Annually laminated speleothems in paleoclimate studies

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New analytical techniques enable the extraction of annual climate information from speleothems for times long before historical climate records began.

Speleothems (stalagmites, stalactites and flowstones) are natural paleoclimatic and paleoenvironmental archives. They are widespread in karstic environments and grow from drip water that degases CO_2 upon entering caves (Fairchild and Treble 2009). If seasonal climate variations outside the cave (e.g. precipitation, temperature, snow melting) or inside the cave (e.g. humidity, air CO_2 partial pressure, air ventilation) are large enough, this seasonality may be preserved as annual laminas in the speleothems (Tan et al. 2006; Baker et al. 2008). Therefore, speleothems have the potential to record past climate with annual resolution.

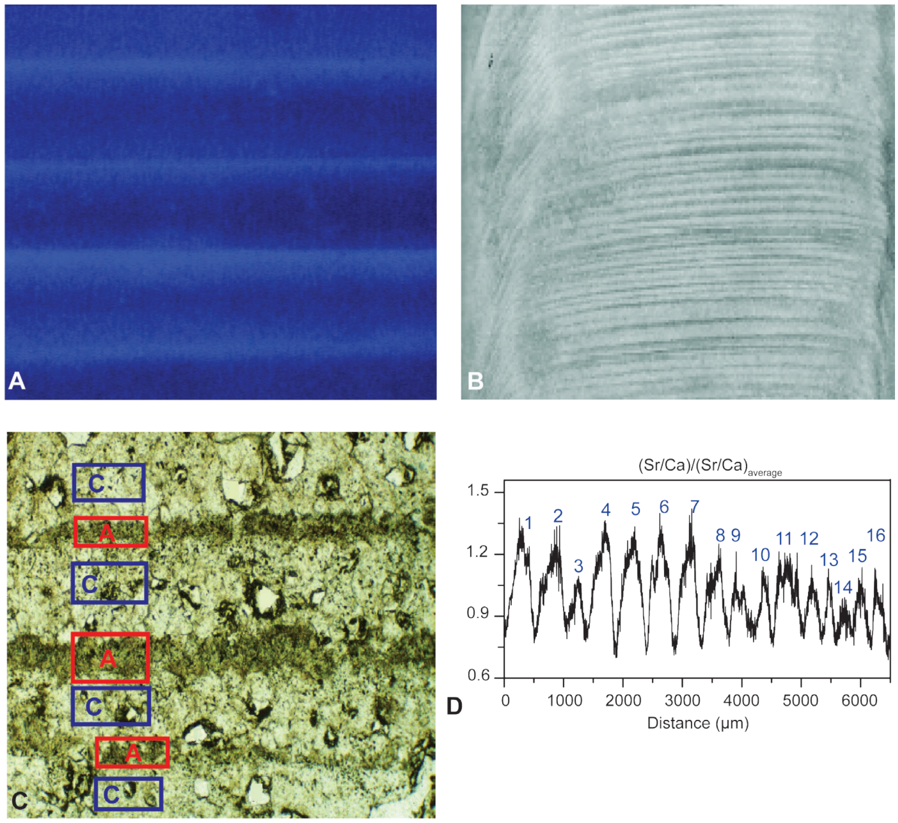

Figure 1: Four types of speleothem laminas. **(A)** Fluorescent laminas excited by UV light. **(B)** Visible laminas observed under reflected-light microscopy. **(C)** Calcite (C) and aragonite (A) couplets, observed under transmitted-light microscopy, and **(D)** geochemical laminas where the normalized Sr/Ca peaks were used to define 16 years. Modified from Tan et al. (2006) and Johnson et al. (2006).

Annual laminas in speleothems

Four main types of speleothem laminas have been reported (Fig. 1): (1) fluorescent laminas, which can be observed by using conventional mercury light-source UV reflected-light microscopy (Shopov et al. 1994) and confocal laser fluorescent microscopy (Orland et al. 2012); (2) visible laminas, which can be observed using conventional transmitted and reflected-light microscopy (Genty and Quinif 1996); (3) calcite-aragonite couplets, which show seasonal alternations of calcite and aragonite growth layers (Railsback et al. 1994); and (4) geochemical laminas (Johnson et al. 2006) defined by the annual variability of their chemical constituents such as stable isotopes ($\delta^{18}O$, $\delta^{13}C$) and trace elements (e.g. Mg, Sr, Ba). To confirm the annual character of banding, the number of layers counted in a speleothem is compared with the duration of growth measured independently by radiometric dating techniques. For samples of late Pleistocene age, ^{230}Th dating is used most commonly (Baker et al. 1993; Tan et al. 2000), while samples younger than 150 years can be dated with ^{210}Pb and ^{226}Ra methods (Baskaran and Iliffe 1993; Condomines and Rihs 2006) or with the atomic bomb testing ^{14}C signature that characterizes the last 50 years (Genty et al. 1998; Mattey et al. 2008).

