A Review of Ice Core Drilling in Cave Environment – Challenges, Achievements and Future Directions

Zoltan Kern1* and Aurel Perșoiu2,3,4*

1Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Eötvös Loránd Research Network, Budapest, Hungary, 2Emil Racoviță Institute of Speleology, Romanian Academy, Cluj-Napoca, Romania, 3Stable Isotope Laboratory, Ștefan cel Mare University, Suceava, Romania, 4Romanian Institute of Science and Technology, Cluj-Napoca, Romania

Worldwide, more than 141 m of ice cores has been extracted from 20 cave ice deposits, with the drilling projects focusing mainly in Central European caves. The fact that half of the cave ice cores (3 out of 6) published in 2020 represent non-European localities, however, predicts that an increasing number of cave ice drilling projects will be carried out in the near future in other geographical areas hosting ice caves. Based on the gathered experience the most commonly encountered technical challenge of ice-core drilling problems in cave environment is englacial rocky/woody debris. The complex stratigraphy of cave ice deposits represents a crucial methodological problem. We propose an (Cave Ice Sedimentary Architecture and Deposition - CiSAD) approach to take into consideration of the stratigraphic peculiarities of the investigated cave ice deposit and additional crucial meta-data before establishing the location of a drilling site best-suited to obtain the highest quality paleoenvironmental data.

Keywords: ice cave, ice core, drilling, paleoclimate, stratigraphy

INTRODUCTION

Ice cores recovered from glaciers have provided several of the longest, oldest and highest-resolution records of climate variability during the mid-to-late Quaternary (Jouzel, 2013). While polar and alpine glaciers have been generally targeted by such studies, the quest to understand past climate variability led to the expansion of drilling efforts towards “non-traditional” perennial ice accumulation such as ice wedges (Meyer et al., 2015; Opel et al., 2018), rock glaciers (Cecil et al., 1998; Krainer et al., 2015) and cave ice. While the first ice core from a cave ice deposit was extracted from Scârișoara Ice Cave (Romania) in 1947 (Serban et al., 1948) and thus the history of cave ice drilling activity is comparable to the semicentennial history of ice core drillings in polar (Dansgaard, 2004; Langway, 2008) and alpine (Oeschger et al., 1977) regions, the field gained more traction only in the past decade. Thus, several studies in Europe in the early 2000s (Citterio et al., 2004; Fórizs et al., 2004; Kern et al., 2004; Holmlund et al., 2005) have proved the potential of perennial ice caves to host valuable, high-resolution, long records of past environmental variability. Building on the early studies, in the 2010s, new ice cores were drilled in caves in Europe, North America and Asia (see below).

While ice core drilling campaigns in the more traditional polar and alpine environment face numerous challenges (Jouzel, 2013; Talalay, 2014; Talalay et al., 2015), cave ice drilling efforts received much less attention and their achievements and challenges have been generally restricted to the small ice caves community (Perșoiu and Lauritzen, 2018). Given the peculiar nature of ice
formation and dynamics in caves and the associated glacial, periglacial and karst-specific processes, drilling in cave glaciers and extracting continuous ice cores have proved a challenge for all teams involved. Various methods, techniques and equipment have been used with diverse degrees of success.

In this paper, we summarize the achievements and the main challenges of cave ice drilling efforts of the past 70 years and identify the best solution available considering both the peculiarities of cave ice deposits and the potential research questions that could be addressed. The article is structured as follows: in section 2, we present the main mechanisms of cave ice formation and the resulting ice bodies; section 3 is dedicated to a brief overview of the past cave ice drilling efforts and the methods used during the past 30 years and in section 4 we discuss potential approaches to maximize the results.

