Preliminary investigation of paleohydrology of Southern Indonesia from stable isotopes in an East Timor speleothem.

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Abstract

New $\delta^{18}O$ and $\delta^{13}C$ isotopes of a speleothem from a South Indonesian island provide the basis for the reconstruction of regional paleohydrology. $\delta^{18}O$ values from speleothem calcite and cave drip water were used to create a hypothetical temperature record, indicating extremely large variation, suggesting that variations in this record are not a result of temperature effects but rather hydrologic effects. A large range in $\delta^{18}O$ and $\delta^{13}C$ values (5.73‰ and 10.5‰ respectively) along the length of the speleothem indicate significant variability in rainfall over the lifespan of the speleothem. These variations, including a marked increase in $\delta^{18}O$ values at the base of the speleothem, may correspond to shifts in the Intertropical Convergence Zone (ITCZ) and changes in the Australian Indonesian Summer Monsoon (AISM). With the inclusion of an age model this record will contribute to past climate records for a region of global climate significance.

Introduction

Humans have demonstrated an incredible amount of adaptability and resiliency over time but are largely at the mercy of local and global climate. In light of current climate change, paleoclimatology reconstruction is crucial in understanding how future climates may develop and the impacts that climate changes may have. Stable isotope analysis of speleothem (secondary CaCO$_3$ cave deposits) calcite allows for reconstruction of past temperature and hydrological conditions (Lachinnet 2009, Williams, et al. 2005). Speleothems provide high resolution, long-term hydrology records because of the stable nature of cave environments and their tendency to reflect external mean temperatures (Lachinnet 2009). Speleothem studies have given insight into variations in Holocene rainfall and climate regimes including evidence for a Younger Dryas period and multiple Heinrich events (eg. Griffiths, et al. 2010; Williams, et al. 2005; Lewis, et al. 2011). The majority of such studies
take place in mid to high-latitude regions and a general consensus indicates a lack of continental data from low-latitude sites (Griffiths, et al. 2010). More low-latitude reconstructions would provide insight into tropical responses to high-latitude temperature fluctuations including those during major climate shifts like the last glacial maximum (Griffiths, et al. 2010).

A complex network of ocean currents, sea surface temperatures and air and moisture circulation drives global climate trends. The Indo-Pacific Warm Pool (IPWP) provides a source moisture and heat that is distributed via the Indonesian Throughflow between the Pacific Ocean and Indian Ocean basins demonstrating a large tropical influence on global climate (Griffiths, et al. 2010, Oppo & Rosenthal 2010). This important low-latitude ocean current is closely linked to climate phenomena including monsoons, the El Nino-Southern Oscillation (in the Pacific) and the Indian Ocean Dipole (IOD) (Oppo & Rosenthal 2010). The southern portion of the IPWP is strongly influenced by the Australian-Indonesian Summer Monsoon associated to the Intertropical Convergence Zone (ITCZ) (Griffiths, et al. 2010).

This study provides isotopic analysis of one speleothem from an Indonesian island located in the southern portion of the IPWP. Stable $\delta^{18}O$ and $\delta^{13}C$ isotopes from the speleothem are used to reconstruct a record of possible past hydrology for the region. This preliminary study sets the basis for future temporal reconstructions of tropical hydrology representing a valuable addition to low-latitude paleoclimate data demonstrating the complex interactions between high latitude climate shifts and low latitude response.

**Geologic Setting**

The speleothem was collected from Wailokourini Cave (126.392E, 8.786S) on the island of East Timor, located in Southern Indonesia (Fig. 1). The cave is at an elevation of 652m and the island lies within the influence of a complex set of climate phenomena described briefly in the introduction. About 65% of modern rainfall is accounted for by the Australian-Indonesian Summer Monsoon (AISM) (Lewis, et al. 2011).

**Speleothem Characteristics**

The Wailakourini speleothem is composed of hundreds of highly variable laminations. These layers vary from highly porous, to more uniform microcrystalline calcite layers with a few very thin dark layers. In general the speleothem is more uniform along the
growth axis and becomes more porous moving away from the central axis resulting in some laminations getting lost in porous sections further from the growth axis. Some of the more porous layers exhibit small tubule formations suggesting secondary crystallization. This may occur after primary deposition, possibly resulting from air exposure during times with reduced drip rate and kinetic fractionation. Potential biological influences are demonstrated by the presence of small gastropod shells embedded in the calcite visible in several places.

