AN ABSTRACT OF THE THESIS OF

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Title: Developing Climate Records from Speleothems, Oregon Caves National Monument, Oregon.

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Peter U. Clark

Abstract: A stalagmite (sample OCNM8-02A) collected from Oregon Caves National Monument (OCNM) was sampled for stable isotope ratios in order to develop a record of Pacific Northwest climate history. Nine U-series dates indicate that the record spans the time period ~ 13.5 – 9.5 ka. The stalagmite growth rate varied from 0.85 to 2.0 mm per 100 years. Measurements along a single stalagmite growth ring found no correlation between $\delta^{13}C$ and $\delta^{18}O$, indicating that the stalagmite was deposited under isotopic equilibrium conditions, a primary requirement for using $\delta^{18}O_c$ in speleothems as a climate proxy. A numerical model that evaluated the net effects of the potential climatic variables on $\delta^{18}O_c$ from OCNM indicated that atmospheric temperature variations above the caves propagate into a measurable signal in $\delta^{18}O_c$ in OCNM speleothems. The isotope record from stalagmite OCNM8-02A indicates that the climate of the Pacific Northwest during the last deglaciation changed synchronously with climate elsewhere in the Northern Hemisphere. Paleotemperature estimates derived from $\delta^{18}O_c$ measurements imply ~ 4 °C cooling during the Younger Dryas period, followed by a ~3.5 °C warming leading into the early Holocene. $\delta^{13}C_c$ measurements indicate increasing biomass over the caves through the recent deglaciation. Forest development stalled over a period slightly lagging the Younger Dryas, possibly implying that regional vegetation responded to the millennial scale cold event.

Developing Climate Records from Speleothems, Oregon Caves National Monument, Oregon

by

David A. Vacco

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APPROVED:

Major Professor, representing Geology

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

David A. Vacco, Author

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CONTRIBUTION OF AUTHORS

This manuscript is the product of a collaboration with four other authors: Dr. Peter U. Clark conceived the project idea, mentored me through its completion, and provided crucial funding. Dr. Alan C. Mix provided partial funding for stable isotope measurements, and recommendations about sampling methods, procedures, and data interpretations. Dr. R. Lawrence Edwards and Dr. Hai Cheng graciously provided all of the Uranium-series dates, and helpfully worked with our ever-changing timetable.

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DEVELOPING CLIMATE RECORDS FROM SPELEOTHEMS, OREGON CAVES NATIONAL MONUMENT, OREGON

INTRODUCTION

Climate records spanning the last deglaciation reveal several large and abrupt climate changes that may have been global in nature (Clark et al., 2002). The mechanisms responsible for these events remain uncertain, but understanding their origin represents an important objective because of the possibility of their recurrence in the future (Alley et al., 2003).

An important approach towards constraining potential mechanisms of abrupt climate change is to develop well-dated climate records with the temporal precision necessary to establish the phasing of changes in the various components of the climate system. Climate dynamics can be inferred from proxy data, revealing the spatio-temporal nature of climate change. The chronology of most climate records of the last deglaciation is based on radiocarbon, however, preventing firm correlations among records. Moreover, many terrestrial records are of too low resolution to identify abrupt climate changes.

Research accomplished here circumvents many of these chronological issues by developing a precisely dated, high-resolution record of the last deglaciation from a speleothem recovered from Oregon Caves National Monument (OCNM). Specifically, I developed an isotope record ($\delta^{18}O$, $\delta^{13}C$) from a stalagmite that is dated by high-precision U-series ages and with a sampling resolution of ~ 30 – 40 yrs. Since the climate of the OCNM region is strongly influenced by the Pacific Ocean, development of this record is significant in providing one of the few precisely dated terrestrial records of Pacific climate variability during the last deglaciation.

OREGON CAVES NATIONAL MONUMENT: GEOGRAPHIC & CLIMATIC SETTING

Oregon Caves National Monument is developed in Triassic marble 65 km inland of the Pacific coast of Oregon (42°05' N, 123°25' W) (Fig. 1). The cave system is developed in the westward facing slopes of the Klamath Mountains, at an elevation of ~1100 m above sea level (Fig. 2). The cave system reaches a depth of approximately 60 m, and groundwater flows from the surface to the cave on timescales of hours to days. The cave drip water is supersaturated with respect to calcium carbonate, leading to the precipitation of speleothems.

This study area is in a key region for understanding late Quaternary climate variability because of its location adjacent to (and directly downwind from) the Pacific Ocean, which has a strong influence on North American and global climate. The latitude of the site (42° 05' N) is along the boundary between the subtropical and subpolar circulation systems, where westerly storm tracks enter North America. The proximity of the site to the Pacific Ocean minimizes terrestrial influences that may otherwise strongly modify climate signals originating from the Pacific.

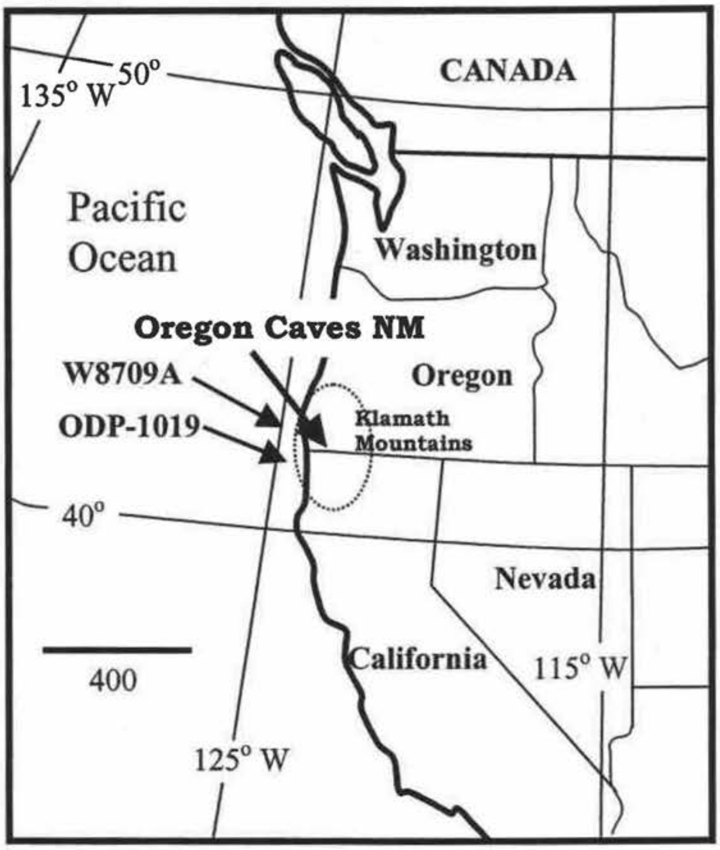

Figure 1. Location map showing Oregon Caves National Monument. The caves are 65 km inland from the Pacific Ocean, in a Triassic Carbonate formation. Also plotted are the locations of marine cores ODP-1019 and W8709A.

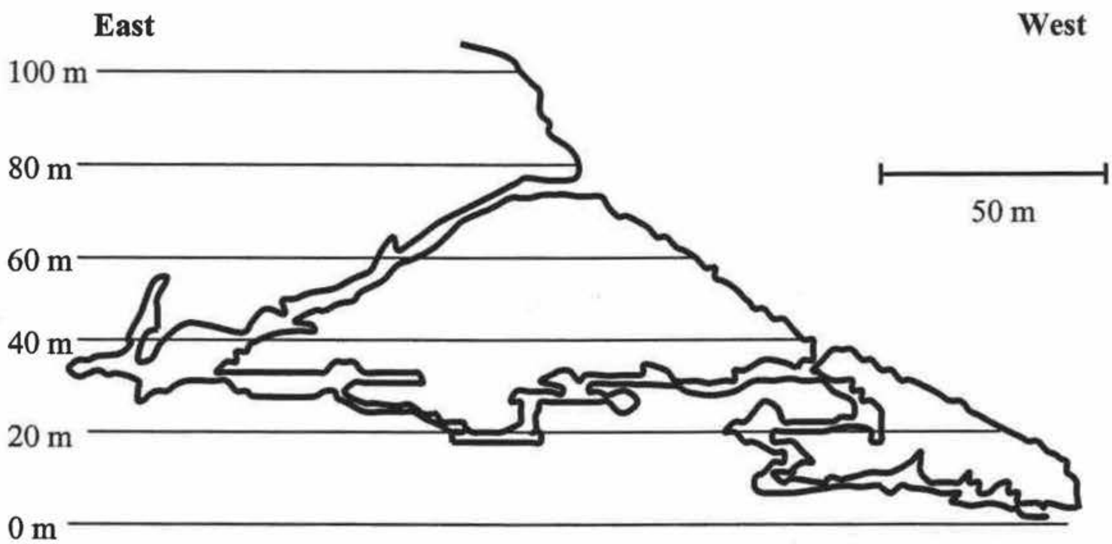

Figure 2. A vertical profile of Oregon Caves National Monument, Oregon, looking southward (modified after Turgeon, 2001). Climate is recorded by calcium carbonate precipitation in the cave chambers.

METHODS

Stalagmite samples were cut in halves, parallel to the growth direction, using a diamond saw. Approximately 200 mg of calcite powder was milled for U/Th dating using a Dremel drill with a 2mm bit. Milling troughs were 2 mm wide in the growth direction, 2 mm deep, and 20 – 25 mm perpendicular to stalagmite growth direction. U/Th dates were obtained on powdered calcite using thermal ionization mass spectrometry at the University of Minnesota (Dorale et al., 2002). Calcite powder was milled for stable isotope measurements using a 350 μm drill bit in a Dremel drill, yielding ~10 μg of calcite. Oxygen and carbon isotope ratios were measured using a Finnigan MAT 252 mass spectrometer at Oregon State University.

