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Modern Cave Monitoring Informs Interpretations of Past Climate Change: Applications to Titan Cave, Wyoming

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Modern Cave Monitoring Informs Interpretations of Past Climate Change: Applications to Titan Cave, Wyoming

By Bryce Belanger,[1] Cameron de Wet,[1] Bryan McKenzie,[2] and Jessica Oster[1]

Abstract

Monitoring of cave environments is an essential process for deciphering records of past climate change preserved in the geochemical composition of speleothems or mineral cave deposits. This study presents data from a multiyear monitoring effort in Titan Cave, Wyoming, a site of interest due to the abundance of speleothems suitable for paleoclimate reconstruction. Titan Cave exhibits annual cave air temperature fluctuations of less than 0.4 degree Celsius, along with consistent relative humidity, drip rate, and partial pressure of carbon dioxide (pCO_2) throughout the year. Small variations in drip rate were noted to be associated with multiseasonal to multiannual regional precipitation trends, such as the widespread western United States drought that lasted from fall 2020 through spring 2022. Stable isotope measurements from drip water (del hydrogen-2 or deuterium [δ^2H], del oxygen-18 [$\delta^{18}O$]) are also relatively constant throughout the year and across different drip sites in the cave, varying by only 2 per mil (‰) in δ^2H and less than 0.4‰ in $\delta^{18}O$. However, stable isotopes ($\delta^{18}O$, del carbon-13 [$\delta^{13}C$]) measured in modern calcite grown on artificial substrates vary spatially and temporally within the cave.

In the Pisa Room of Titan Cave, modern calcite collected from drip sites in the center of the room is more negative in both $\delta^{18}O$ and $\delta^{13}C$ than modern calcite collected from drip sites along the room's wall, suggesting differential water flow paths and (or) in-cave disequilibrium effects. The middle of the Pisa Room was identified as the location best suited for future speleothem paleoclimate reconstruction due to the high density of speleothem growth and calcite $\delta^{18}O$ values closer to equilibrium than in other Pisa Room locations. Based on the documented stability of the cave environment and the relative lack of high-resolution paleoclimate data from this region of the northern Rocky Mountains, Titan Cave was found to be a favorable cave for the development of speleothem paleoclimate records.

Introduction

Karst environments hold great potential for preserving records of past terrestrial climate change. Speleothems, or mineral deposits formed in caves over time, can be dated at high precision and preserve a number of climatic signals in their geochemical makeup, revealing aspects of past climate during the speleothem's growth (Lachniet and others, 2014; Wong and Breecker, 2015; Oster and Kelley, 2016). Speleothems provide the opportunity to reconstruct long-term terrestrial climate change, extending records of past precipitation variability beyond the instrumental and tree ring records (Cheng and others, 2013; Wendt and others, 2018). Geochemical proxies such as ratios of the stable isotopes of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) in the speleothem mineral structure can provide information about past climate variations above a cave. Oxygen isotopes have commonly been used to reconstruct past changes in the $\delta^{18}O$ of precipitation, recording shifts in precipitation intensity, seasonality, temperature, and moisture source region (Bar-Matthews and others, 1997; Tremaine and others, 2011). Carbon isotope ratios are reflective of past shifts in soil respiration, vegetation above the cave, water-rock interactions, prior calcite precipitation, and degassing (Fohlmeister and others, 2020). In many environments, changes in speleothem $\delta^{13}C$ occur as the result of water availability above the cave, effectively recording wetter vs. drier climate conditions over time (Oster and others, 2020).

Although common climatic and environmental controls on proxies have been documented across landscapes and ecosystems, each cave environment is unique and requires intensive study to effectively translate speleothem geochemical data into useful records of past climate change. Rigorous cave monitoring approaches have proven to be an effective method for understanding location-specific karst processes influencing drip water and speleothem geochemistry (Druhan and others, 2021; Oster and others, 2012, 2021; Sekhon, 2021). These modern monitoring approaches focus on collecting and analyzing cave drip water and calcite precipitated on artificial substrates such as glass plates in the cave, along with recording changes in cave temperature, pCO_2, humidity, and drip rate.

In this study, a comprehensive, multi-year dataset is presented that includes measurements of cave temperature, pCO_2, relative humidity, drip rate, and water and modern calcite stable isotope compositions from Titan Cave (TC), in northern Wyoming. Titan Cave is the first known cave to be monitored in the northern Rocky Mountains and hosts

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numerous speleothems dated to significant climatic intervals in Earth's recent past, including the Holocene and Last Interglacial Period. Titan Cave also sits in a region of the Rockies which lacks high-resolution paleoclimate data beyond the tree ring record (Pederson and others, 2011), despite the importance of this information for better understanding long-term climate variability and drought. Results from this study indicate that speleothems from TC are suitable for reconstructing long-term paleoclimate trends due to limited cave ventilation and minimal changes in cave microclimate and drip rate on seasonal timescales. Lastly, intra-cave variations in drip water and modern calcite geochemistry were noted that are anticipated will be present in speleothem paleoclimate reconstructions from TC.

Methods

Site Description

Titan Cave is a wild cave located in northern Wyoming near the border with Montana (fig. 1*A*). The cave is managed by the Bureau of Land Management (BLM) specifically for scientific research, and the only known previous study at this site consisted of preliminary radon testing (unpublished). The cave is located in the Bighorn River area and is less than 1 kilometer (km) from Natural Trap Cave, a significant paleontological site. Natural Trap Cave hosts a well-documented fossil record spanning the last glacial cycle (Kohn and McKay, 2010, 2012; Meachen and others, 2016), but no speleothem records of past climate change. Titan Cave is situated in the upper section of the Mississippian-age Madison Limestone, which consists of gray limestone and red siltstone paleokarst-breccia and ranges from 330 to 900 feet thick in this region (Sandberg and Klapper, 1967). The entrance to Titan Cave (TC), at 1,427 meters in elevation, sits in a small depression in the Tensleep Sandstone of the overlying Amsden Formation.

