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SHORT PAPER

A Test of "Annual Resolution" in Stalagmites Using Tree Rings

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So-called annual banding has been identified in a number of speleothems in which the number of bands approximates the time interval between successive U-series dates. The apparent annual resolution of speleothem records, however, remains largely untested. Here we statistically compare variations in band thickness from a late Holocene stalagmite in Carlsbad Cavern, Southern New Mexico, USA, with three independent tree-ring chronologies form the same region. We found no correspondence. Although there may be various explanations for the discordance, this limited exercise suggests that banded stalagmites should be held to the same rigorous standards in chronology building and climatic inference as annually resolved tree rings, corals, and ice cores.

Key Words: **Speleothems; paleoclimate; annual resolution; tree-ring chronologies.**

Speleothems are gaining importance in paleoclimate studies because they can be dated precisely with U-series mass spectrometry, can be analyzed for many properties, and form in stable cave environments that integrate both surface temperature and hydrology. Replication presents a major challenge because, even within the same cave, speleothems can have different growth rates, temporal resolution, and idiosyncratic histories due to different drip pathways as well as changes in drip position. Despite these problems, speleothem records have been successfully correlated within the same cave (Dorale *et al.*, 1998; Denniston *et al.*, 2000; Wang *et al.*, 2001), across caves within the same region (Musgrove *et al.*, 2001), and with other proxies, such as $\delta^{18}O$ records from Greenland ice cores (McDermott *et al.*, 2001; Wang *et al.*, 2001).

Further opportunities for replication stem from the apparent annual banding of many speleothems in which the number of bands approximates the time interval between successive U-series dates (Denniston *et al.*, 2000; Wang *et al.*, 2001). As yet, however, there have been few efforts to crossdate or verify climatic signals in "annual" bands from speleothems through direct comparisons with yearly instrumental records (e.g., Qian and Shu, 2002) or well-calibrated and annually resolved proxies such as tree rings. Dissimilar temporal resolution and coverage often prohibit direct speleothem-tree ring comparisons, but annual growth bands in Holocene stalagmites are now being reported for regions with contemporaneous tree-ring chronologies (e.g., Proctor *et al.*, 2000; Polyak and Asmerom, 2001).

For example, Polyak and Asmerom (2001) recently reported "a 4000-year annually resolved climate history" from stalagmites in southern New Mexico. In one banded stalagmite (BC2) from Carlsbad Cavern, they used optical microscopy to identify couplets of alternating clear and inclusion-rich calcite, the latter apparently formed by deposition of organics during the dry season. Polyak and Asmerom (2001) developed a time series from the thickness of more than 1600 "annual" bands precipitated between U-series dates of 2796 ± 88 and 835 ± 25 yr B.P. and $\sim$300 bands subsequent to 432 ± 13 yr B.P. Regional trends in effective moisture were inferred from band thickness and were then correlated to key events in the culture history of the southwestern U.S., including the appearance of corn, ceramics, and cotton, as well as changes in settlement pattern and size of human populations (Polyak and Asmerom, 2001). Band thickness figures prominently in these correlations, akin to similar cultural

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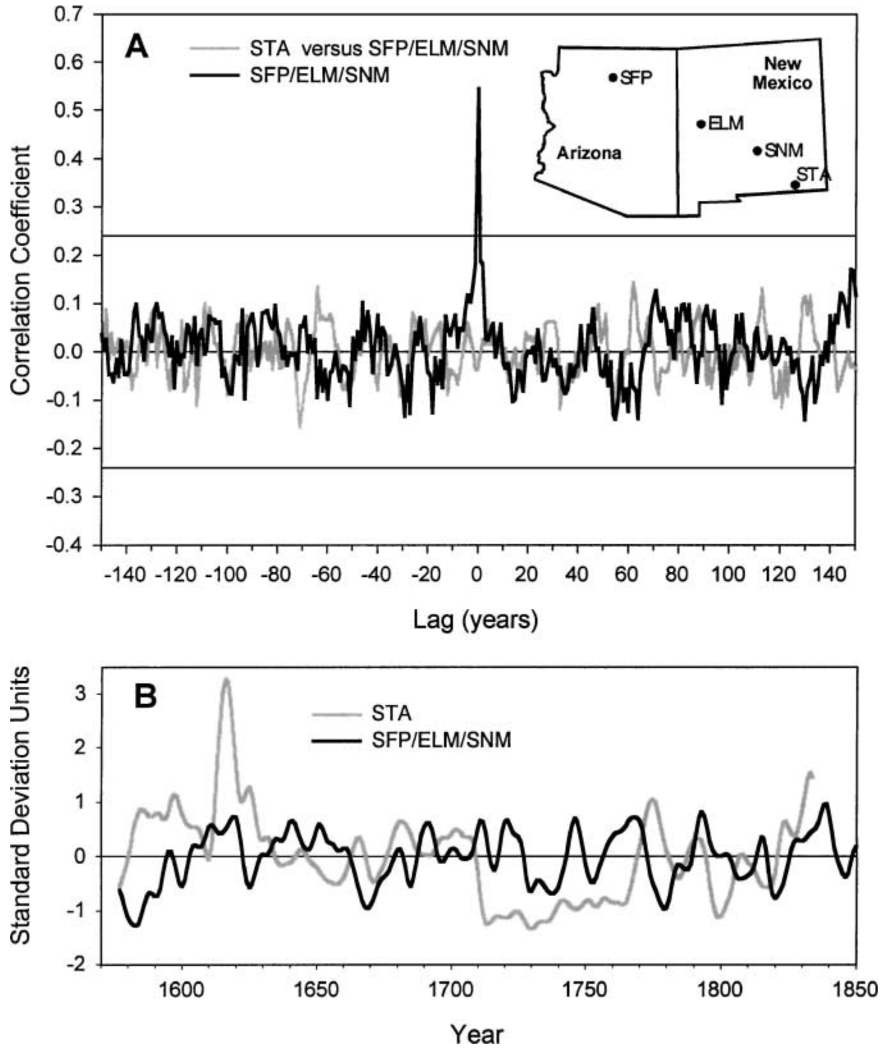