Drip-waters were sampled for stable isotopes from Oregon Caves by placing a clean Nalgene bottle underneath a drip. Nalgene bottles were first washed by soaking them in 0.01 N HCl solution at ~60 °C for six hours (in an oven). After soaking, bottles were rinsed five times with distilled, de-ionized water. Bottles were then air dried overnight in a laminar flow hood. Upon filling the bottles with drip-water, they were sealed by wrapping perifilm around the caps in the clockwise direction (so as to tighten the bottles) and stored in a refrigerator at 5-6 °C (standard refrigerator temperature) until they could be processed for stable isotopes.

PREVIOUS WORK

Turgeon (2001) completed a study of speleothems from OCNM in which he demonstrated that suitable material exists for developing high-resolution climate records. His work revealed that speleothem deposition in OCNM was only active during glacial-interglacial transitions and interglaciations. Our U-series dating of four additional stalagmite samples from OCNM supports this timing of active speleothem deposition (Table 1). Turgeon (2001) interpreted the unconformities between these intervals of interglacial calcite accumulation to represent non-deposition when groundwater froze during extended periglacial conditions.

Table 1. U/Th dates measured on stalagmites A-D, all collected from OCNM.

sample	date, ka	sample	date, ka	sample	date, ka	sample	date, ka
A1	131.1 +/- 2.6	B1	360 +/- 16	C1	400 +/- 33	D1	234 +/- 6.4
A2	120.7 +/- 1.3	B2	7.69 +/- 0.15	C2	240 +/- 6.4	D2	198 +/- 4.3
A3	13.1 +/- 0.18					D3	130 +/- 1.8
A4	5.9 +/- 0.16					D4	4.9 +/- 0.15

Turgeon (2001) also measured $\delta^{18}O$ and $\delta^{13}C$ of the speleothem calcite, with a sampling resolution on the order of 100 to 500 years for the pre-Holocene samples. Of particular interest to this work, one of Turgeon's samples spanned the interval from ~14 to 11 ka (Fig. 3A), encompassing part of the last deglaciation evaluated here. His sampling resolution was low, but the $\delta^{18}O$ record suggests a 3.5 $^{0}/_{00}$ decrease at the time of the Younger Dryas cold interval (Fig. 3A). Turgeon did not comment on this, but a primary component of the research completed here was to sample a well-dated stalagmite at high resolution in order to evaluate whether a Younger Dryas signal indeed exists at OCNM.

Two marine sediment cores from the eastern Pacific Ocean with high-resolution records of the last deglaciation occur offshore from OCNM (Barron et al., 2003; Mix et al.,, 1999; Pisias et al, 2001; Sabin et al., 1996). ODP Site 1019 (41°41' N, 124°56' W) occurs in the region of coastal upwelling, whereas core W8709A-13PC (42°07' N, 125°45'W) lies within the California Current. These two cores, which bracket OCNM latitudinally (Fig. 1), provide upper-ocean temperature proxies that are sensitive to both the position of the North Pacific Subpolar Front (the migration of which is driven by changes in the structure of the near-surface wind field) and the heat content of the North Pacific gyre.

Mix et al. (1999) developed a history of sea surface temperatures (SSTs) in these two cores by measuring the abundance of left-coiling *N. pachyderma* (pachy(L)) relative to the total number of *N. pachyderma* (Σpachy) (Fig. 3B). The boundary conditions of this proxy are that pachy(L)/Σpachy >95% corresponds to SSTs < 5°C, and N.pachy(L)/Σpachy < 5% corresponds to SSTs > 15°C. Barron et al. (2003) determined the SST record from ODP Site 1019 using alkenones (Fig. 3C). Both of these studies found a cold event corresponding to the Younger Dryas, as well as brief warm events at ~ 14.5, 13.4, 11.2, and 10.2 ka.

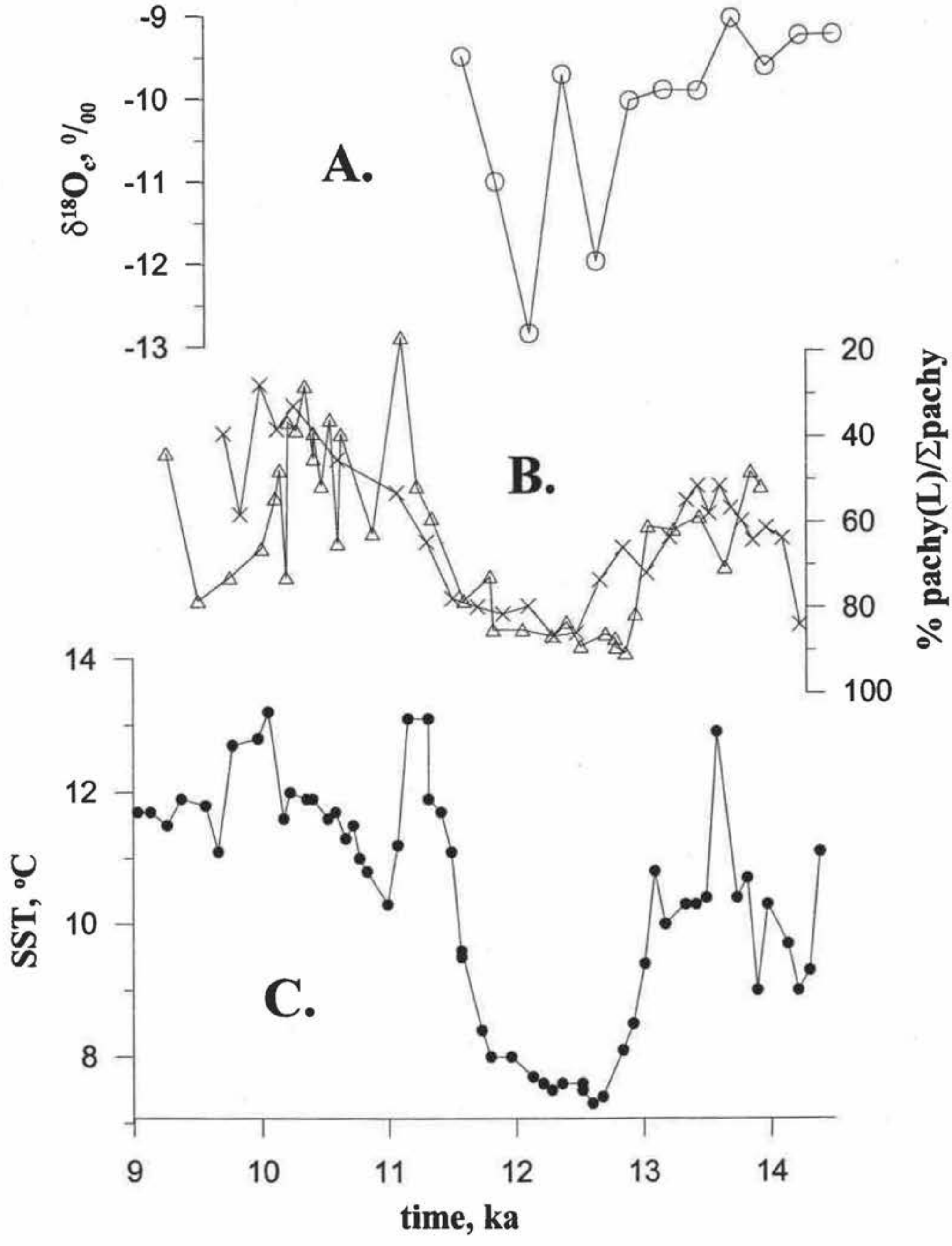

Figure 3. Local climate records from previous studies: (A) $\delta^{18}O_c$ from an OCNM flowstone (Turgeon, 2001). (B) abundance of left-coiling *N.pachyderma* (pachy(L)) relative to the total number of *N. pachyderma* (Σpachy) from marine cores W8709A (×) and ODP-1019 (△) (Mix et al., 1999). (C) SST (°C) from marine core ODP-1019, derived from alkenone measurements.

STABLE ISOTOPE MEASUREMENTS IN SPELEOTHEMS AS CLIMATE PROXIES

Evaluation of Isotopic Equilibrium

Speleothems are primarily composed of calcium carbonate ($CaCO_3$). Many studies of speleothems have demonstrated that stable isotopes of carbon and oxygen that are fractionated by natural processes provide a robust proxy of climate change (Gascoyne et al., 1992; Harmon et al., 1978; Hendy, 1968, 1971). Uranium is incorporated into the calcite in many carbonate depositional systems, making the age of calcite precipitation measurable by U-series disequilibrium dating.

Hendy (1971) established a methodology by which variations in C and O isotope ratios in speleothems can be interpreted as climate proxies. The primary requirement for a valid climate proxy is that the C and O in speleothem calcite are deposited under thermodynamic equilibrium with the drip waters from which the isotopes are derived. During slow degassing, isotopic fractionation between aqueous and solid phases is controlled indirectly by cave temperature under equilibrium conditions. However, if speleothem deposition takes place simultaneously with evaporation of cave water and/or rapid crystallization the isotopic fractionation is modulated by kinetic effects that inhibit isotopic equilibrium between the calcite and dripwaters, thus obscuring the climate signal (Hendy, 1971).

Hendy (1971) devised a test for isotopic equilibrium deposition of speleothem calcite based upon C and O isotope ratio variations along coeval growth layers. Theoretically, $\delta^{13}C$ values of calcite should progressively increase with distance from the source dripwater, as $^{12}CO_2$ is preferentially lost by degassing relative to $^{13}CO_2$, whereas $\delta^{18}O$ values should remain constant owing to the relatively large amount of water available (Fantidis and Ehhalt, 1970). Under evaporative conditions, both $^{12}CO_2$ and $H_2{}^{16}O$ molecules are preferentially fractionated as water travels down the speleothem, thereby providing synchronous enrichments of both ^{13}C and ^{18}O in the calcite deposited from solution.

