Multi-proxy approach of a stalagmite for climate reconstruction in Northwestern Thailand

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1. Introduction

- Thailand paleoclimatic variation is still poorly understood due to the lack of high resolution and long term climatic records.

- Most paleoclimatic data are derived from tree ring (Pumijumnong et al., 1995; Buckley et al., 2007) and pollen (Penny, 2001; Rugmai et al., 2008) etc.

- The long tree ring records are rarely to find, while the pollen record is limited by its low resolution for exploring short term climate variation.

- Hence, more high-resolution proxy records covering long time interval are necessary for better understanding on climate changes in this area.

- In recent years, paleoclimatic studies have been regarded to use stalagmites as paleoclimatic recorder (Johnson et al., 2006; Baker et al., 2007; Wang et al., 2008; Jex et al., 2010).

- Major studies to that regard have focused on stable-isotopes ($\delta^{18}O$ and $\delta^{13}C$), trace element and lamina thickness of stalagmites.

Fig.1 Stalagmite NJ1

- The potential of stalagmites as paleoclimatic proxy in Thailand was first explored since 2008 (Phutong, 2008)
- Based on Thorium-230 ages, Phutong (2008) has reconstructed paleoclimatic records using $\delta^{13}C$ and $\delta^{18}O$ of stalagmite NJ1.
- However, the paleoclimate signal of this study is still unclear and should be verified further.

Cai, B., Pumijumnong, N., Tan, M., Muangsong, C., Kong, X., & Jiang, X. (2010). Effects of intra-seasonal variation of summer monsoon rainfall on stable isotope and growth rate of a stalagmite from Northwestern Thailand. Journal of Geophysical Research, in press.

- For the topmost 26 mm, covering 105 years
- This result demonstrated that both $\delta^{18}O$ and growth rate of stalagmite NJ1 is a robust proxy for regional monsoon intensity.

- However, more detail paleoclimate variations should be developed for the past 1700 years.

- Moreover, the grey level, deriving from detrital sediment, is well known to relate with climatic variation (Quin et al., 1998, 2000). Although numerous speleothems-based proxy studies have successfully done, none of them have utilized the intensity of grey level.

- To this end, stalagmite annual laminae based multi-proxies, were developed and compared with modern climate data, in order to decode the paleoclimate signal logged in $\delta^{18}O$, growth rate and grey level of stalagmite NJ1.

- Then, the higher resolution records for the last 1700 years were analyzed, and the monsoon rainfall fluctuations during past 1700 years were discussed.

2. Site description

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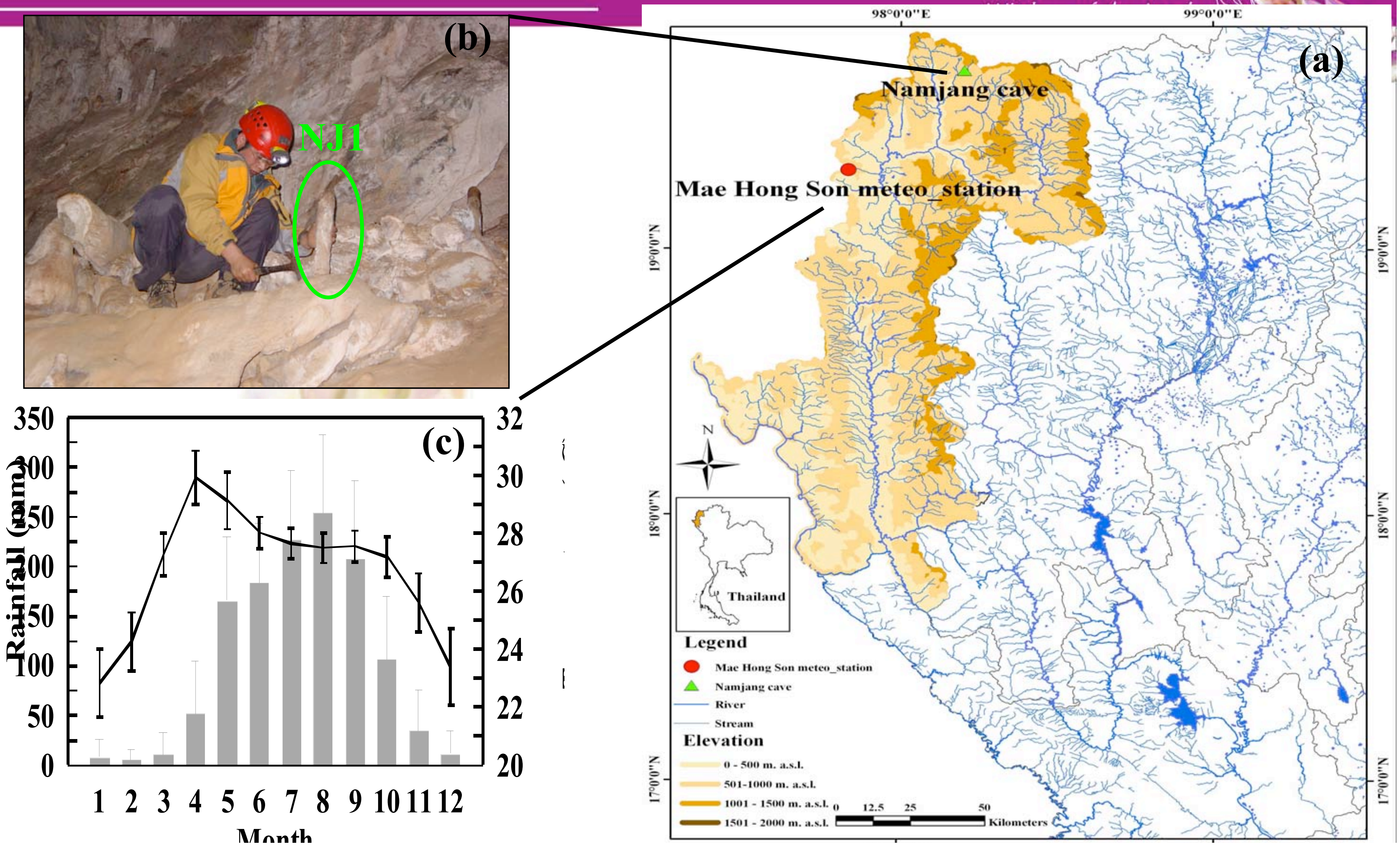

Fig. 2 Map of the study region showing Namjang cave (triangle red point) and the Mae Hong Son meteorological station (circle green point) (a); stalagmite NJ1 (b); the mean and standard deviation variability in monthly rainfall from 1911–2007 AD (grey bars with vertical bars) and temperature from 1951-2007 AD (black line with vertical bars) at Mae Hong Son meteorological station (c).

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❖ However, rainfall amount is characterized by heterogeneous intra-seasonal patterns in the region (Cai et al. 2010, in press).

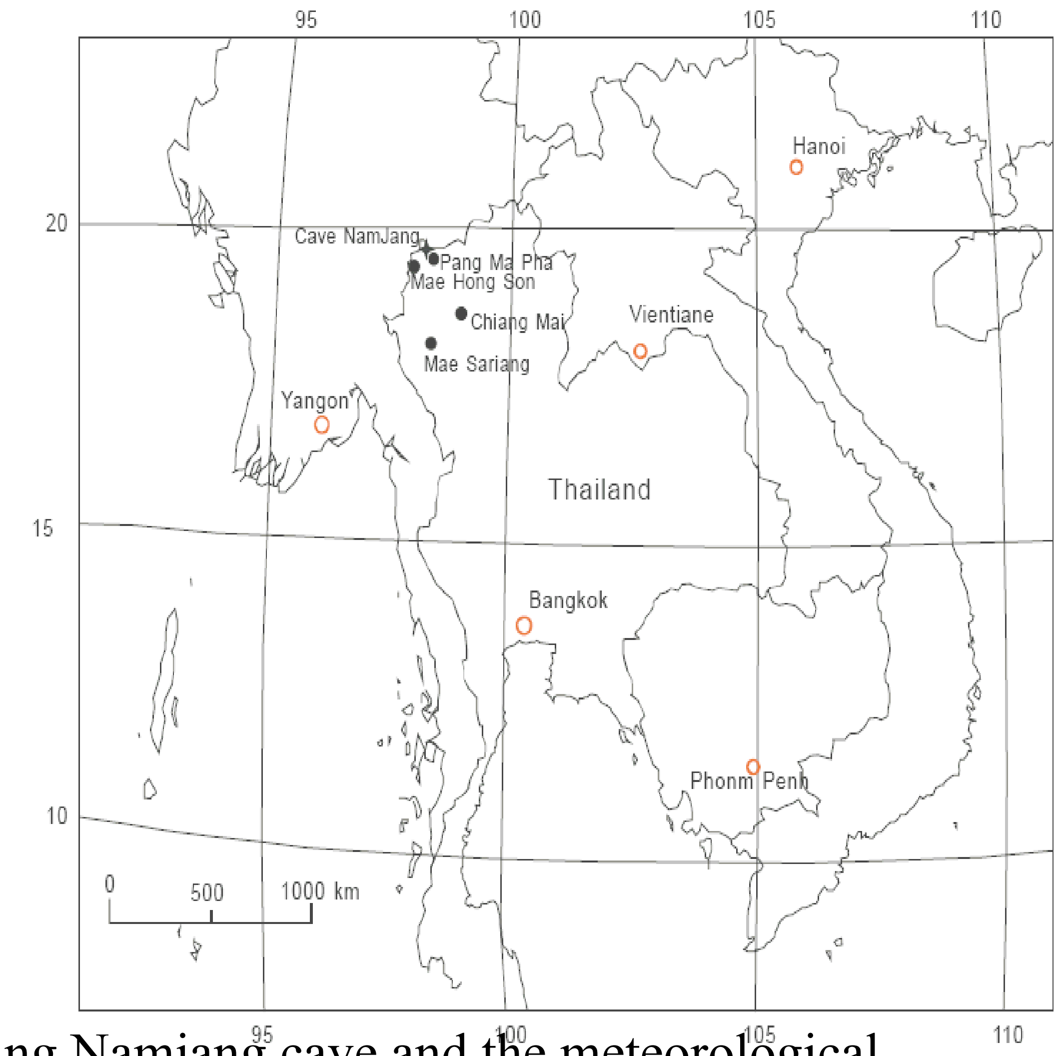

Fig.3 Map of the study region showing Namjang cave and the meteorological observation stations in the regions (Cai et al. submitted manuscript 2009)

