

Cave monitoring and calibration of a $\delta^{18}\text{O}$ -climate transfer function for a Gibraltar speleothem

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Speleothems represent a fast and direct record of local climatic events and provide rich archives of past climate change. Interpretation of speleothem isotope proxies in terms of regional climate change requires a good understanding of what features of local climate they record, and the relationships between local and regional climate systems (McDermott, 2004; Fairchild et al., 2005). Cave monitoring plays a vital role in understanding the links between seasonal and synoptic-scale weather events and the capture of the $\delta^{18}\text{O}$ signal in speleothem calcite, which can be traced back to incoming rainfall via a set of processes that may operate in a multitude of different ways, even within the same cave system.

Cave monitoring in Gibraltar

Cave systems in Gibraltar are in close proximity to the location of the longest instrumental climate (back to 1792) and precipitation isotope (from 1962) records in the Mediterranean region, and are therefore an ideal location to test and calibrate modern capture processes under different cave environments (Mattey et al., 2008). A comprehensive cave monitoring

program began in June 2004 in the New St. Michaels Cave system, using new data logging systems designed specially for the Gibraltar project. These included a drip counter that records water discharge at high resolution and a multi-channel monitoring system that simultaneously records CO_2 concentrations at two hourly intervals from seven different sites within the cave system (Fig. 1).

The seasonality in rainfall, drip rates, cave-air CO_2 concentrations and drip water chemistry are shown in Figure 2. Drip monitoring focused on three sites where speleothem deposition is taking place and reveals strikingly different hydrological regimes, even where drip sites are only meters apart. The site showing the highest

discharge rates in Figure 2 is forming new flowstone from highly supersaturated water that dye tracing has shown to descend down bedding planes from a recharge area near the summit of the rock. The discharge pattern at the flowstone site does not immediately respond to the onset of winter rain and suggests the operation of a siphon, where water is accumulating in a reservoir before siphoning over to create the main discharge, which then gradually declines for the rest of the year.

Drip responses for the two other sites (Gib04 and Dark Rift; Fig. 2) indicate that these sites are fed by water percolating downwards across bedding planes from a recharge zone vertically above the cave. The deeper of the two sites, Gib04a, is lo-

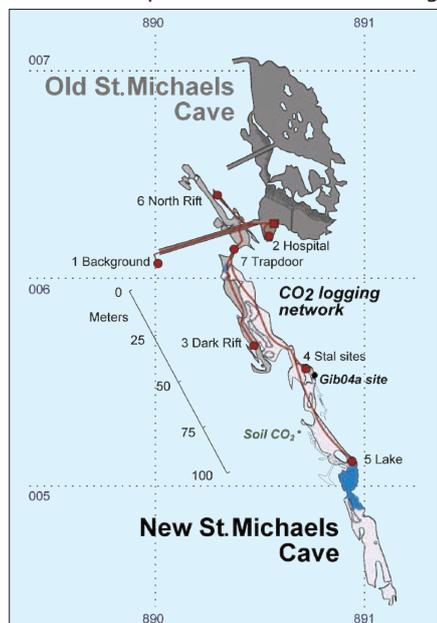


Figure 1: Plan view of the St. Michaels cave system. The show cave (dark gray) and the New St. Michaels system (light gray) are located near the summit at an altitude of 300 m asl. Red circles mark position of monitoring sites at cave entrance (1) and within the cave (2-7); 'Soil CO_2 ' marks the position of the soil monitoring site above the cave. The tube network leading back to the CO_2 analysis and logging system (red square) is shown as red line. Isotope data for a stalagmite from the Gib04a site is shown in Figure 3. Grid lines are 100 m UTM coordinates. Figure adapted from Mattey et al., 2008.