Evaporative effects are thought to be of minor importance except near cave entrances. This is because many dissolution caves are unaffected by air flow and have relatively high humidity (>90 %). Nevertheless, a Hendy test should be conducted to evaluate for isotopic equilibrium calcite deposition. Turgeon (2001) conducted Hendy tests on two samples from OCNM and found no evidence for evaporative effects on the isotopic values.

Hendy tests were run on the stalagmite used for this study. Five stable isotope measurements were made on a single growth ring of stalagmite OCNM8-02A to test for a correlation between $\delta^{13}C$ and $\delta^{18}O$ (Fig. 4A). The linear regression skill was calculated to be $R^2 = 0.58$, well below the 95% significance critical value of $R^2_{crit} = 0.96$. Hence, the Hendy test showed no correlation between $\delta^{13}C$ and $\delta^{18}O$ with 95% confidence, suggesting that our sample was not subject to evaporative effects. Nevertheless, Hendy tests are subject to large uncertainties because the potential for sampling multiple laminae is large. A decisive test for absence of evaporative effects is to replicate two or more time series from two or more speleothems. Such work will be done in the future for OCNM. For the purposes of this work, however, the non-climatic signals affecting stable isotopes in speleothems have been evaluated in terms of their presence and/or negligible strength in OCNM.

Speleothems deposited under isotopic equilibrium should contain constant $\delta^{18}O_c$ values along a single growth band. We based our sampling strategy for stable isotopes in stalagmite OCNM8-02A on this assumption by drilling at varying distances perpendicular to the growth axis. We find no correlation between $\delta^{18}O_c$ and drill point distance from the growth axis (Fig. 4B), indicating that $\delta^{18}O_c$ variability in stalagmite OCNM8-02A is not a function of varying distance from the growth axis. This result further suggests deposition under isotopic equilibrium.

Climate Effects on $\delta^{18}O_c$ in Speleothems

Four major climate related effects can cause variations in $\delta^{18}O$ of cave calcite. These are (i) the temperature dependence of calcite-water isotopic fractionation, (ii) the

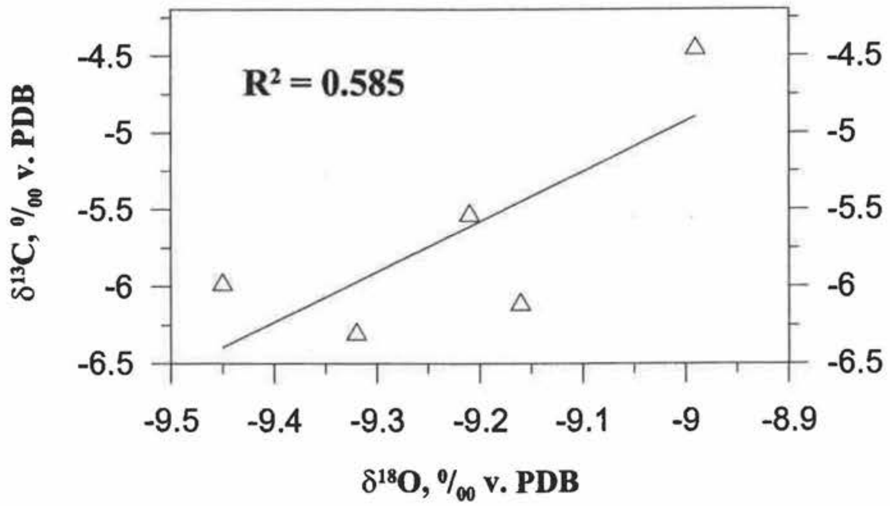

Figure 4A. Measurements of $\delta^{13}C$ and $\delta^{18}O$ taken from a single growth ring of stalagmite OCNM8-02A. They correlate with an $R^2 = 0.58$, well below the 95% significance $R^2 = 0.96$.

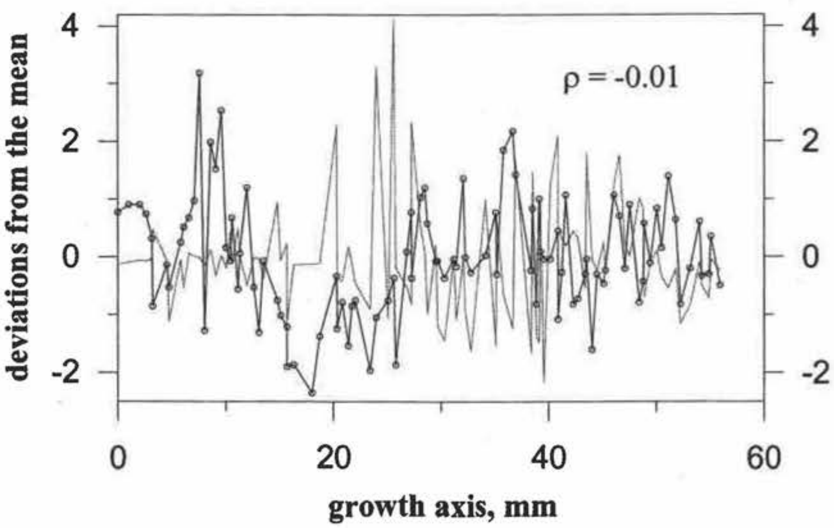

Figure 4B. Drilling locations distance from the growth axis (dotted grey), and $\delta^{18}O_c$ measurements (black circles) plotted over growth axis location (both normalized). Correlation between the two is $\rho = -0.01$.

temperature effect on the isotopic value of meteoric precipitation, (iii) the change in $\delta^{18}O$ of the ocean reservoir in response to changes in continental ice sheet volume, and (iv) changes in the predominant air-mass circulation (Harmon et al., 1978). In order to interpret a stable isotope record from a speleothem, the extent to which each of these four effects contributes to the measured time series must be considered for the specific region and time scale in question.

The change in stalagmite growth temperature can be estimated as follows:

$$\Delta\delta^{18}O_c = \frac{d(\Delta_{c-w})}{dT}\Delta T + \Delta\delta^{18}O_{sw} + \frac{d\delta^{18}O_p}{dT}\Delta T \qquad (1)$$

where ΔT denotes the change in air temperature, $\delta^{18}O_c$ denotes the oxygen isotope ratio of cave calcite, $\Delta_{c\text{-}w} = 1000*\ln(\alpha_{c\text{-}w})$, $\alpha_{c\text{-}w}$ denotes the fractionation factor for $^{18}O/^{16}O$ exchange between calcite and water, $\delta^{18}O_{sw}$ denotes the oxygen isotope ratio of sea-water, and $\delta^{18}O_p$ denotes the oxygen isotope ratio of precipitation falling over the cave. For any cave, the mean cave temperature is the same as the annual mean atmospheric temperature above the cave. It follows that temperature change in the cave is the same as temperature change above the cave (i.e. the ΔT quantity in equation (1) is the same in the precipitation term and the cave temperature term). Hence, it is possible to make rough quantitative estimates of air temperature for the region surrounding the cave of study, assuming that no other significant isotopic signals apply.

The only term that contributes to the $\delta^{18}O_c$ signal that is not a function of temperature is the $\delta^{18}O_{sw}$ term. The $\Delta\delta^{18}O_{sw}$ signal can be accounted for based on records of sea-level change, and the isotopic value of ocean water over time derived from marine sediment records (Schrag et al., 1996, 2002). The details of how the $\delta^{18}O_{sw}$ signal is removed from the OCNM speleothem record are listed in the modeling section below.

Both $\delta^{18}O_p$ and $\alpha_{c\text{-}w}$ have temperature dependence that is critical to interpreting oxygen isotopes in speleothems. The calcite-water relationship has been well established at $-0.24\ ^0/_{00}\ ^{\circ}C^{-1}$ (Harmon et al., 1978) (i.e. warmer cave temperatures correspond to lighter $\delta^{18}O_c$ values). The relationship between temperature and $\delta^{18}O_p$ varies with location, but theoretical work predicts the range to be $0.5 - 0.7\ ^0/_{00}\ ^{\circ}C^{-1}$ (Dansgaard,

1964) (i.e. warmer atmospheric temperatures correspond to heavier $\delta^{18}O_p$ values). We determined the relationship between $\delta^{18}O_p$, $\alpha_{c\text{-}w}$, and $\delta^{18}O_c$ for OCNM by measuring surface air-temperatures above the caves, cave-air temperatures, $\delta^{18}O_p$ for modern meteoric water over the caves, and $\delta^{18}O_w$ for modern cave drip-waters. Stable isotope measurements on drip-waters collected from OCNM are plotted against the corresponding monthly mean air temperature (Fig. 5). Studies have demonstrated that cave drip-waters have the same $\delta^{18}O_w$ values as precipitation above the cave (Yonge et al., 1985). Based on such findings, we calculate the dependence of $\delta^{18}O_p$ on temperature using cave drip-waters. The relationship for OCNM is $d/dT(\delta^{18}O_w) = 0.46\ ^0/_{00}\ ^oC^{-1}$, with a hindcast skill of $R^2 = 0.71$ based on linear regression. The measured dependence of $\delta^{18}O_w$ on temperature agrees with empirical data measured from around the globe (Dansgaard, 1964; Yonge et al., 1985).

Climate effects on $\delta^{13}C_c$ in speleothems

$\delta^{13}C$ variations in speleothems can be used as a proxy of vegetation and precipitation changes. Yonge et al. (1985) established that groundwater-country rock interactions do not fractionate the $\delta^{13}C_w$ value in cave drip-waters, thus $\delta^{13}C_c$ largely reflects the $\delta^{13}C$ of the overlying soil. The ratio of $^{12}CO_2$ to $^{13}CO_2$ in soil depends on two factors: the ratio of C_3-type plants (typically trees and shrubs, average $\delta^{13}C$ of -27 $^0/_{00}$) to C_4-type plants (typically grasses, average $\delta^{13}C$ of -13 $^0/_{00}$) living in the soil (Cerling, 1984, Cerling et al., 1989), and the ratio of atmospheric CO_2 ($\delta^{13}C$ = -7 $^0/_{00}$) vs. biogenic CO_2 ($\delta^{13}C$ = -25 $^0/_{00}$) input into the soil system (Genty et al., 2003). C_3-type plants grow in cool/wet climates whereas C_4 type plants grow in warm/dry conditions.