FIG. 1. (A) Cross-correlation function for comparisons among the tree-ring-based precipitation reconstructions (San Francisco Peaks = SFP; El Malpais = ELM; southern New Mexico = SNM; (Salzer, 2000, in press; Grissino-Mayer, 1996; Grissino-Mayer *et al.*, 1997), and tree-ring reconstructions versus the band thickness record in stalagmite BC2 (STA; see Polyak and Asmerom, 2001) (A.D. 1570–1839). Shown are the average lagged correlation of the three pairwise tree-ring series (black line) and lagged correlation between a composite of the SFP, ELM, and SNM tree-ring series (averaged) versus the stalagmite band thickness series (gray line). The ELM and SNM series were calibrated for annual (August–July) water-year rainfall, whereas SFP was calibrated for previous October–July total precipitation. The horizontal lines are the approximate 95% confidence limits (i.e., ±0.24) including adjustment for multiple correlation tests. (B) The average of the smoothed tree-ring reconstructions is compared with the smoothed stalagmite record. A 13-weight Gaussian low-pass filter was used to smooth the series.

inferences made about wet and dry years and decades reconstructed from regional tree-ring chronologies (Dean *et al.*, 1985).

We tested the "annual" resolution of the Carlsbad Cavern stalagmite by running cross-correlation analyses at 0- to 150-yr lags among three independent tree-ring reconstructions of precipitation in the same region (Grissino-Mayer, 1996; Grissino-Mayer *et al.*, 1997; Salzer, 2000; in press; Fig. 1A) and band width in the BC2 stalagmite for the most recent period of overlap (A.D. 1570–1839). The tree-ring reconstructions were calibrated and verified with independent weather-station records from the 20th century using standard, dendroclimatic methods (Fritts, 1991; Cook and Kairiukstis, 1990).

Cross-correlations among the three tree-ring-based precipitation reconstructions are all significant (r values are 0.62, 0.46, 0.54, $p < 0.001$) at the zero lag, indicating a coherent interannual signal of precipitation variations across the region (Fig. 1A). In contrast, the tree-ring versus stalagmite records show no correlations above 0.05 at the zero lag. Instances of higher positive and negative correlations (−0.36 to +0.26) with individual tree-ring series occur at long lags in some comparisons. It seems unlikely, however, that these lagged patterns are meaningful, given the relatively low correlation values and the inconsistency in sign and lagged year among different pairwise comparisons.

In another analysis we used the computer program COFECHA (Holmes, 1983) to test all possible dating positions of the 270-yr stalagmite series (1570–1839) against the three tree-ring series (separately and as composites) spanning the past 2000 yr. No consistent or convincing crossdating between the stalagmite and tree-ring series was identified. Finally, we graphically compared smoothed versions of the tree-ring reconstructions and stalagmite record to evaluate possible correspondence between the decadal-to centennial-scale variations in the chronologies (Fig. 1B). Again, there is no obvious correspondence.

There are several possible explanations for the lack of correspondence between the stalagmite and tree-ring records. (1) This particular stalagmite record is idiosyncratic and would not correlate with other contemporaneous records from the same or other caves. (2) The U-series dates are too young by at least ∼2000 yr, which we think unlikely. (3) Annual bands are sporadically missing (a few percent missing would thwart cross-dating with COFECHA). (4) The stalagmite bands are not necessarily annual, meaning that more than one couplet can form in a single year (both the fall and foresummer tend to be dry, and a wet summer and wet winter can occur in the same year). (5) The thickness of the stalagmite bands is responding to a different climatic variable than the tree rings. For example, although we used both cool season and annual precipitation reconstructions, tree-ring widths in this region are most strongly correlated to cool-season precipitation. Summer rains dominate annual rainfall amounts in the area of Carlsbad Caverns and could conceivably exert a heavier influence on stalagmite growth. On the other hand, recharge in this area is primarily a winter phenomenon, which suggests that both tree rings and stalagmite bands should track variations in cool-season precipitation. (6) Groundwater travel times may impose variable time lags of years to decades between a season's worth of precipitation and speleothem deposition, smoothing interannual variations and confounding decadal-scale variations recorded in tree rings.

The optimistic view is to downplay the discrepancies between stalagmites and tree rings and maintain that they provide complementary climatic information at different resolutions or scales. Claims of "annual resolution" invite direct comparisons, however, and in such cases stalagmites should be held to the same rigorous standards in chronology building and climatic inference as annually resolved tree rings, corals, and ice cores (Cook, 1995; Baumgartner *et al*., 1989). At the very least, we suggest that the terms "near annual" and "subdecadal" be used to describe the temporal resolution of most banded stalagmites, and that "annual" resolution should be reserved for those records in which the age of individual laminae can be resolved to the exact year. Finally, we suggest that, when available, tree-ring chronologies provide a means to routinely test for annual resolution and climatic signals in contemporaneous speleothem records.

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