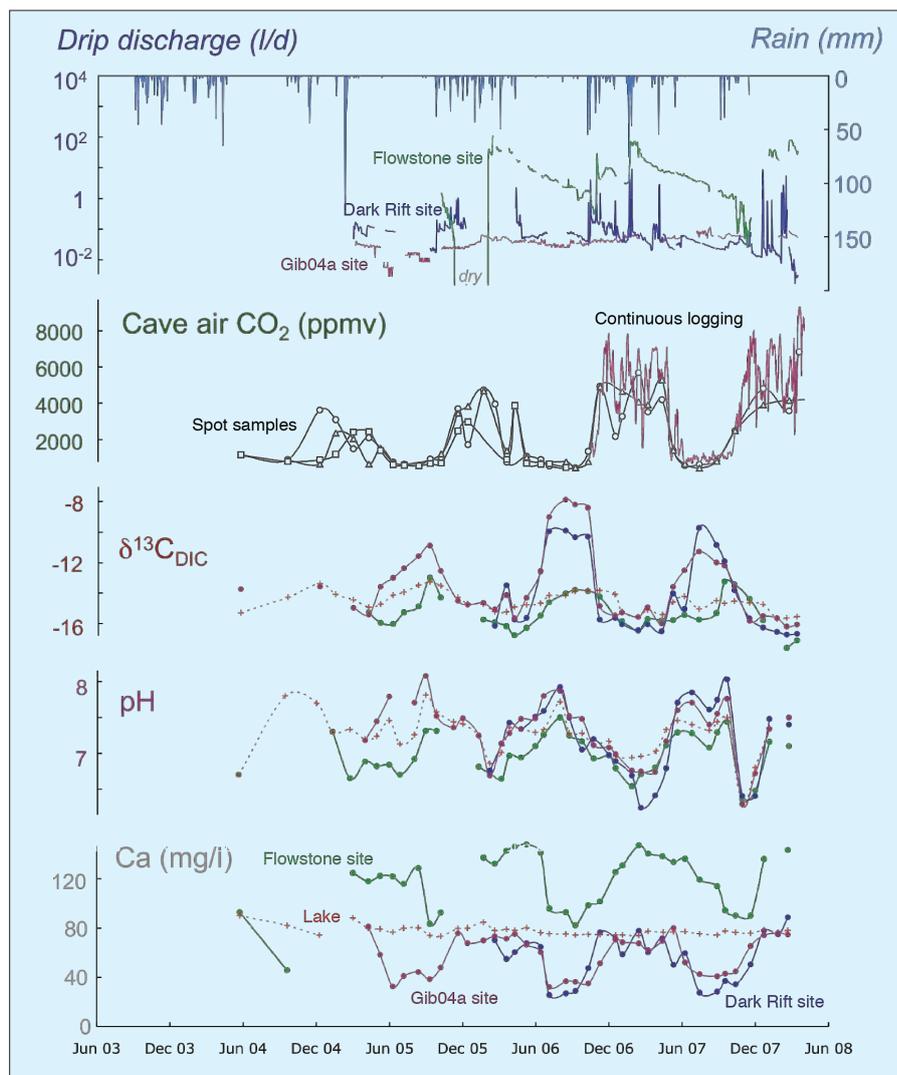


Figure 2: Some results of the cave monitoring in New St. Michaels Cave from June 2004 to April 2008. From top to bottom: Daily rainfall (light blue; Crown Copyright, the Met Office); drip discharge at sites Flowstone (green), Dark Rift (blue) and Gib04a (dark pink), measured at 30-min. resolution by acoustic drip counting; concentration of CO_2 in cave air by spot sampling at three sites (dark gray curves) and by continuous logging at 2-hr resolution at the Gib04a site; $\delta^{13}\text{C}$ of dissolved bicarbonate, pH and Ca ion concentration in drip waters (same color notation as discharge curves) and in the lake (red crosses).