Climate proxies have been established on a sediment core from Bolan Lake, Oregon (Briles, 2003), ~9.5 km southwest of OCNM (Fig. 6). A pollen count analysis indicated that the amount of grasses were minimal in the OCNM region, and essentially constant through the last deglaciation (Fig. 6A). This implies that there were no significant fluctuations in the ratio of C_3/C_4 type plants over the caves. Hence temporal variations in biomass can be isolated as the primary control of $\delta^{13}C_c$ variations in OCNM speleothems, such that lighter $\delta^{13}C_c$ values indicate increased biogenic CO_2 flux into the soil.

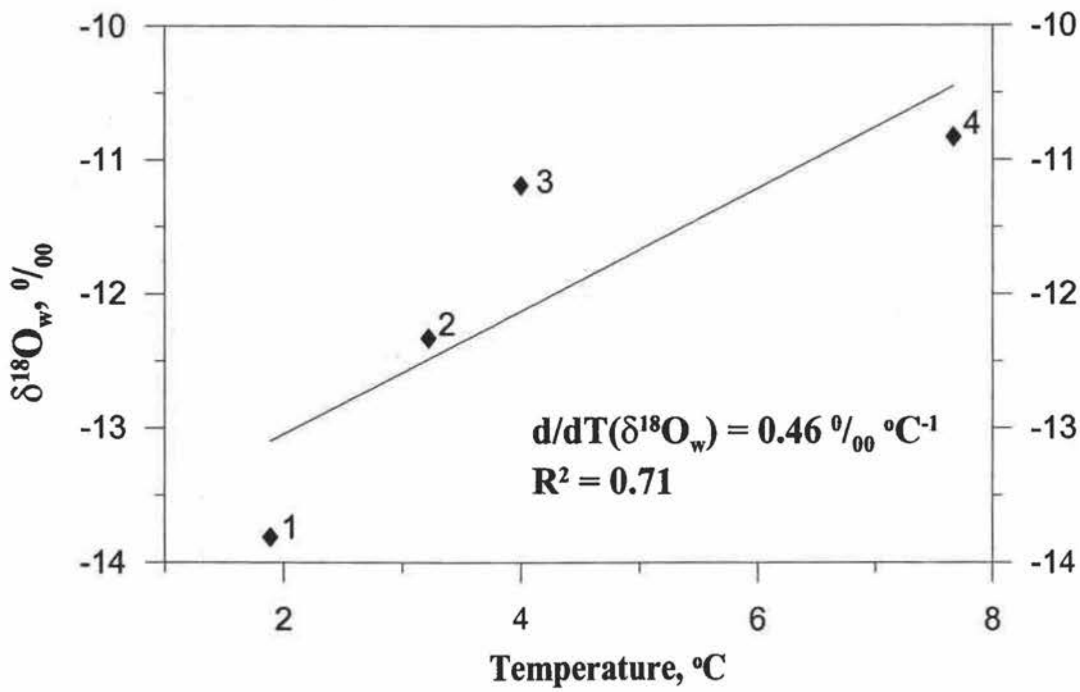

Figure 5. Measurements of $\delta^{18}O_w$ of cave drip-water plotted against the corresponding mean air temperature of the previous month. The measurements yield a relationship of 0.46 ‰ $°C^{-1}$. Sampling to obtain more data points is ongoing. Collection dates were (♦1) 2/27/03, (♦2) 3/27/03, (♦3) 12/16/02, (♦4) 12/1/02.

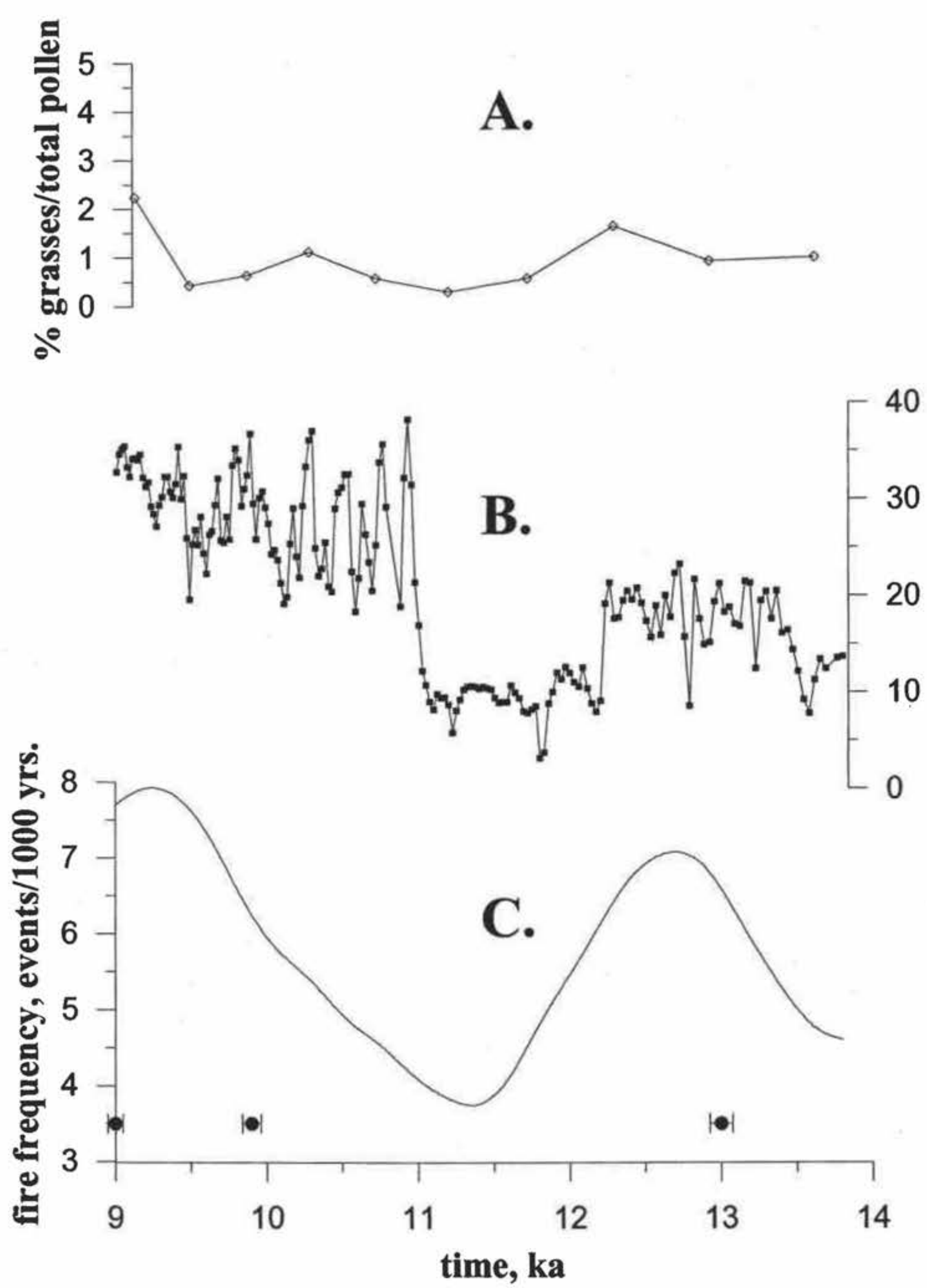

Figure 6. Selected vegetation proxies from Bolan Lake, Oregon (Briles, 2003). Plotted are (A) % grass pollen/total pollen, indicating a nearly constant ratio of C_3/C_4 type plants, (B) % organic carbon, and (C) fire frequency in events per 1000 yrs. Chronology for the Bolan Lake records was established by radiocarbon. The dates are plotted beneath the fire frequency record.

URANIUM-SERIES DATING OF SPELEOTHEMS

The primary method for measuring the age of speleothem deposition is by uranium-series dating. Uranium and thorium isotopes are not fractionated by natural processes. The following is the uranium-238 decay series, only listing isotopes that are of interest for dating speleothems:

$$^{238}U \xrightarrow[4.47x10^9 a]{} {}^{234}U \xrightarrow[2.45x10^5 a]{} {}^{230}Th \xrightarrow[7.57x10^4 a]{} {}^{206}Pb \qquad (2)$$

The half-life of each decay is listed beneath the arrows. Thorium has an extremely low solubility compared to uranium, Thus $^{230}Th = 0$ is a reasonable assumption for any water. When water enters a cave and precipitates calcite in the form of speleothems, uranium will be incorporated into the calcite lattice. Once the system becomes closed with respect to U and Th isotopes, the decay series will begin to approach secular equilibrium. Hence the amount of ^{230}Th in a speleothem directly relates to the age of system closure. Calculation of this age is accomplished by the following equation:

$$\left[\frac{^{230}Th}{^{238}U}\right] = 1 - e^{-\lambda_{230}T} + \left(\frac{\delta^{230}U_{(m)}}{1000}\right)\left(\frac{\lambda_{230}}{\lambda_{230} - \lambda_{234}}\right)\left(1 - e^{(\lambda_{234} - \lambda_{230})T}\right) \qquad (3)$$

where square brackets denote activity ratio, λ_{230} and λ_{234} denote the decay constants of ^{230}Th and ^{234}U respectively (values as stated by Dorale et al., 2002), $\delta^{234}U_{(m)}$ =([$^{234}U/^{238}U$]-1)*1000, and T is the date of system closure. $\delta^{234}U_{(m)}$ is related to the initial amount of ^{234}U by:

$$\delta^{234}U_{(i)} = \delta^{234}U_{(m)} e^{\lambda_{234}T} \qquad (4)$$

where $\delta^{234}U_{(m)}$ refers to the measured ratio, and $\delta^{234}U_{(i)}$ refers to initial (calculated) ratio.

