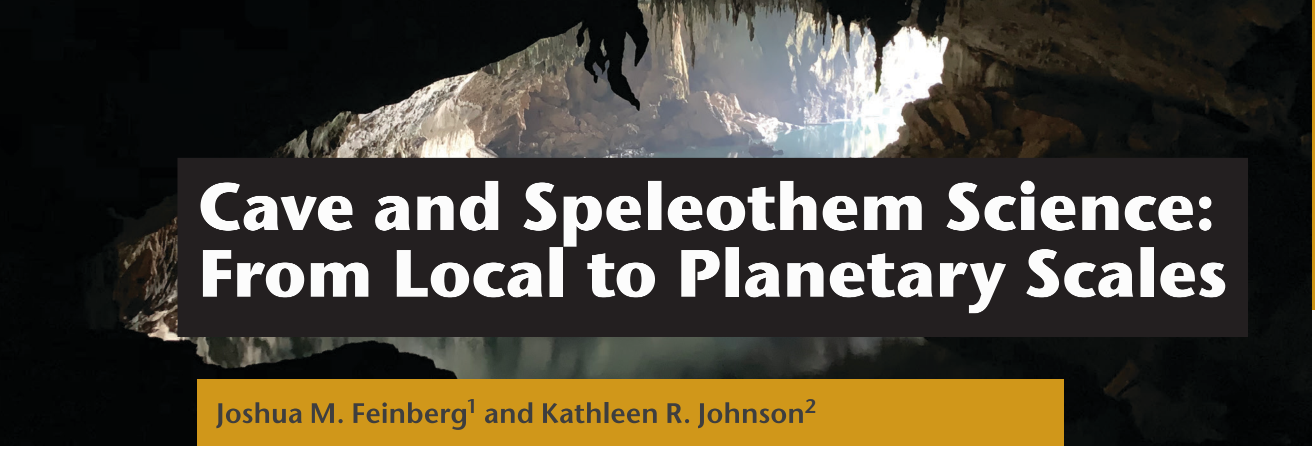

Cave and Speleothem Science: From Local to Planetary Scales

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Caves occur everywhere on our planet, from the tropics to the high latitudes and from below sea level to alpine settings. Cave morphologies provide clues to their formation mechanisms, and their iconic mineralogical features—stalagmites and stalactites—carry a wealth of paleoenvironmental information encoded in their geochemistry and mineralogy. Recent work demonstrates a striking improvement in our ability to decode these paleoenvironmental proxies, and dramatic geochronological advances enable higher resolution records that extend further back in geologic time. Cave research addresses an ever-increasing range of geoscience problems, from establishing the timing and mechanisms of climate change to uncovering detailed records of geomagnetic field behavior.

Keywords: caves; karst; speleothems; stalagmites; stalactites

INTRODUCTION

Caves represent many things to humanity: a source of shelter, a space for recreation and exploration, a window to water in otherwise dry landscapes, a sacred place with strong spiritual and cultural importance to many Indigenous peoples around the world, or in Greco-Roman mythology a mystical entrance to the underworld. Caves are archives of some of the earliest remains of our shared human history, including fossils and cultural objects ranging from stone tools to ceramics and cave art. Such materials represent invaluable waypoints for deciphering human evolution and history. Beyond their anthropological importance, caves and the mineralogic formations within them are an important part of the Earth system (Fig. 1). Caves are an exciting scientific frontier where researchers can chronicle past environmental conditions, observe microbe–mineral interactions firsthand, and learn about the circuitous paths that groundwater travels in the subsurface. This issue of *Elements*, published during the International Year of Caves and Karst (http://iyck2021.org/), aims to illuminate the edges of such frontiers in cave science.

Caves are generally thought of as air- or water-filled voids in the subsurface, with one common definition stating that caves are cavities large enough for a human to enter (Hill and Forti 1997). The physical environment within a cave will vary depending on its size and geometry, number and location of entrances, local climate and hydrology, sedimentology, and human modification. In general, and away from their entrances, caves are dark and often muddy places characterized by stable temperatures and a high relative humidity. Temperatures in caves are a balance of thermal energy from the atmosphere and the Earth's interior. Atmospheric energy can be transferred into a cave through air ventilation, percolating groundwater, and conduction from the surface. A cave's temperature generally become more stable with increasing distance from the entrance and with increasing depth: remote from the entrance, cave temperatures approximate the local mean annual temperature at the surface. If well ventilated, cave air may have CO_2 concentrations similar to that of the atmosphere (~410 ppm, currently). But many caves accumulate the CO_2 that degasses from drip waters or from fracture seeps in the host rock, sometimes reaching dangerous levels as high as 10,000 ppm (Fairchild and Baker 2012).