Bi-peak distribution

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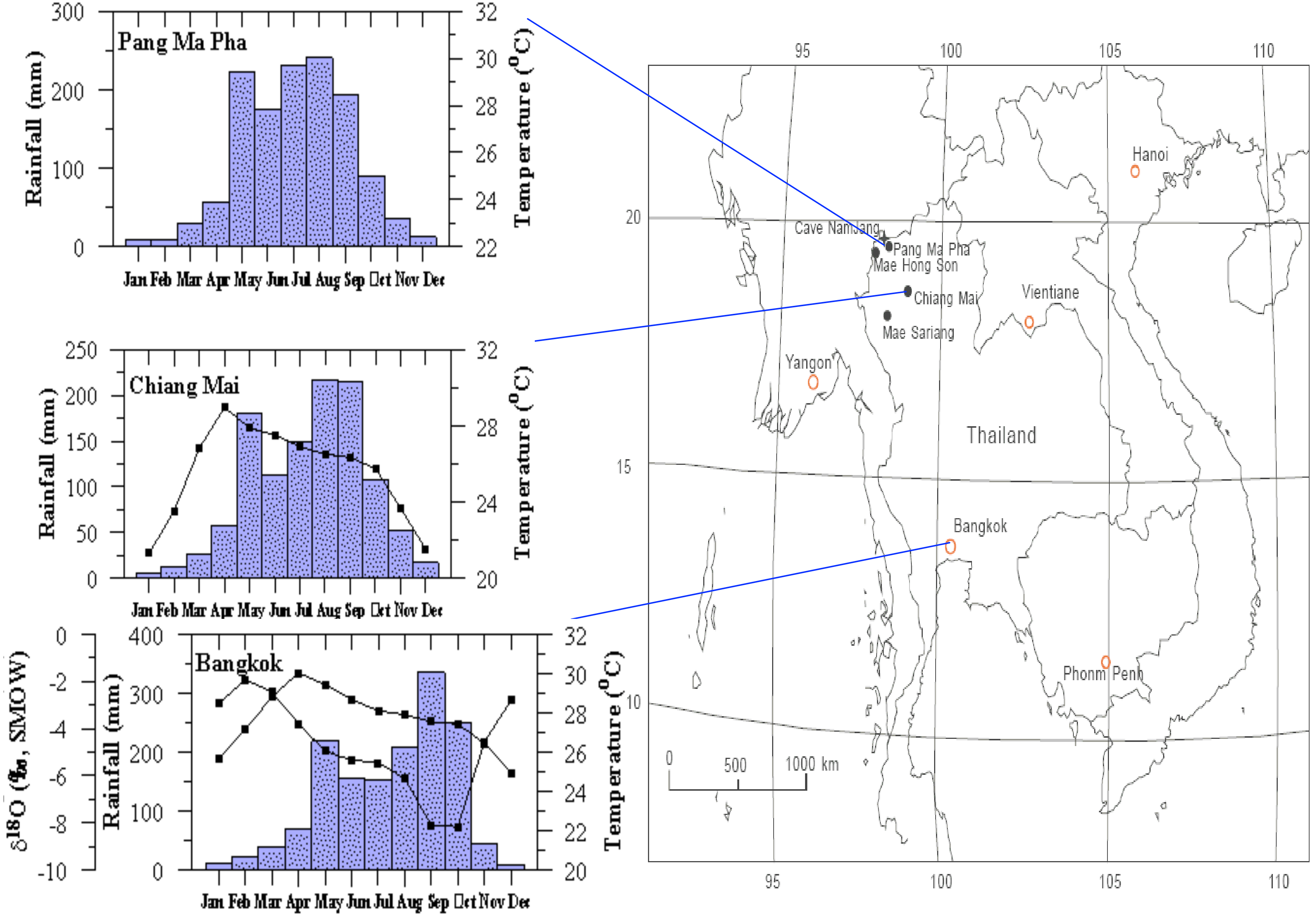

Mono-peak distribution

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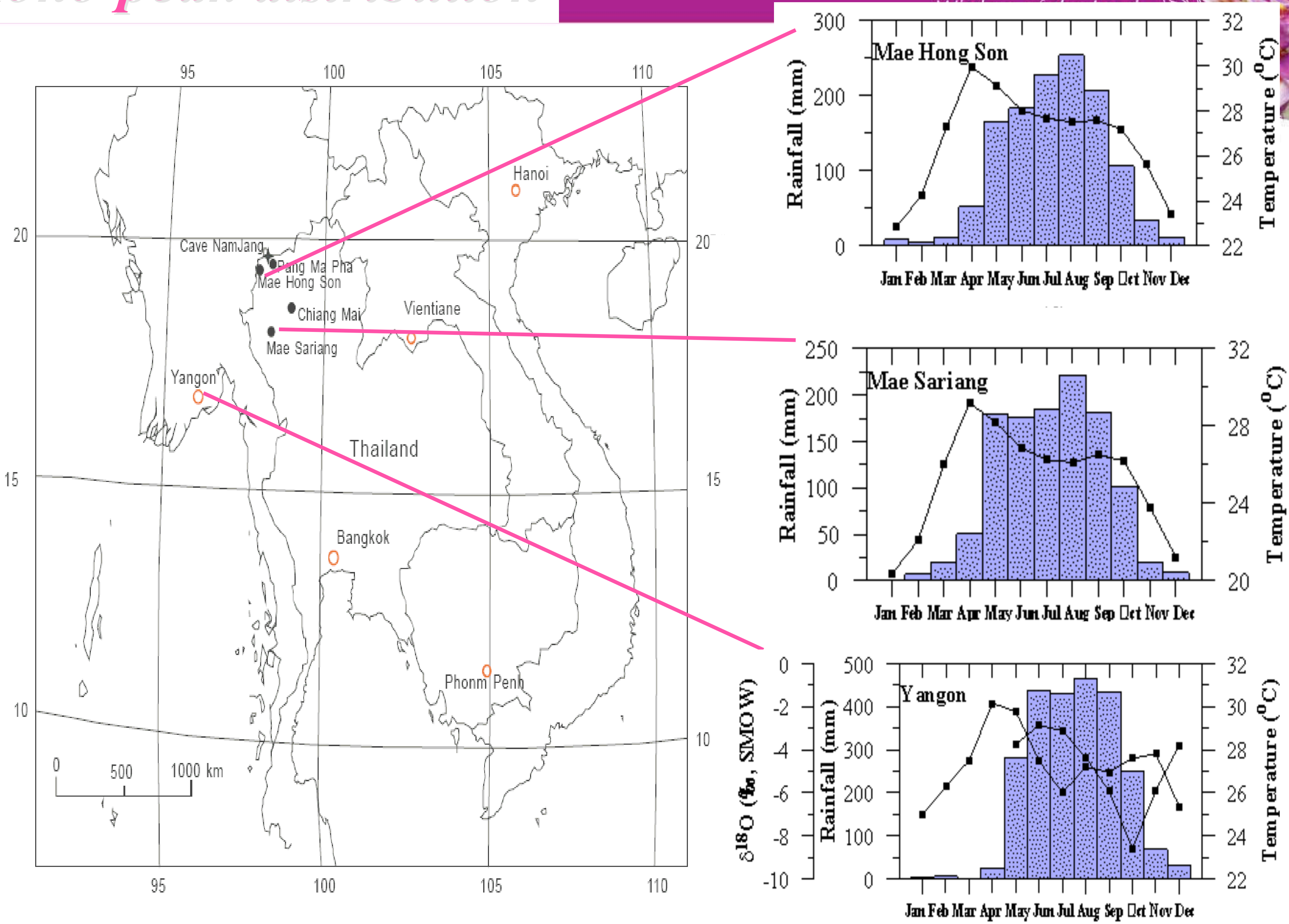
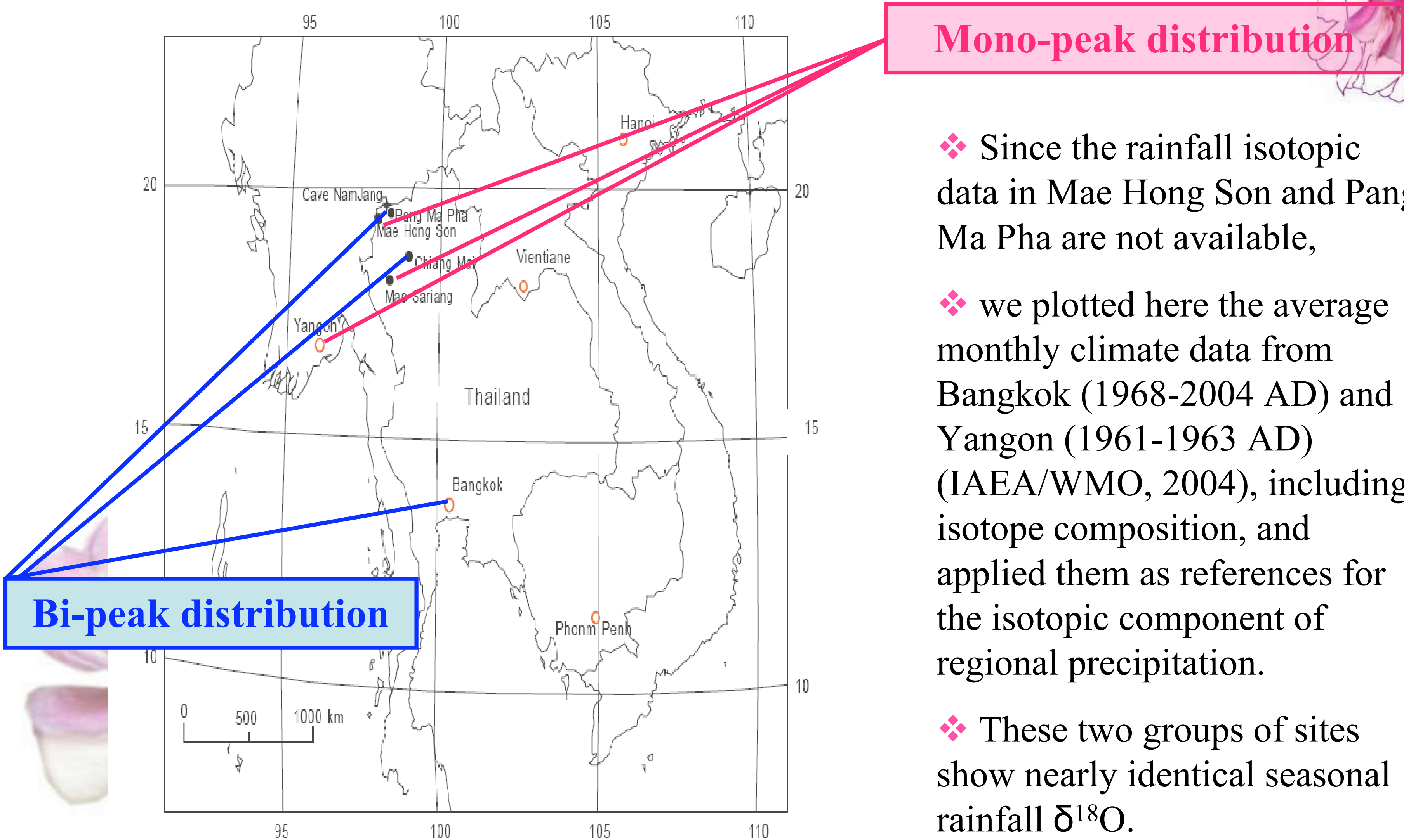
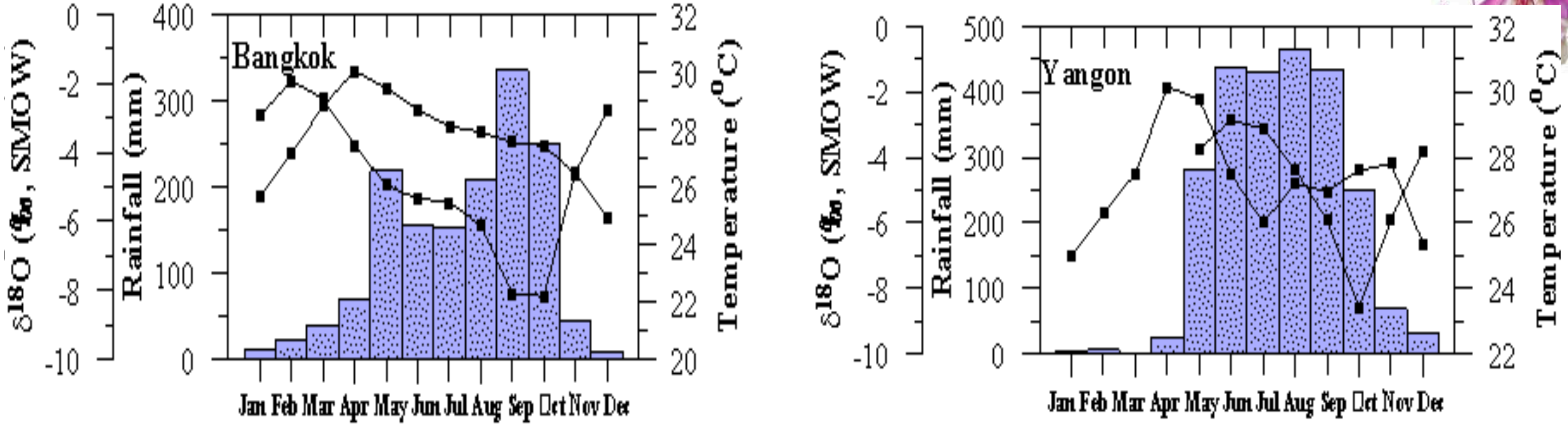




- Since the rainfall isotopic data in Mae Hong Son and Pang Ma Pha are not available,
- we plotted here the average monthly climate data from Bangkok (1968-2004 AD) and Yangon (1961-1963 AD) (IAEA/WMO, 2004), including isotope composition, and applied them as references for the isotopic component of regional precipitation.
- These two groups of sites show nearly identical seasonal rainfall $\delta^{18}O$.