Titan Cave receives both cold-season precipitation (predominantly snow) and shoulder season/summer precipitation from convective storms. Moisture in this region is sourced from air masses originating in the Arctic, the Gulf of Mexico, and the Pacific Ocean (Bryson and Hare, 1974). However, high elevation regions can experience significantly different climatologies compared to lower elevation areas. For example, precipitation at high elevation in the Rocky Mountains is generally dominated by Pacific-sourced winter westerly storm systems (Sjostrom and others, 2006), whereas lower elevation areas may receive greater fractions of summertime precipitation due to the influence of the North American Monsoon (Despain, 1987). Precipitation data from Deaver, WY, about 30 kilometers from TC at a similar

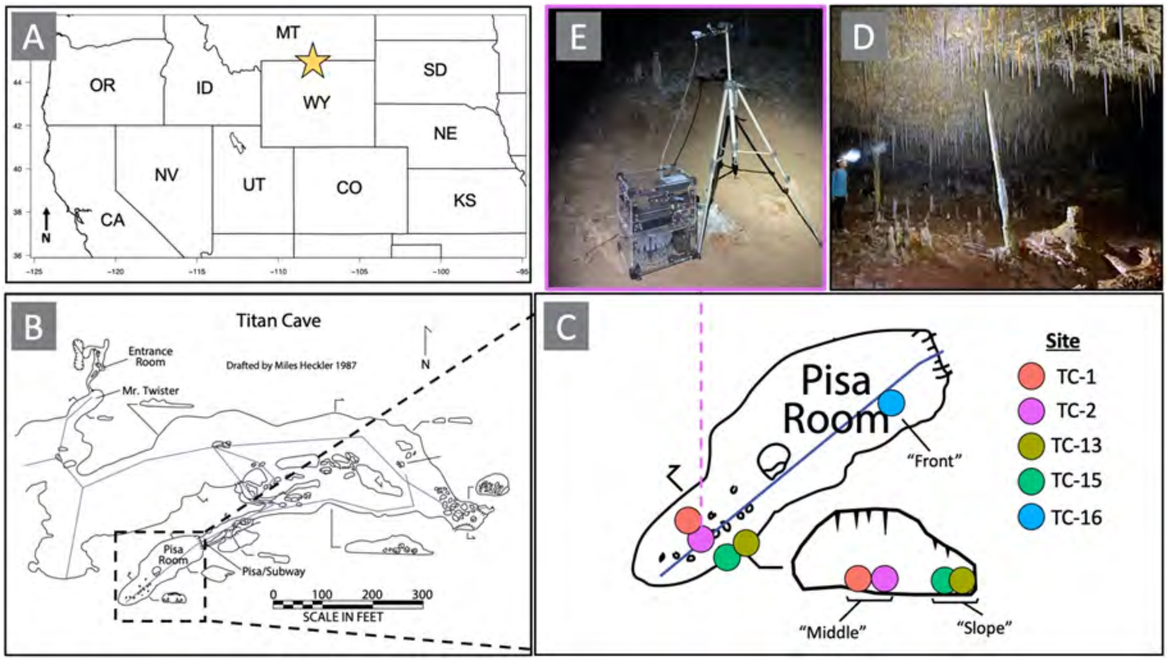

Figure 1. Location map of Titan Cave and inset maps to show drip site location and details. Counterclockwise, from top left: *A*, Location map of Titan Cave (yellow star), located on the western side of the Bighorn Mountain Range in north-central Wyoming; *B*, Titan Cave map with key locations marked; *C*, Zoomed-in map and cross section of the Pisa Room, with drip sites TC-1, 2, 13, 15, and 16 marked; *D*, Image of the Pisa Room in Titan Cave showing stalactite and stalagmite cave formations; *E*, Image of the SYP autosampler used to collect drip water at site TC-2. Photographs from Bryce Belanger.

elevation, indicate that winter snowfall and summer rainfall equally contribute to the annual precipitation budget in this region (Applied Climate Information System, 2024).

Sample collection and cave monitoring at TC takes place in the Pisa Room, roughly 300 meters from the cave entrance (fig. 1*B*). Because of the geometry of the cave, the Pisa Room is poorly ventilated and sits beneath an estimated 25–50 meters of overlying host rock. The Pisa Room is characterized by thousands of active and dormant speleothem formations (primarily stalactites and stalagmites), ranging from centimeters to over 3 meters in length (fig. 1*D*). At present day, the cave itself is mostly dry with limited actively dripping sites.

Cave Monitoring Overview and Sample Collection

Active cave monitoring at TC has been ongoing since September 2019. Visits to the cave have occurred on a biannual basis, usually in the fall and spring. A 2-year hiatus in visitation occurred due to the COVID pandemic between September 2019 and September 2021. Within the Pisa Room, air temperature and humidity were logged continuously from May to October 2022 using an Onset HOBO InTemp Data Logger. The data logger was relaunched in 2023 but data have not been retrieved as of April 2024. Drip rate is also logged continuously at multiple sites using Driptych Stalagmate acoustic drip loggers. Monitoring efforts have been focused on the section of the Pisa Room farthest from the cave entrance at five active drip sites, TC-1, TC-2, TC-13, TC-15, and TC-16 (fig. 1*C*). These sites were selected due to the presence of modern drip water and proximity to stalagmites recovered for paleoclimate reconstruction.

Stalagmate drip loggers were active at site TC-1 from November 2019 to January 2023, site TC-2 from September 2021 to May 2022, and site TC-15 from September 2021 to October 2023. Cave air pCO_2 was measured in the Pisa Room using a Vaisala CARBOCAP GMP252 CO_2 probe or an AZ Instrument Corp. 77535AZ EB handheld pCO_2 meter during each visit to the cave.

Drip water was sampled from TC using two methods. First, water was sampled instantaneously from multiple drip sites during biannual visits to the cave. Limited water availability and long drip intervals have restricted water sampling via this method. The few samples retrieved (n=6) via instantaneous sampling were collected for analysis of $\delta^{18}O$ and $\delta^{2}H$ in pre-cleaned 2-milliliter (ml) vials with limited headspace. In an effort to expand drip water sampling efforts at TC, a Waikato Scientific SYP water autosampler was installed in the Pisa Room at site TC-2 in late May 2022 and has been collecting water at 4-day intervals (fig. 1*E*). The 10-ml vials fill in approximately 12 hours, providing adequate water for $\delta^{18}O$, $\delta^{2}H$, and trace element analyses at sub-weekly resolution. In October 2023, freshly fallen snow was collected for stable isotope analysis in pre-cleaned 15-ml Falcon tubes. All water samples were kept refrigerated until analysis.

Water Sample Analysis

Drip water (n = 125) and snow (n=2) samples were analyzed on a Picarro L2130-i Isotopic Water Analyzer at Vanderbilt University. Each measurement consisted of four preparatory injections to minimize memory effects, and four measured injections. Samples were measured at least twice and corrected using external U.S. Geological Survey (USGS) reference water standards through the USGS LIMS for Lasers data reduction scheme (Coplen, 1998). Data are presented in per mil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) international standard. Typical precision of stable isotope measurements is about 0.02‰ for oxygen and about 0.1‰ for hydrogen (1σ).

