CAVE DEPOSITS (SPELEOTHEMS) AS ARCHIVES OF PAST ENVIRONMENTS AND CLIMATES

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I had already been a researcher for 20 years when, despite never having been a recreational caver, the call came to go underground. The succeeding 20 years saw a wonderful sequence of research projects in which together with collaborators from elsewhere in the UK and Europe, and from Australia, I unravelled some of the secrets about how caves work and how climate history is encoded in calcareous deposits. These speleothems including downward-growing stalactites and upward-accreting stalagmites, both "dripstones", and flowstones, which form from water flowing over the walls and floor of a cave. Near the end of this 20-year period, and together with my erstwhile Birmingham colleague, Andy Baker, we published the first book (*Speleothem Science*, Wiley, 2012) to explain all these phenomena and to guide the next generation of research students.

Figure 1. Stalagmite from the Margaret River area of SW Western Australia. Reduced rainfall in recent years has had the effect of reducing the amount of dripwater and the stalagmite is now only growing in the central area.

The understanding that we reached is that we should regard caves as part of a system that transfers a weather and climate signal from the atmosphere, through the soil and the cavernous limestone bedrock into the cave. Carbonate minerals dissolve in the CO_2-rich soil and $CaCO_3$ precipitates when excess carbon dioxide degasses from the dripwater. Hence the cave itself has what we term a *physiology* in which heat, water and gases are exchanged. The regulated conditions also suggested the metaphor of an incubator. In the speleothem incubator, conditions of constant temperature and steadily dripping water can maintain steady growth of individual stalagmites up to 100 thousand years or so. Figure 1 illustrates an example of what happens if these conditions are disturbed too much. Now the stalagmite is only growing in a small area on its top surface because the drips become slower, in this case related to climatic drying. The chemistry of this dripwater is almost certainly different too, being more evolved by degassing of carbon dioxide and prior precipitation of calcium carbonate.

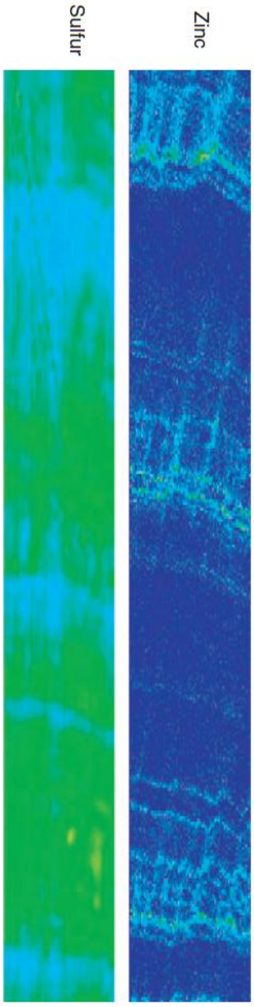

Figure *2. High resolution chemical records of trace element variation in a stalagmite from Alpine Austria. Growth is right to left and shows the years 1977 to 1979 (the images are about 0.3 mm long). Each autumn season multiple rainfall events lead to the peaks in zinc whilst a more gentle variation in sulphur is caused by seasonal changes in the pH of dripwater reflective of changing carbon dioxide content of the cave atmosphere. (Wynn et al., 2014)*

Figure 2 gives an example of the use of sophisticated microanalytical techniques to decode the stalagmite's history. These maps were made by chemically scanning (using X-ray fluorescence) the cut surface of a stalagmite using synchrotron radiation. They show how the chemistry of the stalagmite changes through the year and indeed such annual growth bands can often also be seen in cut surfaces of stalagmites. This seasonality reflects the seasonal water cycle, altering the amount of dripping water, but also the seasonal temperature cycle which affects the way the cave is ventilated. Typically in the winter it is easier for cold outside air to penetrate the cave and its carbon dioxide level drops, increasing the pH of dripwater and increasing the rate of speleothem formation.

Many speleothem researchers in contrast have focused their attention on much longer periods of time, seeking to build up records of the ice ages. This is possible since speleothems, as long as they lack a lot of suspended sediment, can be readily dated using the relative amounts of different uranium and thorium isotopes. In fact they can be much better dated than traditional archives of climate during the Quaternary Period (when the ice ages occurred). These archives are primarily marine cores from the deep sea and cores through the major ice sheets such as in Antarctica.