PERENNIAL ICE ACCUMULATION IN CAVES

Perennial ice accumulations in caves are found in most karst regions of the Northern Hemisphere, in a latitudinal band stretching between ~19 and 80°N (Pilitich et al., 2016; Barton et al., 2020), and from 30 m a.s.l. (above sea level) in Svalbard (Lauritzen et al., 2018) to 3,350 m a.s.l. (above sea level) on Mount Alberta, Canada (Yonge et al., 2018). The most significant processes responsible for the formation of perennial ice deposits in caves are freezing of water and snow accumulation, with glacial intrusion and hoarfrost deposition playing only minor roles (Persoiu and Lauritzen, 2018; Kwiecien et al., 2022). Snow deposits occur at the base of near vertical entrance shafts in high-to-mid altitude mountains, forming deposits up to 80 m in thickness (Persoiu and Onac, 2019). The reduced thickness of the snowpack does not result in pressures high enough to compact snow to ice (Langway et al., 1993). In most of the cases, the deposits consist of firn (density well below 0.83 g/cm³) with intercalated layers of ice, formed by freezing of meltwater percolated through the snow mass. Contrary, ice formed by the freezing of water, so-called congelation ice, attains a density approaching the upper limit for ice (0.917 g/cm³). The freezing process (Persoiu et al., 2011) occurs as both thin films of inflowing water form successive layers of ice (floor ice) or as stagnant water freezes from top to bottom, to form a thick layer of ice trapping allochthonous sediments, in-situ forming cryogenic cave calcite (CCC, Žák et al., 2008) and occasional air bubbles (lake ice).

The vast majority of existing cave glaciers in caves are formed by water-freezing processes. They have formed since at least the early Holocene (Persoiu et al., 2017; Sancho et al., 2018), experiencing periods of growth and decay, under the complex interplay of seasonally varying air temperatures and precipitation amounts (Stoffel et al., 2009; Spötl et al., 2014; Kern et al., 2018). The various climate and environmental proxies archived in these deposits (e.g., isotopologues of water and CCC, pollen, surface-derived sediments) offer a unique window in the past history of the environment and have been targeted with increased scrutiny over the past decades.

PAST CAVE ICE DRILLING PROJECTS

The first documented cave ice core was extracted from Scârisoara Ice Cave (Romania) in 1947 (Serban et al., 1948), and additional trials were performed in the 1960s (Serban et al., 1967) although these first attempts could extract only short (< 1 m) ice cores. Following these pioneer works there was a halt in the cave ice drilling projects for more than 3 decades. The next documented ice core (and the first outside Europe) was extracted from Candelaria Ice Cave (New Mexico, United States) in 1995 (Dickloss et al., 1997). Subsequently, Europe became the hotspot of cave ice drilling activities during the first decades of the 21st century. Twenty-three drilling projects took place in 20 ice caves (Table 1) and the total length of the extracted ice cores is ∼141 m (Figure 1A). First reports of cave ice drilling projects have usually been published following the biennial International Workshops on Ice Caves (IWIC). All but one cave ice drilling campaigns documented in the scientific literature were performed in the temperate mid-latitudes of the northern Hemisphere (Figure 1B). The only cave ice core representing a polar latitude was extracted from Svarthammarhøya (Norway) (Lauritzen et al., 2005). The publication evidence shows the greatest concentration of cave ice cores in Central Europe, the Southern Alps (Italy and Slovenia) and the Western Carpathians (Romania) (Figure 1A). Replicated ice cores were extracted from subterranean ice deposits only in Romania and Cave 29 (New Mexico, United States) (Table 1).

The main objectives of these drilling projects were to reconstruct past climate variability using the isotopologues of water as climate proxies, a process initiated through the pioneering work of Serban et al. (1967) shortly after similar efforts were initiated in Greenland. These early efforts were continued in 20th century, with varying degrees of success, mostly due to difficulties in building reliable chronologies of ice accumulation (Kern, 2018). Thus, cave ice-based studies addressed the geochemistry and stable isotope geochemistry of cave ice (Kern et al., 2009; Kern et al., 2011a; Kern et al., 2011b; May et al., 2011), the dynamics of past winter (Persoiu et al., 2017) and summer (Bădăluța et al., 2020) air temperatures, past environmental and vegetation changes (Feurdean et al., 2011; Sancho et al., 2018; Leunda et al., 2019) and the dynamics of cave ice accumulations (Stoffel et al., 2009; Persoiu and Pazdur, 2011; Spötl et al., 2014; Kern et al., 2018). Over the past few years, several studies investigated microorganism in cave ice deposits, with specifically designed drilling strategies (Sattler et al., 2013; Itcu et al., 2018) allowing the recovery of millennia-old microbial (Mondini et al., 2019; Paun et al., 2019) and fungal (Brad et al., 2018) communities. Considering the wide geographical distribution of potential and confirmed area of cave glaciation (Mavlyudov, 2008; Mavlyudov, 2018) the current overrepresentation of Europe does not reflect the spatial distribution of the known ice caves in the World. There is great potential in cave ice science, including drilling the cave ice deposits, outside Europe as well. Interestingly, three of the six published cave ice drilling projects were carried out in non-European ice caves (Cave 29, New Mexico, United States - Onac et al., 2020, Kinderlinskaya and Askinskaya caves, Russia - Trofimova et al., 2020) in the closing year of the data collection of this review.
(Table 1). This may suggest that cave ice drilling projects may also start in parts of the geographical distribution range of ice caves outside Europe in the near future.