❖ For instance, in Bangkok, rainfall $\delta^{18}O$ shifts from ~-5.3 ‰ in early monsoon season to less than -8 ‰ during the late monsoon season. In Yangon, it shows similar much negative values of $\delta^{18}O$ in the late season (~-3.3 to ~-6.3), even though the seasonal rainfall pattern is different with that of Bangkok.

❖ The different monsoonal rainfall distributions, yet similar rainfall $\delta^{18}O$ between the two neighboring meteorological stations, strongly suggests that the regional climate is under the influence of the same monsoon system, and the local precipitation isotopic signature can represent variations of monsoon intensity in much broader region.

3. Methodology

3.1 Sample preparation

❖ The sample was cut into two halves along the growth axis after its surface was cleaned with tap water.

❖ Then one half of the cut surface was polished

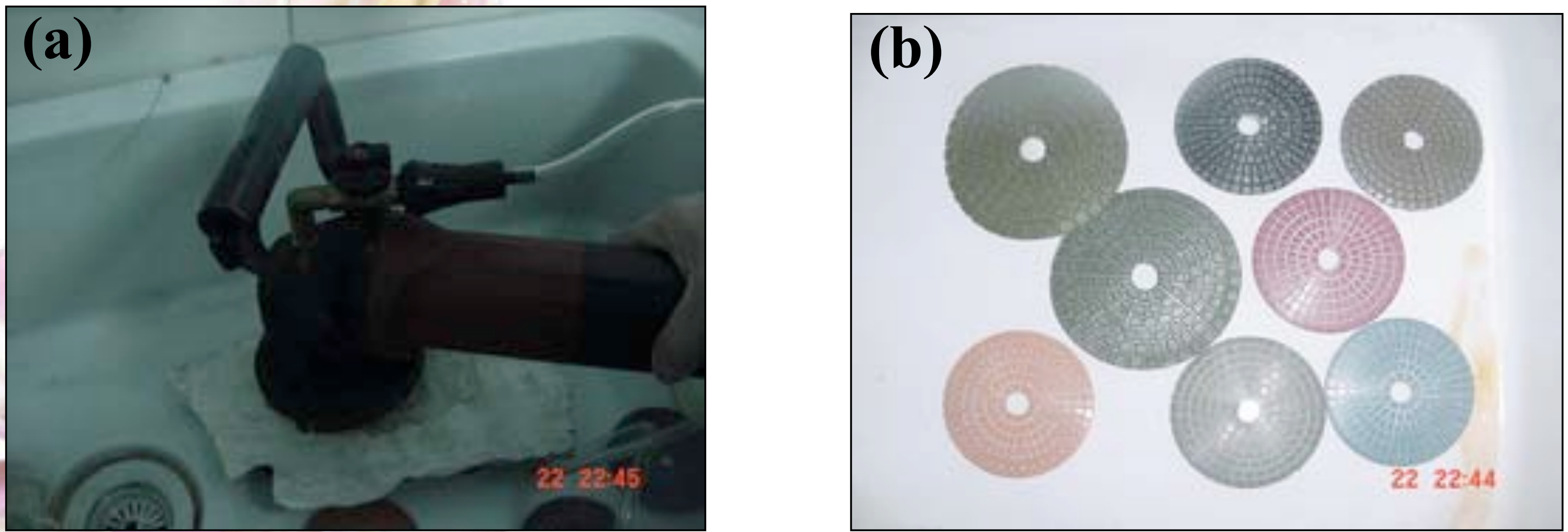
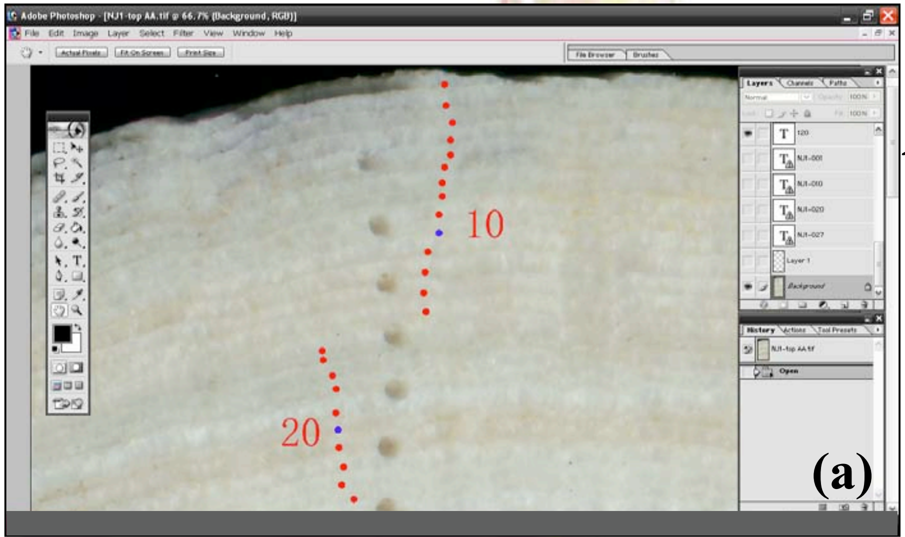


Fig.4 Polishing (a); polish pads (b)

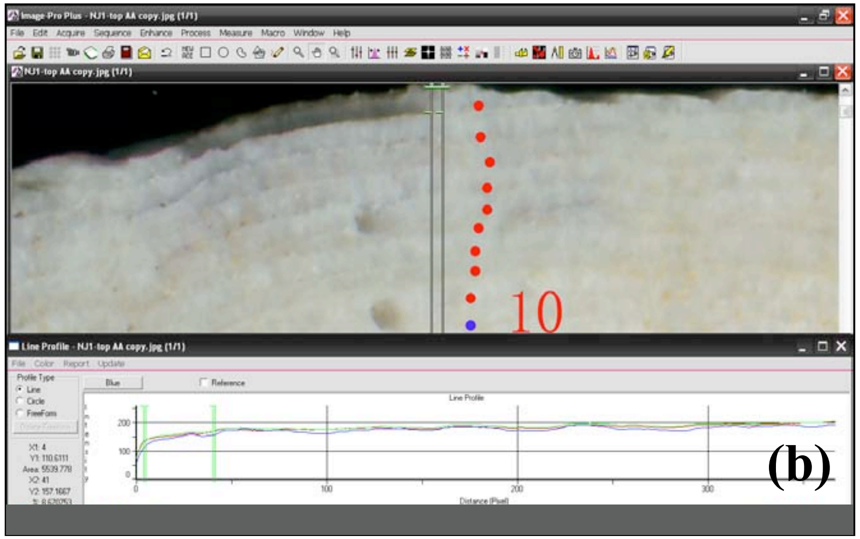
3.2 Stalagmite laminae counting and measuring

❖ The polished section of stalagmite was scanned using a high resolution scanner (Microtek) at RGB/3200 dpi conditions.



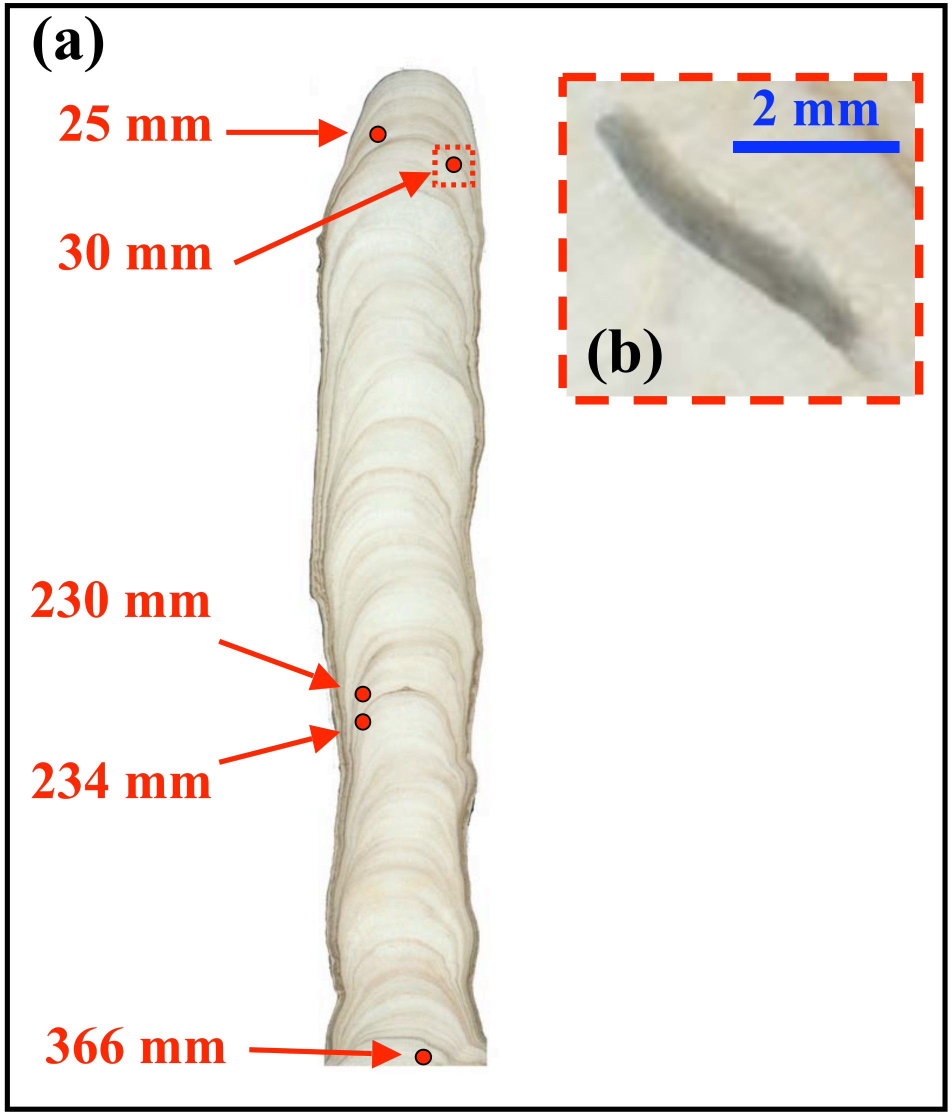
The digital image was marked and counted with Adobe Photoshop software (Fig. 5).

Laminae thickness and grey level were measured using Image-Pro Plus 5.1 software (Fig. 6).



❖ These works were done in Key Laboratory of Cenozoic Geology Environment, Institute of Geology and Geophysics, Chinese Academy of Science, China.