The U/Th dating technique is useful for systems that closed from tens up to 800,000 years ago (Dorale et al., 2002). The exact upper limit to the technique depends on the initial amount of ^{234}U in the system when it closed. Theoretical uncertainties over the last 10^4 years for this technique are on the order of 10^1 - 10^2 years, with precision largely determined by the cleanliness of the sample (non-radiogenic ^{230}Th will adhere to detritus such as clay that may be deposited in the speleothem).

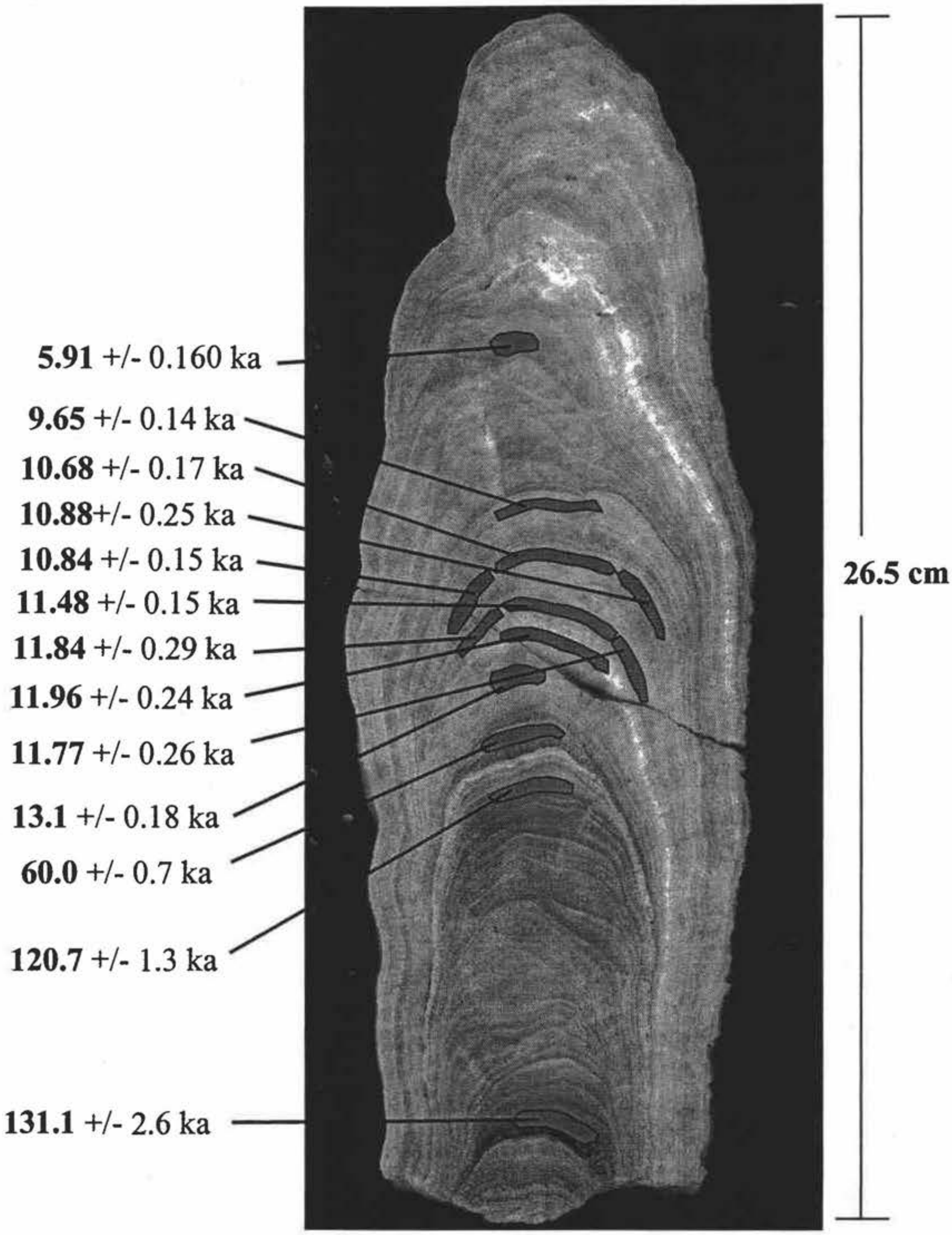

Fig 7. Image of Stalagmite OCNM8-02A showing U/Th dates and their sampled locations. Each ellipsoid represents the approximate location that was drilled for dating.

Uranium-series dates were measured on segments of stalagmite OCNM8-02A (Table 2) to determine the timing of deposition (Fig. 7) and the calcite growth rates (Fig. 8A). The initial $^{230}Th/^{232}Th$ was calculated by the isochron technique to be 12.0 +/- 2.5 ppm, using three coeval samples (Fig. 8B).

The dates reveal that the stalagmite was deposited during three periods: ~ 131 to 120 ka, ~ 60 ka, and since ~ 13.3 ka. High thorium concentrations in samples A5, A6, and A8 indicate that these samples contain high amounts of detritus (such as clay) compared to the other samples. Such "dirty" calcite has larger dating uncertainty, because the sample contains a significant amount of initial ^{230}Th, which increases the calculated U/Th age.

Table 2. U/Th ages measured at the University of Minnesota. Samples A11, A10, and A8 are from the same stalagmite growth layer, as are samples A13, A12, and A9.

sample	age, ka	uncertainy, ka	^{232}Th, ppt	$^{230}Th/^{232}Th$, ppm
A1	131.15	2.6	255	4230
A2	120.73	1.33	190	13410
A5	58.7	0.72	2904	259
A3	13.1	0.18	433	829
A6	11.96	0.24	1317	163
A11	11.84	0.29	2450	126
A10	11.77	0.26	2590	131
A8	11.48	0.24	2308	140
A13	10.88	0.25	1832	130
A12	10.84	0.15	2450	263
A9	10.68	0.17	475	469
A7	9.65	0.14	630	340
A4	5.91	0.16	154	722

Cave drip water can potentially penetrate into a speleothem, causing recrystallization and destruction of any climate signals that have been recorded in the calcite stable isotopes. Such a phenomenon also alters the concentrations on ^{234}U and ^{230}Th and disrupts the radiogenic clock in the calcite. U/Th dates measured on OCNM8-02A are in stratigraphic order, indicating that the $^{234}U/^{230}Th$ isotopic system has remained closed after calcite deposition. Hence it is reasonable to infer that stalagmite OCNM8-02A did not undergo calcite recrystallization within the section that was sampled.

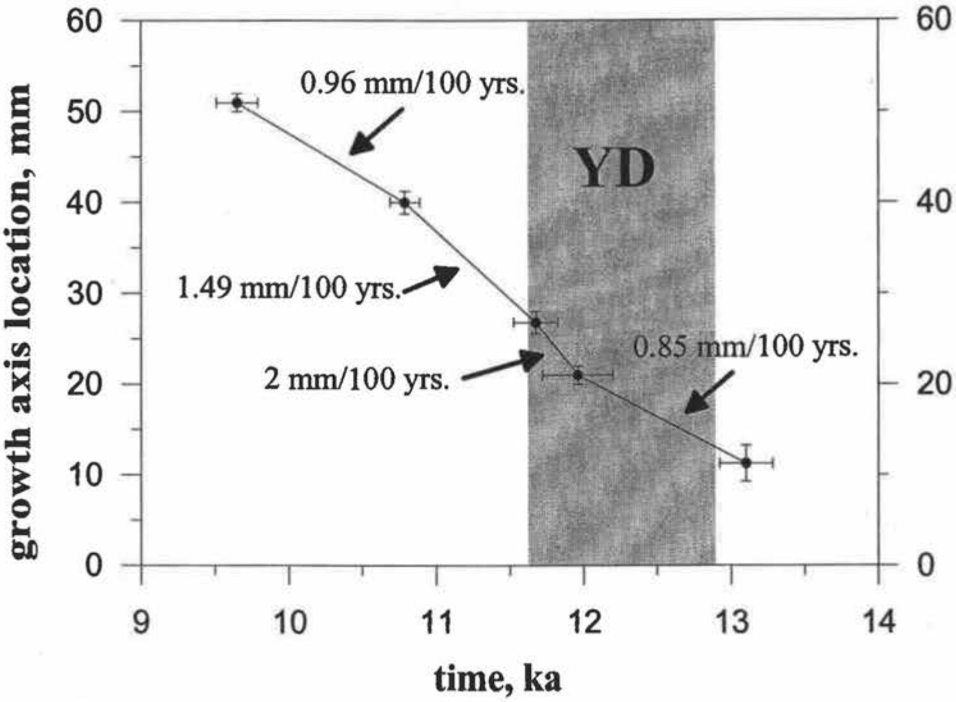

Figure 8A. Dates and corresponding growth axis locations sampled from stalagmite OCNM8-02A. Horizontal error bars represent dating uncertainties, and vertical error bars represent the width of the trough that was drilled.