With few exceptions, where the morphology of the caves and ice blocks allowed for direct access to lower (and thus older) ice layers, most of the drilling efforts were concentrated on drilling vertical boreholes through the ice. Thirteen of the 23 ice core drilling projects employed a machine operated auger and simple manual drilling device was used in eight projects (no technical details were reported for 2 cases, Table 1). Because several of the largest ice caves (e.g., Scărișoara Ice Cave in Romania, Dachstein-Rieseneishöhle in Austria) are managed as show caves, the installed electric wiring allowed operating a drilling device driven by an electric motor in these caves. Light-weight, portable drill systems developed by and named after the Snow, Ice and Permafrost Research Establishment (SIPRE, Rand and Mellor, 1985) and Polar Ice Coring Office (PICO, Koci and Kuivinen, 1984) were used most frequently in these cases (Table 1).

Complete darkness in the caves and the general remote location of ice deposits within caves challenges the use of solar powered drilling devices, so a solar-powered drilling rig (FELICS abbreviated from Fast Electromechanical Lightweight Ice Coring System, Ginot et al., 2002) was used only for one project (Monléï Ice Cave, Luetscher et al., 2007). Poor ventilation in caves further excluded the usage of on-spot generated electric energy (health risk and cave pollution impact due to stagnation of exhaust fume). In a special situation a generator was operated outside the Focul Viu Ice Cave (Maggi et al., 2008; Bădăluță et al., 2020). Thus, due to limitations in access to the caves, manual augers were usually the only available drilling option. The most frequently applied device consisted of a self-designed simple walled auger coupled to an Eijkelkamp soil auger handle and rod system. The main weaknesses of this system are that the undisturbed sampling is not assured and the relatively small diameter of these augers strongly limited the available ice amount to be recovered (Kern et al., 2007b).

**CHALLENGES AND SUGGESTIONS FOR FUTURE ICE CORE DRILLING PROJECTS IN CAVES**

The “best” cores recovered from cave glaciers should contain an undisturbed sequence of ice layers, with no hiatuses induced during drilling and capable to offer data that responds to multiple research questions. All these are challenged by the characteristics of the ice itself and of the ice blocks, the processes acting after deposition and the difficulties of drilling in a cold, dark and remote environment. In the following, we will discuss the main issues and propose potential solutions (or at least suggestions to be improved upon).

The main challenges encountered during drilling cave ice deposits result from the nature of the ice itself (see section 2 above). Combining the high density of the ice with the (generally) low power (electric or manual) applied to the drilling machines results in low penetration speeds. The succession of clear ice and
layers of impurities (containing both cryogenic cave calcite and surface-derived sediments) that build-up most of the cave ice blocks results in a sedimentary structure with very low cohesivity between the individual layers, prone to shearing, thus resulting in low-quality ice cores. Second, once formed, cave ice blocks have a dynamic that is shaped by both glacial and karstic-specific processes (Perşoiu and Lauritzen, 2018). The high plasticity of ice, combined with the usually inclined topography of the cave floor and the possible presence of breakdowns below the ice, leads to slow flow-like movement of the entire ice mass. The flow is further complicated by the uneven melting at the sole and sides of the ice blocks and the morphology of the surrounding walls, so that folds and tilting of the ice layers up to the vertical (Figure 2) are a common occurrence (Perşoiu and Pazdur, 2011; Spötl et al., 2014). Additionally, as most of the ice caves are located close to or well below the altitude of the 0°C isotherm, annual melting affects both the surface and sides of the ice blocks, with extreme ablation events possibly leading to the ablation of several years’ worth of annual accumulation (Colucci et al., 2016a; Perşoiu et al., 2021). Ablation could affect either the entire surface of an ice block or only part of it, and also acts on time scales ranging from years to centuries.

