Coeval stalagmite records from the Rocky Mountains record Holocene climate change

Poster #: X5.174

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Project Overview

Tree ring records show cool-season droughts in the western US have been characterized by three spatial patterns over the past 500 years: "western-wide drought", "wet north/dry south", and "dry north/wet south", which can persist on timescales of decades to centuries (Wise, 2016).

However very few high-resolution, well-dated records of past precipitation in the northern Rockies extend beyond the tree ring record (~1400 CE), limiting our understanding of the occurrence and persistence of these patterns of natural climate variability on longer timescales and further in the past.

This study uses trace element to calcium ratios (Sr/Ca, Mg/Ca, Ba/Ca, P/Ca) and stable isotope ($\delta^{18}O$, $\delta^{13}C$) variations from two coeval stalagmites to construct a Holocene paleoclimate record for Titan Cave, northern Wyoming, extending the hydroclimate record of the northern Rockies and providing the opportunity to assess longer-term natural climate variability in the region. We show that modern drought patterns in the Rocky Mountains were established by approximately 2.8 ka.

Figure 1: (Left) Map of western United States showing approximate location of Titan Cave (yellow star) and proximal late-Holocene paleoclimate archives including: Bison Lake (red circle), Minnetonka Cave, Upper Freemont Glacier, Beartooth ice patch, and Crevice Lake. (Inset) Map showing Gulf of Alaska relative to area of interest.

Stalagmite age models

12 subsamples from both TC-2 and TC-7 were analyzed for U-series dating by Yanjun Cai at the Institute of Global and Environmental Change, Xi'an Jiaotong University and by Warren Sharp at the Berkeley Geochronology Center.

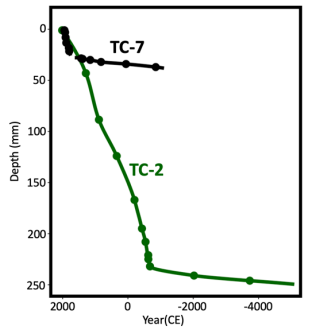


Figure 2: TC-2 (green) and TC-7 (black) age-depth models generated using COPRA software (Breitenbach et al., 2012).

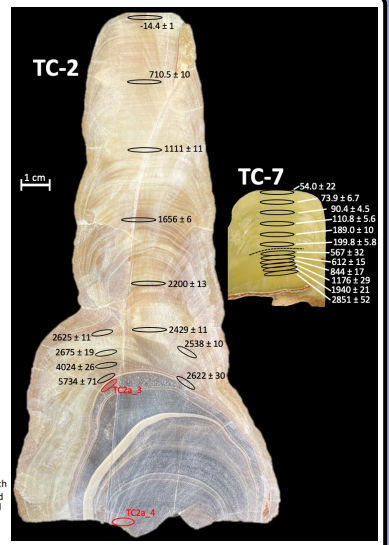


Figure 3: TC-2 and TC-7 stalagmites with ages shown in years BP (BP = 1950) and 2σ uncertainty. TC-2 ages shown in red are currently being analyzed at the Berkeley Geochronology Center.

Results + Discussion

Our results demonstrate that Titan Cave stalagmites faithfully record regional northern Wyoming hydroclimate signals during the Holocene. TC-2 and TC-7 grew within 10 meters of each other, and $\delta^{18}O$ records follow near-identical trends, suggesting that both are controlled by environmental factors and not kinetic/disequilibrium effects. The consistent offset between TC-2 and TC-7 $\delta^{18}O$ likely reflects differences in water flow path to the drip sites the stalagmites formed under (Treble et al., 2021). We interpret these records to reflect the relative proportion of snow vs. rain at the cave site, with increased speleothem $\delta^{18}O$ reflecting decreased snow. Trace element to Ca ratios are similarly weighted to each other in PCA space and follow consistent trends across the duration of the record. This suggests they are controlled by a consistent environmental factor. We interpret these ratios to reflect the amount of relative moisture at the cave site. Under drier conditions, increased prior calcite precipitation (PCP) leads to elevated Sr, Mg and Ba to Ca ratios. Drier conditions also yield decreased soil/organic inputs to the cave, reflected in decreased P/Ca ratios.

