Principal Component and time series analysis of a stalagmite geochemical record from Yucatán, Mexico

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Introduction

Advanced statistical analyses of paleoclimate data is a powerful approach to calibrating proxy signals of environmental events and processes. For stalagmites, multivariate geochemical records respond to subannual variations in environmental trends and high-magnitude events. Although large trace element datasets can pose difficulties for analysis and interpretation due to natural processes acting on varying time scales and magnitudes, Principal Component Analysis (PCA) reduces the complexity of geochemical data by identifying the combinations of elements which best explain the overall patterns of variability in speleothems[1]. This study seeks to expand stalagmite analysis by applying PCA to a large high-resolution LA-ICP-MS stalagmite trace element dataset from northern Yucatán, Mexico, in order to detect signals from volcanic ash deposition, land use changes, and leads and lags in the climate system, which can provide important insights into climatic forcing and feedback mechanisms, over the last ~500 years. Future analyses could extend this record of environmental variability to 200 B.C.E.

Hypothesis

By applying advanced statistical analysis to the multivariate dataset, we aim to separate volcanic eruptions from other factors such as changes in land use on the ranch above the cave, and climate anomalies.

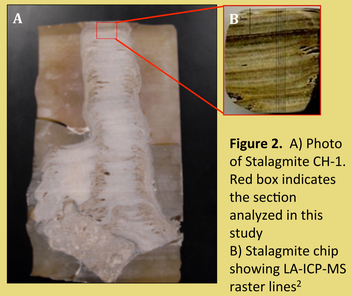


Figure 2. A) Photo of Stalagmite CH-1. Red box indicates the section analyzed in this study
B) Stalagmite chip showing LA-ICP-MS raster lines[2]

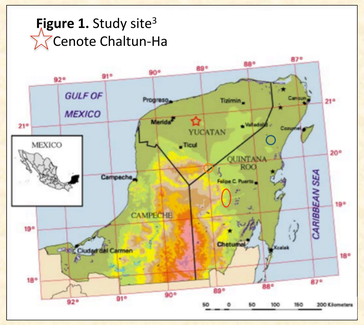


Figure 1. Study site[3]
Cenote Chaltun-Ha

Field Methods and Sample Preparation

- Stalagmite CH-1: collected July 2007 from Cenote Chaltun Ha, Huhí, Yucatán, Mexico
- Historical calibration target period : last ~500 years
- A 1.9 cm x 2.2 cm chip was cut and polished for geochemical analysis (Figure 2)

Age Model

- Stalagmite CH-1 was dated using radiometric and layer counting techniques4.
- Refined age model assuming linear growth for each annual layer (Figure 3)

Geochemical Analysis

- Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analysis at Columbia University Lamont-Doherty Earth Observatory, NY[2].
- 19 elements were analyzed ^{11}B, ^{23}Na, ^{26} Mg, ^{27}Al, ^{29}Si, ^{31}P, ^{43}Ca, ^{47}Ti, ^{49}Ti, ^{55}Mn, ^{57}Fe, ^{85}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{138}Ba, ^{140}Ce, ^{232}Th, and ^{238}U

Data Analysis

- Concentrations normalized to ^{43}Ca , NIST 610, and NIST 612 using Lasy Boy[6]
- Z-scores were calculated in RStudio[7]
- PCA was applied to standardized data using the *pca* function in RStudio[7]
- Used scree plot and standard deviation values to determine significance of PC
- Each significant PC was compared to historical data: volcanic eruptions in the Yucatán region[2], the land use change initiated by the Spanish conquest (~1542)[3], the land use change associated with Henequen (*Agave Fourcroydes*) production (1900-1916)[3], and precipitation anomalies[5]

Figure 3. Refined Age Model[4]