3.3 ^{230}Th dating



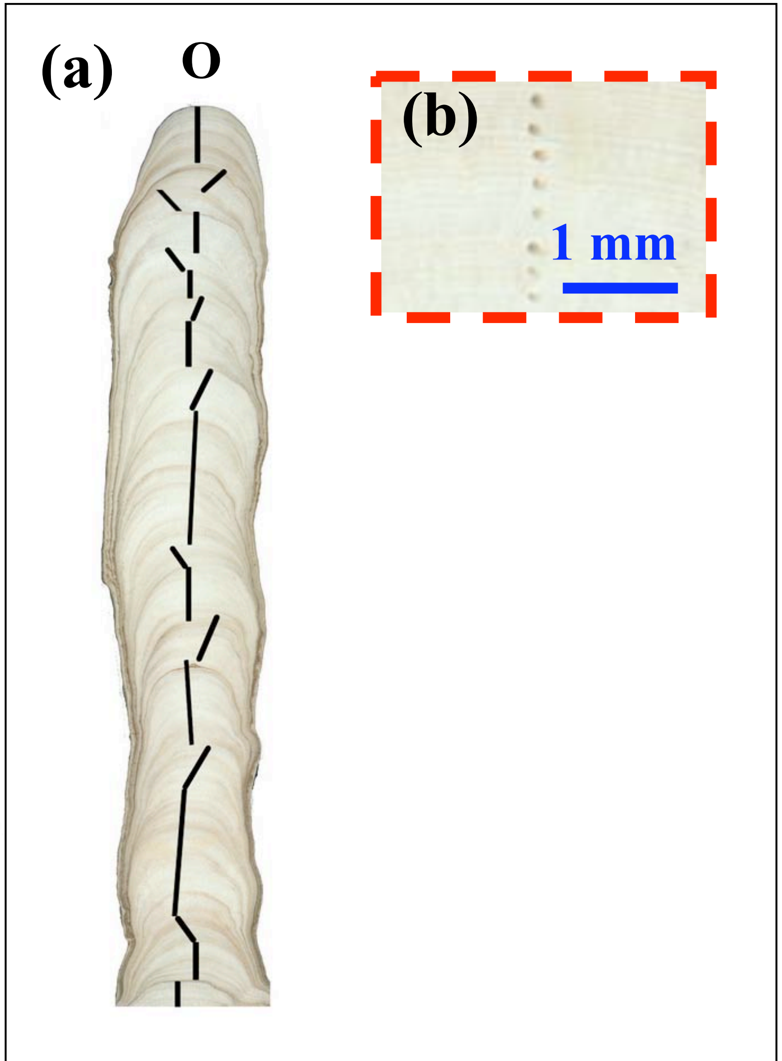
- Sub-samples were drilled along growth bands using a carbide dental burr in diameter of 0.9 mm at 25 mm, 30 mm, 230 mm, 234 mm and 366 mm, respectively apart from the top.

- The measurements were performed on a magnetic sector inductively coupled plasma-mass spectrometer (ICP-MS, Finnigan Element) at the Department of Geology and Geophysics, University of Minnesota, following Shen et al. (2002).

Fig.7 Polished section of stalagmite NJ1 shows samples for ^{230}Th dating at depth of 25 mm, 30 mm, 230 mm, 234 mm and 366 mm, respectively apart from the top (a); amplified image shows that a sample for ^{230}Th dating analysis at 30 mm was drilled (b)

3.4 Stalagmite chronology

- The chronology of NJ1 is based on annually lamina counting which were verified by ^{230}Th dating.



3.5 Oxygen isotope analysis

- Sub-samples for oxygen isotope analysis were extracted using a 0.5 mm carbide dental burrs along the growth axis.
- Oxygen isotope analysis was performed on a MAT-253 mass spectrometer (Thermo-Finnigan) linked to a Gas Bench-II at Key Laboratory of Cenozoic Geology Environment, Institute of Geology and Geophysics, Chinese Academy of Science, China.
- All oxygen isotope values are reported in parts per mil (‰) relative to the Vienna PeeDee Belemnite standard (VPDB) in delta (δ) notation.

Fig.8 Polished section of stalagmite NJ1. Black lines indicate the sampling location of oxygen isotope (labeled O) (a); and amplified image shows that sub-samples for oxygen analysis were drilled (b).

3.6 Comparisons with instrumental data

❖ In order to understand the paleo-climatic signal preserved in stalagmite NJ1, we tested correlations between stalagmite record and hydrometeorological record at the local meteorology station Mae Hong Son (1911-2002 AD) by comparing the $\delta^{18}O$, growth rate and grey level values with

Yearly averaged of rainfall data

5-year running averaged of rainfall data

Annual rainfall

Monthly rainfall

Seasonal rainfall

The monthly data are April through November only, because for 50% of the years the other months have no rainfall at all.

The seasonal rainfall was divided into the early monsoon season, from May to July (MJJ), and the late monsoon season from August to October (ASO).

4. Results and discussion

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4.1 Stalagmite chronology
4.1.1 ^{230}Th ages

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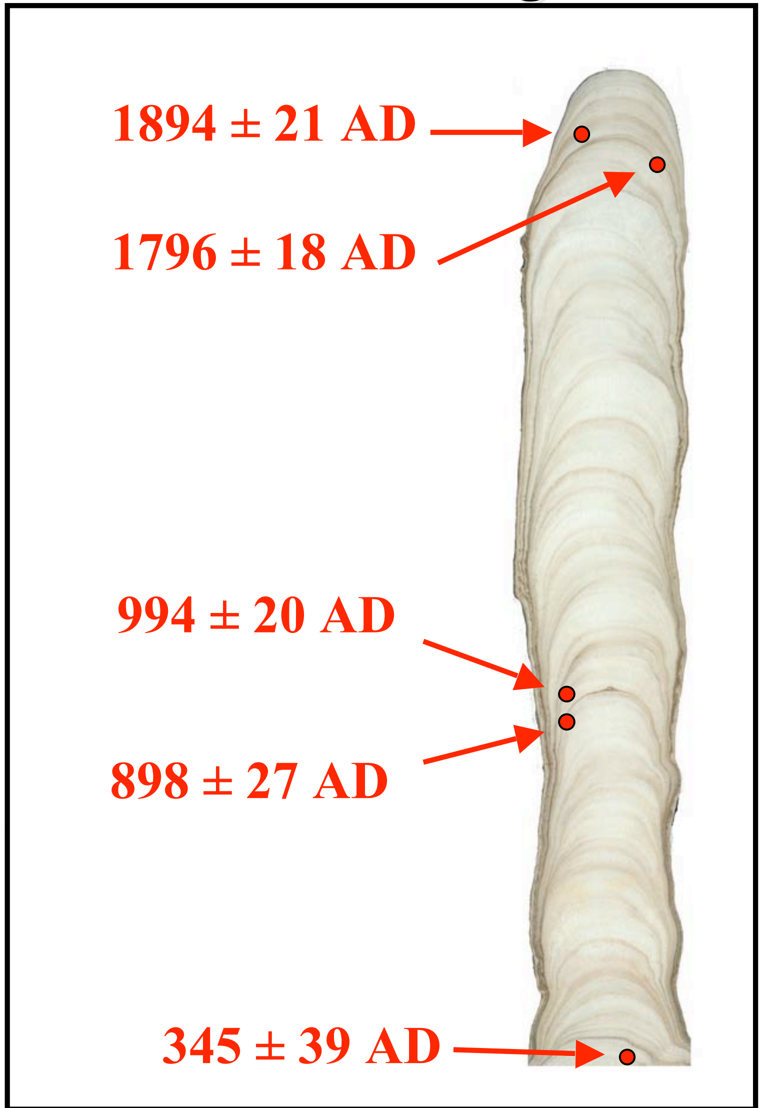

Fig.9 ^{230}Th age results of stalagmite NJ1

- The ^{230}Th dating results indicate two possible growth hiatus, characterized by abruptly decreasing of growth rate.

- The first hiatus occurred between 994 AD and 898 AD, another between 1894 AD and 1796 AD.

- These hiatuses were further identified by compared the results from ^{230}Th dating and lamina counting.

4.1.2 Lamina counting result

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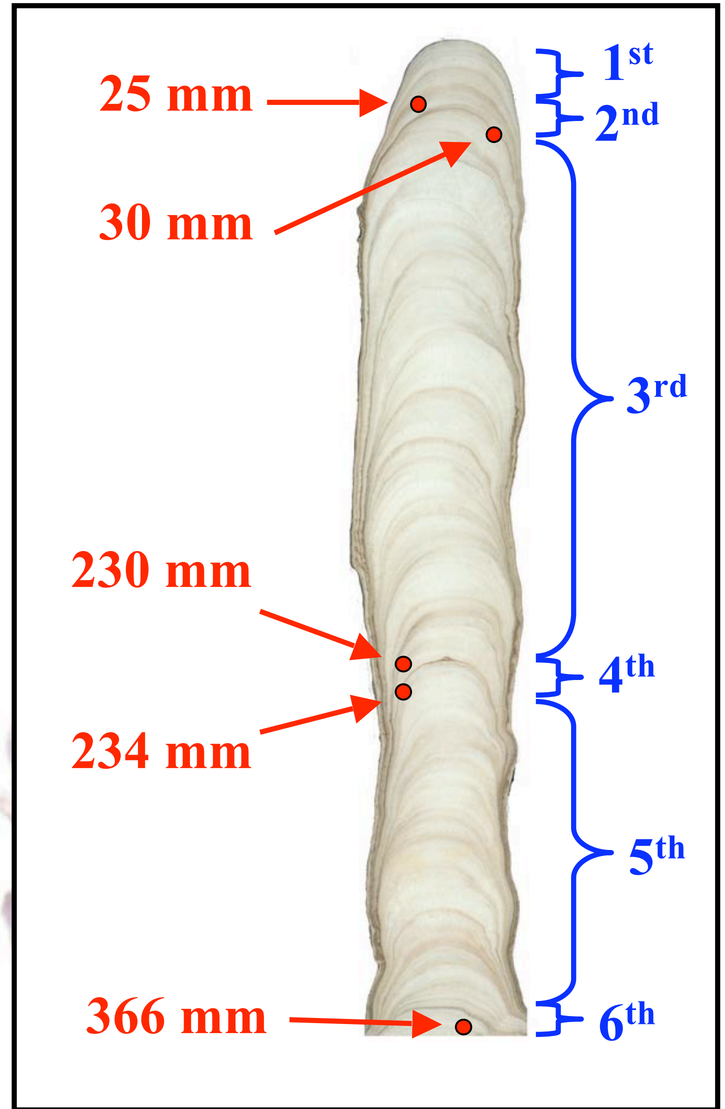

- There are 1562 laminae were counted totally in NJ1.

- In order to compare the isotope dating and lamina counting, stalagmite NJ1 was divided into six sections by five ^{230}Th dating points.

- In each section, laminae amount was compared with ^{230}Th dating result.