Figure 3 illustrates the very successful studies on Chinese stalagmites from monsoonally influenced regions. Here the different isotopes of oxygen in rainwater vary through the year and depending on the intensity of the monsoon. This controls the oxygen isotope composition of dripwater and in turn that of the oxygen atoms contained in the $CaCO_3$ speleothem. We know that over long periods of time there are climatic fluctuations whose timing is controlled by the so-called Milankovitch cycles – periodic wobbles in the Earth's orbit that influence the amount of radiation received from the sun in different regions. These are beautifully preserved in the monsoon-proxy speleothems. Also preserved at times is a high-frequency variation which is also seen in studies in the Atlantic area – this reflects the stuttering Gulf Stream circulation during ice ages.

Speleothems are also a great climate archive because they have so many properties that can be climatically influenced. These include the growth rate itself, the isotopes of carbon preserved, the fluorescent properties of the organic matter, the abundance of a wide variety of trace elements, and the chemistry of water in tiny inclusions in the calcium carbonate. The carbon isotopes for examples may reflect abundances of plants with different photosynthetic modes, or total vegetational abundance, or relative importance of degassing (which can be seasonally modulated). A new frontier area is supplied by the use of biomarkers. These are specific groups of organic molecules extracted from the solid carbonate speleothem. It turns out that they often reflect colonies of bacteria – either in the soil or else growing in the cave itself. New work done by other researchers at Birmingham in collaboration with Chinese workers is showing that these bacteria are revealing new properties including the ability to reconstruct both temperature and rainfall variation in the past.

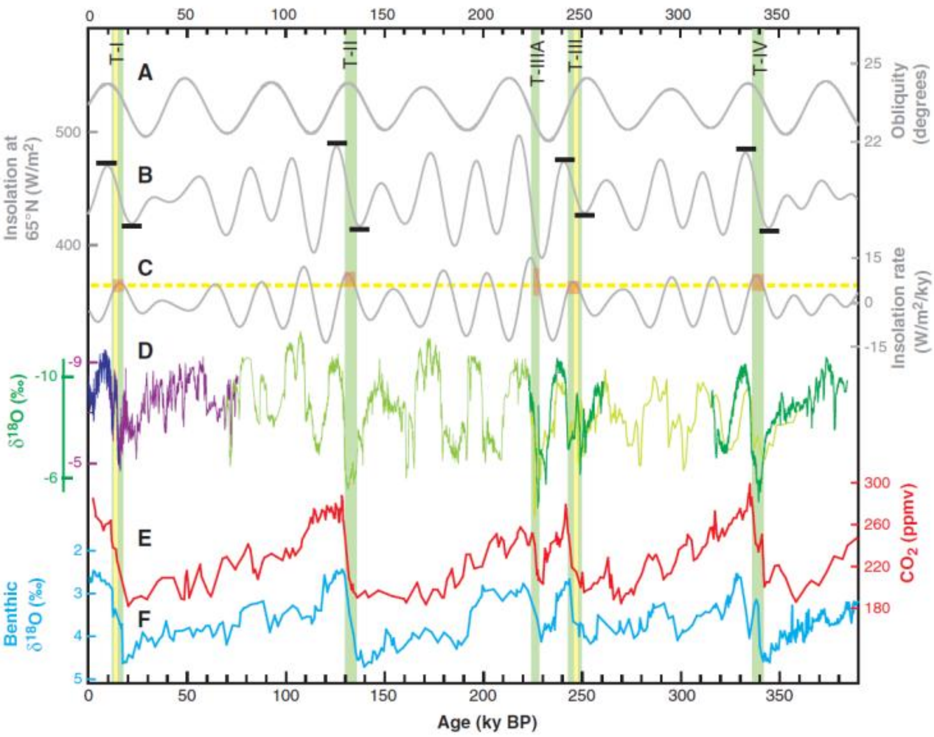

Figure 3. Comparison of measurement of the oxygen isotope composition ($\delta^{18}O$) of stalagmites from monsoonally influenced area of China (green colours) with that of open marine calcareous organisms from the sea floor (blue) and carbon dioxide in the atmosphere (red). Variations are controlled by the strength of insolation from the sun (top grey curves) and these speleothems capture all the major global changes in climate over the ice ages of the last few hundred thousand years. (Cheng et al., 2009)