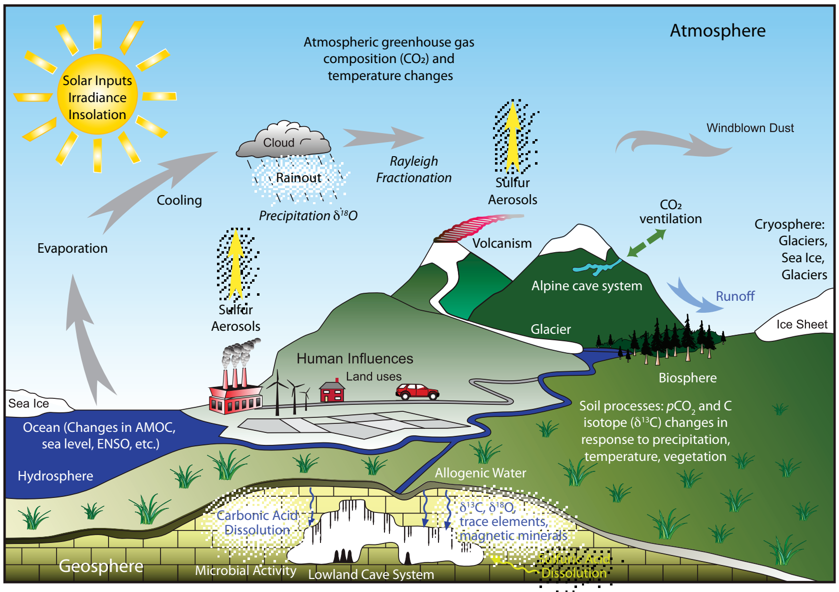

Figure 1 Diagram showing how caves are influenced by and interact with the atmosphere, biosphere, geosphere, and hydrosphere. Abbreviations: AMOC = Atlantic Meridional Ocean Circulation; ENSO = El Niño–Southern Oscillation. Modified from Fairchild and Baker (2012).

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Caves are often formed by the dissolution or hydromechanical erosion of host rock, although caves may also occur as lava tubes in volcanic settings, within melted ice at the base of glaciers, or even as small shelters between large boulders on talus slopes. In this issue, we focus most directly on cavities formed by the dissolution of carbonate rocks—such as limestone, dolomite, and marble—by naturally occurring acidic groundwater. Carbonate rocks make up 10%–15% of Earth's land surface (Goldscheider et al. 2020) (Fig. 2) and their dissolution by natural waters produces a rich diversity of features that collectively characterize karst terranes and occur across a wide range of length scales—underground rivers, caves, sinkholes, blind valleys, and a general lack of surface streams and lakes (Ford and Williams 2007). Speleology is the study of the processes that create and modify caves, and speleogenesis is the term used to describe the process of cave formation and evolution.

Speleogenesis in Karst Terranes

Karst terranes and aquifers can be broadly divided into regimes dominated by dissolution and precipitation (Fairchild et al. 2006). Dissolution regimes can be either hypogenic or epigenic.

Hypogenic karst systems are formed through dissolution by water whose acidity has been produced at depth and may include waters from hydrothermal systems or deep-seated waters naturally rich in hydrogen sulfide (H_2S) or carbon dioxide (CO_2) (Jones and Northup 2021 this issue). Hypogenic karst is less common than epigenetic karst, yet some of the world's most spectacular caves, such as Lechuguilla Cave and the Carlsbad Caverns (both in New Mexico, USA), were formed by hypogenic processes. When hydrogen sulfide is introduced into an oxidizing environment, sulfuric acid is produced and acts as a powerful cave-former:

$$H_2S + 2O_2 \leftrightarrow HSO_4^- + H^+ \quad (1)$$

$$CaCO_3 + 2HSO_4^- \leftrightarrow Ca^{2+} + 2SO_4^{2-} + H^+ + HCO_3^- \quad (2)$$

Sulfide-oxidizing microorganisms play a critical role in sulfuric acid speleogenesis, contributing not only to the formation of sulfuric acid that drives dissolution in such environments but also to the precipitation of gypsum and a vast range of other cave minerals (Hill and Forti 1997). Furthermore, these microorganisms form the basis for a vast cave food web and play an important role in element cycling in hypogenic karst terranes (Jones and Northup 2021 this issue).