4.1.2 Lamina counting result

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Table 1 Comparison of results from laminae counting and ^{230}Th dating

Section	Distance from top (mm)	Dating point	Amount of layers	Calculated ages * (year)	Difference value**	Remarks
1st	0 - 25	Top to NJ1-25	105	111± 21	6	
2nd	25-30	NJ1-25 to NJ1-30	26	98 ± 39	72	Hiatus
3rd	30-230	NJ1-30 to NJ1-230	815	802 ± 38	13	
4th	230 -234	NJ1-230 to NJ1-234	24	97 ± 47	73	Hiatus
5th	234 - 366	NJ1-234 to NJ1-366	562	553 ± 66	9	
6th	366 - 375	NJ1-366 to Base	30	-	-	

* Calculated ^{230}Th ages between dating points

** Difference value = Amount of layers – calculated ages

4.1.3 Reconstruction of time scale

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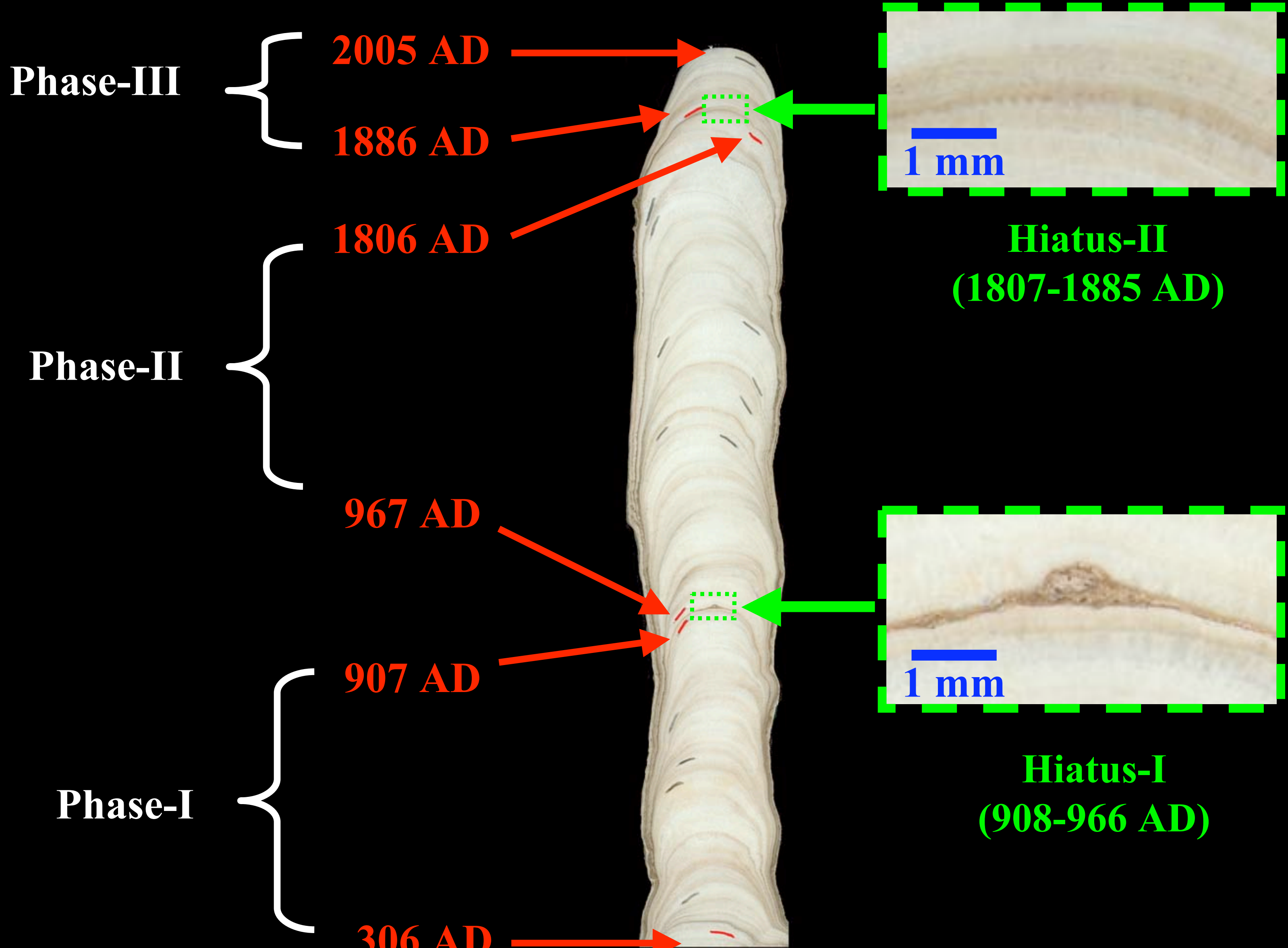
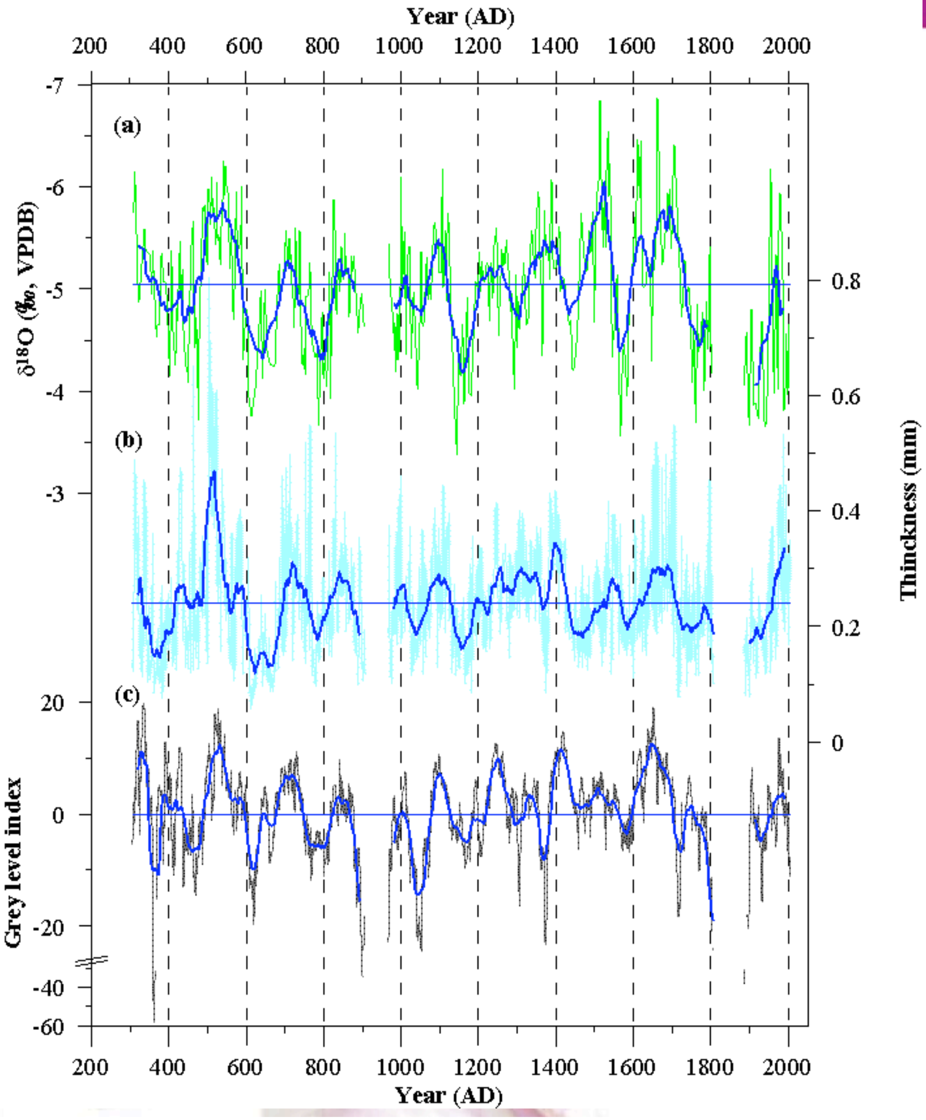


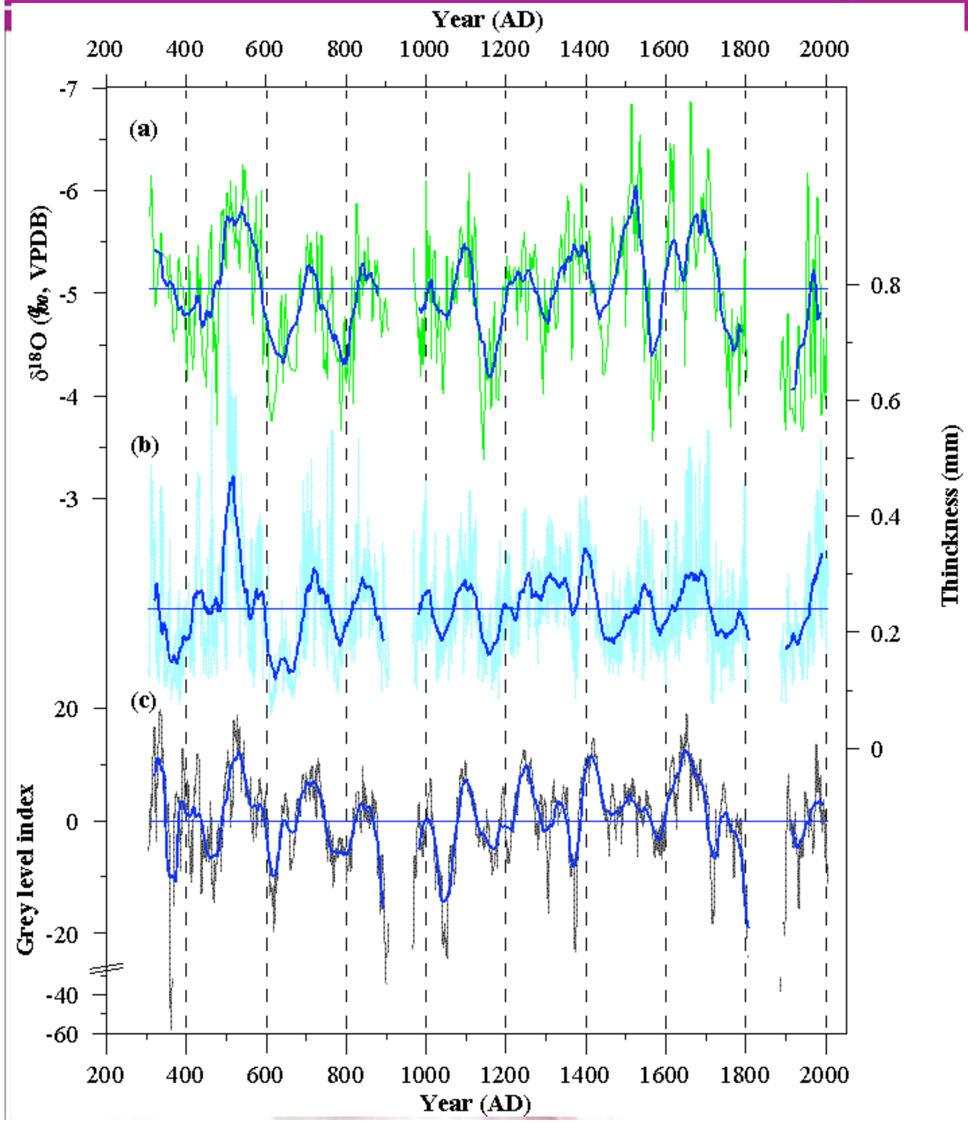
Fig.10 Growth phases of stalagmite NJ1; amplified images show Hiatuses (labeled Hiatus-I and Hiatus-II) at depth of 27 and 232 mm, respectively apart from the top

4.2 Variation in oxygen isotope



- The NJ1 $\delta^{18}O$ ratios fluctuate significantly throughout the whole profile, with amplitudes as large as 3.5 ‰ (from -6.87 to -3.38 ‰), with a mean value of -5.05 ‰.
- There are ten distinct intervals of relatively positive $\delta^{18}O$ values, occurring in years around 450, 650, 790, 1050, 1150, 1300, 1440, 1560, 1760 and 1930 AD, respectively.
- Minimum values are observed at time-periods 490-590, 1050-1110, 1200-1280, 1320-1410, 1465-1540, 1600-1720 and 1950 AD, respectively.