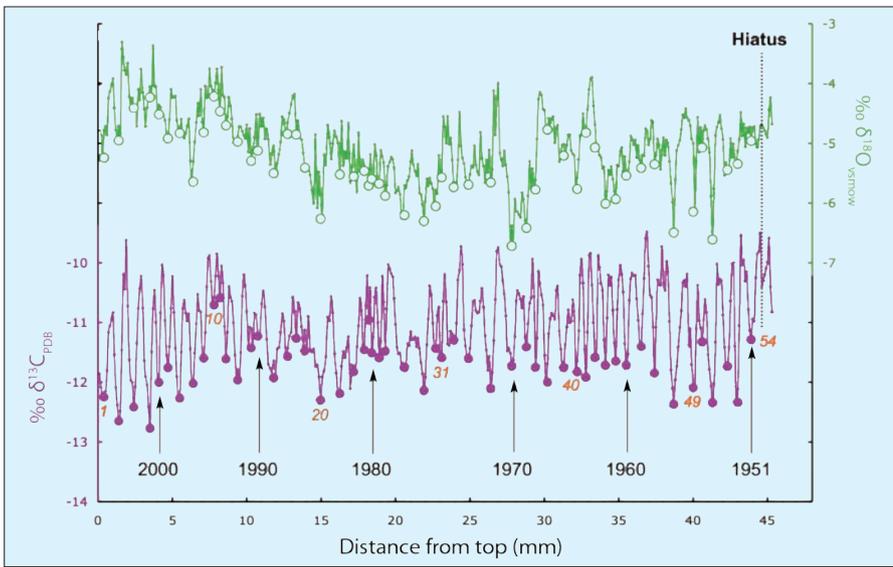


Figure 3: The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ time series obtained by contiguous micromilling in 100 μm steps plotted as a function of distance from top of Gib04a. $\delta^{13}\text{C}$ minima, representing calcite deposition in April, are marked with closed circles and the corresponding $\delta^{18}\text{O}$ values are plotted as open circles. Annual cycle numbers (orange) and age model relative to year 2004 are also shown. Figure adapted from Matthey et al., 2008.

cated only a few meters from the siphon site described above but shows a very different drip response to rainfall. Here, discharge rates are very low throughout the year, in the order of 40 to 80 ml/day, with only a weak response to incoming winter rain. In contrast, the Dark Rift site, situated among bedding planes at a higher level where the roof thickness is thinner, shows a fracture flow response where drip rate is highly correlated with rain events.

Cave air CO_2 concentrations have been measured from spot samples taken at monthly intervals since 2004, and continuously from October 2006 by the multichannel logging system. CO_2 concentrations show strong seasonality caused by

a reversing ventilation pattern driven by the difference in temperature between the cave interior and exterior. Ventilation is not just taking place through local artificial or natural entrances, as these can be temporarily closed off with no effect on the overall seasonal pattern. The results suggest that the ventilation is a diffuse process exploiting fissures through the Gibraltar limestone, which allows large-scale winter convection of CO_2 -rich ground-air through the high-level cave systems.

The cave-air CO_2 levels change by almost an order of magnitude from summer to winter and pCO_2 is the main forcing mechanism controlling drip water degassing and calcite precipitation. The