Epigenic karst forms as a result of meteoric waters that cascade under gravity through the atmosphere, the soil ecosystem, the weathered bedrock (epikarst), and finally into the bedrock system itself (Fairchild and Baker 2012) (Fig. 1). Epigenic systems involve the incorporation of carbon dioxide gas ($CO_{2(g)}$) into water to form carbonic acid (H_2CO_3). This "weak" acid forms primarily in the high CO_2 conditions of soil ecosystems and, as it percolates along bedrock fractures, bedding planes and joints, it progressively dissolves carbonate minerals [$(Ca,Mg)CO_3$] to release calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) ions into groundwater; more generally:

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \quad (3)$$

$$CaCO_3 + H_2CO_3 \leftrightarrow Ca^{2+} + 2HCO_3^- \quad (4)$$

Epigenic caves are strongly influenced by overlying soil dynamics, as the partial pressure of CO_2 (pCO_2) in groundwater is mainly the result of soil microbial activity and root respiration. Rainfall and the availability of water both have an impact on drainage and groundwater acidity, which, in turn, later controls bedrock weathering. Groundwater acidity is regionally controlled by temperature, soil activity, CO_2 production, the organic content of the soil, and surface vegetation (Fairchild and Baker 2012). These parameters are specific to location and to the local biome and are influenced by floral biodiversity (trees vs. grasses), leaf type (broad vs. needles), and plant spacing (forest vs. savannah) (Fairchild and Baker 2012).

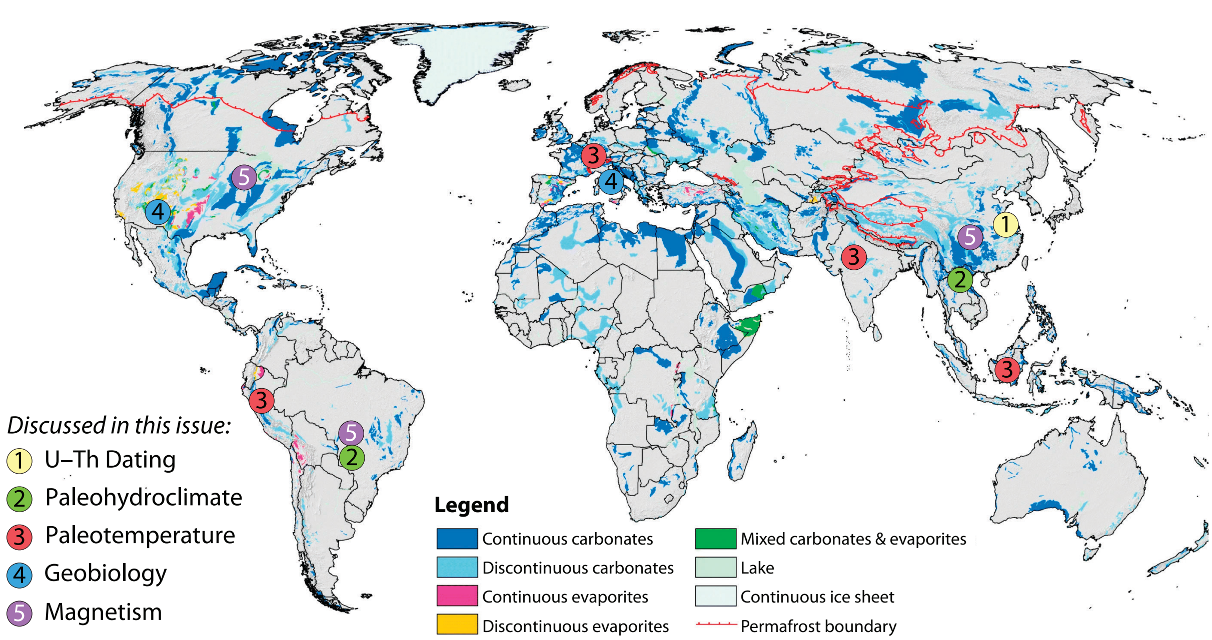

Figure 2 Caves and karst are ubiquitous around the world, occurring primarily in carbonate and evaporite rocks. Caves discussed in this issue of *Elements* are labelled from 1 to 5 and correspond, respectively, to the articles by Wendt et al. (2021 this issue), Johnson (2021 this issue), Meckler et al. (2021 this issue), Jones and Northup (2021 this issue), and Feinberg and Hobart (2021 this issue). Modified after the World Karst Aquifer Map by Goldscheider et al. (2020).