Modern Calcite Collection and Analysis

Modern calcite was collected at sites TC-1, TC-2, TC-13, TC-15, and TC-16 in the Pisa Room. Glass plates, frosted via abrasion on a polishing wheel at 70-micrometer grit size, were carefully placed under each drip site and allowed to accumulate calcite precipitating from drip water between visits to the cave. Following recollection, samples of precipitated calcite were gently scraped from the frosted glass plates using a razor blade. The powdered calcium carbonate samples were then analyzed for $\delta^{18}O$ and $\delta^{13}C$ using a Thermo Finnigan DeltaV Plus isotope ratio mass spectrometer coupled to a Gasbench-II at Vanderbilt University. Carbonate powders were weighed into LabCo exetainers and dried overnight at 50 degrees Celsius (°C). Vials were then flushed with helium for 10 minutes. Anhydrous orthophosphoric acid was added to the vials, and the samples were allowed to react at 70 °C for at least 1 hour. Samples were corrected using in-house standards Thermo Calcite and VU-Coral that are referenced to the international standards IAEA-603 and NBS-18, respectively. Corrections were conducted using the USGS LIMS for Light Stable Isotopes data reduction scheme (Coplen, 1998). Data are presented in per mil (‰) relative to the Vienna PeeDee Belemnite (VPDB) international standard. Typical precision of stable isotope measurements is about 0.08‰ for oxygen and about 0.05‰ (1σ) for carbon.

Results

Cave Air Temperature, Relative Humidity, and pCO_2

Cave air temperature remained nearly constant in the Pisa Room from May 2022 until October 2022, averaging 9.59 °C with a standard deviation of plus or minus 0.05 °C. July was the warmest 30-day interval during the monitoring period (9.63 °C) and September 13th to October 13th was the coldest interval (9.55 °C). Relative humidity was close to 100 percent (%) and thus variations were not well-captured by the data logger. Average Pisa Room cave air pCO_2 was 577 parts per million (ppm) with approximately 100 ppm variability between Spring and Fall (table 1).

Drip Rate

Drip rate at all monitored sites in the Pisa Room is consistently slow, rarely reaching rates faster than one drip every 2 minutes (fig. 2). Site TC-15 has the slowest drip rate, averaging 0.12 drips per minute (dpm) during the monitoring period, which spans from September 2021 until October 2023, with a short hiatus due to a dead drip logger battery. TC-15 drip rate is nearly constant, excluding a slight positive trend toward faster drip rates from June through August 2023. During the overlapping period in the two records, trends in drip rates are nearly identical at sites TC-1 and TC-2, however, mean drip rate is roughly twice as fast at TC-1 (0.47 dpm) compared to TC-2 (0.20 dpm) (fig. 2). Drip rates at TC-1 and TC-2 show high correlation (Pearson's $R = 0.91$, $p < 0.0005$), displaying nearly synchronous changes on hourly to daily timescales. This strong coherence is unsurprising as the sites are only about 2 meters apart. TC-1 drip rate declines steadily during the monitoring period, decreasing by roughly 0.05 dpm per year from 2019 to 2023. TC-1 drip rate begins decreasing less rapidly in Summer 2022, synchronous with increasing summer rainfall in Deaver, WY (fig. 2).

Water Isotopes

Pisa Room drip water $\delta^{18}O$ values range from –20.26 per mil (‰) to –19.9‰, and $\delta^{2}H$ values range from –158.94‰ to –157.07‰ (fig. 3). Water collected for $\delta^{18}O$ at 4-day intervals using the autosampler at site TC-2 ranges between only –20.26‰ and -20.16‰ from May 2022 to October 2023. Considering the analytical uncertainty of 0.02% (1σ), the variability in site TC-2 drip water $\delta^{18}O$ appears to be extremely limited (fig. 4). Limited inter-site $\delta^{18}O$ variability within the Pisa Room was also noted. Drip water $\delta^{18}O$ collected instantaneously at sites TC-1 and TC-15 in October 2023 are identical within analytical uncertainty (–20.06‰ and –20.08‰), and instantaneously collected drip water from TC-1 in September 2021 is also similar (–20.02‰). Drip water collected near the cave entrance (site MT drip on fig. 3) in September 2021 and October 2022 is notably more enriched in ^{18}O, with values of –18.19‰ and –17.75‰ measured, respectively. Two snow samples collected from above TC in October 2023 have an average $\delta^{18}O$ value of –23.90‰ and a $\delta^{2}H$ value of –175.54‰.

Modern Calcite Stable Isotopes

Modern plate calcite $\delta^{13}C$ values range from –6.11‰ to 0.65‰ and $\delta^{18}O$ values range from –17.33‰ to –15.43‰ (figs. 5 and 6; table 2). Within the Pisa Room, systematic variations in modern calcite $\delta^{13}C$ and $\delta^{18}O$ were noted, based on drip site location (fig. 5), in addition to changes with time (fig. 6). Sites TC-1 and TC-2, located in the center of the Pisa Room, record more negative calcite $\delta^{13}C$ and $\delta^{18}O$ values compared to sites TC-13 and TC-15 which sit closer to the cave wall.

Table 1. Pisa Room instantaneous pCO_2 measurements.

[ppm, parts per million]

Visit Date	9/15/21	5/27/22	10/13/22	6/5/23	10/26/23
Pisa Room pCO_2	654 ppm	585 ppm	No data	469 ppm	600 ppm