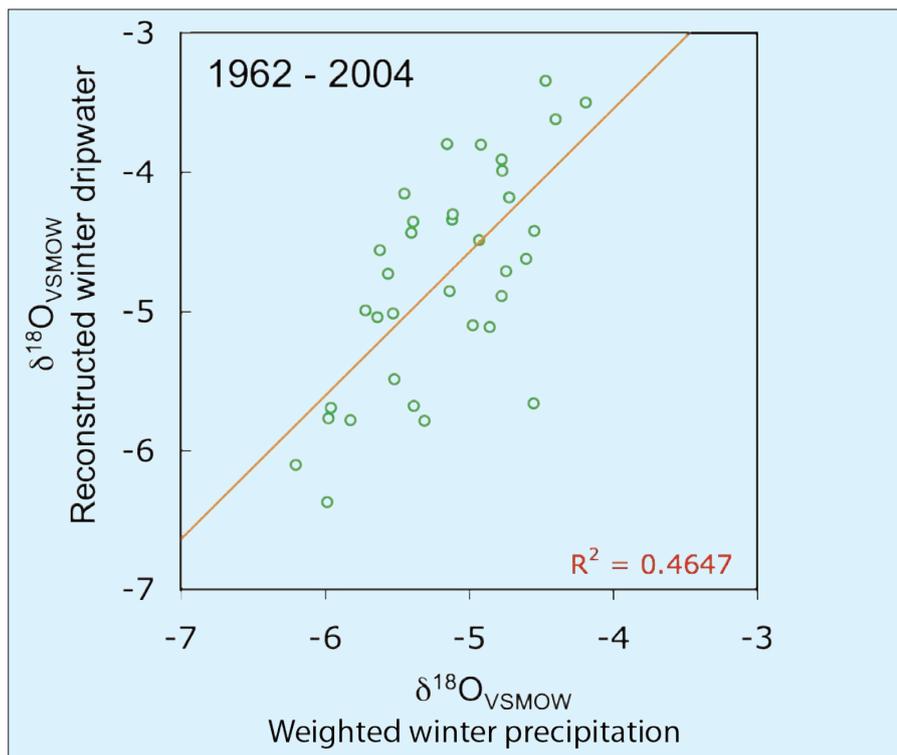


Figure 4: Correspondence of the $\delta^{18}\text{O}$ of reconstructed winter dripwater with $\delta^{18}\text{O}$ of weighted October-March precipitation for 1961 to 2004 (IAEA/WMO, 2004). Figure adapted from Matthey et al., 2008.

seasonal changes in cave air CO_2 strongly influence drip water pH, $\delta^{13}\text{C}$ of dissolved bicarbonate and Ca concentrations, which all co-vary with CO_2 (Fig. 2). The enhanced degassing when the cave is ventilated with outside air during the summer drives $\delta^{13}\text{C}$ to higher values (Baker et al., 1997; Bar-Matthews et al., 1996; Spötl et al., 2005), resulting in rapid deposition of calcite, which develops a distinctive compact fine-grained microporous texture. High CO_2 levels in the winter result in slower calcite precipitation to form more massive elongate crystals, and year-by-year the speleothem fabric develops as pairs of laminae representing alternate summer and winter growth (Matthey et al., 2008).

An actively growing speleothem at the Gib04 site with well-developed paired laminae also preserves spectacular seasonal oscillations in $\delta^{13}\text{C}$ in the calcite (Fig. 3) (Matthey et al., 2008). Monitoring of drip water bicarbonate $\delta^{13}\text{C}$ demonstrates that the minimum $\delta^{13}\text{C}$ values in the calcite must develop towards the end of the winter season (April-May), and this places a crucial time marker on the more complex $\delta^{18}\text{O}$ record of the annual hydrological cycle. The isotopic composition of Gibraltar rainfall varies by up to 8‰, with winter rainfall dominated by the lowest $\delta^{18}\text{O}$ values but variability in the $\delta^{18}\text{O}$ of drip water, and hence the calcite depositing from it, can become attenuated by mixing and storage in the feeding aquifer (Cruz et al., 2005).

The attenuated oxygen isotope record in the active Gib04a speleothem still preserves a component of annual cyclicity that is superimposed on longer-term trends. The weak annual $\delta^{18}\text{O}$ cycles in the Gib04a speleothem record (Fig. 3) may be a result of evaporation of groundwater in the soil (Bar-Matthews et al., 1996) and operation of kinetic fractionation (Mickler et al., 2004), which may increase under 'summer' cave conditions when calcite supersaturation and precipitation rates increase as a response to low levels of cave CO_2 . The annual $\delta^{13}\text{C}$ cycles provide both a seasonal time marker and a precise chronology, which enables the $\delta^{18}\text{O}$ of late winter-deposited calcite to be identified for each calendar year. The calcite $\delta^{18}\text{O}$ values recalculated as drip water then provide an upper limit on the annual composition rainfall from 1951 to 2004, and can be compared to the local GNIP rainfall record, providing one of the first opportunities to test a speleothem "isotope recorder" against long instrumental records.