Ice cave monitoring studies reported cave ice temperature usually in the range of -4 to 0°C (Luetscher et al., 2008; Strug et al., 2008). Attempting of core drilling in such warm ice is not recommended with the SIPRE augers (U.S. Ice Drilling Program, 2019). Drilling ice close to melting point, is extremely difficult with electromechanical drills because as the drill penetrates into warm ice, the ice particles from the cutting area melt and freeze again in a stiff mass stuck on the cutting ring face (Murariu et al., 2013) and the performance of the drill rapidly deteriorates to a point where penetration...
TABLE 2 | The main problems and solutions in ice core drilling in cave environment.

| Problem                              | Cause                                | Solution                                           |
|--------------------------------------|--------------------------------------|----------------------------------------------------|
| Drilling stopped and drill hole was abandoned | rock and wood in the ice             | avoiding such objects visible under the ice surface, GPR survey to check major objects in deeper ice layers |
| Broken core                          | CCC layers creating shearing surfaces | High speed drilling                                 |
| —                                    | Vibrating extension rods             | Modify the connections between the extension rods to make the entire pole rigid |
| Skidding of cutters on top of the ice at the bottom of the hole | Refrozen water and CCC               | Screws inserted between the cutters to scratch the top of the hardened surface |
| Blocked drill in the drilling hole   | Heat generated by friction melting of the ice and keeping a motionless auger at the bottom of the drill hole resulted in quick freezing of water |
| Ice chips at the bottom of the drill hole, machine idling on top a rotating ice mass | Warm (0 to –2°C) temperatures and broken ice chips accumulating at the bottom of the drill hole |

stops (Talalay et al., 2015). As a practical solution it was suggested that the drillers can be forced to stop, bring back up the core barrel frequently and the drilling can be continued after cleanout the ice (Murariu et al., 2013), an approach that was successfully used in Scărișoara Ice Cave (Romania).

Clastic and organic debris are commonly observed in cave ice deposits and represent another type of difficulty seldom experienced in surface ice bodies. Clastic debris is produced by periglacial processes leading to intense weathering of the cave walls and continuous accumulation (and subsequent incorporation in ice) of pieces of limestone of varying sizes. Cave ice drilling projects frequently reported that such rocky (Lüetscher et al., 2007; Vrana et al., 2007; Sattler et al., 2013; Bădluță et al., 2020) or woody (Kern et al., 2004; 2011b) debris embedded in the ice caused problems or completely stopped the drilling effort. The coarse rocky debris can wear out the cutting edge of the auger in a relative short time, so an easily replaceable cutting teeth system can be required in the field (see section 4.1). Obviously the spots with large rocks or logs visible in a shallow depth in the transparent ice must be avoided when looking for a drilling spot (see section 4.2). However, surveying the deeper interior of the ice block can be extremely useful before the selection of the drilling spot. Ground Penetrating Radar (GPR) is capable imaging the internal structure of the ice and its basal topography (Hausmann and Behm, 2011; Colucci et al., 2014; Gómez Lende et al., 2016; Munroe, 2021). GPR survey of the ice block not only helps to avoid the sectors of the cave ice with embedded rocks but also provides information about the thickness of ice cave deposits hence finding the thickest accessible cave ice sequence.

The combination of all these factors generally leads to a complex stratigraphy of any cave ice block, making a unitary interpretation rather impossible. To address these challenges, we have developed 1) a dedicated drilling device for cave glaciers (Murariu et al., 2013) and 2) a “Cave Ice Sedimentary architecture and deposition (CISAD)” approach to investigating subterranean cave ice deposits. This approach has been used in several past (Pešoiu et al., 2017; Bădluță et al., 2020) and ongoing studies in caves in Romania, Norway, Greece, Slovakia, Slovenia, Croatia etc.

