Stalagmites and paleoclimate

Cheng, H. et al., 2009, Ice Age Terminations. Science, 326, 248-

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1. Understanding how water moves from the surface to a cave

Conceptual hydrological models of stalagmite drip water geochemistry. (a) Two-layer soil-epikarst model for Mg, Sr, Ca fluxes (Fairchild, Baker et al 2006) (b) Single reservoir with overflow feed model for δ¹⁸O and pCO₂ (Baker et al. 2010). (c) Single reservoir model with underflow feed for δ¹⁸O Baker and Bradley (2010) and (d) lumped parameter δ¹⁸O model of Bradley, Baker et al (in press).
2. Tracers of water movement from the surface to a cave

So, rainwater will reach a cave, often with complex choice of flow paths.

What climate and environmental signals will it carry?

1. From the atmosphere
2. From the soil and vegetation
3. From the geology
4. From the cave

Picture drawn by Kevin Burkhill, Cartography, Birmingham
Schematic diagram of the sources of elements and processes involved in their transport to caves. Arrows indicate element fluxes as particulates, colloids or solutes in aqueous solutions (Fairchild and Treble, 2009). Stalagmites preserve archives of these processes.
Rainfall (H$_2$O)

Most useful are oxygen isotopes.

$^{16}$O and $^{18}$O

Vary geographically (with latitude, with altitude, with source region) and with time (within event, seasonally, between years)

Relative amounts of each isotope can provide information of rainfall amount and source
Rainfall interacts with soil and vegetation

Water can be stored as soil water.

Water can be lost and fractionated by evaporation.

Soils are rich in carbon dioxide produced from microbial respiration. This is dissolved into the water.

Soil and vegetation biomarkers are transported by the water
Soil water reaches the limestone.

Limestone is dissolved and the water enters the ground water.

Mixing of ground water of different flow paths

Mixing of water isotope tracer.

Loss and degradation of the biomarker tracer.

Addition of geological tracers such as Mg and Sr.
Water reaches the cave

The CO$_2$ dissolved in the water degasses, and stalagmites and stalactites are formed.

Water isotopes might fractionate if this process is rapid. The isotopes are preserved in the speleothem (CaCO$_3$).

Biomarkers and geological tracers are also preserved in the speleothem. Again, some changes will occur during speleothem formation.
3. Ethiopian Climate Variability
Climatology (text book version)

N Hemisphere winter

N Hemisphere summer
Climatology and socio-economics

Drought and subsequent famine in Ethiopia is due to ‘spring rains’ failure in the north and low and variable rainfall in the south.

Poverty and subsistence farming is the cause of famine (GDP $700; 39% below poverty line). Irrigation was rare until recently, a large amount of the population is dependent on the success of the small rains for germination of the annual crop, as much as it is on the regularity of the big rains.

Overpopulation is also an issue – rapid population growth (74 M people, growing at 2.23%, life expectancy 55 yrs). Plus global rising costs of food purchase.

We need to understand how rainfall variability is related to large-scale climate processes. There is a periodicity in rainfall amount and seasonality – is it predictable and how will it change with anthropogenic global warming?
Ethiopian Caves

Eight years of field monitoring (1-3 trips per year, 5 caves):
- major element water hydrochemistry, rain and drip water stable isotopes, cave climate (data loggers)

Cave exploration – several new caves

Stalagmite sampling – almost all stalagmites contain continuous visible annual growth lamina.

Bero Caves
Bero-1 Stalagmite

Bero Cave, SE Ethiopia

Sampled in 2005 and actively dripping.

Continuous annual laminae

Growth phases of ~100-600 yrs and long hiatuses

Several U-Th and radiocarbon analyses

~Annual-biennial samples drilled for $^{18}$O.
$^{18}$O (thick red line) and annual growth rate (thin line). Notice the clear decadal periodicity in the isotope record. What it is recording?
Oxygen isotope data very smooth and predictable. Suggests that the water has been stored for some time.

Growth rate more ‘spikey’. Suggests that there is some sort of non-linear response.

Combine the two – the stalagmite is being fed by a storage overflow...
We ran a hydrological model to understand the $^{18}$O record.

Input data: isotope and climate data from Addis Ababa.


Output: scenarios for drip water $\delta^{18}$O from 1990 – 2005.

Varying the model parameters confirms that the stalagmite is responding to rainfall amount and seasonality.

Note the negative isotope shift in the 1997-99 spring rains failure.
Oxygen isotopes are recording decadal variations in total rainfall amount and seasonality.
Rainfall Variability 1948 - 2009

Data: 1948-2009; NCEP/NCAR reanalysis (3° x 3° grid, 33-42E, 3-12N) – treat with caution!

Ratio of Spring (April, May) to Summer (July, August) rainfall
Data: 1948-2008; NCEP/NCAR reanalysis – treat absolute values with extreme caution!
Six stalagmites and the last 10000 years from Ethiopia...

...a persistent decadal variability in rainfall seasonality and amount
Conclusions

• Persistent multidecadal variability in rainfall seasonality and/or amount in Ethiopia

• Likely cause is semi-regular failures in spring rains and/or enhanced summer rains.

• Variability likely driven by variations in sea surface temperatures (ENSO, IOD) which effects strength of summer monsoon rains.

Future Research?

• Ethiopia: need to provide independent (GCM) evidence of forcing behind a ~20 yr periodicity in East African rainfall. Collaboration with CCRC, UNSW.

• New long term strategic development of paleoclimate stalagmite record(s) in SE Australia, with focus on timing of groundwater recharge.

• ‘Super Science’ funded groundwater and climate monitoring facility at Wellington, UNSW.

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www.groundwater.com.au
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Rainfall in Ethiopia: the future?


The East African Monsoon

Summer rainfall: processes on an annual (top) and seasonal to multiannual timescale

Segele, Z.T et al., 2009. J. Clim, 22, 3396-
HYSPLIT: Addis Ababa Rainfall Back Trajectories