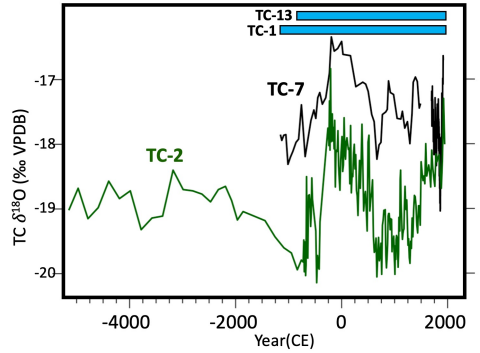


Figure 4: TC-2 (green) and TC-7 (black) $\delta^{18}O$ data measured at Vanderbilt University via IRMS. Blue lines show growth intervals of two other Titan Cave stalagmites (TC-1 and TC-13).

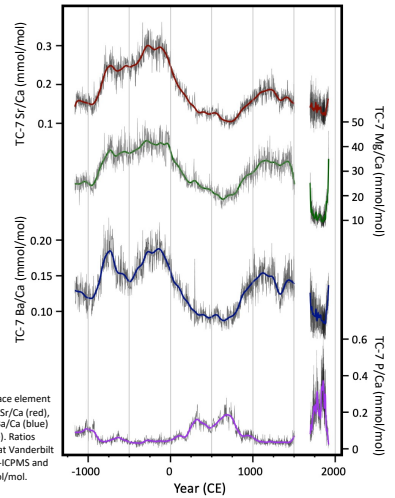
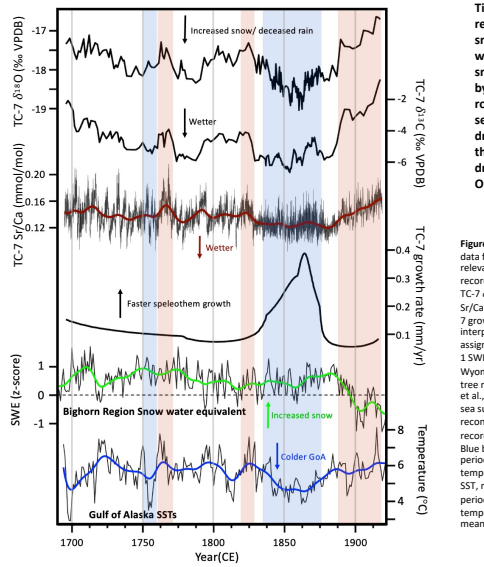


Figure 5: TC-7 trace element record including Sr/Ca (red), Mg/Ca (green), Ba/Ca (blue) and P/Ca (purple). Ratios were measured at Vanderbilt University via LA-ICPMS and reported in mmol/mol.



Titan Cave proxies align closely with other coeval records of past North American climate. Wet, snowy conditions at Titan Cave are correlated with colder Gulf of Alaska SSTs and increased snowpack in the Bighorn Mountains, as recorded by tree rings (Fig. 7). These correlations are robust regardless of TC-7 age-depth model selection (Fig. 8). Fig. 9 (right panel) shows that dry conditions at Titan Cave are synchronous with the onset of glacial retreat in the Tetons and drought in the Yellowstone region recorded by Old Faithful geyser dormancy.

Figure 7: (LEFT) Time series data for TC-7 stalagmite and relevant coeval climate records. From top to bottom: TC-7 $\delta^{18}O$; TC-7 $\delta^{13}C$; TC-7 Sr/Ca trace element ratio; TC-7 growth rate since 1695 CE interpolated from COPRA-assigned age-depth date; April 1 SWE in the Big Horn region, Wyoming reconstructed from tree ring records. (Pederson et al., 2011); Gulf of Alaska sea surface temperatures reconstructed from tree ring records (Wilson et al., 2009). Blue bars mark extended periods of time with GOA temperatures less than mean SST, red bars mark extended periods of time with GOA temperatures greater than mean SST.

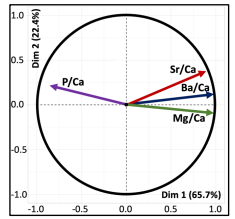


Figure 6: Results of principal component analysis of TC-7 trace element to Ca ratios.

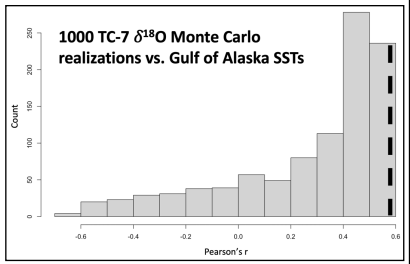


Figure 8: Histogram showing frequency of Pearson's r calculated from multiple comparisons of TC-7 $\delta^{18}O$ with Gulf of Alaska SSTs (from Wilson et al., 2009). 1000 realizations of the TC-7 $\delta^{18}O$ record were produced using Monte Carlo analysis considering the analytical uncertainty associated with each TC-7 ^{230}Th-U age. Dashed line in the Pearson's r reported for the mean proxy record. Multiple MC realizations of the $\delta^{18}O$ record were produced using COPRA software.

