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# Meteorological controls on ventilation, cave air $CO_2$ and speleothem deposition in Gibraltar caves: the challenge of extrapolating the modern system into the past

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Gibraltar caves, in common with many other systems, undergo seasonally reversing dynamic ventilation. Variation in cave air $pCO_2$ closely controls $CO_2$ degassing of drip waters and speleothem fabrics. Proxy capture and isotope fractionation are controlled by the mixing of advective $CO_2$-rich ground air with background atmosphere. Extrapolating the significance of the ventilation-advective system to times past is hampered by artificial entrances which have altered airflow patterns in natural caves. Although modelling of advective airflow shows that tunnels amplify ventilation in Gibraltar caves, ‘modern-style’ paired laminations are observed in older speleothem, provide compelling evidence for a ventilation-advective system permeating Gibraltar karst in the past.

This study focuses on the meteorological controls acting on cave air $pCO_2$ in the modern dynamic system and identifying which of these are relevant to an interpretive framework that can be applied over longer timescales. We compare data for cave air $CO_2$ measured simultaneously at 2h intervals at eleven locations in New St Michaels Cave (NSM, 240-270 m altitude) and Ragged Staff Cave, (RS, 0 - 70 m altitude). These detailed records reveal lateral and vertical spatial patterns of cave air $pCO_2$ over six seasonal cycles. The most striking properties of the $CO_2$ records are 1) annual seasonality in cave air $pCO_2$ showing an antiphase relationship between caves in NSM and RS, and 2) that the high $pCO_2$ seasons (November to April in NSM and April to November in RS) are disrupted by frequent and large fluctuations in $pCO_2$ which occur on hour-day timescales.

With respect to palaeoclimate reconstructions, the first order controls on $pCO_2$ are 1) the processes that regenerate and maintain the ground air reservoir (soil organic matter production rates and downwash by rainwater recharge), and 2) the range in seasonal mean daily temperatures which creates buoyancy-driven ground air advection throughout the unsaturated zone. Rapid fluctuations in cave air $pCO_2$ during the high $pCO_2$ (incoming ground air) season are second-order effects which may also accumulatively control the net extent of seasonal degassing associated with calcite deposition. These are caused by changes in the ground air-atmosphere mixing ratio linked to synoptic-scale patterns of 1) diurnal temperature range and 2) ambient wind conditions.

Rapid changes in the balance between ventilation and ground air advection occur when the when rock core temperature is bracketed by the diurnal range on cool summer days or warm winter days. These conditions are often associated with Atlantic frontal systems. Longer periods of persistently weaker seasonality would also impact on the net seasonal $pCO_2$ and decadal patterns in the speleothem $\delta 13C$ record. A secondary but important systematic control by wind direction on cave air $pCO_2$ is also observed, but this is often overridden by fluctuations in daily temperature. Should seasonal temperatures become more stable, the $\delta 13C$ record may include a component of variation related to the local wind-field. Whilst monitoring refines palaeoclimate reconstructions this deeper knowledge also shows that interpretive frameworks may need to be adapted for application to different palaeoclimatic regimes.