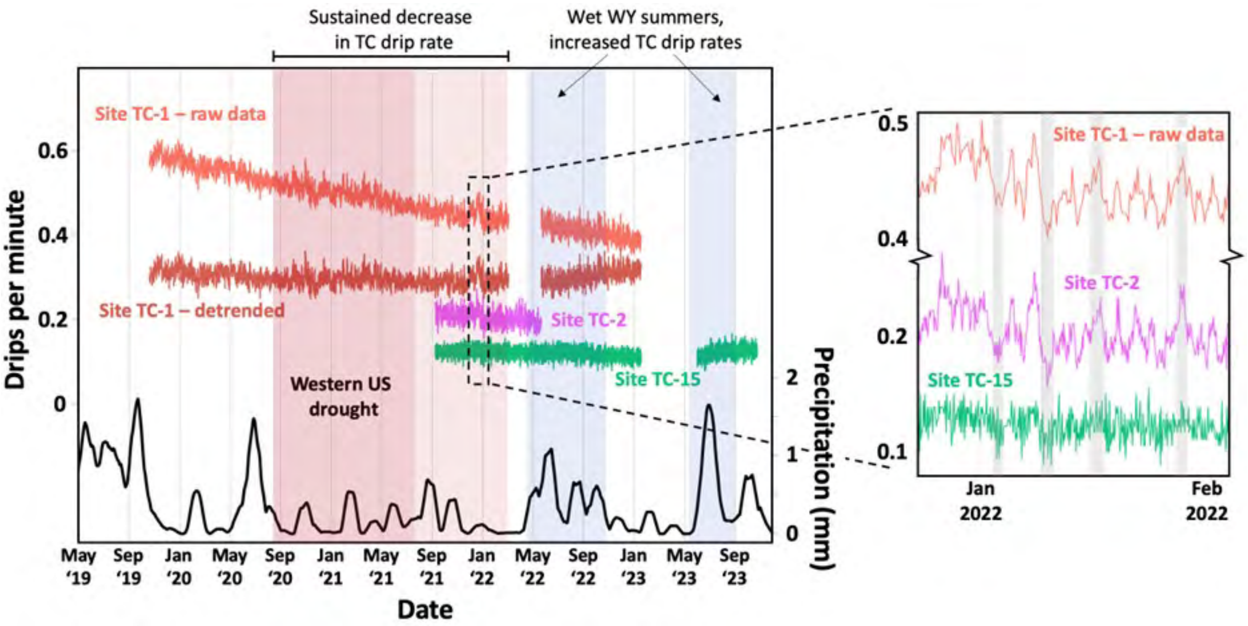

Figure 2. Titan Cave (TC) drip logger data and Deaver, WY weather data (Western Regional Climate Center, 2024) from May 2019 to December 2023. From top to bottom, TC-1 drip logger raw data (red), TC-1 drip logger data detrended using detrend function in R (maroon), TC-2 drip logger data (magenta), TC-15 drip logger data (green), and 15-point moving average of mean daily precipitation (in mm) over previous 30-day period in Deaver, WY (black). Western US drought selected based on Seager and others (2022) is highlighted by the dark red vertical bar labelled "Western US drought." Lighter red vertical bar demarcates extended dry conditions at TC. Blue vertical bars demarcate rainier summers at TC following drought conditions. Inset graph at right shows drip logger data from 12/20/21 to 2/8/22. Note break in y-axis. Gray bars highlight consistencies in drip rate response across all three sites.

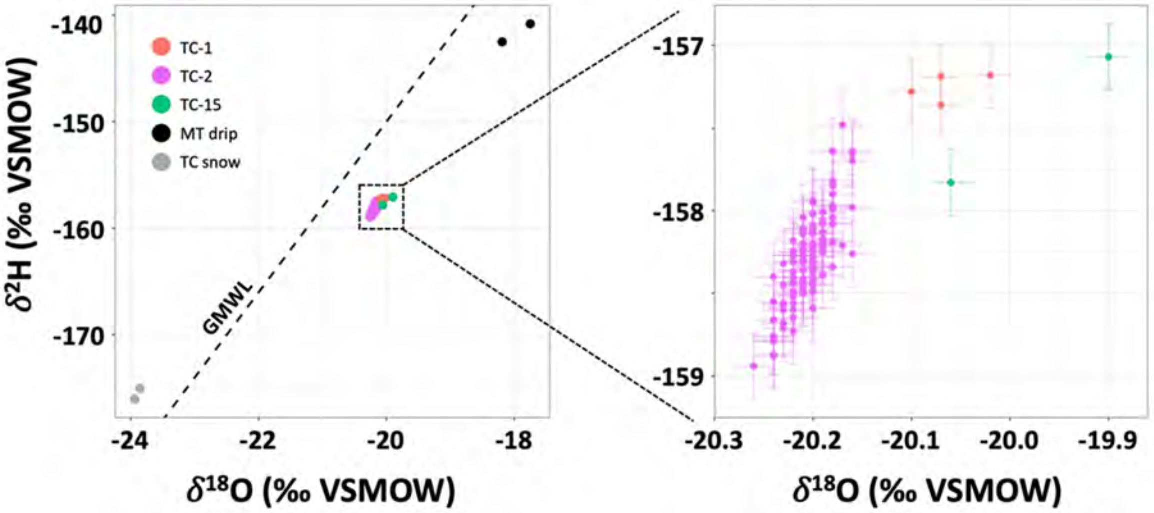

Figure 3. All Titan Cave water stable isotope data. "TC snow" samples (gray) were collected from fresh snow directly above the Pisa Room on 10/26/23. "MT drip" samples (black) were collected from the Mr. Twister section of the cave (see figure 1*B*) on 9/15/21 and 10/13/22. Site TC-1 samples (red) were collected on 9/15/21, 6/18/22, and 10/26/23. Site TC-15 samples (green) were collected on 6/18/22 and 10/26/23. TC-2 samples (magenta) were collected using the SYP autosampler from 5/31/22 to 10/26/23 at 4-day intervals. Representative error bars for repeat analyses (0.1 per mil [‰] for δ^2H and 0.02‰ for $\delta^{18}O$ [both 1σ]) are shown. Error bars are smaller than symbols in main figure. Dashed line represents global meteoric water line (GMWL) with slope=8 and y-intercept=10.

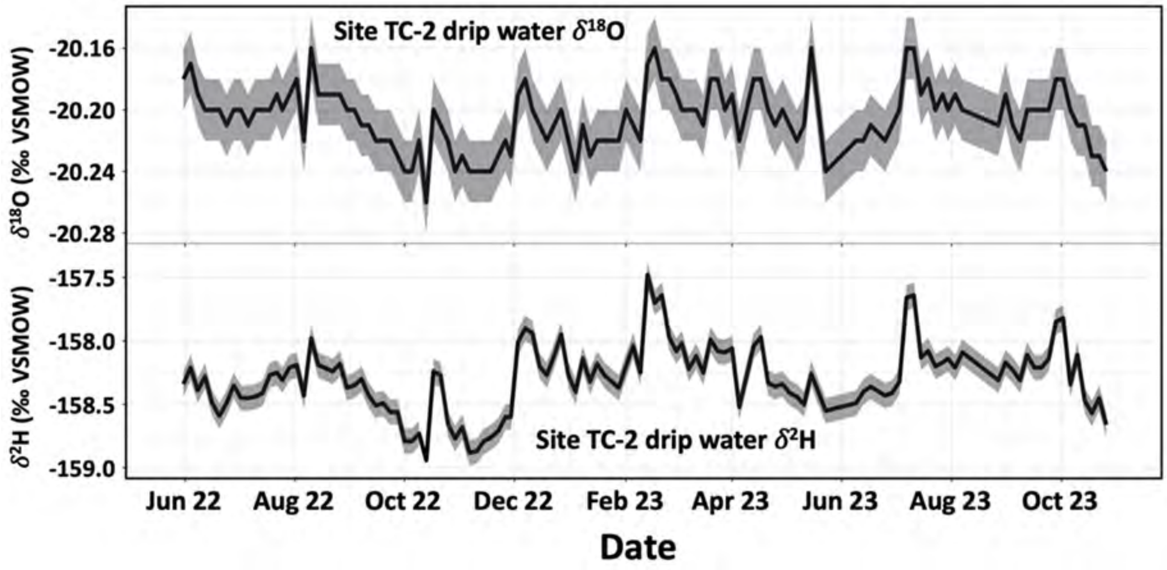

Figure 4. Stable oxygen isotope ($\delta^{18}O$) timeseries measured from site TC-2 drip waters in the Pisa Room of Titan Cave. Waters were collected at 4-day intervals (over about 12 hours) from 5/31/22 to 10/26/23, using the SYP water autosampler. Representative error bars (1σ) for repeat analyses (plus or minus 0.02‰) are shown.