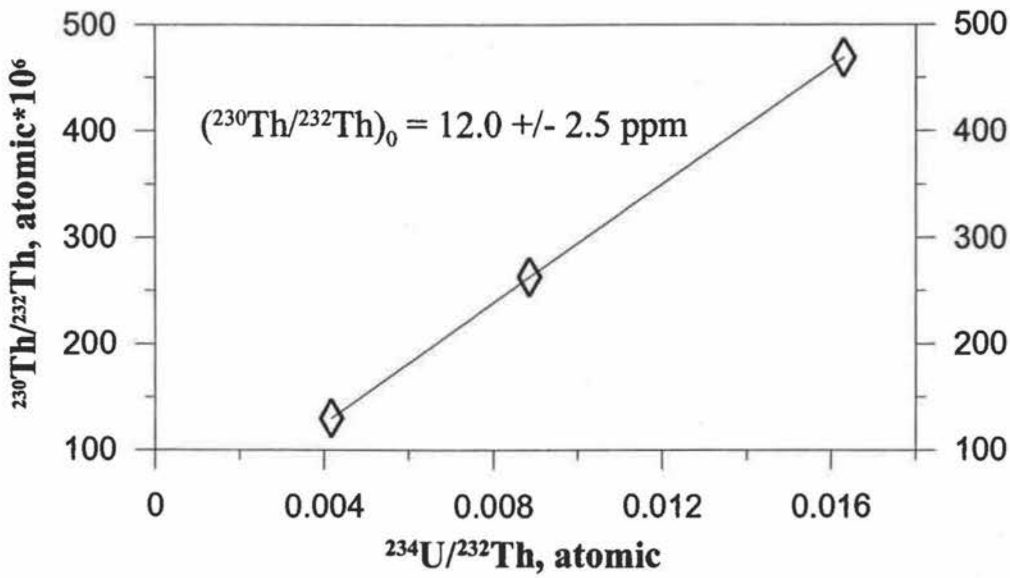

Figure 8B. Isochron plot of the three coeval late Holocene samples. Regression yields an initial $^{230}Th/^{232}Th$ of 12.0 +/- 2.5 ppm, $R^2 = 0.9999$.

MODELING TEMPERATURE EFFECTS ON $\delta^{18}O_c$

We modeled the $\delta^{18}O$ in Oregon Caves in order to examine the potential climate influences on the $\delta^{18}O_c$ values of speleothems. This allows evaluation of the sensitivity of $\delta^{18}O_c$ to air temperature, which we infer as the primary climate signal in OCNM. The variables incorporated in this model are $\delta^{18}O_{sw}$, $\delta^{18}O_p$, and the fractionation dependence on cave air temperature. Numerical finite-difference methods were used to quantify the net effect of these three processes on calcite deposition. Other known factors that affect oxygen isotope variations in speleothems were excluded from this model (i.e. the rain-out effect; Craig, 1961; Dansgaard, 1964; Yonge et al., 1985) because we assume they have negligible impact on OCNM.

Air temperature history over the caves is assumed by this model to be closely coupled with the SST record determined for ODP-1019 by Barron et al. (2003) (Fig. 9A). The purpose of this experiment is estimate the sensitivity of $\delta^{18}O_c$ to temperature changes, hence the temperature record that we used is arbitrary. The mean of the SST record was changed to reflect the modern mean annual temperature over the caves (T ~ 8.4 °C). The temperature history was used to create a $\delta^{18}O_p$ record for precipitation falling on the caves using a temperature dependence of 0.46 $^0/_{00}$ $°C^{-1}$ (Fig. 9B) based on measurements from this study.

A record of deglacial sea-level rise illustrates that mean sea-level increased nearly linearly by 50 meters over the time period 14.7 – 10 ka (Bard et al., 1990; 1996; Edwards et al., 1993; Fairbanks,1989; Fleming et al., 1998). $\delta^{18}O_{sw}$ was modeled using a modern value of 0 $^0/_{00}$, an LGM value for the Pacific Ocean of 1.0 $^0/_{00}$ (Schrag et al., 1996), and linearly interpolating the $\delta^{18}O_{sw}$ values over time using the deglacial history of sea-level rise ($\delta^{18}O_{sw}$ curve plotted in Fig. 9D). The resulting record reflects the Pacific Ocean becoming isotopically lighter as the ice sheets melted. We have thus inferred that a $\delta^{18}O_{sw}$ signal due to sea level rise is present in the OCNM8-02A stalagmite.

We used the calcite-water fractionation dependence on cave temperature of –0.24 $^0/_{00}$ $°C^{-1}$ (Hendy, 1971). The net effect of $\delta^{18}O_p$, $\delta^{18}O_{sw}$, and temperature on $\delta^{18}O_c$ was modeled using equation (1) above, and the following algorithm.

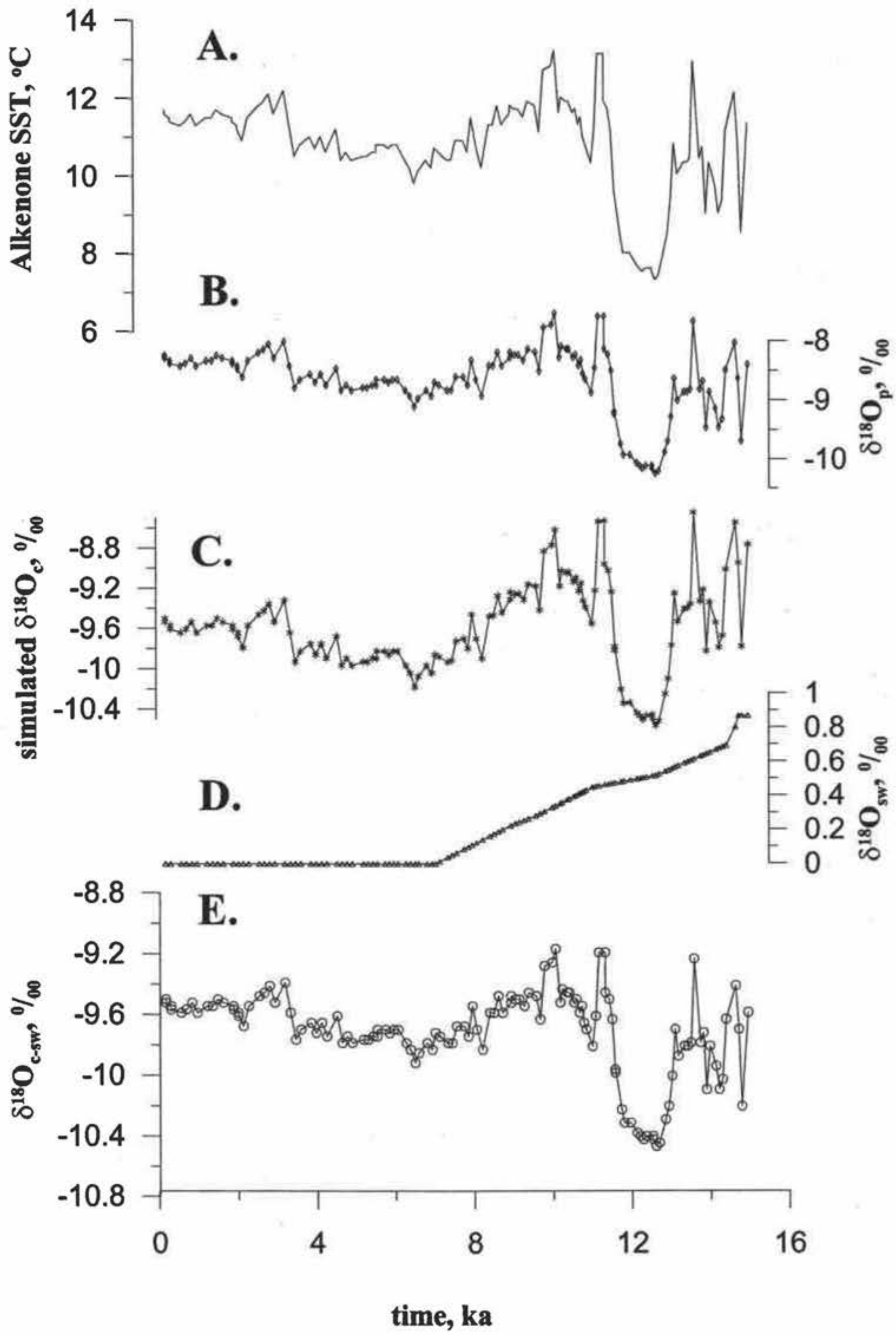

Figure 9. Modeled sensitivity results of $\delta^{18}O_c$ to temperature. Plotted are (A) the ODP-1019 Alkenone temperature record from Barron et al (2003), (B) $\delta^{18}O_p$ signal using a temeprature dependence of 0.46 $^0/_{00}$ °C^{-1}, (C) the resulting $\delta^{18}O_c$ signal, (D) $\delta^{18}O_{sw}$ driven by sea level rise, and (E) $\delta^{18}O_c$ with the sea level signal removed.

$\delta^{18}O_c(1) = -9.5\ ^0/_{00}$

for i = 2 to n

$$\delta^{18}O_c(i)=\delta^{18}O_c(i-1)+[\delta^{18}O_p(i)-\delta^{18}O_p(i-1)] + [\delta^{18}O_{sw}(i)-\delta^{18}O_{sw}(i-1)] + [-0.24*(Temp(i)-Temp(i-1)]$$

The resulting $\delta^{18}O_c$ curve (Fig. 9C, sea-level signal removed Fig. 9E) indicates that a 4.5 °C warming in temperature over OCNM results in an increase in $\delta^{18}O_c$ of 1.0 $^0/_{00}$. This indicates that temperature variations progagate into a measurable signal in the $\delta^{18}O_c$ of stalagmites. A relationship of 4.5 °C $^0/_{00}{}^{-1}$ will be used below as a qualitative "yard-stick" to interpret the $\delta^{18}O_c$ record from OCNM. It is important not to interpret $\delta^{18}O_c$ from OCNM speleothems explicitly based on this air temperature relationship, however, because there are other processes that affect $\delta^{18}O_c$ deposition that are still unconstrained for OCNM, such as rain-out and orographic effects on $\delta^{18}O_p$ (Dansgaard, 1964).

Other climate signals that were excluded by this model may have some effect on OCNM speleothems, such as fluctuations in $\delta^{18}O_p$ values due to changing source regions of air masses coming from the Pacific Ocean. Climate models that have simulated global climate change over the last deglaciation (Bartlein et al., 1998) indicate that the near-surface wind fields around the North Pacific Ocean and PNW remained similar during the last deglaciation, suggesting that the source region for $\delta^{18}O_p$ over OCNM did not change significantly. Hence, we assumed that there is no $\delta^{18}O$ signal due to changes in air-mass source region.

