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The impact of fire on the geochemistry of speleothem-forming drip water in a sub-alpine cave

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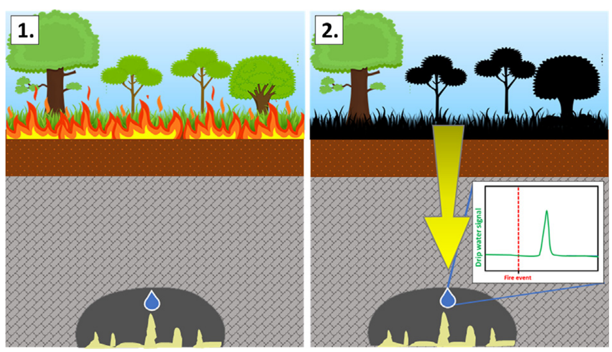
HIGHLIGHTS

- Speleothem paleoclimate records could be inaccurate if the impact of fire is not accounted for.
- We explored the interaction of fire (biosphere) and cave drip water (lithosphere and hydrosphere).
- Drip water geochemistry was measured before and after a low severity fire event.
- Low severity fires affect trace element and $\delta^{18}O$ speleothem-forming drip water.
- B and Pb are potential tracers of paleofire in speleothem proxy records.

GRAPHICAL ABSTRACT



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ABSTRACT

Fire dramatically modifies the surface environment by combusting vegetation and changing soil properties. Despite this well-documented impact on the surface environment, there has been limited research into the impact of fire events on karst, caves and speleothems. Here we report the first experiment designed to investigate the short-term impacts of a prescribed fire on speleothem-forming cave drip water geochemistry. Before and after the fire, water was collected on a bi-monthly basis from 18 drip sites in South Glory Cave, New South Wales, Australia. Two months post-fire, there was an increase in B, Si, Na, Fe and Pb concentrations at all drip sites. We conclude that this response is most likely due to the transport of soluble ash-derived elements from the surface to the cave drip water below. A significant deviation in stable water isotopic composition from the local meteoric water line was also observed at six of the sites. We hypothesise that this was due to partial evaporation of soil water resulting in isotopic enrichment of drip waters. Our results demonstrate that even low-severity prescribed fires can have an impact on speleothem-forming cave drip water geochemistry. These findings are

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Wildfire
Paleofire

significant because firstly, fires need to be considered when interpreting past climate from speleothem $\delta^{18}O$ isotope and trace element records, particularly in fire prone regions such as Australia, North America, south west Europe, Russia and China. Secondly, it supports research that demonstrates speleothems could be potential proxy records for past fires.

1. Introduction

Fire changes the surface environment by combusting vegetation and altering the soil geochemistry (Neary et al., 1999; Raison, 1979; Santín et al., 2012). The combustion of vegetation, litter layer and topsoil change the soil geochemistry by mobilising elements as ash which may then be leached (Campos et al., 2015a; Santín et al., 2015). Ash composition varies according to nutrient content of different vegetation types (Yusiharni and Gilkes, 2012). Fire temperature and elemental solubility affect the type and concentration of elements in ash and thus their availability for leaching into the environment.

To our knowledge, there has been no research into the transfer of ash-derived elements into the vadose zone. However, the transport of ash-derived elements to surface water has been well-documented because of concerns about contamination of water for human consumption (Abraham et al., 2017a, 2017b), heavy metal remobilisation from industrial sites (Odigie and Flegal, 2011) and the negative effects of wildfires on aquatic ecosystems (Silva et al., 2015). Caves provide the opportunity to quantify this process as the geochemistry of water infiltrating into the cave from the vadose zone can be directly measured.

There has been limited research on cave drip water response to wildfires (Nagra et al., 2016; Treble et al., 2016) and some evidence for limited wildfire impact on speleothem geochemistry in regards to the post-fire $\delta^{18}O$ signal in cave drip water (Nagra et al., 2016), the solute concentration in drip water (Treble et al., 2016) and decreases in soil CO_2 concentration (Coleborn et al., 2016b). These studies were carried out to consider firstly, the impact of wildfires on caves to ensure effective fire management of karst environments and secondly, to assess the potential of using speleothem proxies (e.g. $\delta^{18}O$) to record historic wildfires and thirdly, to correct the paleo-climate interpretation for fire signals.