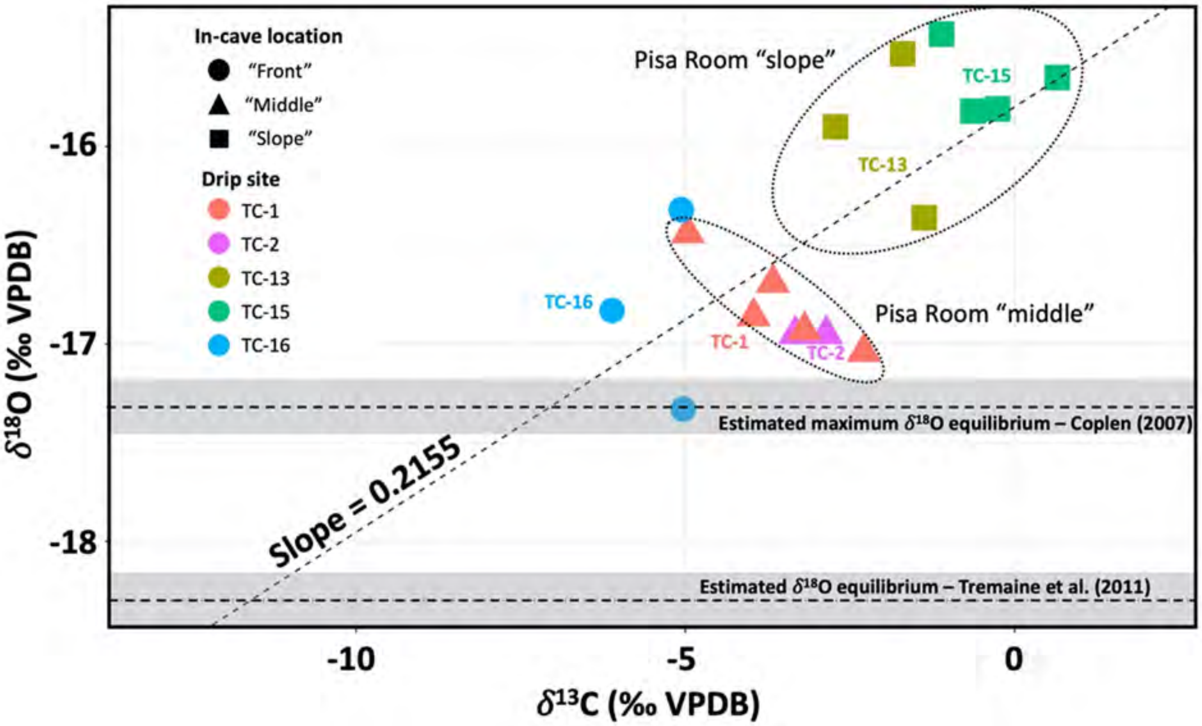

Figure 5. Stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope data collected from calcium carbonate formed on glass plates in the Pisa Room of Titan Cave. Sites TC-1 and TC-2 are located in the middle of the Pisa Room under a high cave ceiling (see figure 1*C*), sites TC-13 and TC-15 sit against the room wall under a low cave ceiling, and site TC-16 is in a separate part of the room under a high ceiling. Linear regression of the data yields a slope of 0.2155. Estimated equilibrium calculated using Tremaine and others (2011) and Coplen (2007) as described in text. See table 2 for raw data and timing of plate calcite collection.