**Methods**

**Isotope Analysis**

Calcite samples were drilled from the stalagmite collected by Mark Quigley and Brendan Duffy from Wailakourini Cave. A drip water sample was also taken in the cave to be tested for oxygen and hydrogen isotopes. The speleothem was cut along the approximate axis of growth for transportation to New Zealand on a table saw in East Timor. The speleothem broke into six pieces during an earthquake post collection.

Samples were drilled at .5mm intervals along the approximate growth axis using a .4 mm carbide tip in a hand-held dremel drill. Isotope analysis was run at this resolution for section 1. It was determined that 1.5 mm resolution would be sufficient for the rest of the sections resulting in a total of 369 samples. Some porous sections crumbled under the drill bit leaving some variation in sample resolution, for these sections all available samples were run. The calcite samples and drip water sample from the Wailakourini Cave were analyzed in the University of Canterbury Stable Isotope lab using a Thermo-Finnigan Gas Bench with a Thermo-Finnigan Delta V continuous-flow mass spectrometer for stable carbon and oxygen isotope composition. Atmospheric CO$_2$ was removed using Helium gas in a Thermo-Finnigan Gas Bench heated to 70°C and CO$_2$ was released from the calcite via acidification by 100% phosphoric acid. Precision (1σ) of δ$^{18}$O and δ$^{13}$C values, expressed in percent variation from a known standard, was better than ±0.1‰ (Logan 2011). Hendy tests were drilled along six laminations (Fig. 2A) using a .5 mm diamond ball tip in a hand-held dremel drill. Six to eight samples were drilled along each lamination at roughly regular intervals and run for stable isotopes.

**Temperature Reconstruction using the Wailakourini Speleothem**
Raw calcite $\delta^{18}O$ values along with the drip water $\delta^{18}O$ collected from Wailakourini cave were used to reconstruct a temperature record based on the following equations,

$$1000\ln\alpha(\text{calcite-H}_2\text{O})=18.03(10^3T^{-1})-32.42 \quad (\text{Kim & O'Neil, 1997})$$

$$1000\ln\alpha = 17500/T - 29.89 \quad (\text{Demeny et al. 2010})$$

$\alpha$ is the fractionation factor and $T$ is in kelvin and $1000\ln\alpha = \delta^{18}O_{cc} - \delta^{18}O_{\text{drip water}}$. The temperature reconstruction is shown in Fig. 3

**Results**

**Hendy Test Results**

$\delta^{18}O$ values from each Hendy test were plotted against distance as well as against $\delta^{13}C$ with linear regressions (Fig. 2). These plots show weak correlation between isotopes in Hendy test 4.2 ($r^2=.041$) and 2b ($r^2=.067$). The remaining Hendy tests show positive correlations between $\delta^{18}O$ and $\delta^{13}C$ indicating covariation along those laminations. A notable correlation ($r^2=.647$) was also found between $\delta^{18}O$ and $\delta^{13}C$ along the growth axis (Fig. 4).

**Temperature Reconstruction**

Temperature reconstruction based on the equation determined by Kim and O'Neil resulted in a range of values from 8.6°C to 37.3°C. This represents a different in values of >28°C along the length of the speleothem (Fig 3). This reconstruction was carried out using only one modern day drip water sample from Wailakourini cave, which likely is not representative of the range of drip water values throughout the cave in the past. Highly variable rainfall regimes in Indonesia probably result in highly variable drip water values based on assumptions of the rainfall amount effect and other factors impacting isotope fractionation of water entering cave systems (Gat, 1996; Lachinet, 2009).
Isotope Results

Wavelet analysis run in PAST (Paleontological Statistics software) of $\delta^{18}$O and $\delta^{13}$C indicate strong periodicity of $\delta^{18}$O along the length of the speleothem at a uniform frequency and a similar but weaker trend in $\delta^{13}$C.