Epigenic speleogenesis occurs as acidic water moves along connected networks of fractures and conduits, with most caves formed just at or below the water table (FIG. 1). Regional base-level changes, due to tectonic uplift and/or river downcutting, can lower the water table causing different levels of caves to form. This leads to extensive and geometrically complex cave systems that reflect the interaction of regional geology, hydrology, climate, vegetation, and tectonics over millions of years. Groundwater flow through karst terranes ranges from diffuse matrix flow, which is defined as the movement of water through the carbonate bedrock as it is controlled by the rock's original porosity and permeability, to faster flow through fractures or conduits that formed long after the bedrock was formed. Karst aquifers provide critical water resources to 25% of the global population (Ford and Williams 2007), with some large cities, such as San Antonio (Texas, USA), Rome (Italy), and Damascus (Syria) relying almost exclusively on karst waters (Goldscheider et al. 2020). The unique rapid flow and complex hydrogeology of karst aquifers make them particularly sensitive to climate, changes in land use, environmental contamination, and overuse.

Caves and Karst in the Earth System

Caves and karst represent an important part of the Earth system (FIG. 2) through interactions with the biosphere, the atmosphere, the hydrosphere, and the geosphere. The karst critical zone region, located between the water table and Earth's surface (FIG. 1), is an incredibly dynamic environment shaped by physical and chemical weathering, transport and deposition of sediment and dissolved solutes, rich and diverse lifeforms, and human activities. The karst critical zone plays an important role in global biogeochemical cycles, including the carbon and water cycles. Unlike silicate weathering, carbonate weathering by dissolution is not considered an important sink for atmospheric CO_2 on long timescales, because CO_2 consumed during dissolution is roughly balanced by CO_2 released by $CaCO_3$ precipitation in the ocean (Zhao et al. 2020).

$$Ca^{2+} + 2HCO_3^{-} \rightarrow CaCO_3 + H_2O + CO_{2(g)} \quad (5)$$

However, it is still unknown whether transient fluctuations in atmospheric CO_2 may be, in part, influenced by minor imbalances in these processes on short timescales. Furthermore, carbonate dissolution by H_2SO_4 in hypogenic cave systems or in regions with sulfide-rich carbonate bedrock (Jones and Northup 2021 this issue) may prove to be an important source of atmospheric CO_2 (Torres et al. 2014), because no CO_2 is consumed during dissolution (Reactions 1 and 2) but CO_2 is still released by precipitation of $CaCO_3$ (Reaction 5). In addition to occurring naturally, rock dissolution from anthropogenically derived H_2SO_4 and HNO_3 may further influence karst weathering processes and carbon cycling (Zhao et al. 2020). Whereas the future response of karst systems to anthropogenic climate change, sea level rise, and land use change remains uncertain, research on karst ecology, biogeochemistry, hydrology, and ecosystem services is fundamental to ensuring sustainability of these critical resources.

SPELEOTHEMS

The precipitation-dominated regime within karst terranes, characterized by the formation of speleothems (secondary minerals formed in cave environments) occurs primarily in the epikarst above the water table (FIG. 3). Over 300 different cave minerals have been identified, representing all major mineral classes and a wide range of physicochemical and biologically mediated formation mechanisms (Hill and Forti 1997; Onac and Forti 2011). Most commonly, speleothems are composed of the $CaCO_3$ polymorphs calcite and aragonite, precipitated from dripping, flowing, or standing water (Reaction 5). When water with sufficient dissolved Ca^{2+} and high concentrations of bicarbonate is exposed to the relatively low pCO_2 cave atmosphere, CO_2 degasses leading to saturated or supersaturated conditions with respect to $CaCO_3$, and, thus, deposition of a new generation of carbonate (Reaction 5). Although calcite is the most stable and common $CaCO_3$ polymorph, aragonite can precipitate in caves whose drip waters have Mg/Ca ratios >1 (often in dolomitic settings): these occur more frequently in drier conditions (Fairchild and Baker 2012). Similarly, when dissolved sulfate levels become particularly high, gypsum can be deposited:

$$Ca^{2+} + SO_4^{2-} + 2H_2O \leftrightarrow CaSO_4 \cdot 2H_2O \quad (6)$$

Speleothems are typically classified based on their morphology and formation mechanism, rather than their mineral composition (Hill and Forti 1997). The most important and archetypal speleothems are $CaCO_3$ *dripstones* (FIG. 3), deposited by dripping water in caves, and *flowstones*, deposited by thin sheets of water flowing along cave walls or floors. Dripstones include stalagmites, which grow from the ground up, and stalactites, which hang from the ceiling and start out as hollow "straws". When a stalagmite and stalactite meet, a column is formed. Flowstones are layered travertine deposits on cave floors or walls, and include draperies or curtains, which are thin rippled deposits that often decorate cave walls. Dripstones are characterized by visible laminations that are linked to changes in the calcite crystal fabric, the concentration of particulates or organic matter, and/or to changes in the concentration of fluid inclusions (Frisia and Borsato 2010) (FIG. 3). Although some stalagmites contain annual lamina (Baker et al. 2021), most visible laminae represent longer periods of time ranging from decades to millennia and are often linked to environmental and climate perturbations (Fairchild and Baker 2012).