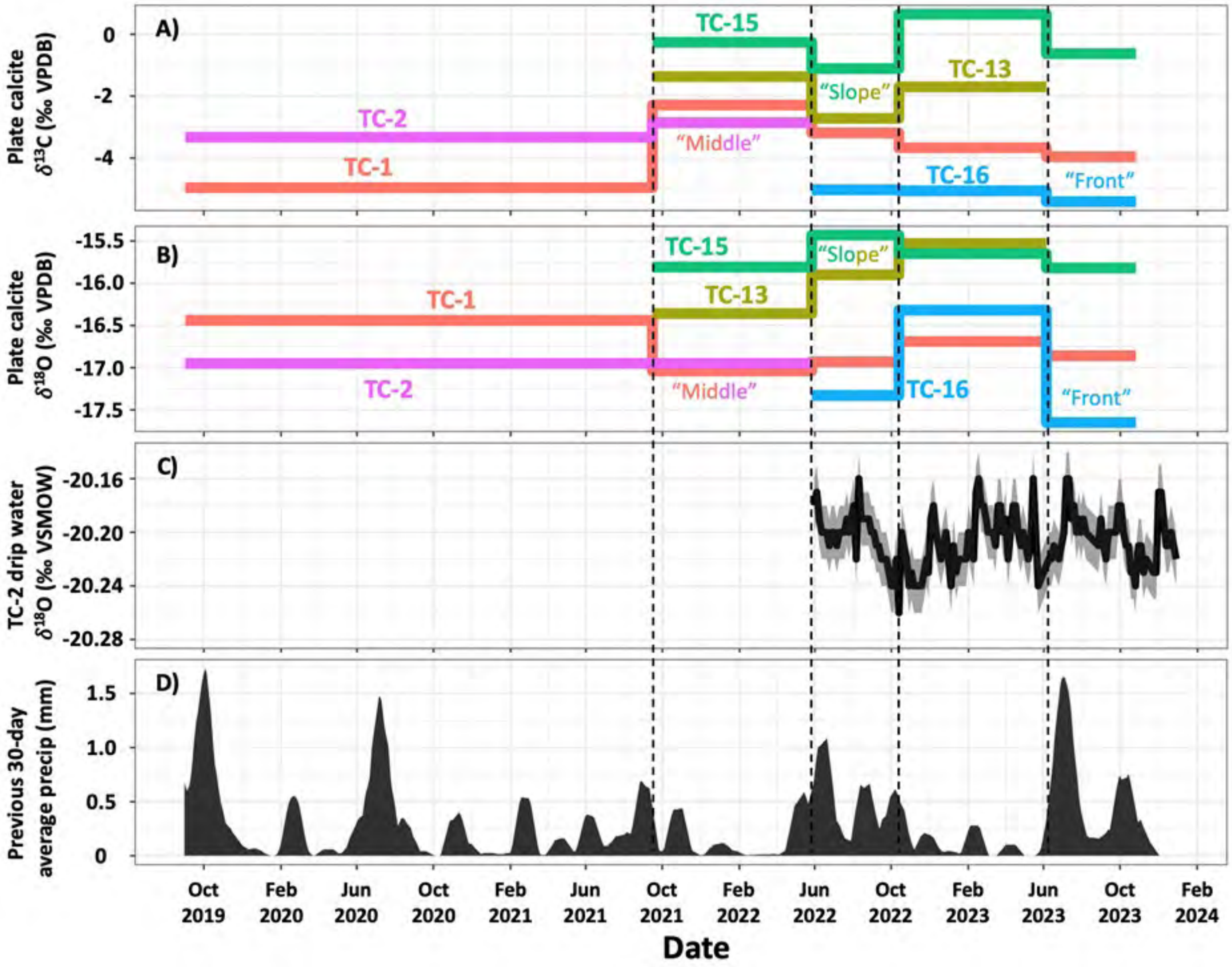

Figure 6. Pisa Room stable isotope data and Deaver, WY weather data (Western Regional Climate Center, 2024). *A*) Stable carbon ($\delta^{13}C$) and *B*) oxygen ($\delta^{18}O$) isotope timeseries from farmed calcium carbonate precipitated on glass plates at sites TC-1, 2, 13, 15, and 16. *C*) Site TC-2 drip water stable isotope ($\delta^{18}O$) timeseries (same as fig. 4). *D*) 15-point moving average of mean daily precipitation (in mm) over previous 30-day period in Deaver, WY. Dashed lines mark when glass plates were collected and replaced.

Table 2. Titan Cave plate calcite stable isotope data.

[$\delta^{13}C$, del carbon-13; $\delta^{18}O$, del oxygen-18; ‰ VPDB, per mil Vienna PeeDee Belemnite]

Site	Start Date	End Date	$\delta^{13}C$ (‰ VPDB)	$\delta^{13}C$ uncertainty (1σ)	$\delta^{18}O$ (‰ VPDB)	$\delta^{18}O$ uncertainty (1σ)	Location in Pisa Room
TC-1	9/1/19	9/15/21	–4.96	0.06	–16.44	0.08	Middle
TC-1	9/15/21	5/27/22	–2.29	0.02	–17.04	0.04	Middle
TC-1	5/27/22	10/13/22	–3.19	0.02	–16.93	0.04	Middle
TC-1	10/13/22	6/5/23	–3.67	0.02	–16.69	0.07	Middle
TC-1	6/5/23	10/26/23	–3.96	0.03	–16.86	0.03	Middle
TC-2	9/1/19	9/15/21	–3.33	0.03	–16.95	0.07	Middle
TC-2	9/15/21	5/27/22	–2.86	0.06	–16.95	0.09	Middle
TC-13	9/15/21	5/27/22	–1.37	0.09	–16.36	0.10	Slope
TC-13	5/27/22	10/13/22	–2.72	0.08	–15.9	0.03	Slope
TC-13	10/13/22	6/5/23	–1.7	0.04	–15.53	0.04	Slope
TC-15	9/15/21	5/27/22	–0.26	0.06	–15.81	0.09	Slope
TC-15	5/27/22	10/13/22	–1.11	0.04	–15.43	0.04	Slope
TC-15	10/13/22	6/5/23	0.65	0.05	–15.65	0.07	Slope
TC-15	6/5/23	10/26/23	–0.63	0.04	–15.82	0.03	Slope
TC-16	5/27/22	10/13/22	–5.03	0.03	–17.33	0.07	Front
TC-16	10/13/22	6/5/23	–5.06	0.09	–16.32	0.07	Front
TC-16	6/5/23	10/26/23	–6.11	0.06	–16.83	0.09	Front

Discussion

The suite of monitoring data collected from Titan Cave across multiple years allows for the systematic and cave-specific interpretation of geochemical variability recorded in drip water and modern plate calcite at this site. In this section, individual monitoring datasets from TC are discussed. These data are then summarized and synthesized as it relates to interpretations of past climate change in the Bighorn region as recorded via TC speleothems.

Cave Air

Titan Cave air temperature, pCO_2, and humidity are remarkably constant throughout the year and over the duration of the monitoring period. In the Pisa Room, cave air temperature varies by less than 0.1 °C seasonally, suggesting limited exchange with surface air and restricted air flow to this room in TC where speleothem growth is occurring. Our interpretation of poor ventilation to the Pisa Room is further supported by relative humidity measurements, which remain close to 100% and vary by less than 1% throughout the monitoring period. Cave air pCO_2 is also relatively constant and remains about 200 ppm greater than atmospheric levels throughout the year, further supporting our interpretation of limited surface air ventilation to the Pisa Room.

Drip Rate

Drip rates in the Pisa Room show muted changes in response to weather events and seasonal shifts above the cave. In contrast to other caves in the United States (Oster and others, 2012; Sekhon, 2021), TC drip rates are relatively insensitive to precipitation events and spring snowmelt. Instead, TC drip rates increase or decrease by only 10–20% on seasonal to multi-year timescales as a reflection of longer-term variations in precipitation amount.

The most notable trend in TC drip rate data is the sustained decrease in site TC-1 drip rate from fall 2019 through winter 2023. This trend is relatively constant and uninterrupted by precipitation seasonality or individual rainfall or snowmelt events. Overall, this trend is interpreted to reflect the drought conditions sustained in north-central Wyoming from fall 2020 through spring 2022. Well-documented drought in the western US (including Wyoming) occurred from summer 2020 to spring 2021 (Seager and others, 2022). Decreasing drip rates at site TC-1 during this interval suggest that multi-seasonal to multi-annual precipitation trends above TC have the strongest control on drip rate at this location. Notably, an examination of detrended TC-1 drip rate data shows a positive trend beginning in summer 2022, the same time when a rainy summer in Wyoming led to the amelioration of drought conditions in the region (fig. 2). Site TC-15 also records a small (approximately 5%) uptick in average drip rate during the even wetter summer of 2023.

A potential inconsistency in these interpretations is the lack of a drip rate change at site TC-1 coincident with rainy conditions in summer 2020 (fig. 2). The absence of a drip rate response to this event further highlights the smoothing of climate signals being transferred to the cave environment at TC. However, it may also demonstrate the importance of summer evaporation on TC drip rate, as average daily pan evaporation in Powell, WY (about 50 kilometers southwest of TC) was 70% higher in summer 2020 (no drip rate increase) compared to summer 2022 when detrended TC-1 drip rate data show a positive trend (Western Regional Climate Center, 2024). Titan cave drip rates also increase slightly during summer 2023, however, pan evaporation data are not available for this period. Overall, TC drip rate data suggest that multi-seasonal to multi-year precipitation trends are relayed to the cave environment, while the signal of short-term rainfall and snowmelt events are smoothed by water mixing and slow infiltration times in the karst above TC.