The correspondence between the $\delta^{18}\text{O}$ of reconstructed winter drip water and $\delta^{18}\text{O}$ of winter rainfall (as weighted

GNIP ONDJFM monthly values) is plotted against the $\delta^{18}\text{O}$ of reconstructed winter drip water and shown in Figure 4, which shows a significant correlation with $r^2 = 0.47$ and a slope of ≈ 1 . Such good correspondence between the instrumental precipitation isotope record and the oxygen isotope signal encoded in speleothem calcite shows that precipitation isotope time series can successfully be reconstructed from speleothem calcite and is an important milestone in producing a calibrated $\delta^{18}\text{O}$ -climate transfer function, which can then be applied to longer speleothem records.

Conclusions

Monitoring of cave processes over multi-annual time periods provides essential insight into the way that speleothems record climate, and is an important step towards defining the response times of the

cave and speleothem “recording systems” to changes in local climate and water balance. Close monitoring of just three sites in Gibraltar reveal significant differences in drip hydrology and speleothem forming processes, and to properly understand the drip water isotope evolution it could be necessary to monitor over 5–10 hydrological cycles to reveal the long term patterns. Monitoring for shorter periods still provides vital insight into the local processes that may bias the isotopic signal, and provides a framework for developing the calibrated $\delta^{18}\text{O}$ -climate transfer functions that are necessary to unlock the quantitative records that speleothems are capable of providing.

Acknowledgements

We thank John Ballestrino and Richard Durrell for help with cave sampling and Dylan Sheriff, the Gibraltar Tourist Office, Tito Vallejo and the guides of St. Michaels Cave for their coopera-

tion. Thanks to Jacqui Duffet and Rebecca Fisher for help with the analyses. Many of the ideas in this work were developed through discussion with Tim Atkinson and Ian Fairchild.

References

Bar-Matthews, M., Ayalon, A., Matthews, A., Sass, E. and Halicz, L., 1996: Carbon and oxygen isotope study of the active water-carbonate system in a karstic Mediterranean cave: Implications for paleoclimate research in semiarid regions, *Geochimica Et Cosmochimica Acta*, **60**(2): 337-347.

Fairchild, I.J., Smith, C.L., Baker, A., Fuller, L., Spötl, C., Matthey, D., McDermott, F. and EIMF, 2005: Modification and preservation of environmental signals in speleothems, *Earth Science Reviews*, **75**: 153-195.

Matthey, D., Lowry, D., Duffet, J., Hodge, E. and Frisia, S., 2008: A 56 year seasonally resolved oxygen and carbon isotope record from a modern Gibraltar speleothem: reconstructed dripwater and relationship to local precipitation, *Earth and Planetary Science Letters*, **269**: 80-95.

McDermott, F., 2004: Palaeo-climate reconstruction from stable isotope variations in speleothems: a review, *Quaternary Science Reviews*, **23**(7-8): 901-918.

Spötl, C., Fairchild, I.J. and Tooth, A.F., 2005: Cave air control on dripwater geochemistry, Obir Caves (Austria): Implications for speleothem deposition in dynamically ventilated caves, *Geochimica Et Cosmochimica Acta*, **69**(10): 2451-2468.