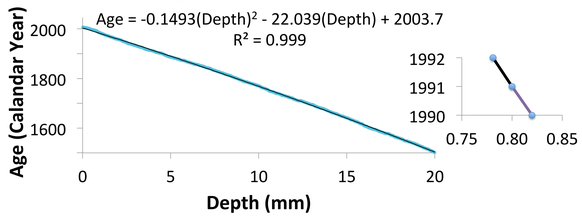
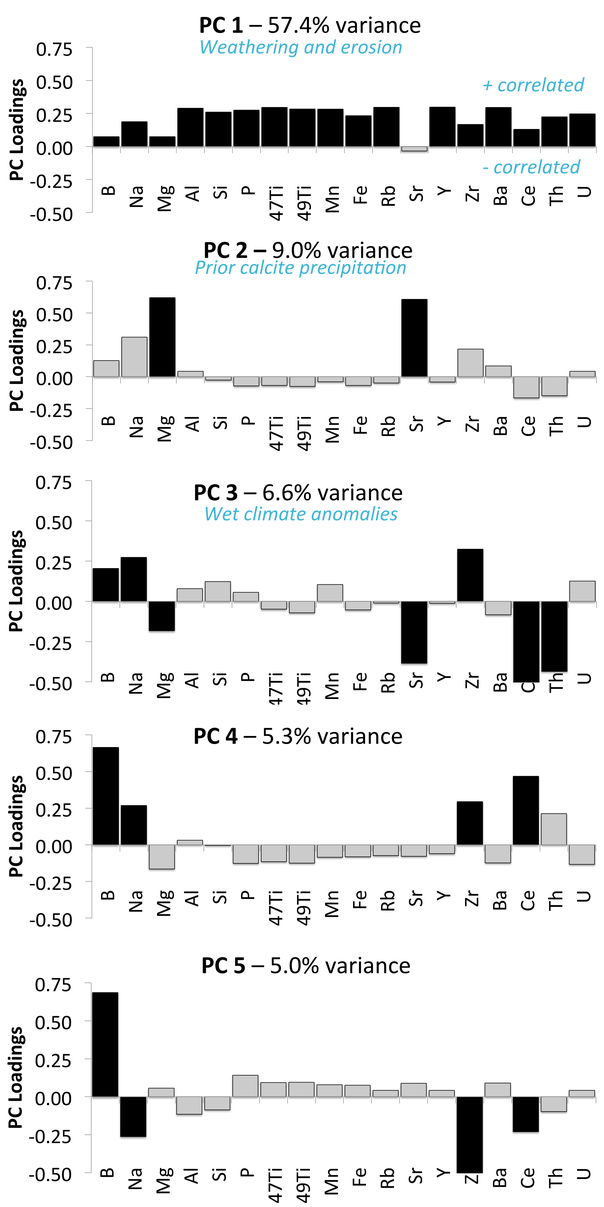


Figure 4. Trace element loadings for each principal component (PC)



Results

- Figure 4 shows loadings for the first five PCs, explaining >83% of the total variance in the dataset.
  - **PC1-high + loadings on most elements**
  - **PC2-high + loadings for Mg, Sr**
  - **PC3-high + loadings for Zr, Na, B. – for Ce, Th, Sr, Mg**
  - **PC4-high + loadings for B, Ce, Zr, Na**
  - **PC5-high + loading for B. – loadings for Zr, Na, Ce**
- Figure 5 shows the change in each PC vs. time.
  - **PC1-responds to short lived events and values are persistently high between 1580-1600 and 1883-1915**
  - **PC2-responds to short lived events and values are persistently high between 1558-1606**
  - **PC3-responds to short lived events and values are persistently high between 1575-1600 and 1902-1920**
  - **PC4- values are persistently high between 1575-1595**
  - **PC5-values remain relatively consistent**

Discussion

- PC1 is sensitive to weathering and erosion, including fresh tephra deposition. PC1 responded to:
  - 12 known volcanic eruptions, and land-use changes: Spanish settlement, and Henequen cultivation.
- PC2 responds to prior calcium precipitation associated with dry climate anomalies by increasing Sr and Mg substitution. PC2 responded to:
  - 5 volcanic aerosol-forced drying, and land-use changes: Spanish settlement, Henequen production, and decreased precipitation (1600-1655).
- PC3 is sensitive to wet climate anomalies. PC3 responded to:
  - Increased precipitation, particularly (1775-1825) and (1885-1915), and Spanish settlement
- PC4 and PC5 are closely related to each other on > annual time scales, but are uncorrelated at ~weekly time scales
  - PC4 leads during increases but lags when decreasing

Future Work

- Apply LA-ICP-MS and PC analysis to the entire stalagmite
- Look for geochemical and climatic signals from major volcanic events including 1250's, 536
- Perform Spectral Analysis on the PCs to identify hidden periodicities

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References

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Figure 5. Principal component vs. time