Small fluctuations in drip rate on hourly to daily timescales are nearly identical at sites TC-1 and TC-2. When comparing daily averaged dpm from sites TC-1 and TC-2, a Pearson's R value of 0.91 ($p < 0.0005$) is calculated. During their overlapping period of record from September 2021 to March 2022, drip rates at both sites varied by a maximum of only 0.1 dpm. However, these slight variations in drip rate are mirrored at both sites, suggesting a common control on water delivery. Sites TC-1 and TC-2 are separated by only 2 meters in the Pisa Room, therefore this common control on drip rate could be linked to a shared flow path between the sites. Drip water stable isotope values are nearly identical between the two sites, providing further support for a shared flow path to TC-1 and TC-2. Site TC-15, which is separated from TC-1 and TC-2 by roughly 10 meters, also shows similar drip rate trends. When comparing daily averaged dpm from sites TC-1 and TC-15, a Pearson's R value of 0.83 ($p < 0.0005$) is calculated, and a value of 0.86 ($p < 0.0005$) is calculated when comparing TC-2 and TC-15. Both correlations are strong although weaker than between TC-1 and TC-2. This is possibly due to extremely slow drip rates at TC-15 (less than 0.15 dpm) and limited drip rate variability, in addition to the physical distance between the sites.

Water Isotopes

Water isotopes in cave drip water can reflect numerous processes, both above and within the karst environment. Due to slow drip rates within TC and the Pisa Room, the majority of drip water collection occurred at site TC-2 using the SYP autosampler. As with drip rate, there is little variation in drip water δ^2H and δ^{18}O at TC-2 during the monitoring period (figs. 3 and 4). In both 2022 and 2023, drip water δ^2H and δ^{18}O values increased in July and August by about 0.5‰ and about 0.05‰ respectively, before falling steadily during October (fig. 4). This pattern suggests a slight seasonal control on drip water isotopic composition. Increasingly negative δ^2H and δ^{18}O during the fall could reflect the delivery of moisture sourced from more northern regions during the shift from summer to winter precipitation regimes (Oster and others, 2020). However, this theory does not explain the return to more positive isotopic values during December 2022. An extended period of drip water collection at TC-2 is necessary to elucidate multi-year trends in water isotope composition. Because of the limited variability of drip water δ^2H and δ^{18}O on seasonal timescales, multi-year trends in precipitation are possibly responsible for isotopic shifts recorded in TC speleothems. As with TC drip rate, event to seasonal-scale variability in precipitation δ^2H and δ^{18}O above TC is not transferred through the epikarst to the Pisa Room.

A small number of instantaneously collected TC drip waters provide important details regarding intra-cave variations in δ^2H and δ^{18}O values. Within the Pisa Room, sites TC-1, TC-2, and TC-15 all record similar δ^{18}O values between –20.25‰ and –19.9‰. Limited variability in drip water δ^{18}O between sites provides further evidence that delivery of water to sites throughout the Pisa Room is controlled by shared karst processes, and therefore will respond similarly to climatic and environmental changes. Because of limited systematic departures from the global meteoric water line, evaporation of water prior to dripping is likely not influencing drip water stable isotope composition in the Pisa Room (fig. 3).

Modern Calcite Stable Isotopes

Stable oxygen and carbon isotopes in speleothems (and modern calcite) are influenced by various processes acting over multiple timescales. Possible controls on long-term δ^{13}C variability include the ratio of C3 to C4 vegetation above the cave (Burns and others, 2016; Fohlmeister and others, 2020), temperature as it relates to soil respiration (Fohlmeister and others, 2020), and atmospheric CO_2 concentrations at the time of speleothem growth (Breecker, 2017). On shorter timescales, changes in water supply and variations in soil respiration, CO_2 degassing, and prior calcite precipitation likely play a larger role in dictating seasonal to multi-year δ^{13}C fluctuations at TC (Ersek and others, 2012, Oster and others, 2012, 2020).

Speleothem δ^{18}O reflects the δ^{18}O of precipitation above the cave site, potentially modified by evaporation and water mixing in the karst, and changes during calcite precipitation via non-equilibrium processes and temperature-dependent fractionation in the cave (Baker and others, 2019). Coeval speleothem records from the same cave do not always display the same trends or mean values, demonstrating the possibility for control on speleothem δ^{18}O by flow path variability (Treble and others, 2022) and in-cave disequilibrium processes (Mickler and others, 2004, 2006). Progressive CO_2 degassing before and during calcite precipitation in the cave leads to positive excursions in δ^{13}C and δ^{18}O due to the preferential loss of ^{12}C and ^{16}O into the gas phase (Dreybrodt and Scholz, 2011). Therefore, when a positive linear relationship is observed between δ^{13}C and δ^{18}O, it can indicate disequilibrium processes (Hendy, 1971; Mickler and others, 2004, 2006). The slope of this linear relationship can vary due to the degree of carbon isotope exchange between dissolved inorganic carbon (DIC) in the drip water and CO_2 in the cave atmosphere (Parvez and others, 2024).

At Titan Cave, plate calcite $\delta^{13}C$ and $\delta^{18}O$ values are variable in both space and time (figs. 5 and 6). Most notably, drip sites in the middle of the Pisa Room (TC-1, TC-2) are consistently more negative in $\delta^{13}C$ by about 2‰ and $\delta^{18}O$ by about 1.5‰ compared to the sites located near the room's wall (TC-13, TC-15). Because of the lack of consistent drip water sampling across sites, a karst (flow path hydrology) control on this observed isotopic variability cannot be ruled out. In this case, we would expect plate calcite at sites TC-1 and TC-2, which display more negative isotopic ratios, to receive proportionally larger amounts of recharge from snowmelt or isotopically lighter water sources compared to TC-13 and TC-15. Additionally, we would expect less CO_2 degassing in the epikarst above TC-1 and TC-2 due to faster/less disrupted water flow. These are both reasonable assumptions given the faster drip rates observed in the center of the Pisa Room that are more responsive to surface precipitation, indicative of more fracture-based flow. This would allow increased recharge during periods of snowmelt (more negative $\delta^{18}O$) and less time for prior calcite precipitation (PCP) in the karst (more negative $\delta^{13}C$). Following the classification scheme of Smart and Friederich (1986) all TC drips are determined to be dominated by seepage (or diffuse) flow due to their low maximum water discharge and low drip rate variability (Baldini and others, 2006; Tremaine and Froelich, 2013; Wong and Breecker, 2015). However, although absolute differences in drip rate and drip variability are small, relative differences in these metrics between drip sites is quite large, suggesting that flow paths to various TC drips may be different despite all falling under the seepage/diffuse flow classification.