Cave Ice Drilling Auger
The ISER-HD1 auger is a modified PICO electric drill (Koci and Kuivinen, 1984), build by Heavy Duties SRL (Cluj-Napoca, Romania). It consists of a core barrel with a cutting head, extension rods and a 220 V driving engine (Murariu et al., 2013). The barrel is 100 cm long and with an interior diameter of 10 cm. In addition to the original PICO device, the cutting head was fitted with four cutters made of 42CrMo4 alloy steel, with a rake (leading) angle of 30° (may vary from 30° to 45°) and a relief angle of 10° (may vary from 10° to 15°). The slightly lower angles of the main cutters were chosen to allow for slower penetration under low power in the

1Emil Racoviță Institute of Speleology – Heavy Duty
cave ice deposits with a density far higher than that of surface ice in mountain and polar glaciers. Additionally, the low angles allow for easier cutting through layers of CCC up to 3 cm thick and through occasional wood found in ice (Bădăluţă et al., 2020). Adjustment screws were incorporated between the cutters to regulate the penetration speed. Both the screws and the cutters were fitted with screws to allow for quick replacement in the field, as the presence of CCC and allochthonous dues worn out the cutting edge. In the few cases when a thin layer of refrozen water and CCC formed an impenetrable hard surface at the bottom of the drillhole, the adjustment screws were replaced with long screws reaching below the main cutters and these were used to break-up the refrozen layer. The cutting head has two helical paths that direct the ice chips towards similarly placed helical spirals along the barrel and further inside it, through several 30 cm diameter holes. Two spring-loaded core dogs were fitted to the cutting head to hold the core after each run. The extension rods are made of aluminum alloy 6060 (Murariu et al., 2013) and the engine is a 220 V, 1.8 kW reversible engine, with a variable maximum speed of 1,300 rpm. This device was tested in two ice caves in Romania, Scârlătova Ice Cave and Focul Viu ice Cave, on several occasions between 2012 and 2016. The drilling auger has been deployed to drill both vertically and horizontally, allowing the recovery of ice core down to a depth of 25 m below surface (Bădăluţă et al., 2018), using power drawn from both the national electric grid and a gasoline generator. The main problems and solution we have encountered are listed in Table 2.

Cave Ice Sedimentary Architecture and Deposition (CISAD) Approach

Forced by the shape of the cave passage system, cave ice deposits often have complex geometries (Gómez-Lende and Sánchez-Fernández, 2018) and dynamic processes active in ice caves regularly obscure and/or modify further the original morphology and stratigraphy of the perennial ice blocks targeted by drilling efforts. Consequently, the assumption that an ice core drilled vertically through the ice block will intersect only chronologically ordered layers is often falsified by the findings (see for example figures in Holmlund et al., 2005; Stoffel et al., 2009; Spöl et al., 2014; Lauritzen et al., 2018). These problems are mainly affecting smaller cave glaciers, whereas large ice blocks (> 30,000 m³) are less affected, at least partly, and layers in stratigraphic order can be drilled (Maggi et al., 2008; Kern et al., 2009; Perişoiu et al., 2017; Bădăluţă et al., 2020). However, even such large cave glaciers can be affected by post-depositional processes (Figure 2), with newly formed ice layers covering old ones (Figure 2A) and potential contamination of old ice with modern water and organic matter, tilting of the strata (Figure 2B) and successive periods of melting and accumulation resulting in a complex cut-and-fill structure (Figure 3). The aim of virtually all ice core drilling efforts is to obtain an undisturbed record of past environmental variability but this is hampered by the problems detailed above. To partly address this conundrum, we propose an approach that takes into account the mechanisms leading to ice formation and accumulation and those affecting the already formed ice block.

First, the processes responsible for ice formation must be understood, especially when the stable isotope composition of oxygen and hydrogen in water is the main target. Whereas snow accumulation will likely result in the successive accretion of ice layers preserving the original δ¹⁸O and δ²H values, in a manner similar to ice wedges (e.g., Meyer et al., 2015). Contrary, downward freezing of stagnant pools of water will result in an ice layer with a strong δ¹⁸O and δ²H gradient (Perişoiu et al., 2011), with the upper (first to freeze) layer enriched in the heavy isotopes (¹⁸O and ²H). Consequently, drilling through such a layer will yield a stable isotope gradient, potentially be interpreted as indicating a climatic change, albeit a false one. Therefore, analyzing the stable isotope composition of ice core retrieved from cave ice deposits requires the identification of genetic layers, either in ice cores or in the field (Figure 3) and sampling should be done considering this layering. For example, the ice layers indicated by red arrows in Figure 3 likely formed as shallow pools of water froze. The stable isotope composition of oxygen and hydrogen in that ice would reflect that of the original water (and thus hold a putative climatic information) only of the entire layer of ice is considered as one sample—and thus drilling should be made accordingly.