Treble et al. (2016) showed that there was a multi-decadal impact on cave drip water response due to the post-fire vegetation regrowth above the cave that was largely attributed to the increased demand for water and nutrients by the overlying forest. Regrowth resulted in a long-term rising trend in drip water solutes as transpiration increased. An exception to this was SO_4 concentration which demonstrated an overall falling trend attributed to increasing nutrient demand from the regenerating vegetation. In shallow systems, there is potential for drip water to be evaporated during storage in the unsaturated zone and thus be enriched in ^2H and ^{18}O (Cuthbert et al., 2014). Nagra et al. (2016) showed that post-fire evaporation plays an additional important role in modifying drip water hydrochemistry in shallow cave systems, concluding from the presence of ^{18}O-enriched drip waters that evaporation was the dominant process modifying drip water composition. Coleborn et al. (2016b) demonstrated that wildfires have a long-term (5–10 year) impact on soil CO_2 concentration. The authors measured lower soil CO_2 concentrations in a woodland area burnt in a fire 5 years prior and attributed this to reduced above-ground biomass. They suggested that this could lead to lower karst dissolution rates and decreased calcite precipitation in underlying caves.

This research reports the first prescribed fire deliberately ignited to investigate the short-term (<1 year) impact of a fire on speleothem-forming drip water geochemistry. This research is motivated by a need for science-based evidence for fire management strategies in karst environments. Understanding the impact of fire on cave drip water is essential for interpreting speleothem paleo-environmental proxies, such as ^{18}O and trace elements, because fires could be impacting drip water geochemical composition and ultimately speleothem composition, which could be misinterpreted as climate variability.

A prescribed fire was ignited in April 2015 and pre-and post-fire elemental concentration (Ca, Mg, Sr, B, Fe, Pb, Si, Na, Cu, Ni, Ti and Zn), SO_4 and stable water isotope data was collected from 18 drip sites in South Glory Cave, New South Wales, Australia. South Glory Cave is located within the Yarrangobilly Caves karst system, which has been extensively studied in terms of the hydrology (Campbell et al., 2017; Markowska et al., 2015; Tadros et al., 2016). The hydrology of South Glory Cave is well-understood from a previous study (Coleborn et al., 2016a).

2. Site description

2.1. Climate and fire history

The study site is in south-east New South Wales in Kosciusko National Park (Fig. 1). The region is sub-alpine and the climate is temperate montane with mild summers and no dry season (Köppen Climate CFb) (Stern et al., 2012). The mean annual precipitation is 1172 mm (Bureau of Meteorology, 2017) with more precipitation falling in winter (June–August) than summer (December–February). The mean monthly rainfall for summer and winter is 79 mm and 125 mm, respectively. The mean annual temperature is ~10 °C with mean minimum and maximum temperatures of ~9–25 °C in summer and ~−1–10 °C in winter (Markowska et al., 2015). The vegetation is classified as sub-alpine open snow gum (*Eucalyptus pauciflora* subsp. *pauciflora*) and black sallee (*E. stelullata*) woodland Coleborn et al. (2016b). The region is characterised by alpine humus soil dominated by organomineral horizons (Costin et al., 1952).

Yarrangobilly Caves was burnt during the fire seasons 1938–39, 1964–65, 2002–2003, in addition to the 2015 prescribed fire for the purposes of this study (described in detail in Section 3.1). Prescribed fires are used as a land management tool for 'hazard-reduction' purposes, increasing productivity or fertility of the land (Harper et al., 2018) and to conserve biodiversity (Office of Environment and Heritage, 2017), and are deliberately ignited and controlled by humans. Conversely, wildfires are generally unplanned and uncontrolled events and can be ignited through natural causes such as lightning strikes or intentionally and unintentionally by humans. Hazard-reduction prescribed fires are generally low to moderate intensity (Morley et al., 2004) and are used to reduce the amount of fuel on the surface and thus suppress the intensity of subsequent wildfires fires that are harder to control and more destructive. Wildfire intensity varies and is determined by the complex interaction of fuel load (Graham and McCarthy, 2006), climate (Podur and Wotton, 2010), wildfire frequency (Fidelis et al., 2010) and timing and length of fire season (Turetsky et al., 2011).

2.2. Yarrangobilly caves

South Glory Cave is part of Yarrangobilly Caves located in the Snowy Mountains, New South Wales. The cave system is located within the karstified unsaturated zone of westward sloping limestone bedrock (Worboys, 1982). The limestone is massive, highly karstified Silurian