Fig. 11 The $\delta^{18}O$ (a), growth rate (b) and grey level (c) profiles of stalagmite NJ1. The thick blue lines indicate 11 points running average for $\delta^{18}O$ (a), and 31 points running average for growth rate (b) and grey level (c). The thin horizontal lines indicate the average values



4.3 Variation in growth rate

- The growth rate of stalagmite NJ1 varies from 0.06 mm/yr to 0.80 mm/yr, with an average value of 0.24 mm/yr (Fig. 11 (b)).

Fig. 11 The $\delta^{18}O$ (a), growth rate (b) and grey level (c) profiles of stalagmite NJ1. The thick blue lines indicate 11 points running average for $\delta^{18}O$ (a), and 31 points running average for growth rate (b) and grey level (c). The thin horizontal lines indicate the average values

4.4 Variation in grey level

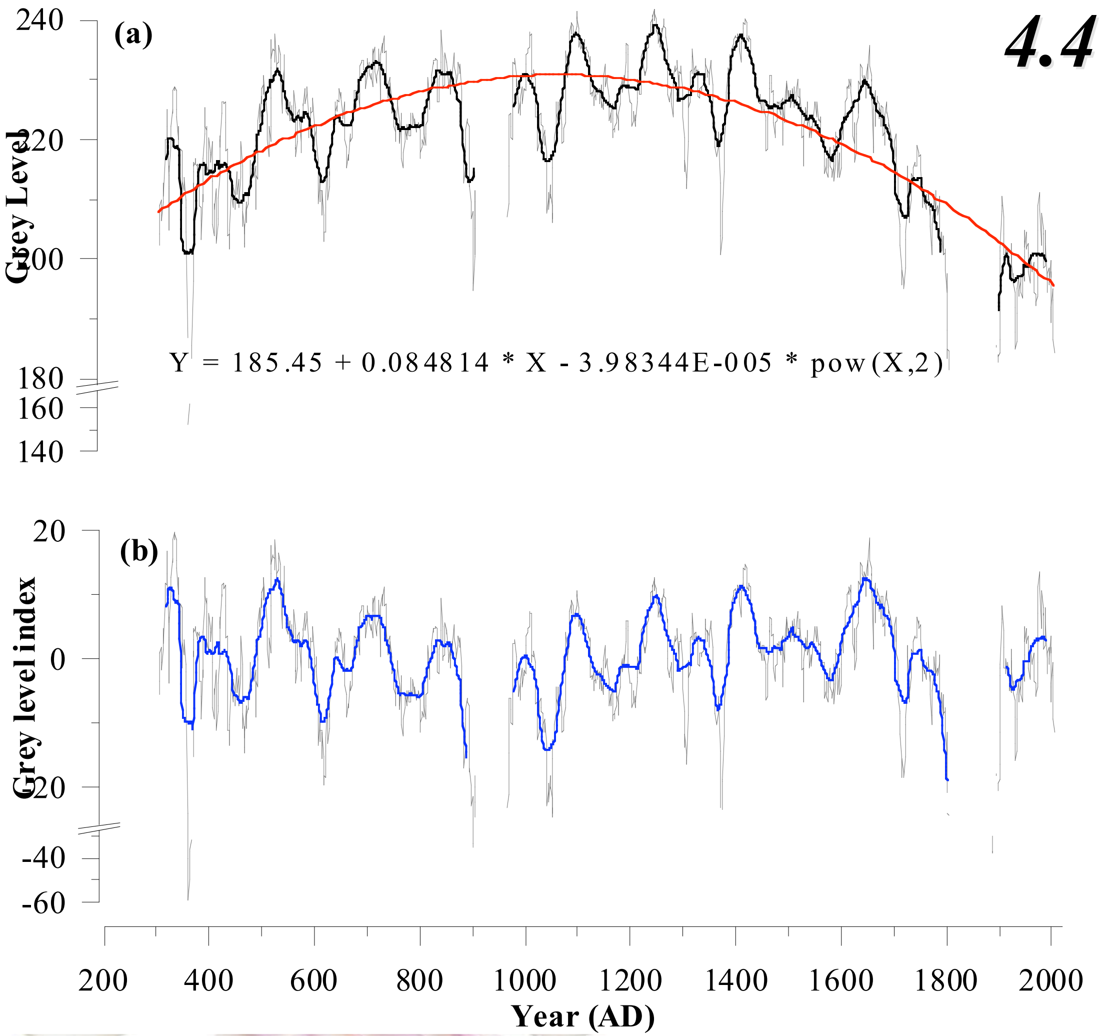


Fig. 12 (a) The time series of grey level and its polynomial trend (red line). (b) The detrended fluctuation of grey level (grey level index). The blue line indicates the 31 points running average

- The grey level varies between 149 (darker) and 242 (brighter).
- The grey level profile shows distinguishing low frequent trend (2nd degree polynomial), superimposed by a series of centennial to multi-decadal fluctuations (fig. 12 (a)).
- The low frequent variation maybe resulted from the color collection process, because the stalagmite surface used for scanning is not absolutely flat, which could yield a small angle between stalagmite surface and scanner panel.
- In order to remove this low frequent trend, the original data was subtracted by using the fit line.
- The detrended values were termed "grey level index" (Fig. 12 (b)).

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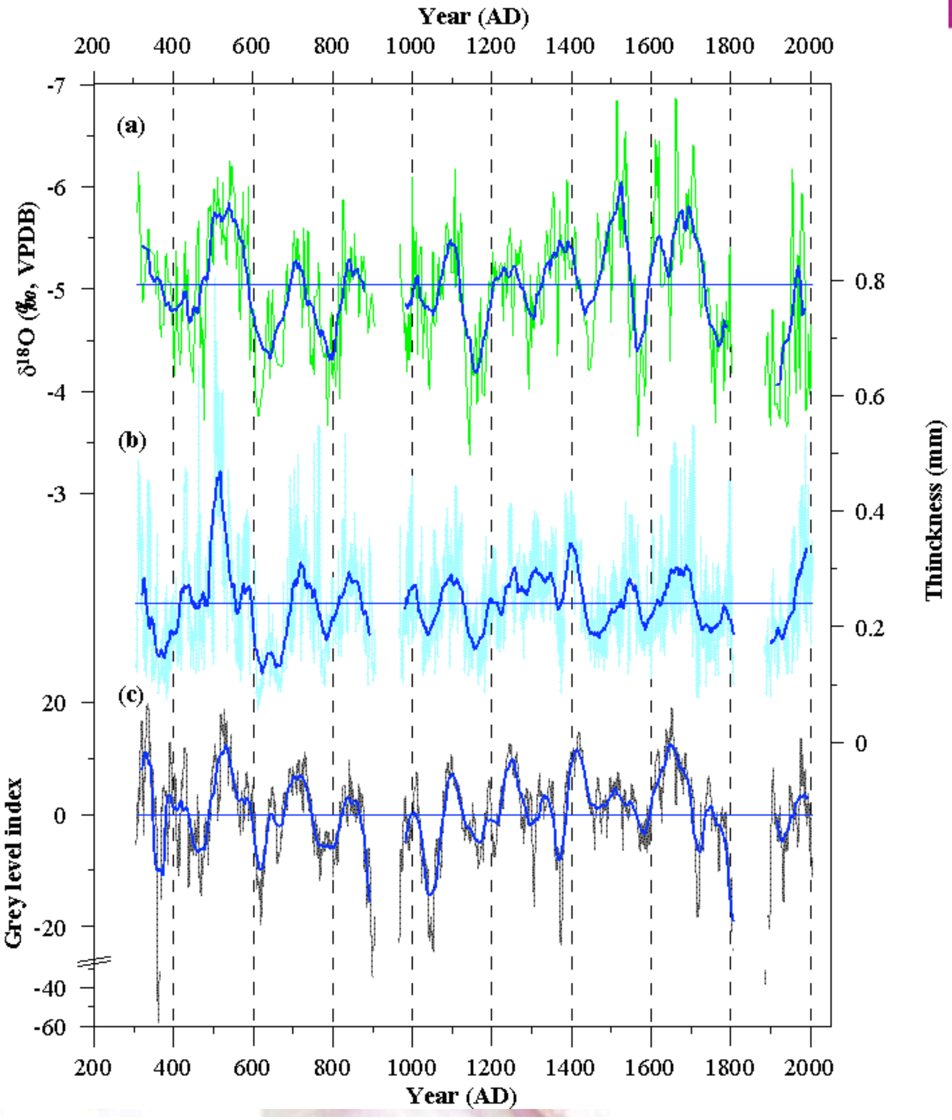


Fig. 11 The $\delta^{18}O$ (a), growth rate (b) and grey level (c) profiles of stalagmite NJ1. The thick blue lines indicate 11 points running average for $\delta^{18}O$ (a), and 31 points running average for growth rate (b) and grey level (c). The thin horizontal lines indicate the average values

4.4 Variation in grey level

- The time series of grey level index exhibits a series of centennial to multi-decadal fluctuations similar to those of growth rate.
- The brighter in color correlate to bigger in growth rate.
- There are 9 intervals with relative higher value (brighter) center at approximately 400, 500, 720, 840, 1100, 1250, 1410, 1640, and 1980s, respectively (Fig. 11 (c)).

4.5 Understanding lamina thickness (growth rate), grey level and oxygen isotope

4.5.1 Comparisons with instrumental data

Table 2 Pearson Correlations (r values) between Mae Hong Son rainfall data (1911-2002 AD) and stalagmite growth rate, grey level and $\delta^{18}O$ values. Statistically significant values are shown in bold

Month & season	Yearly averaged rainfall 1911-2002 AD			5-year running averaged rainfall 1911-2002 AD		
	Growth rate	Grey level	$\delta^{18}O$	Growth rate	Grey level	$\delta^{18}O$
April	0.07	-0.09	-0.05	0.02	-0.02	-0.12
May	-0.06	-0.09	0.09	-0.11	**-0.24**[b]	0.19
June	0.02	-0.12	0.05	-0.14	-0.15	0.05
July	-0.04	-0.02	0.15	**-0.26**[b]	**-0.25**[b]	**0.36**[a]
August	0.03	-0.02	-0.05	-0.14	-0.04	-0.01
September	**0.22**[b]	-0.08	**-0.25**[b]	0.08	0.17	**-0.43**
October	-0.03	0.08	-0.05	0.13	**0.22**[b]	-0.15
November	0.07	0.04	-0.01	0.01	0.04	0.04
Annual	0.12	-0.10	-0.09	-0.08	-0.05	-0.12
May-Oct (M-O)	0.06	-0.10	-0.04	-0.14	-0.08	-0.04
May-Jul (MJJ)	-0.04	-0.12	0.16	**-0.26**[b]	**-0.32**[a]	**0.30**[a]
Aug-Oct (ASO)	0.13	-0.03	**-0.21**[b]	0.03	0.17	**-0.33**[a]

a Statistically significant at the 0.01 level
b Statistically significant at the 0.05 level

4.5.2 Understanding growth rate

❖During the monsoon season, monsoonal rainfall season initiates in May and continues through October with major peak during August-September-October (ASO) and minor peak during May-June-July (MJJ) (Singhrattna et al., 2005).

❖ The growth rate of stalagmite NJ1 correlates well with September rainfall, this could probably be assumed that the growth rate of the stalagmite depend on September rainfall amount which is the major peak in seasonal rainfall distribution (Singhrattna et al., 2005).

❖ Because of the drip rate is important factor that control stalagmite growth (Genty et al., 2001), the higher September rainfall may maintain drip water at higher level during the next dry season, hence, increase growth rate of stalagmite.

4.5.3 Understanding grey level

- The grey level is possibly influenced by drip water supply during strong monsoon rainfall season.