In addition to dripstone and flowstone, there are a multitude of other types of speleothems found in caves (FIG. 3), often with exotic and evocative names. These include: 1) *rimstone dams* (or *gours*), which can grow to be several meters high and accumulate due to turbulence-driven degassing when water overflows from pools (Reaction 5); 2) *cave pearls*, which form as a result of concentric layers of calcium carbonate accumulating around a central nucleus that is physically moved around under the force of dripping water; 3) *cave popcorn* or corraloids, which often coat cave walls and the surfaces of other speleothems and are formed from splashing or seeping water; 4) *helictites*, which are delicate needle-like deposits that grow in multiple twists and turns due to the capillary forces that allow them to seemingly defy gravity; 5) *draperies,* which are thin sheets of semitranslucent calcite created by degassing water that travels down an inclined ceiling; 6) calcite *rafts*, which are thin floating layers of calcite that form as a result of degassing from cave pools; 7) *moonmilk*, which is a soft, powdery microcrystalline deposit (Hill and Forti 1997). Despite speleothem formation traditionally being thought to result from inorganic physicochemical processes, it is increasingly recognized that microbial activity plays a key role in the formation of moonmilk and other speleothems (Jones and Northup 2021 this issue). Some slimy stalactite-like formations, aptly known as *snottites*, are even composed entirely of microbial biofilms produced by sulfide-oxidizing bacteria (Jones and Northup 2021 this issue).

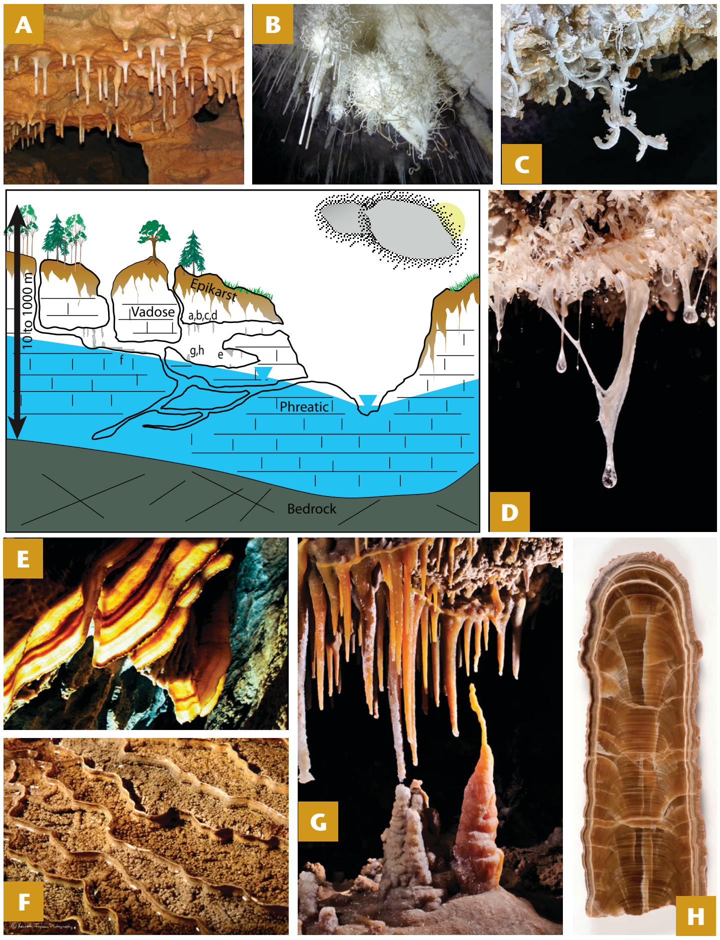

Figure 3 Diagram at middle left showing epikarst (brown), vadose (white), and phreatic zones (blue). The setting for various types of speleothem is indicated in the schematic by letters 'A' to 'H', which correspond to the surrounding photos of the speleothem feature in question. After J. Martin (https://carbonatecriticalzone.research.ufl.edu/). (**A**) Soda straws. Photo: J. St. John. (**B**) Helictite. Photo: P. Rowe. (**C**) Gypsum flower. Photo: J. Wheet. (**D**) Snottite. Photo: K. Ingham. (**E**) Calcite drapery (cave bacon). Photo: K. Ankiewicz. (**F**) Rimstone dams with cave pearls. Photo: K. Ingham. (**G**) Stalagmites and stalactites. Photo: K. Ingham. (**H**) Sectioned stalagmite showing growth layering. Photo: J. Woodhead.