If it is assumed that flow paths and drip water $\delta^{18}O$ are consistent between sites in the Pisa Room, disequilibrium processes must be invoked to explain intra-cave differences in the isotopic composition of calcite. Calcite formed at all drip sites within the Pisa Room is more positive in $\delta^{18}O$ than would be expected at TC based on measured drip water $\delta^{18}O$ values (fig. 5). Given a constant Pisa Room temperature (9.59 °C) and average measured drip water $\delta^{18}O$ (–20.2‰ VSMOW), the equilibrium relationship of Tremaine and others (2011) predicts speleothem $\delta^{18}O$ values of approximately –18.3‰ VPDB, or about 1‰ more negative than any measured TC plate calcite value. Using the most positive $\delta^{18}O$ water isotope value (–19.9‰ VSMOW) and lowest temperature (9.46 °C) value, the Tremaine and others (2011) equation still yields an equilibrium $\delta^{18}O$ value as low as –18.0‰ VPDB. To determine if equilibrium relationship selection is the source of this offset, the same cave parameters and the equilibrium relationship of Coplen (2007) were employed, which was calculated using a different set of empirical data than Tremaine and others (2011). This equation predicts a calcite $\delta^{18}O$ value of –17.4‰ VPDB, which only aligns with calcite $\delta^{18}O$ values measured at site TC-16 (fig. 5). This suggests a departure of TC plate, and thus potentially speleothem, calcite to more positive $\delta^{18}O$ values due to preferential degassing of ^{16}O during calcite formation at most or all Pisa Room drip sites.

A positive correlation also exists between the measured $\delta^{13}C$ and $\delta^{18}O$ of TC plate calcite (slope = 0.2155, $R^2 = 0.46$) (fig. 5). This slope falls within the range of slopes reported by Parvez and others (2024) in an investigation of disequilibrium and carbon isotope exchange between cave air CO_2 and DIC in the drip water. In this situation, the slower drip rates observed along the walls of the Pisa Room (sites TC-13 and TC-15) would enable increased time for degassing and isotopic exchange prior to calcite precipitation, therefore driving $\delta^{13}C$ and $\delta^{18}O$ to more positive values. At the center of the cave (sites TC-1 and TC-2), faster drip rates lead to more rapid replenishment of DIC and H_2O reservoirs with fresh cave water, thus maintaining more negative isotopic values closer to equilibrium. Plate calcite timeseries data (fig. 6) show that these relationships are consistent through time, as $\delta^{13}C$ and $\delta^{18}O$ at TC-1 and TC-2 are always more negative than at TC-13 and TC-15, despite variability from one plate collection interval to the next.

On the basis of these observations, it is possible that both karst processes, in-cave degassing, or both, are contributing to the intra-cave variations in plate calcite $\delta^{13}C$ and $\delta^{18}O$. Future trips to Titan Cave will focus on collecting drip water from additional sites within the cave to further investigate variability in drip water $\delta^{18}O$.

Implications for Paleoclimate Reconstruction at Titan Cave

Titan Cave monitoring efforts have demonstrated the suitability of TC speleothems for paleoclimate reconstruction. Constant cave temperature, relative humidity, and pCO_2 limit opportunities for seasonal biases to arise in TC speleothems. In caves where temperatures and calcite growth rates exhibit large seasonal variations, changes in $\delta^{18}O$ may be driven by changes in temperature-dependent equilibrium fractionation instead of recording shifts in hydroclimate (Mickler and others, 2004). Similarly, constant relative humidity limits season-specific changes in the degree of disequilibrium fractionation, influencing calcite $\delta^{13}C$ and $\delta^{18}O$. Consistent cave air pCO_2 is also important for limiting growth biases, as calcite precipitation is reduced when pCO_2 is high (Baldini and others, 2008), and seasonal variations in pCO_2 can drive PCP shifts independent of hydroclimate controls (Oster and others, 2012). Elevated pCO_2 levels may also drive increased carbon isotope exchange (Skiba and Fohlmeister, 2023). This risk is limited at TC due to consistent pCO_2 throughout the year.

Additionally, TC drip rate does not fluctuate seasonally or as a result of event-scale precipitation. Rather, a sustained, multi-year drought resulted in the slow reduction in drip rate at some sites. Drip water collected via the SYP autosampler at

4-day intervals over 16 months records only 0.1‰ variability in $\delta^{18}O$, just beyond the limits of analytical uncertainty. Titan Cave plate calcite also records minimal shifts in isotopic composition, with calcite $\delta^{18}O$ and $\delta^{13}C$ varying by only 1‰ and 2‰, respectively, at a single drip site (fig. 5). Furthermore, plate calcite $\delta^{18}O$ and $\delta^{13}C$ do not shift dramatically as the result of seasonal variations or changes in precipitation amount (fig. 6). A -1‰ shift in $\delta^{13}C$ at sites TC-1, TC-13, and TC-15 was observed during the relatively wet summer of 2022, possibly reflective of more rapid water infiltration and reduced PCP. These observations indicate that TC speleothems will document time-averaged records of hydroclimate in the Bighorn region.

Analysis of stable isotopes in plate calcite from multiple Pisa Room sites provides critical context for reconstructions of paleoclimate using TC speleothems. Modern calcite data show that variable water flow paths and/or disequilibrium effects may be driving differing degrees of $\delta^{18}O$ and $\delta^{13}C$ change in the center of the Pisa Room compared to the sides (figs. 5 and 6). These observations provide two key insights when interpreting Pisa Room speleothem records. First, similar offsets between coeval speleothem records may exist in the Pisa Room. If this is the case, it should reflect (1) spatial variability in karst processes, or (2) differential Rayleigh fractionation processes within the cave. If temporal trends in $\delta^{18}O$ and $\delta^{13}C$ are consistent among stalagmites from different sites within the cave, this should confidently be interpreted to reflect regional hydroclimate change. Second, speleothems growing in the center of the Pisa Room will likely record isotopic values closer to equilibrium compared to those growing along the wall and are thus best suited for paleoclimate reconstruction.

Conclusions

This study presents data from the first known comprehensive, multi-year cave monitoring campaign in the Rocky Mountains in the western conterminous United States. The dataset includes measurements of cave temperature, relative humidity, pCO_2, drip rate, and water and modern calcite stable isotope compositions from Titan Cave, Wyoming. Monitoring efforts reveal a remarkably stable cave environment, with consistent cave temperature, humidity, and pCO_2 throughout the year. Small fluctuations in drip rate were observed that are consistent with multi-seasonal to annual trends in precipitation, along with slight shifts in drip water and plate calcite stable isotope values on similar timescales. Modern plate calcite $\delta^{18}O$ and $\delta^{13}C$ values show intra-cave variability along with a systematic trend away from isotopic equilibrium conditions in specific areas of the cave. Thus, the middle of the Pisa Room was identified as the location best suited for future speleothem paleoclimate reconstructions due to the high density of speleothem growth and calcite $\delta^{18}O$ values closer to equilibrium than at other Pisa Room locations. Because of the documented stability of the cave environment and abundant suitable stalagmites, Titan Cave was found to be a favorable cave for the development of speleothem proxy records.

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