$\delta^{18}$O values from the Wailakourini speleothem varied from -8.08‰ to -2.4‰ with a range of 5.72‰ and an average of -5.45‰. $\delta^{13}$C values ranged from -12.2‰ and -1.68‰ with a range of 10.51‰ and an average of -9‰ (Fig 6). The $\delta^{18}$O and $\delta^{13}$C record was divided into three categories based on the range of $\delta^{18}$O values. Sections B and D fit into the first category defined as having a range in $\delta^{18}$O values between 1‰ and 2‰ over the given interval. This category produced the lowest $r^2$ values (B=0.06 and D=0.24) when a least squares linear regression was calculated between oxygen and carbon isotopes. Sections A and C fit into category 2 which defined by having a range in $\delta^{18}$O values between 2‰ and 3‰. The $r^2$ values for this category were both 0.6 showing an increase in correlation between $\delta^{18}$O and $\delta^{13}$C. The third category was section E with a range of $\delta^{18}$O values >3‰ and producing an $r^2$ value of .96 demonstrating a high degree of correlation between carbon and oxygen isotopes. Section E also had the highest average $\delta^{18}$O value at 4.6‰. The lowest average $\delta^{18}$O value was across section A at -6.13.

Interpretations

Hendy Tests

Positive correlation between $\delta^{18}$O and $\delta^{13}$C along a lamination shows that the calcite was not deposited under equilibrium fractionation (Hendy, 1971). Equilibrium fractionation depends on temperature and aridity of the cave as well as the drip rate (Lachinet 2009). Our results indicate that calcite was either deposited under conditions of kinetic fractionation, which would make the speleothem a poor paleotemperature proxy, or these fractionation patterns could be explained by influence from a common environmental driver (Williams, et al. 2005, Lachinet 2009). Environmental drivers could include monsoonal amount effects, temperature effects, increases in biogenic respiration during wet periods, hydrologic balance changes, or changes in climate regimes (Quigley, et al. 2010, Lachinet 2009) such as monsoon or ENSO intensity and cyclicity. In addition, one of the criteria of the Hendy test assumes that $^{13}$C is not linked to climate (Dorale & Liu, 2009). This assumption is not correct because climate is an important...
driver for soil conditions and vegetation productivity (Williams et al., 2005; Dorale & Liu, 2009). With only one speleothem from this site, the Hendy test is the only means of determining whether or not climate factors have been preserved in the speleothem. A composite record would more definitively show whether these results are a product of kinetic fractionation or environmental drivers.

Climatic influence on the Wailakourini Speleothem

Because it is extremely unlikely that East Timor had temperature fluctuations ranging over 28°C, this suggest that this isotope values in the Wailakourini speleothem do not reflect temperature and are instead influences primarily by hydrological factors. Wavelet results indicate some sort of cyclic environmental driver within the cone of influence along the length of the speleothem (Fig 5). Without an age model the exact period cannot be determined but this could be a result of differential rainfall during monsoon season or effects of different ENSO phases which are known to have a large impact on modern day south pacific island hydrology (Hu, et al. 2005).

Porous layers along the length of the spleothem imply a high degree of kinetic fractionation took place, suggesting dryer periods, which is consistent with a climate defined by distinct annual wet and dry periods. An age model will drastically improve interpretations of this record, however the oxygen and carbon isotopes become more closely correlated as the range in $\delta^{18}O$ values increases across different sections of the speleothem. The most likely interpretation is that during these periods, some common environmental factor caused increased variation in $\delta^{18}O$ in section E as well as a slight increase (~.5‰) in values and which resulted in a high degree of covariance. $\delta^{18}O$ values are impacted by source effects, the conditions (temperature, humidity) under which evaporation occurs, different air parcel pathways and elevation gains between the source and the cave site, as well as interactions with vegetation and soil components among others (Gat, 1996; Lachinet, 2008; Hendy, 1970). Most importantly to this study, $\delta^{18}O$ is often used as a proxy for paleorainfall via the amount effect, in which $\delta^{18}O$ values of rainfall are inversely correlated to local rainfall (Lewis, et al. 2011, Lachinet 2009). Based on this, results from this speleothem indicate a more arid period across section E. Without dates we can only speculate what may have caused this signal of aridity in the tropics. Other Indonesian Speleothems have shown than southern Indonesian precipitation is highly sensitive to shifts in the ITCZ and demonstrate complex responses to abrupt northern
hemisphere cooling (Griffiths, et al. 2010) suggesting that the Wailakourini speleothem may do the same. Such studies have suggested that there was a reduction in the AISM and a southward shift in the ITCZ in the early Holocene, resulting in more arid conditions in Indonesia and increase monsoon activity in Arid Australia (Quigley, et al. 2010, Griffiths, et al. 2010). A resumption of the modern monsoon regime was observed sometime between 10-14ka based on a speleothem record from Flores as well as lake level reconstructions from interior Australia (Griffiths, et al. 2010). If oxygen isotopes were largely controlled by monsoon rainfall in the Wailakourini speleothem, this could explain the reduction in $\delta^{18}O$ values in section D. This is similar to trends seen in the Heinrich stadial 3 in which the ITCZ moved south far enough to significantly reduce monsoonal rainfall in southern Indonesia (Lewis, et al. 2011). With the addition of dates the Wailakourini speleothem, more specific interpretations will be possible.