- Because more discharge water in cave could keep the cave in higher moisture level and reduce dust emission.

- Moreover, the relationship between the growth rate and grey level ($r=0.21$, $p<0.05$) indicates that the variation of grey level may be controlled by the same climatic condition and increasing growth rate of stalagmite maybe decrease detrital particle content per unit volume of carbonate deposition.

- Furthermore, the high drip rate does not allow sufficient time for trapping detrital particles, these particles are removed by splashing of the next drip resulting in high grey level (whitish) (Yadava et al., 2004).

- This significantly positive correlation between rainfall in the late monsoon season and grey level, therefore, demonstrated that the grey level of stalagmite NJ1 should provide a proxy of rainfall in the late monsoon season.

- However, the reason for negative correlations between the grey level and rainfall in the early rainy season is still unclear. It indicated that the climate response of the grey level is complex.

4.5.4 Understanding oxygen isotope

- The $\delta^{18}O$ of stalagmite NJ1 had a significantly negative correlation with September rainfall amount as well as total rainfall in the late monsoon season (ASO rainfall), which are the major peak in seasonal rainfall distribution of this area (Singhrattna et al., 2005).
- These correlations act in the same direction as the "amount effect" (Burns et al. 2001; Burns et al.; Fleitmann et al., 2004).
- Therefore, demonstrated that rainfall in the late monsoon season has the primary control in the climatic signal of NJ1-$\delta^{18}O$.

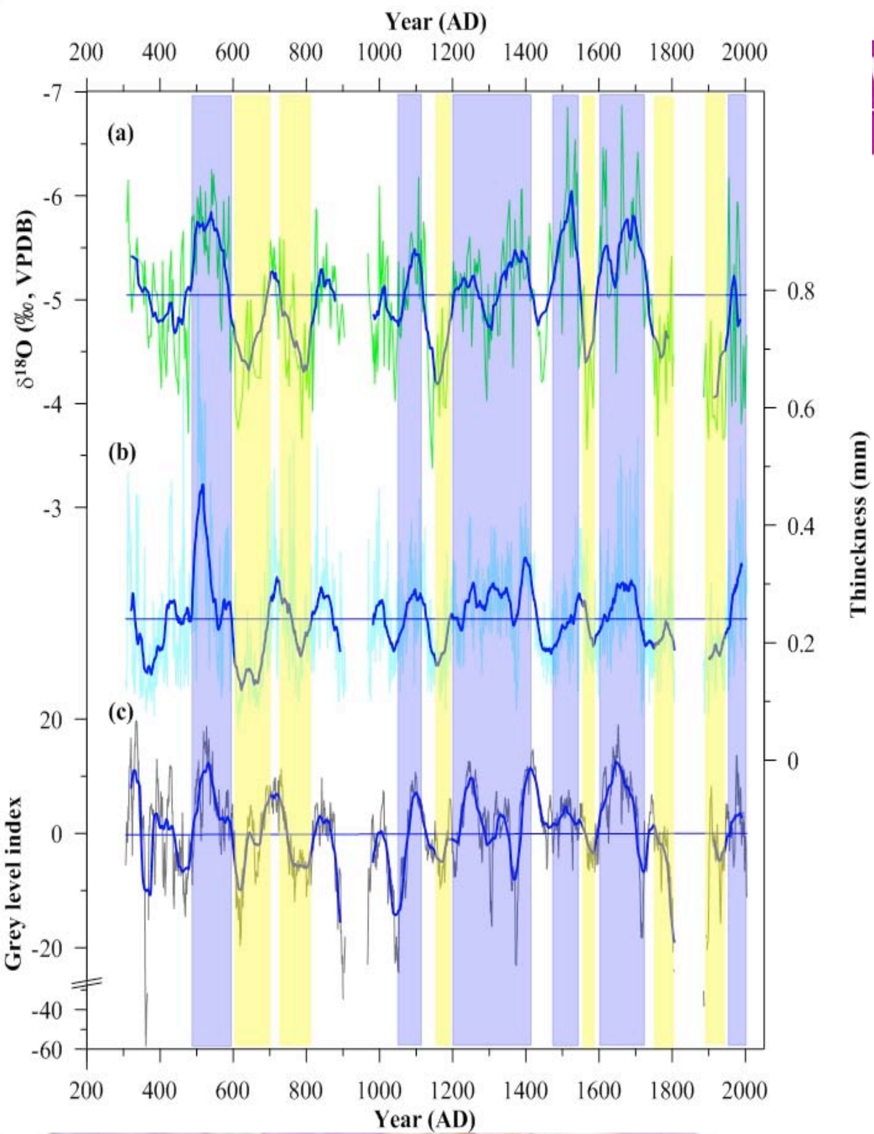
- We interpret the $\delta^{18}O$ variations in stalagmite NJ1 as indicators of rainfall amount.

- The lighter speleothem $\delta^{18}O$ implies more proportion of ASO rainfall, possibly stronger Thailand Monsoon.

4.6 Thailand Monsoon Rainfall History Over The Last 1700 Years

4.6.1 Thailand monsoon variability

- The results as discussed earlier suggest that $\delta^{18}O$, growth rate, grey level values of stalagmite NJ1 should provide a proxy of monsoon rainfall.
- The minimum of $\delta^{18}O$, associating with maximum of growth rate and grey level, indicates more rainfall in ASO, possibly stronger Thailand monsoon (TM).



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4.6.1 Thailand monsoon variability

❖ Hence, the variations in all three parameters demonstrate six periods of stronger TM occurred at approximately 490-590 AD, 1050-1110 AD, 1200-1410 AD, 1465-1540 AD, 1600-1720 AD and 1950-2000 AD respectively.

❖ They also reveal six periods of relatively weak TM occurred at approximately 600-700 AD, 710-810 AD, 1150-1190 AD, 1560-1590 AD, 1750-1800 AD and 1886-1950 AD, respectively.

Fig.13 The blue and yellow bars indicate strong and weak TM, respectively, of stalagmite NJ1

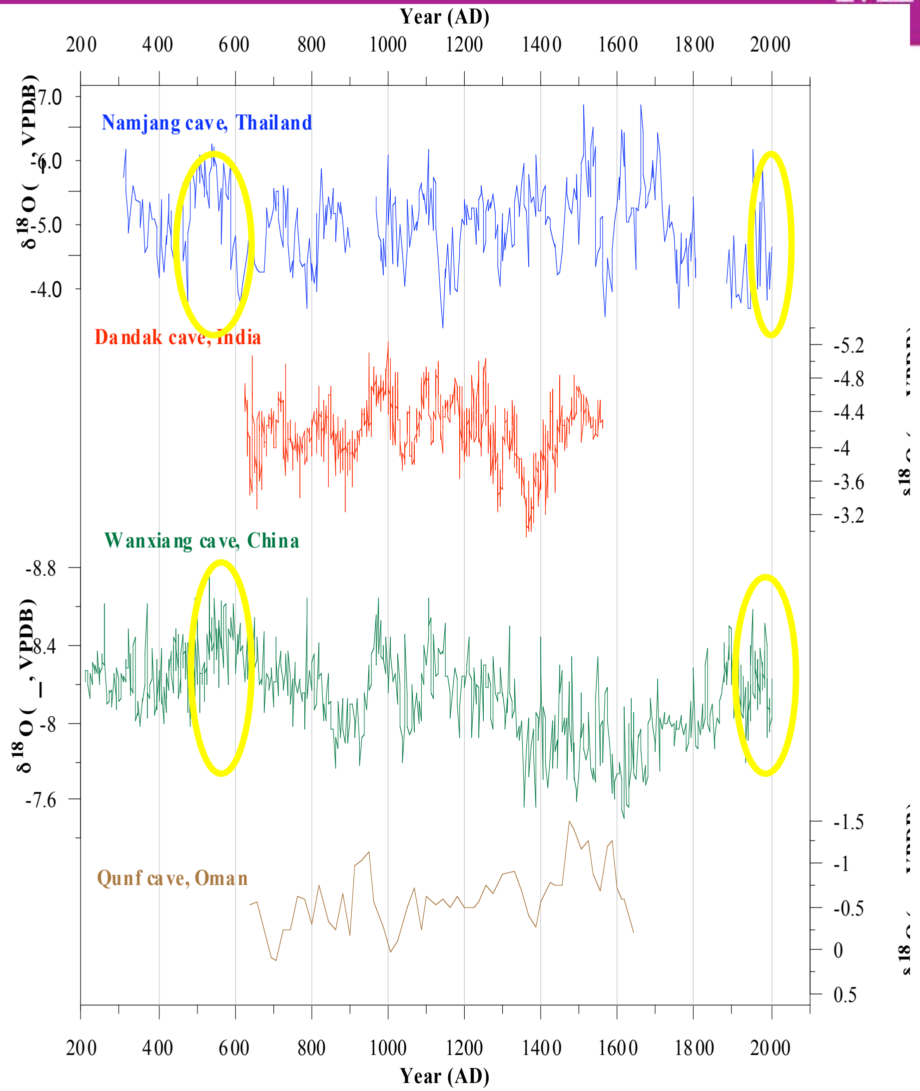

Fig.14 Comparison of the stalagmite $\delta^{18}O$ records from the Namjang cave (blue curve), Dandak cave (red curve) (Berkelhammer et al., 2010), Wanxiang cave (green curve) (Zhang et al., 2008), and Qunf cave (brown curve) (Fleitmann et al., 2007)

Strong TM

- Compared with stalagmite records from Asia,

- Variation of TM recorded by NJ1 exhibits similar characters with Chinese stalagmite in some time periods such as the strong monsoon in late sixth century and twenty century.

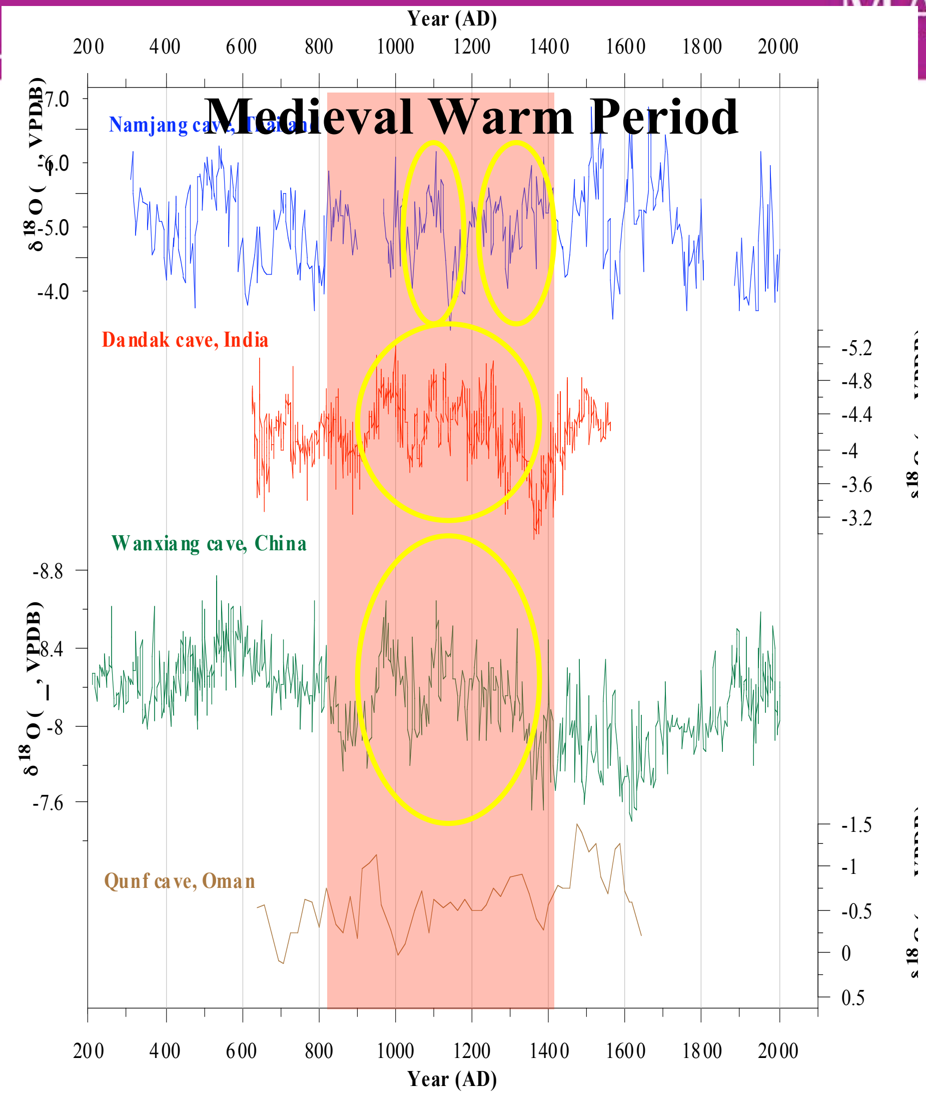

Fig.14 Comparison of the stalagmite $\delta^{18}O$ records from the Namjang cave (blue curve), Dandak cave (red curve) (Berkelhammer et al., 2010), Wanxiang cave (green curve) (Zhang et al., 2008), and Qunf cave (brown curve) (Fleitmann et al., 2007)

Strong TM (Wet periods)

- Moreover, strong monsoon in Thailand during the Medieval Warm Period (MWP) similar with strong monsoon in China and India.