Application in paleoclimate studies

The annual laminations in speleothems provide accurate age indications for paleoclimate proxies measured within the speleothem, and allow reconstructing the accurate timing and structure of abrupt climate changes. The temporal relationships between the regional expressions of an abrupt event are crucial for understanding its origination and its transferring mechanisms. For example, Liu et al. (2013) reconstructed the timing and structure of the 8.2 ka event in the East Asian monsoon region based on $\delta^{18}O$ and Mg/Ca ratios of a stalagmite from central China. Their results show that the duration and evolution of precipitation during this event is indistinguishable from temperature recorded in Greenland ice cores, suggesting a rapid atmospheric teleconnection between the North Atlantic and the East Asian monsoon region. Likewise, $\delta^{18}O$ records from other Chinese stalagmites indicate that the Asian monsoon transition into the Younger Dryas (YD) extended over ca. 340 years (Liu et al. 2008; Ma et al., 2012), while the shift out of the YD took less than 38 years (Ma et al. 2012).

Precise chronologies are also crucial for comparing proxies from speleothems with instrumental meteorological data to identify their climatic and environmental significances. For example, Baker et al. (1998) found a correlation between the content of high-molecular-weight organic acids and annual rainfall in an annually laminated stalagmite from England, and used this correlation to reconstruct precipitation during the last interglacial. In a stalagmite from central Belize, variations of $\delta^{13}C$ co-vary with the observed Southern Oscillation Index (Frappier et al. 2002) and were shown to be influenced by changes to the carbon budget of the overlying rainforest. The forest is sensitive to the local weather and, in turn, controlled by the Southern Oscillation.