**Conclusion**

The initial isotope analysis of the Wailakourini speleothem reveals trends indicating the influence of a large-scale climatic driver. With the additions of dates, this record will be a valuable addition to tropical hydrology reconstructions, giving valuable insight into the interconnections between high-latitude climate shifts and tropical hydrological response. Stable isotopes from Indonesian Speleothems do not typically record temperature fluctuations but are extremely sensitive to changes in hydrology as a result of shifts in the ITCZ and subsequent impacts to the AISM. Further study of the Wailakourini speleothem will allow for paleohydrology reconstruction with the development of an age record and contribute to regional paleoclimate reconstructions in an area largely lacking in data. Future studies beyond the development of an age model could include creating a composite record from East Timor and other Indonesian islands to determine fractionation patterns more conclusively.

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Figure 1 A. Map showing the location of East Timor indicated by the yellow box in relation to the Indonesian throughflow (white dotted lines) and the ITCZ (blue line) in its modern day location. The Indonesian throughflow is an ocean current connecting Pacific Ocean water impacted by ENSO and the Indian Ocean waters influenced by the Indian Ocean Dipole. This mixing of waters as well as the rainfall associated with the ITCZ and the Indian Monsoon impact the local climate of East Timor. B. Map of East Timor showing the location of Wailakourini Cave (Elevation 652m). (Images from Google Earth)
Figure 2  A. Picture of the Wailakourini speleothem with the six sections labelled and showing the locations of the six Hendy tests. B Results of the six hendy tests showing d18O(green) and d13C(purple) values along each lamination tested. C. Graphs showing the linear regression between d18O and d13C valued for each Hendy test with $r^2$ values. Those $r^2$ values above .7 indicate covatiation(Hendy 1971) suggesting that either kinetic fractionation or some common environmental driver was impacting the isotope values along these laminations.
Figure 3 Temperature reconstruction using the Kim and O’neil equation and $\delta^{18}O$ values from the Wailakourini speleothem. The large range in temperature values suggests that this record is not accurately reflecting past temperatures.

Figure 4 $\delta^{18}O$ versus $\delta^{13}C$ values for 368 samples from the wailak speleothem with a trendline based off a simple linear regression and $r^2$ value. An $r^2$ greater than 4 is considered significant for speleothem studies.
Figure 5 Wavelet analysis of $\delta^{18}$O(left) and $\delta^{13}$C(right) values along the length of the speleothem. The dark orange color indicates periodicity of $\delta^{13}$C along the length of the speleothem at a uniform wavelength. $\delta^{13}$C demonstrates a weaker trend similar to $\delta^{18}$O.

Figure 6 Graph showing raw $\delta^{18}$O(green) and $\delta^{13}$C(purple) values as well as 5-point running means(black) along the length of the speleothem representing increase in age along the x-axis. Data has been grouped into three zones based on range of $\delta^{18}$O values. Sections B and D have values with a range of >1‰ and <2‰, A and C values have ranges >2‰ and <3‰ and section E has a range of >3‰. $R^2$ values are shown for each section based on a least squares linear regression correlating $\delta^{18}$O and $\delta^{13}$C.
Works Cited