Environmental Information from Speleothems

Caves hold an incredible wealth of information about modern and past environments, which themselves provide important constraints on the Earth system response to global climate and environmental change. Studies of cave sediments, speleothems, and ecosystems have substantially advanced our understanding of past changes in temperature and rainfall patterns (Johnson 2021 this issue; Meckler et al. 2021 this issue), global monsoon intensity and atmospheric circulation (Johnson 2021 this issue), permafrost extent (Vaks et al. 2013), global sea level (Polyak et al. 2018; Dumitru et al. 2019), vegetation and soil processes (Fairchild et al. 2006), and even Earth's magnetic field (Feinberg and Hobart 2021 this issue). Calcite, and sometimes aragonite, stalagmites are particularly important archives of past climate and environmental change because of their relatively simple stratigraphy, their often continuous formation over thousands of years, their suitability for precise U-series dating, and the presence of multiple physical and chemical paleoenvironmental proxies in their growth layers (Fairchild et al. 2006). The most ideal stalagmites for paleoclimate reconstruction are candle-shaped stalagmites having a compact columnar calcite fabric: these are indicative of a slow and steady drip rate and are commonly associated with calcite precipitation under quasi–isotopic equilibrium conditions (Mühlinghaus et al. 2007).

The rapid increase in speleothem-based paleoclimate records over the past few decades has been driven in part by advances in U–Th dating methods (Wendt et al. 2021 this issue) and by advances in proxy development, analytical techniques, and improved understanding of the environmental controls on the physical and chemical properties of speleothems (Feinberg and Hobart 2021 this issue; Johnson 2021 this issue; Meckler et al. 2021 this issue). Our understanding of the mechanisms through which surface climate information is translated by the karst system into physical and chemical signals in speleothems has been further refined through cave monitoring studies, laboratory studies involving the formation of "cave-analogue" carbonates, and the development of hydrologic and geochemical forward proxy system models (Frisia 2010; Johnson 2021 this issue). Together, this work has helped secure speleothems' place among the most valuable terrestrial archives of past climate. Much of this issue of *Elements* is focused on the different ways through which paleoenvironmental information is obtained from carbonate stalagmites, using examples from around the world (Fig. 2).

Chemical and physical proxies within U–Th dated speleothems have been used to develop robust paleoenvironmental records spanning the past several glacial–interglacial cycles, with the longest continuous time series from China having been produced from multiple overlapping stalagmite records extending back ~640,000 years (Wendt et al. 2021 this issue). The most widely used geochemical proxy in speleothems is the oxygen isotope ratio (expressed as $^{18}O/^{16}O$ or $\delta^{18}O$) of speleothem carbonate, which serves primarily as a tracer of the hydrologic cycle. But, carbon isotopes ($^{13}C/^{12}C$ or $\delta^{13}C$, and ^{14}C) and trace element concentrations (e.g., Mg, Sr, P), which are sensitive to local water balance, are increasingly used in combination with $\delta^{18}O$ (Johnson 2021 this issue). Furthermore, a wealth of other geochemical proxies are being explored that are showing incredible promise for developing more detailed, and potentially quantitative, paleoclimate records. For instance, calcium isotope ratios ($\delta^{44}Ca$) have proven useful for quantifying past precipitation changes (Owen et al. 2016), a major outstanding challenge in paleoclimatology. Several emerging proxies (e.g., clumped isotopes, fluid inclusions, organic biomarkers) hold great promise as paleothermometers, which could potentially provide critical information for constraining Earth's climatic sensitivity to atmospheric greenhouse gas concentrations (Meckler et al. 2021 this issue).