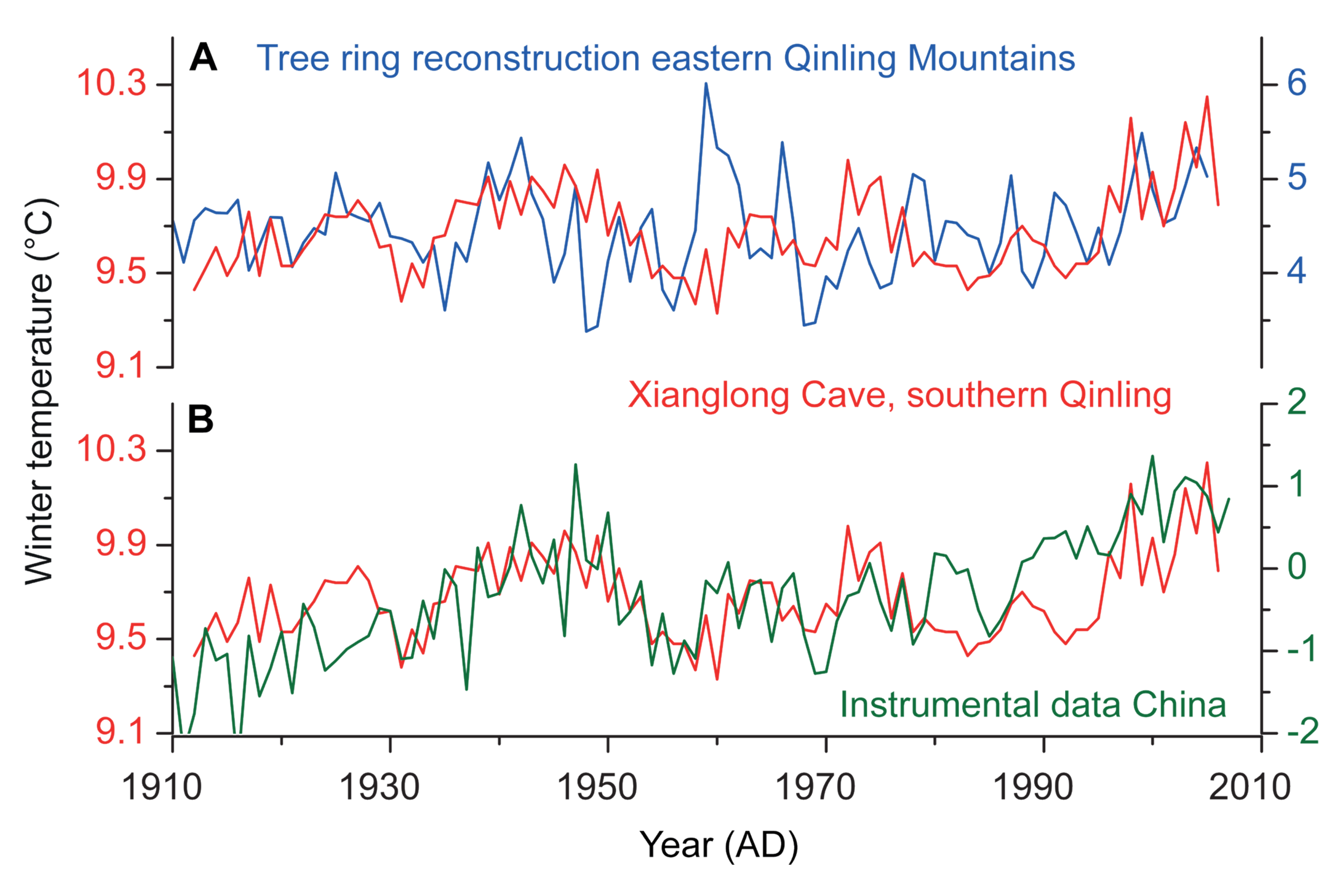

Figure 2: Comparison of temperature from September to May reconstructed by speleothem layer thickness from Xianglong Cave in southern Qinling Mountains, central China (red lines) with **(A)** tree ring-based winter temperature reconstruction from nearby, and **(B)** surface winter temperature across China during the last hundred years. Modified from Tan et al. 2013.

The layer thickness of annual laminas can be used to infer the speleothem growth-rate per year. Growth rates have been used to quantitatively reconstruct past temperature (Tan et al. 2003), as well as precipitation and associated changes in atmospheric circulation (Proctor et al. 2000).

Tan et al. (2006) reviewed the applications of stalagmite laminas to paleoclimate reconstructions and compared them to the dendroclimatological approaches. Baker et al. (2007) suggested that a transfer function reflecting the mixing of water from rainfall events and groundwater storage could be used to reconstruct high-resolution hydroclimatic records from stalagmites. More recently, Tan et al. (2013) developed a two-variable linear regression between stalagmite growth rate and temperature that accounts for smoothing and lag effects of stalagmite growth in response to climatic changes. With this regression, they quantitatively reconstructed temperature changes from September to May between AD 1912 and 2006. This stalagmite-based reconstruction is coherent with a nearby tree-ring temperature reconstruction (Fig. 2), which documents the sensitivity of this archive to air temperatures (Tan et al. 2013).

Perspectives

Annually laminated speleothems are often found in caves with a shallow depth and an outside climate that exhibits strong seasonality (Tan et al. 2006). Recent methodological advances have the potential to expand the applications of speleothems as paleoclimate recorders and to reduce their uncertainties in climate reconstruction. For example, digital image analysis, e.g. with a hyperspectral scanner, allows for faster and more accurate counting of laminas compared to traditional optical analyses (Jex et al. 2008). High-precision and high-resolution in situ measurements of stable isotopes and trace elements using ion microprobe (Orland et al. 2009), laser-ablation inductively coupled plasma mass-spectrometry (Johnson et al. 2006), and synchrotron radiation micro X-Ray fluorescence (Borsato et al. 2007) have all revealed annual and sub-annual variations in speleothem chemistry. As a result, improved speleothem chronologies can be built by measuring geochemical variability along the growth axis. Furthermore, by pairing images of annual laminas with seasonal-resolution measurements of geochemical variability in speleothems, seasonal climate patterns can be reconstructed. For example, the combination of fluorescent imaging and ion microprobe analysis of $\delta^{18}O$ in speleothems from Israel has been used to identify regional changes in seasonality across abrupt climate events and over millennial time scales (Orland et al. 2009, 2012).

Future research should focus on quantitative and qualitative reconstructions of paleoclimate and paleoenvironment by using multiple proxies from annually laminated speleothems, including stable isotopes, trace elements, as well as layer thickness. Finally, efforts are being made to apply statistical approaches better suited to reconstruct past climate quantitatively using speleothem records (Tan et al. 2006, 2013).

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