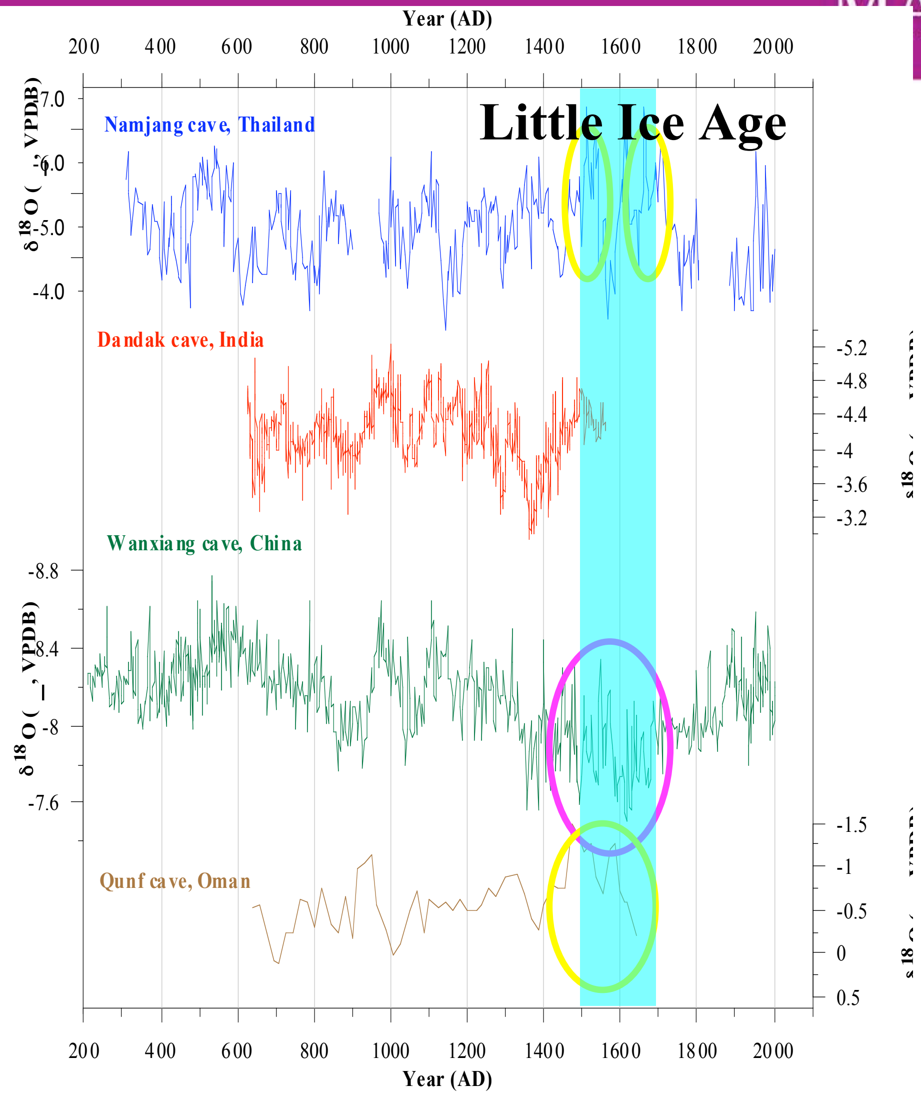

Fig.14 Comparison of the stalagmite $\delta^{18}O$ records from the Namjang cave (blue curve), Dandak cave (red curve) (Berkelhammer et al., 2010), Wanxiang cave (green curve) (Zhang et al., 2008), and Qunf cave (brown curve) (Fleitmann et al., 2007)

Strong TM

❖ In contrast, they show notable difference character;

The stronger TM during time periods of 1465-1540 AD and 1600-1720 AD differ from Chinese stalagmite which exhibits the weak Asian monsoon during the Little Ice Age (LIA).

❖ However, these wet climate during the LIA in Thailand were also recorded in other regions such as Oman (Fleitmann et al., 2007), India (Yadava et al., 2004; Berkelhammer et al., 2010) and central China (Tan et al., 2009).

❖ Thus, the discrepancy of stalagmite records in LIA from different areas of Asian indicates that the climate in LIA is complex.

Weak TM

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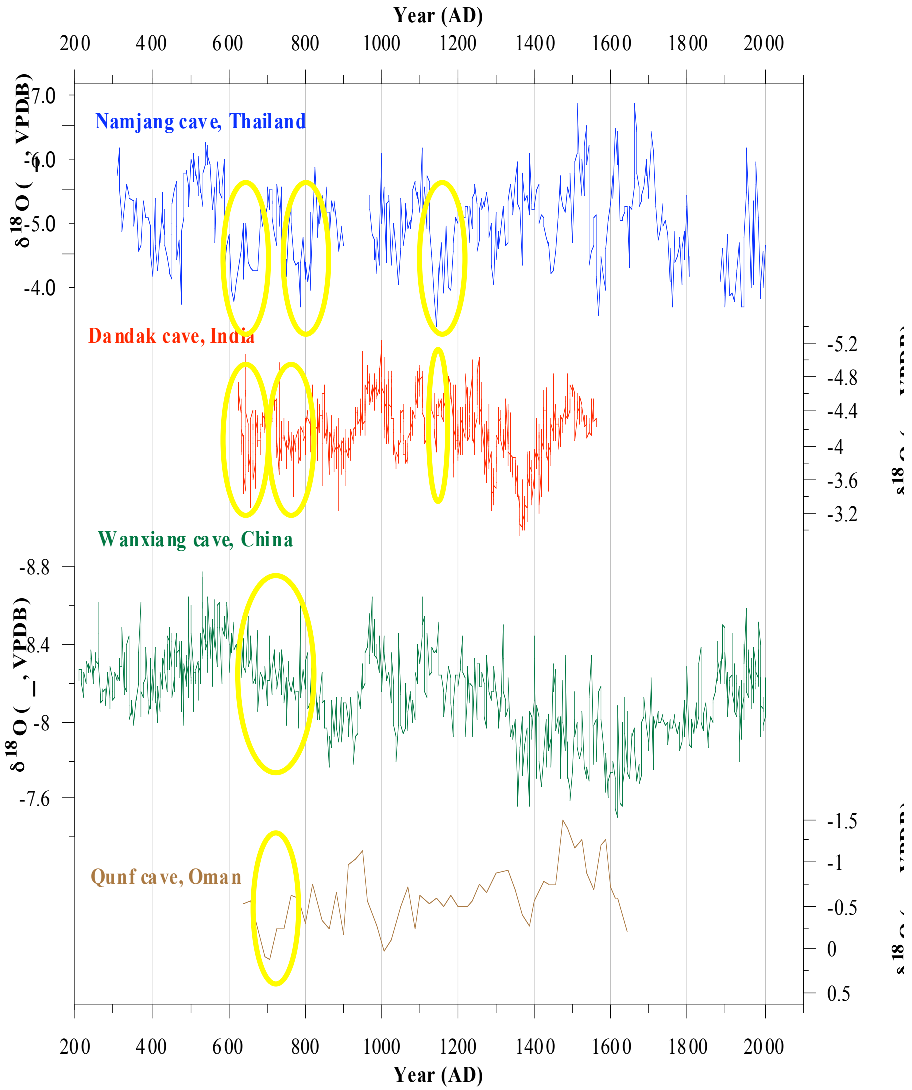

- The weak TM events occurred during 600-700 AD, 710-810 AD, 1150-1190 AD are coincide with weak monsoon rainfall in India (Berkelhammer et al., 2010), China (Zhang et al., 2008) and Oman (Fleitmann et al., 2007).
- Thailand decadal scale droughts recorded by tree ring (Buckley et al., 2007) in mid 1700s coincides with weak TM during 1750-1800 AD recorded by stalagmite NJ1.
- Variation in weak monsoon rainfall from India (Yadava et al., 2004), southern Oman (Fleitmann et al., 2004) and central China (Tan et al., 2009) coincides with the last period of low monsoon rainfall between 1886 and 1950 AD in Thailand.

Fig.14 Comparison of the stalagmite $\delta^{18}O$ records from the Namjang cave (blue curve), Dandak cave (red curve) (Berkelhammer et al., 2010), Wanxiang cave (green curve) (Zhang et al., 2008), and Qunf cave (brown curve) (Fleitmann et al., 2007)

5. Conclusions

- The stalagmite NJ1 from Namjang cave, Thailand records climate over the last 1700 years.
- Periods of relatively more ASO rainfall occurred at approximately 490-590 AD, 1050-1110 AD, 1200-1410 AD, 1465-1540 AD, 1600-1720 AD and 1950-2000 AD, respectively.
- Periods of relatively less ASO rainfall occurred at approximately 600-700 AD, 710-810 AD, 1150-1190 AD 1560-1590 AD, 1750-1800 AD and 1886-1950 AD, respectively.
- Some of these variations agree well with stalagmite records from China (Zhang et al., 2008; Tan et al., 2009), India (Yadava et al., 2004; Berkelhammer et al., 2010) and Oman (Fleitmann et al., 2004; Fleitmann et al., 2007), but discrepancy among these records is also observed.
- This study demonstrates that stalagmite NJ1 can be used to document paleoclimate variability in northwestern Thailand.

6. Acknowledgment

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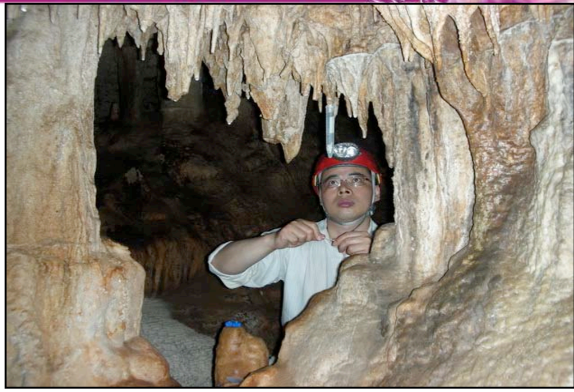

Thank you for your attention