DISCUSSION: PALEOCLIMATIC INTERPRETATIONS OF THE $\delta^{18}O_c$ RECORD FROM STALAGMITE OCNM8-02A

Millennial Scale Variability in the OCNM8-02A Record

We developed a time series of $\delta^{18}O_c$ for stalagmite OCNM8-02A by first linearly interpolating growth rates based on the U/Th dates (weighted means were used in the case of multiple dates on a single layer). The time series of $\delta^{18}O_c$ from stalagmite OCNM8-02A, with the sea-level signal removed, is dominated by millennial and centennial scale variability (Fig. 10). The record contains a shift in mean value: the period of 12.9 to 11.7 ka has a mean value of –10.4 $^0/_{00}$, whereas the period from 11.6 to 9.3 ka has a mean value of –9.8 $^0/_{00}$. The lighter period of 12.9 to 11.7 ka was also preceded by a period of heavier $\delta^{18}O_c$ values, indicating millennial scale changes of the mean climate state in the OCNM region.

The two primary climatic controls on $\delta^{18}O_c$ variations in speleothems are temperature changes and varying amounts of precipitation. Three distinct end-members of climate processes driving $\delta^{18}O_c$ variability can be considered for stalagmite OCNM8-02A.

End-member 1: Temperature changes are the only climate signal contained in the stalagmite. Such a scenario means that an absolute temperature history can be calculated using the temperature to $\delta^{18}O_c$ relationship derived from the OCNM speleothem model (Fig. 11A). This case reveals that the upper limit of atmospheric temperature change recorded by OCNM8-02A is 4 °C. The increase in mean at ~11.67 ka represents a 3 °C warming, and the event at ~11.0 ka represents a 2.5 °C warm oscillation.

End-member 2: The rain-out effect is the only climate signal recorded by the OCNM8-02A stalagmite. In this case increased precipitation results in lighter $\delta^{18}O_c$ values. Further sampling will quantify the relation between $\delta^{18}O_p$ values and precipitation amount.

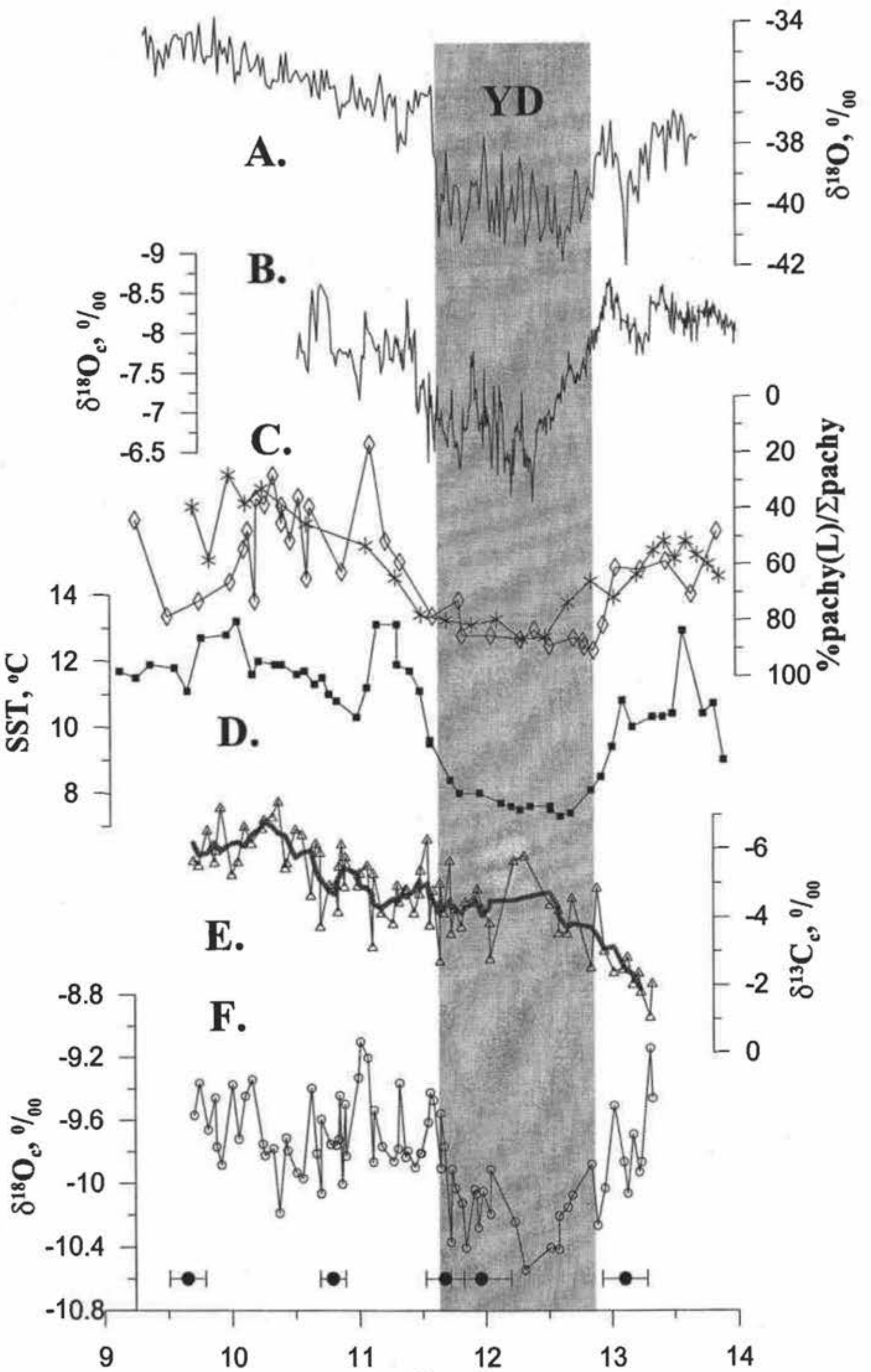

Figure 10. (A) the GISP2 ice core $\delta^{18}O$, (B) $\delta^{18}O_c$ on speleothems from Hulu Cave, China, (C) % *pachy*(L)/Σ*pachy* from ODP-1019 & W8709A, (D) Alkenone SST from ODP-1019, (E) OCNM8-02A $\delta^{13}C_c$ record (black triangles) and $\delta^{13}C_c$ smoothed (thick grey), and (F) OCNM8-02A $\delta^{18}O_c$. U/Th dates are plotted with uncertainties, beneath the OCNM $\delta^{18}O_c$ time series.

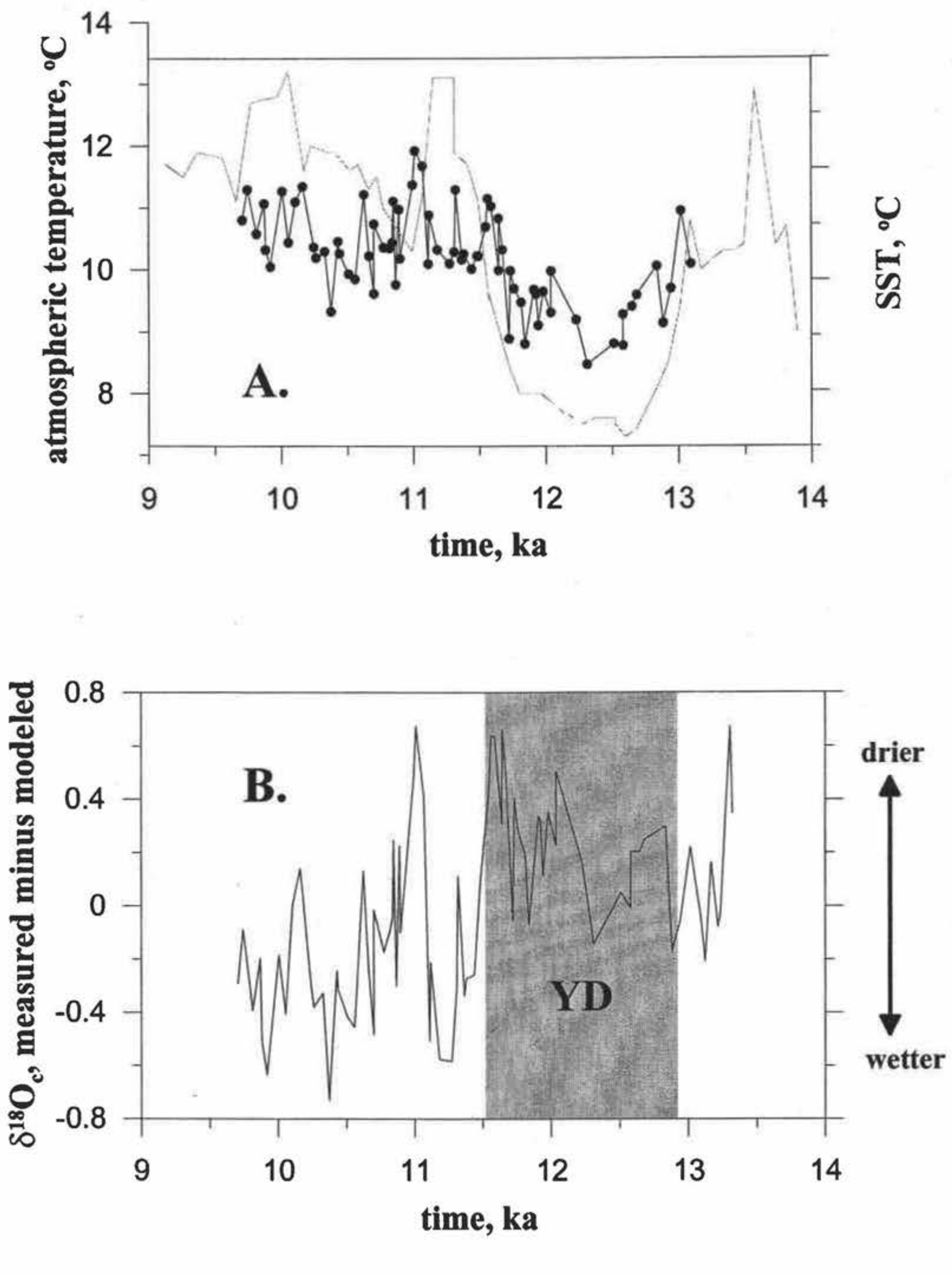

Figure 11. (A) end-member 1 plot of hypothetical temperature over OCNM (black) and the ODP-1019 Alkenone SST record (grey), (B) end-member 3 plot of hypothetical precipitation record over OCNM by subtracting the modeled $\delta^{18}O_c$ signal (Fig. 9E).