Second, the post depositional processes affecting any ice block result in often complex stratigraphy, that preserves the history of the glacier but not always that of the climate changes during its lifetime. Before drilling for a continuous record of past climate change, this stratigraphic history must be understood (Citterio et al., 2003; Stoffel et al., 2009). For example, the ice block shown in Figure 3 (Svarthammarholma, Norway) underwent several episodes of melting, tilting and accumulation. The structure and composition of the lower layers (unit A), suggest slow freezing of shallow pools of water. Several episodes of enhanced melting with inflow of external water carrying soil and macrofossils (dark layers in the lower half of unit A) interrupted this accumulation. The upper part of unit A was likely affected by a severe melting episode, that led to the removal of part of it (Figure 3). On top of this truncated unit A, a new layer of ice formed—unit B. Melting at the sole of the glacier tilted the block, leading to the inclined appearance of both units A and B. Subsequently, shallow ponds formed on top of unit B and a new unit started to develop—unit C. Depending on location, this unit is between 0.5 and 4.4 m thick (see the left and right ends of unit C in Figure 3). The ice layers within unit Care a combination of lake ice and floor ice. A severe flooding episode likely affected the ice block (thick brown layer capping unit C) and ice accumulation resumed afterwards, with both lake and floor ice
accumulating (unit D). The consequence of these different processes is that a continuous ice core cannot be directly extracted from the sequence shown in Figure 3. First, the likely loss of ice due to the melting events that truncated units A, C and possibly B resulted in the loss of continuity of the record. Second, depending on the position of a potential core, the age of successive ice layers could be very different. Third, the genetically different types of ice layers visible in unit C, must be targeted differently in order to obtain meaningful stable isotope data (the strong kinetic fractionation associated with the freezing of lake water shown by the red arrows likely resulted in extremely variable δ18O and δ2H values). Fourth, freezing, melting, refreezing and inflow of water mixed the organic matter that could provide a chronological anchor for the entire sequence. The layers capping units A, B and C likely contain a mixture of 1) organic matter derived from the top of any of the considered units following melting, 2) material transported during the melt event and 3) material deposited when accumulation resumed. In this case, as well as in others (Persoiu and Pazdur, 2011; Spötl et al., 2014; Kern et al., 2018; Munroe et al., 2018; Sancho et al., 2018), this sequence of events could have been separated in time by years or centuries, thus preventing the formation and preservation of a continuous sequence of climatic events. The white dashed lines numbered one to five shown in Figure 3 suggest the potential location of drilling efforts that would maximize the length of a paleoclimate record. Obviously, vertical drilling would totally miss this, hence horizontal drilling is the only possible course of action.

In the light of the above, we propose the following approach—which we call the Cave Ice Sedimentary Architecture and Deposition (CISAD) approach—in establishing the location of a drilling site best-suited to obtain valuable paleoclimate data. The morphology of ice caves usually allows drilling to be performed either vertically or laterally (i.e., on a layer-by-layer approach, Figure 2B), depending on the results of the CISAD analyses.

1. Detailed stratigraphic investigation of the ice sequence and delimitation of genetically unitary stratigraphic units
2. Identification of the ice layer forming processes (snow accumulation, freezing of water as either floor or lake ice), uniquely important for the interpretation of stable isotope data.
3. Establishment of the chronology of ice deposition, separately for each stratigraphic unit. The most important one and also the most difficult to date are the layers separating individual units, we thus recommend avoiding them and target the layer closest to the bottom and top of the unit that contain datable material (14C, 2H).

While this methodology will inevitably lead to the loss of continuity (but we stress that this has already been lost if unconformities are present in the sequence) and of “some” years from a potentially long record, it nevertheless is the only one that offers trustful ages.

4. Correlation of the “floating” records based on relative positions (stratigraphy-based), rather than on depth below surface (above bottom) or chronology. The later issue is especially important, as, depending on the process affecting an ice block in the past, different parts of it could preserve partly overlapping sequences, but which could be discontinuous and hence the desire to obtain continuous records might lead to erroneous results.

5. Detailed knowledge of the ice forming mechanism(s) and of those responsible for proxy incorporation in ice (e.g., stable isotopes, pollen) are mandatory.

AUTHOR CONTRIBUTIONS

ZK and AP designed the project and contributed equally to the writing of the manuscript.

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