The above proxies are all based on measurements of speleothem chemistry. However, additional information can be obtained from other physical speleothem properties. For instance, variations in speleothem growth rate, crystal fabric, and even stalagmite diameter can be indicative of changes in surface climate. Stalagmite growth rates (or vertical extension rates) depend primarily on the saturation state of cave drip waters with respect to calcite, as defined by the saturation index (Ω):

$$\Omega = \log\left(\frac{\{Ca^{2+}\}\{CO_3^{-}\}}{K_s}\right) \quad (7)$$

where K_s is the solubility product and $\{Ca^{2+}\}\{CO_3^{-}\}$ is the ion activity product (Fairchild and Baker 2012). Positive values of Ω represent supersaturated conditions, whereas negative values represent undersaturated conditions. In cave drip waters, the saturation state is controlled by multiple environmental factors, including soil pCO_2, the extent of CO_2 degassing and prior calcite precipitation in the epikarst, and the pCO_2 of cave air, all of which may be influenced by surface climate. Furthermore, speleothem growth rate is often influenced by drip rate and the presence of particulate or colloidal impurities, both of which may be linked to precipitation above the cave. In some cases, annual growth rate itself has been utilized as a paleoclimate proxy (Baker et al. 2021), but in many other cases there is no obvious relationship with surface climate due to the multitude of potential controls. The growth rate of stalagmites can vary from a few microns per year to as high as several millimeters per year, with a recent analysis of 39 annually laminated speleothem records showing a mean growth rate of 0.163 mm/y and a median growth rate of 0.093 mm/y, in agreement with theoretical studies (Baker et al. 2021). In addition to growth rate, calcite crystal fabrics—including micritic, dendritic, fibrous, and columnar types—have been shown to reflect drip rate and drip water chemistry (saturation state and presence of "impurities"), with fabric changes sometimes co-occuring with chemical and isotopic shifts in the speleothem record (Frisia and Borsato 2010). Columnar calcite fabrics are the most common and are best suited for paleoclimate reconstructions because they reflect quasi-equilibrium calcite precipitation under a slow and steady drip rate at relatively low supersaturations. Dendritic fabrics, with high numbers of crystal defects, form under very low drip rates and high supersaturation conditions and are characterized by elevated $\delta^{13}C$, which reflects prolonged periods of CO_2 degassing. Given that speleothem crystal fabrics are sensitive to climatically linked parameters such as drip rate, temperature, and solution chemistry, changes in fabric type can, at times, serve as an additional proxy to support paleoenvironmental interpretation of speleothem geochemical records (Frisia and Borsato 2010; Fairchild and Baker 2012). However, a currently limited understanding of the complex relationship between speleothem fabrics and environmental parameters prohibits their use as a stand-alone proxy at this point.

As with any proxy method, each speleothem proxy has its own complicating factors and sources of uncertainty (Johnson 2021 this issue; Meckler et al. 2021 this issue). The most robust records use multiple proxies, often in combination with cave monitoring and/or proxy system modeling, to infer past climate conditions. Over the last several decades, paleoenvironmental records from speleothems, primarily stalagmites, have revolutionized our understanding of global climate variations on orbital to decadal timescales. Precise absolute dating of these records has enabled us to clearly identify atmospheric teleconnections between different regions, to determine the timing and mechanisms of hydroclimate change, to construct detailed records of Earth's magnetic field variations, and to determine the magnitude of tropical temperature changes and sea level rise during interglacial periods. Paleoclimate data from caves are being widely used to test and improve global climate models and to investigate the relative importance of externally forced climate changes and internal ocean–atmosphere variability in driving regional hydroclimate changes.

Paleoenvironmental information may also be gleaned from the sediments that accumulate within cave settings. For example, varying proportions of the common clay minerals kaolinite, illite, and vermiculite can differentiate between humid and more arid environments, and such information is increasingly useful for studying the conditions associated with hominin dispersal (Huang et al. 2020). Extreme environmental processes, such as typhoon storm surge deposits in coastal caves and local floods in epigenic caves, can be recorded as discrete changes in sediment grain size accompanied by reworked fossils (Mirea et al. 2021).

In addition to the rich geomicrobiological world that exists in caves, larger floral and macrofossil remains occur within cave sediments. Pollen, spores, and even diagnostic forms of phytoliths can be incorporated into cave sediments and speleothems and used to interpret changing vegetation and grassland dynamics above cave systems. Fossil remains—such as bones, shells, and teeth—can be transported into caves along with siliciclastic sediments by energetic sinking streams. Fossil remains also occur within collapse sediments associated with sinkhole deposits (*dolines*). Such macrofossils can be dated radiometrically using ^{14}C methods and provide important chronological tie points within otherwise complicated cave stratigraphies. Such floral and faunal assemblages recently provided snapshots into the ecologies of a wide range of settings, including Pleistocene faunas in Korea (Choe et al. 2020), Stone Age sediments in South Africa (Esteban et al. 2020), and high altitude alpine karst development in the Carpathians (Tirla et al. 2020).