<u>End-member 3</u>: The temperature history over OCNM exactly matches the alkenone SST record from ODP-1019 (Barron et al., 2003). The scenario must follow all of the previous climatic assumptions in addition to the assumption that all differences between the observed $\delta^{18}O_c$ record from OCNM8-02A and the numerically modeled $\delta^{18}O_c$ (based on the alkenone record from Barron et al., 2003) are caused by rain-out effect. Subtracting the two time series under these assumptions results in a record of precipitation over OCNM (Fig. 11B). The results indicate a dry period (heavier $\delta^{18}O_c$ values) between 12.9 and 11.7 ka, followed by increasingly wet atmospheric conditions, although with substantial centennial scale variability.

The amplitude of the modeled $\delta^{18}O_c$ time series is based on an assumed value of $d/dT(\delta^{18}O_p) = 0.46\ {}^0/_{00}\ {}^oC^{-1}$. The amplitude of variability in the resulting precipitation record is based on this assumption, hence it should only be interpreted qualitatively. The resulting time series reveals a cold and dry period concordant with the Younger Dryas event observed in GISP2. It is important, however, to note that this method of interpreting the OCNM record *creates* a Younger Dryas event in OCNM by utilizing the ODP-1019 record as the correct temperature record for OCNM.

The record from stalagmite OCNM8-02A contains events that are concordant with the deglacial history recorded in the GISP2 ice core (Fig. 10). The $\delta^{18}O_c$ record suggests that PNW atmospheric temperatures decreased by up to 4 °C at ~ 13.1-12.9 ka. The influx of biogenically derived CO_2 into the soil above OCNM was increasing linearly up to ~ 12.8-12.5 ka. The period of ~ 12.8-11.76 ka is marked by colder atmospheric temperatures and a constant flux of biogenic CO_2, apparently in response to the Younger Dryas cold event. The end of the Younger Dryas event was marked by a ~ 3 °C warming. An increase in vegetation density lagged this warming by ~600 years.

Comparison with NE Pacific marine cores (Fig. 10) shows temperature histories that are parallel to the OCNM record, including a Younger Dryas cold event and an 11 ka warm event. These results may indicate a coupled ocean-atmosphere response to the

North Atlantic Younger Dryas event originating in the North Atlantic. Simulations with coupled ocean-atmosphere models (Schiller et al., 1997) have yielded up to 2.5 °C cooling in the eastern Pacific and the PNW in response to the Younger Dryas cold event. This is comparable to the ~ 3 °C cooling exhibited in the atmosphere by the OCNM8-02A record, and in the ocean by the ODP-1019 record. The OCNM8-02A record contributes to the growing archive of evidence for hemispheric cooling during the Younger Dryas, implying rapid transmission of cold temperatures from the North Atlantic to the rest of the globe (assuming that changes in the Atlantic thermohaline circulation were responsible for the Younger Dryas).

Centennial Scale Variability in the OCNM8-02A record

The millennial scale variability was removed from the OCNM8-02A record using a ten point running mean smoother (Fig. 12A). The residuals of that smoothing were evaluated in terms of strength of centennial scale modes. Autocorrelation analysis yielded 95% significance correlations over the lags 140 – 250 yr (Fig. 12B). Spectral analysis of the record showed a narrow-banded signal having a period of 190 years (Fig. 12C). Both of these analyses indicated the presence of a bicentennial scale signal. Other studies have found that cycles of similar period correlate strongly with solar cycles (Bond et al., 2001). The OCNM8-02A is very short (4000 yrs) relative to such a signal, thus these analyses are susceptible to bias. It is also possible that the calculation of residuals using a 10 point running mean filter introduced centennial scale variability into the record. The best way to discover the presence of centennial scale climate variability over the PNW is to recover a much longer record.

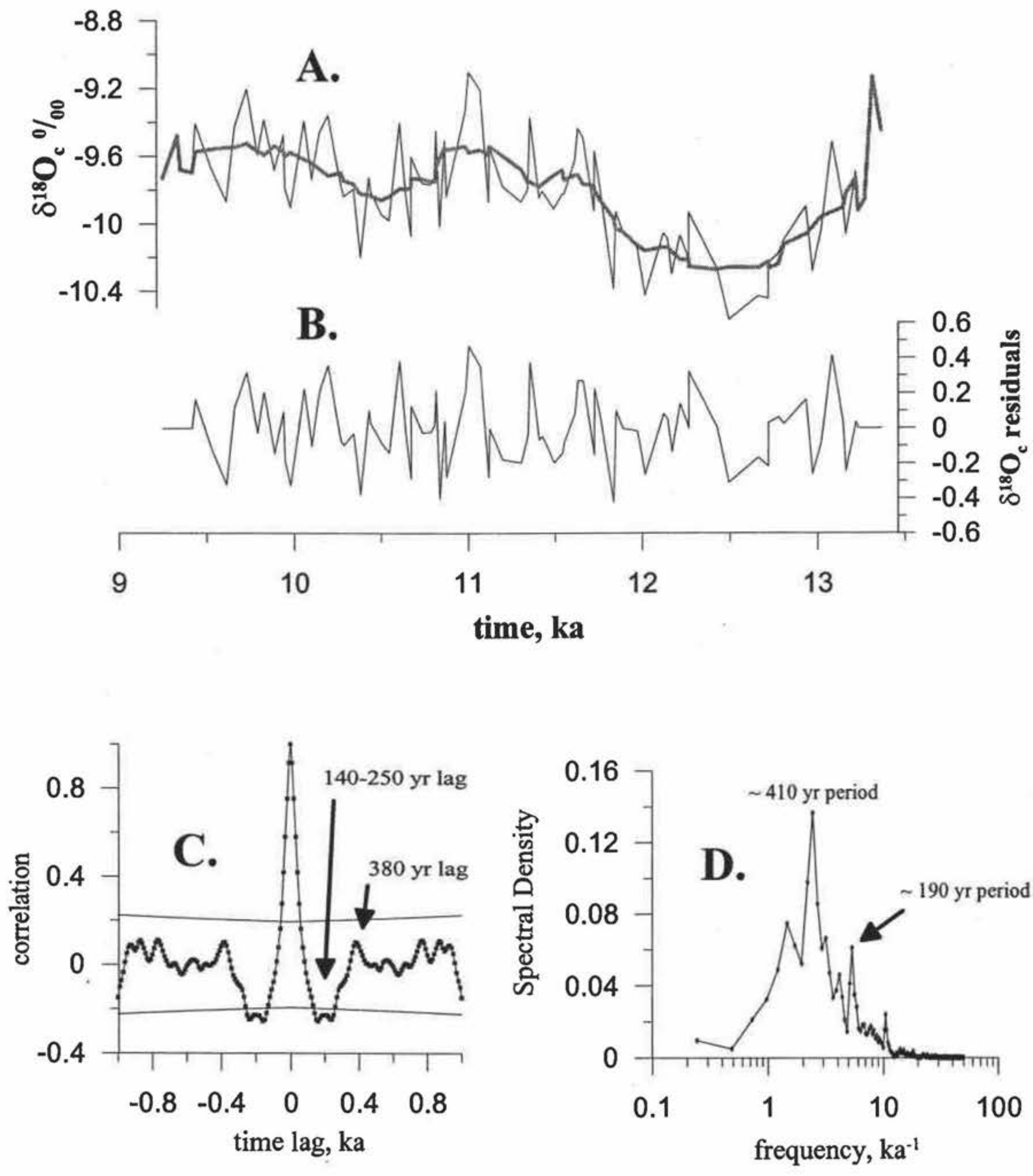

Figure 12. (A) OCNM8-02A record (black) with a 10 point running mean smoothing (grey). The residuals (B) were analyzed with (C) an autocorrelation, and (D) spectral analyses. The band plotted around zero correlation (C) represents significance with 95% confidence. Hence the correlations over lags 140 - 250 yrs. are significant.

CONCLUSIONS: OCNM SPELEOTHEMS AS A CLIMATE PROXY

This study has established that speleothem deposition in OCNM was such that interpretable climate records can be recovered from the calcite. Calcite deposition age can be measured using U-series techniques that give tight constraints (uncertainties on the order of 200 years during the last deglaciation). U/Th dates from this study and from Turgeon (2001) revealed that OCNM speleothems were deposited continuously during interglacial periods, and at sufficient rates that multi-decadally resolved sampling is possible (30-50 yrs per sample point). Also, speleothem stable isotope deposition took place under equilibrium such that climate signals can be isolated and compared to other records.

The climate record developed from $\delta^{18}O_c$ and $\delta^{13}C_c$ in the stalagmite from OCNM revealed that the Younger Dryas cold event influenced atmospheric temperatures in the Pacific Northwest. Forest density ceased its increasing trend apparently in response to this cold event. At the onset of the Holocene, mean atmospheric temperatures increased approximately 3.5 - 4.5 °C. The speleothem climate record from OCNM has thus indicated that regional climate paralleled global climate through the last deglaciation.

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