Caverns* by Edwin Swift Balch (1900). Balch began visiting ice caves in America and later visited ice caves around the globe. In late September 1877, he encountered ice in the debris of King's Ravine on Mt. Adams in the White Mountains of New Hampshire. Always accompanied by local hikers and local inhabitants, Balch sought ice caves of any kind for the following 22 years. At the end of that time, Balch pursued the goal of passing on his comprehensive knowledge about underground ice deposits. In addition to providing locations of ice caves around the globe, Balch put forward theories about the formation of ice in caves, while also reporting about his experiences and adventures in ice caves. With the simplest of means, such as cigar smoke and simple thermometers, Balch tried to determine air flows and temperature differences. In his books and articles (Balch, 1897; Balch, 1899; Balch, 1900), he also gathered information from locals, documenting their knowledge of ice caves back to 1725. Other scientists of this time limited their research to single caves such as the Decorah Ice Cave (Kovarik, 1898) or the Craters of the Moon (Stearns 1924; Limbert 1924), conducting more detailed research.

Figure 6. Glacier mouth of Pure Imagination Cave of Sandy Glacier on Mt. Hood, Ore. (June 21, 2015).

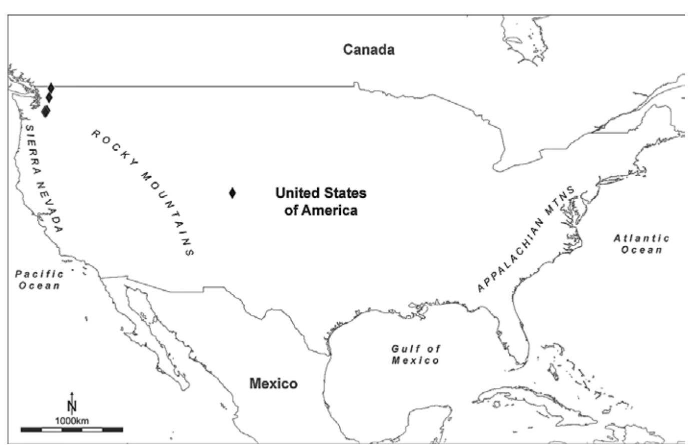

Figure 7. Glacier ice caves in the contiguous United States.

Second Era of North American Ice Cave Research

The results of this first era were followed up in the second era. In their publications, Merriam (1950) and Halliday (1954) compiled lists of American ice caves, trying to group them in different ways. In his article "Ice Caves," Merriam documented ice caves and grouped them by state to create a map illustrating the locations of the 36 known American ice caves. Halliday, however, classified ice caves into different categories, providing an example for each category. As outlined above, he based his classification on the cave type, independent of the type of ice (Halliday 1954). In addition to providing ice cave inventories, these publications dealt with problems of ice cave research, including enduring issues concerning a clear nomenclature. Different theories concerning the formation of ice were discussed, and air temperature data from within caves, as well as from their vicinity, were compared and analyzed. These had often been obtained by third parties. Besides those by these two authors, there were a few individual publications addressing ice caves, such as a report about an ice cave in the desert west of Albuquerque, New Mexico, by Kennedy (1938) and the note of a cave with ice in central Utah by Rogers (1942).

Current State of American Ice Cave Research

Following these two eras of American ice cave research that concluded in the 1950s, the interest in this phenomenon decreased. Research about various aspects of ice caves in North America has picked up again only in the last decade. These studies mainly focused on lava tube ice caves in California, talus-and-gorge ice caves in New England, glacier ice caves in Alaska, along with the possibility of ice caves on Mars.

The changes in ice level in various lava tube ice caves in the Lava Beds National Monument, California, have been observed since 1990. Fuhrmann (2001, 2007) and Kern and Thomas (2012) have analyzed the trends of ice levels in various caves, partially reconstructing ice levels based on photographs from the decades before the beginning of the time series of new measurements. Mineral deposits helped reconstruct previous ice levels (Fuhrmann, 2007).

Observations of the talus-and-gorge ice caves in New England began in October 2008 (Fig. 8). Since then, Holmgren and Pflitsch (2011) have continuously monitored air temperatures in the talus slopes and gorges, as well as air temperatures at different positions in the debris. Additionally, thickness measurements of the cave ice in different talus-and-gorge ice caves in New Hampshire and Maine are conducted at the potential time of minimum ice extent. In recent years, the ice thickness has been recorded by regular measurements (Holmgren and Pflitsch, 2011). These multi-annual observations of the alternation between phases of ice buildup and ice depletion over the course of a year serve as excellent climate indicators for short- and long-term changes in the climate of an entire region (Holmgren and Pflitsch, 2012).

Glacier ice caves (englacial drainage systems) continue to be heavily investigated by Gully and his colleagues. In Alaska, Gulley examined one of the longest valley glaciers in the world, the Matanuska Glacier, which is approximately 39 km long. The focus of his research is the formation and shaping of glacier ice caves, as well as the evolution of existing glacier ice caves. Factors that might trigger or amplify these processes are of particular interest (Gulley, et al., 2009; Gulley, 2009).

The southernmost ice caves in the world are located in Antarctica. These ice caves, located on Mt. Erabus on Ross Island are being studied by scientists from New Mexico Tech who examine the microclimate and morphology of fumaroles of ice. Special measurement techniques, such as temperature measurements using fiber optics to identify geothermal point sources should be highlighted (Curtis and Kyle, 2011).

A research field that has developed in recent years and is of special interest for the US is the research concerning the potential presence of extraterrestrial ice caves on Mars. Ice caves could prove the existence of water on Mars, potentially allowing life on Mars. This research asks whether ice caves exist and what their possible uses may be (Perşoiu et al., 2011; Pflitsch et al., 2011; Williams et al., 2010).

Summary

In the first era of American ice cave research, roughly from the 1880s to the 1930s, the highest number of previously unknown ice caves were mentioned in the literature. With intensifying industrialization, public and scientific interest in ice caves decreased. In the subsequent second era, from approximately 1930 to the 1950s, fewer new ice caves were described. During this era, publications mainly summarized previously known American ice caves, attempting to classify these by the cave type or the state in which they lay.

Only in the last decade has ice cave research regained some of its significance in the United States. However, only a fraction of American ice caves still exist. Today's scientists view ice cave research as an opportunity to obtain information about climate changes in the past. For climate scientists, ice caves can be a true treasure. As a natural climate archive, they contain information about the climate of the past and present. The scientific database of American ice caves is not yet on the same level as in Europe, but has constantly improved. Sufficient study areas featuring different ice cave types are available on the American mainland. Ice cave research provides a niche for a large variety of scientific disciplines. In 2014, the 5th International Workshop on Ice Caves took place Idaho Falls for the first time outside of Europe. The preservation of these natural and cultural treasures is a major objective of ice cave research.

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