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Understanding climate proxies in southwest-Australian speleothems

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There are two avenues for comparing speleothem-derived climate proxy data against instrumental climate measurements: Via speleothems that have grown through the 20th century, and by carrying out dripwater monitoring studies. Both provide opportunities to investigate how speleothem geochemistry responds to changes in intra- and inter-annual variations in climatic parameters. Much work remains to understand these processes in general, and it is becoming increasingly apparent that such exercises are necessary to understand processes in individual caves, owing to the broad variation in climatic, geological and geomorphic environments that host speleothems. Here, we provide an overview of recent research findings from several cave sites in southwest Australia. Multiple geochemical proxies ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, P, U, Mg, Sr, Ba and Na) from calcite speleothems from this region have provided the longest duration (80 complete years from 1911-1992) calibration dataset between speleothem geochemistry and the instrument climate record. We use this case study of modern speleothem $\delta^{18}\text{O}$ and trace elements to provide examples of techniques for calibration and to highlight the importance of carrying out such investigations.

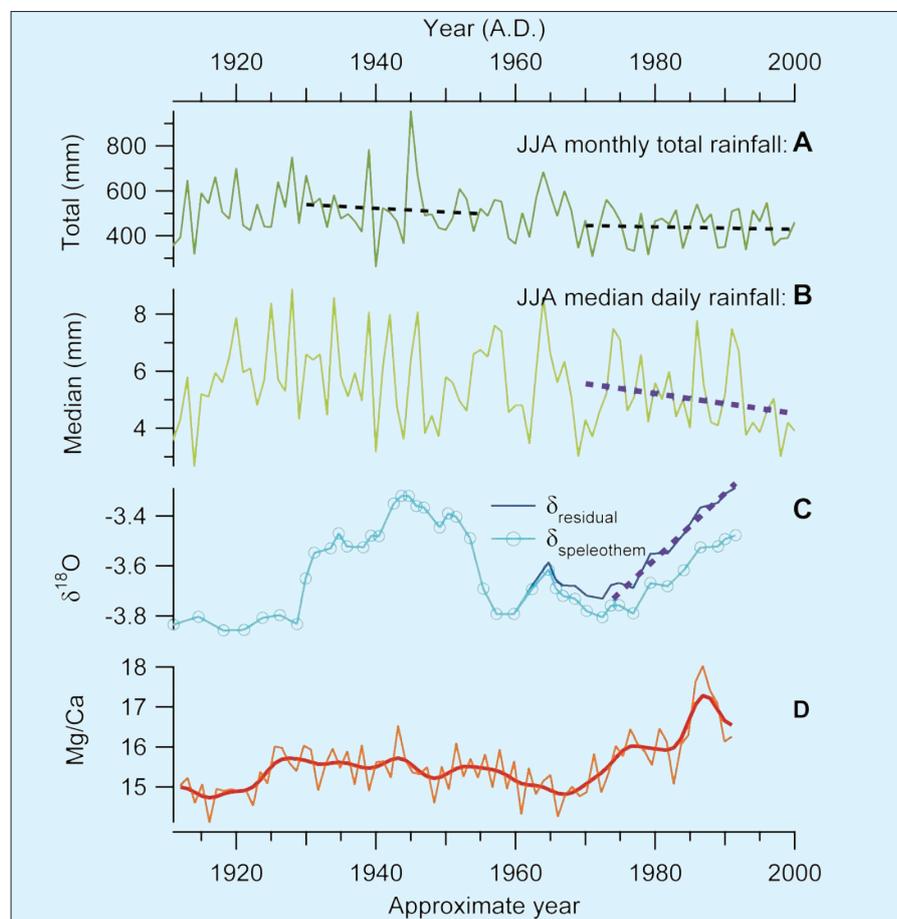


Figure 1: **A**) Perth total June-August rainfall (instrumental), **B**) median daily rainfall (instrumental), **C**) Moondyne Cave speleothem $\delta^{18}\text{O}$ and **D**) Mg/Ca ratios ($\mu\text{mol/mol}$). Speleothem $\delta^{18}\text{O}$ ($\delta_{\text{speleothem}}^{18\text{O}}$) is corrected ($\delta_{\text{residual}}^{18\text{O}}$) for the rise in mean temperature. Speleothem $\delta^{18}\text{O}$ increases during 1930-55, owing to a change in moisture source region (Fischer and Treble, in press).