Discussion

A key aspect of this work is to determine the timing of western US dipole initiation. We show the dipole pattern became prevalent in the region after ~2.8 ka (800 BCE), as is indicated by diverging trends in $\delta^{18}O$ between Titan Cave speleothems (north) and Bison Lake sediments (south). The emergence of this drought pattern likely marks the onset of modern tropical Pacific controls on Western US hydroclimate. We also observe region-wide droughts, most notably from 2.2-2.0 ka (red bar in Fig. 9). These drought patterns are driven in part by internal climate variability with secondary influence by Pacific sea surface temperatures (Wise, 2016). Aleutian Low extremes are expected to become more frequent and persistent in the future (Giamalaki et al., 2021), therefore understanding natural variability in this system is crucial for predicting drought in the western US.

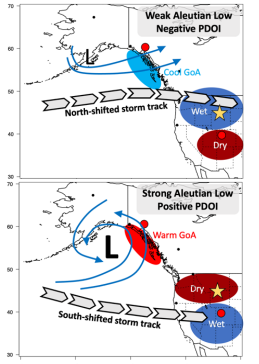
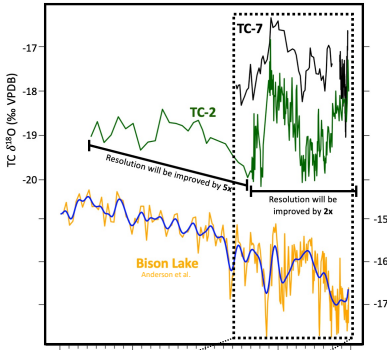


Figure 10: Simplified climatologies associated with a strong (bottom) and weak (top) Aleutian Low, based on this study, Anderson et al. (2016), Nagashima et al. (2021), Pederson et al. (2011), and Wise (2016). Yellow star is Titan Cave, red circles are Jellybean Lake, Alaska and Bison Lake, Colorado.



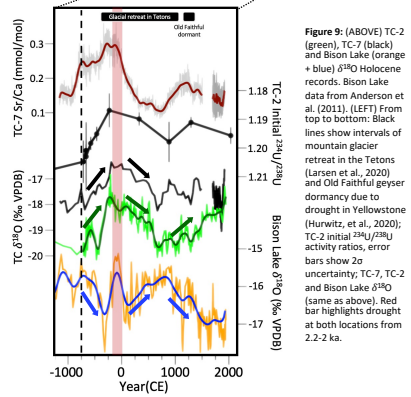


Figure 9: (ABOVE) TC-2 (green), TC-7 (black) and Bison Lake (orange + blue) $\delta^{18}O$ Holocene records. Bison Lake data from Anderson et al. (2011). (LEFT) From top to bottom: Black lines show intervals of mountain glacier retreat in the Tetons (Larsen et al., 2020) and Old Faithful geyser dormancy due to drought in Yellowstone (Hurwitz, et al., 2020); TC-2 initial $^{234}U/^{238}U$ activity ratios, error bars show 2σ uncertainty; TC-7, TC-2 and Bison Lake $\delta^{18}O$ (same as above). Red bar highlights drought at both locations from 2.2-2 ka.

Future work

Research at Titan Cave is ongoing. Future work includes:

- **Completing the TC-2 stable isotope and trace element records**
- **Analyzing TC stalagmites that grew during past warm periods (MIS 5)**
- **Analyzing novel proxies ($\Delta^{17}O$) in TC speleothems, plate calcite, and drip waters**
- **Continuing active monitoring in Titan Cave and analyzing drip waters collected using the Syp autosampler (Fig. 11)**

Figure 11: Image of Syp autosampler (Waikato Scientific) installed in Titan Cave in May 2022. Water is being collected over four-day intervals and analyzed for stable isotopes and trace elements.

Acknowledgments

Many thanks to Warren Sharp, Christopher Kinsley, Brian Jones and Christina Polito Halter at the Berkeley Geochronology Center for assistance with U-Series dating. Thank you to Bryan McKenzie and Lisa Marks at the Bureau of Land Management for access to Titan Cave. Thank to lab manager Richard Bradshaw and the entire Oster lab group for assistance with this work.

EGU23-4539
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