Geophysical Information from Caves

Novel scientific approaches using speleothems are providing new insights into large-scale geophysical processes, including earthquake records and studies of Earth's magnetic field. Studies of collapsed speleothems have been linked to historical earthquakes and demonstrate the potential of caves as archives of paleo-earthquakes (Pace et al. 2020; Zhao et al. 2020). To determine the age of a paleo-earthquake, researchers use U–Th dating on the uppermost surface of collapsed speleothems, as well as the oldest portions of speleothems growing on either the fractured stumps of fallen stalagmites or the fallen stalagmites themselves. Straw stalactites knocked loose during the recent 2008 Wenchuan (China) earthquake fell such that their long axes were preferentially oriented parallel with the coseismic surface wave propagation direction (Zhao et al. 2020). Speleothem earthquake damage decreases with increasing cave depth as the peak ground acceleration associated with an earthquake is attenuated (Zhao et al. 2020). Researchers have modeled the tensile force needed to break a speleothem, but there are usually too many unconstrained variables to accurately constrain the earthquake moment from the remains of collapsed stalagmites (Pace et al. 2020).

As speleothems grow, they can also incorporate trace concentrations of magnetic minerals such as magnetite, goethite, and hematite, which record the direction of the Earth's magnetic field at the time of a speleothem's formation. The ability to precisely date speleothems and measure time using annual laminations enables geophysicists to constrain how quickly the Earth's geomagnetic field varies (Feinberg and Hobart 2021 this issue).

FUTURE DIRECTIONS

Research in cave science is expanding at an astonishing pace on a variety of fronts, only some of which are described in this issue. Workers are exploring caves in novel environments and adopting new technologies to glean fresh information about the natural and anthropogenic processes that occur in our rapidly modern changing world.

Speleothem research is undergoing a rapid growth, both geographically and temporally, and novel proxies are leading to new types of paleoenvironmental information. Recent improvements in U–Pb geochronology enable dating of speleothems that together span much of Earth's geologically recent history (back to at least the Pliocene), opening the possibility for studies of ancient climate and environmental changes (Dumitru et al. 2019). Researchers are now working in high-elevation and high-latitude cave environments, which are among the most sensitive to climate change. Such work has led to the discovery of a new form of cryogenic cave carbonate that is allowing scientists to identify when icy conditions persisted in caves that may be entirely ice-free today and to determine when permafrost was likely to have thawed in the past (Spötl and Cheng 2014). Similarly, research on the timing of carbonate speleothem formation in Siberia (Russia) has been used to date periods of permafrost thaw, providing crucial insight into the sensitivity of permafrost to past climate change (Vaks et al. 2013). At more temperate latitudes, researchers have discovered that speleothems can preserve evidence of past wildfires. These combustion events temporarily alter the $\delta^{18}O$ and trace element composition of drip water in underlying cavern systems, even for low-severity fires (Treble et al. 2016; Coleborn et al. 2018). This approach may allow speleothems to act as archives for past natural and anthropogenic fires. In coastal caves, located near sea level, phreatic overgrowths are being dated to develop reconstructions of sea-level high stands during past warm climates, such as the last interglacial period (Polyak et al. 2018) or the Pliocene (Dumitru et al. 2019).

As data loggers and sensors become smaller, cheaper, and more robust, cave researchers are monitoring the physical and chemical conditions inside caves at ever increasing detail. Such monitoring efforts help us better understand the hydrogeology and water resources of karst landscapes and provide a critical role for paleoclimate researchers who seek to link the isotope and trace element geochemistry preserved within speleothems to past environmental conditions at the surface.

Our ability to map caves has improved substantially with the adoption of a form of light detection and ranging (LiDAR) system called terrestrial laser scanning (TLS). Caves have traditionally been mapped using compass clinometers and/or total stations, but TLS allows the 3-D contours of passageways and surfaces to be rapidly and quantitatively scanned by cave researchers, allowing for calculations of cave volumes, the examination of speleothems and eroded/scoured surfaces, and the virtual reproduction of archaeologically sensitive cave sites for the public to explore.

Caves are fragile environments whose ecosystems, cultural heritage, and aesthetic beauty can be disrupted by frequent visitation and sampling. Future cave research will only be possible if these environments and their speleothems are carefully conserved. Additionally, there is a strong need for an archive of speleothem samples that will allow future researchers to conduct experiments on well-characterized materials without disrupting sensitive cave environments.

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