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Stalagmite grey level as a proxy of the palaeoclimate in northwestern Thailand

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ABSTRACT: Stalagmite grey level provides limited information about palaeoclima as its interpretation depends on numerous factors. One of the best approaches entails calibrating grey level sequences with instrumental climate data. In this study, grey level variation covering a 105-year span was analysed in a lamina stalagmite, known as Namjang1 (NJ1), from Namjang cave (98° 12′ 12″ E, 19° 40′ 30″ N), in north-western Thailand. The grey level time series positively correlated with the five-year running average of rainfall in October ($r = 0.22$, $p < 0.05$), the five-year running average of ratio of August to October to May to July rainfall ($r = 0.38$, $p < 0.01$), and the five-year running average of ratio of August to October and May to October rainfall ($r = 0.35$, $p < 0.01$). This indicates that the calibrated grey level record can provide a high resolution proxy of rainfall in the late monsoon season. The observed correlation between grey level and rainfall in the late monsoon season is consistent with our previous study on the same stalagmite that used $\delta^{18}O$ and growth rate parameters (Cai B, Pumijumnong N, Tan M, Muangsong C, Kong X, Jiang X, Nan S, *J Geophys Res*, **115**, D21104), which further demonstrates that this stalagmite is a robust proxy of rainfall in the late monsoon season in north-western Thailand.

KEYWORDS: decadal variation, laminated, monsoon rainfall, seasonal variation

INTRODUCTION

Palaeoclimatic variation in Thailand is still poorly understood due to the lack of high resolution and long term climatic records. Most palaeoclimatic data are derived from tree rings[1–3] and pollen[4,5]. Unfortunately, there are few long tree ring records, while pollen records are limited by their low resolution for short term (e.g., decadal-centurial time scale) climate variation. Hence, higher resolution records that cover longer time intervals are necessary to better understand short-term climate change in this area. In recent years, palaeoclimatic studies have used stalagmites as palaeoclimatic recorders[6–9]. Major studies have focused on stable-isotopes ($\delta^{18}O$ and $\delta^{13}C$), trace elements, and the lamina thicknesses of the stalagmites[6–9]. The potential of stalagmites as palaeoclimatic recorders in Thailand was first explored in 2008[10]. Based on Thorium-230 ages, Phutong[10] reconstructed palaeoclimatic records using the $\delta^{13}C$ and $\delta^{18}O$ of the stalagmite. Cai et al[11] have further investigated the climate signal that is preserved within the oxygen isotopic composition ($\delta^{18}O$) of the stalagmite and growth rate parameters. These results demonstrate that both the $\delta^{18}O$ and growth rate of stalagmite NJ1 are robust proxies for regional monsoon intensity.

The grey level derived from detrital sediment correlates with climatic variation[12,13]. Although numerous speleothems-based proxy studies have been successfully done[6–9], none have used grey level intensity. Compared to other stalagmite parameters, the grey level is easily measured. However, a stalagmite grey level-based palaeoclimatic proxy has not yet been broadly used, as the interpretation of grey level is still ambiguous owing to its reactivity to several factors (e.g., soil organic matter, surface vegetation, climate, etc.)[13]. The best approach to identify the climatologic signal of grey level involves calibrating the grey level sequence with modern instrumental records. In this study, a grey level profile covering the past 105 years was reconstructed for an annually laminated stalagmite. This profile was then compared with instrumental data to decode the climate signal contained in the stalagmite grey levels.

SITE DESCRIPTIONS

Namjang cave (98° 12′ 12″ E, 19° 40′ 30″ N, elevation ∼923 m above mean sea level at the entrance) is located in Pang Ma Pha, Mae Hong Son province, Thailand (Fig. 1a). It was developed in Permian limestone and dolostone formation. The cave is approximately 6 m wide and 56 m long. The vegetation covering this site consists of mixed-deciduous forest. The columnar stalagmite NJ1 (Fig. 1b), which is 41.7 cm high and 6.5 cm in diameter, was collected in the first chamber located approximately 18 m away from the cave entrance and 9 m above the floor, in April of 2006[10]. The highly seasonal climate of the study area is dominated by the Asian monsoon system. Two major air streams affect the climate of this area, which are referred to as south-west and north-east monsoons. The south-west monsoon leads to intensive rainfall from May through October. Mean monthly rainfall at Mae Hong Son, which is the closest meteorological station (approximately 45 km southwest of the cave), and long rainfall series data (rainfall data from 1911–2007) during the monsoon season indicate a monthly precipitation of approximately 191 mm/yr (Fig. 1a and c). The northeast monsoon produces a winter season from November until February. This is followed by the summer season from March until April which is the transitional period between the northeast and southwest monsoons. The mean monthly temperature of this area (using temperature data from 1951–2007) ranges from approximately 23 °C in January and December to 30 °C in April (Fig. 1c).

MATERIALS AND METHODS

Stalagmite NJ1 was collected in April of 2006[10]. The sample was cut into two halves along the growth axis after its surface was cleaned with tap water[10]. Next, one half of the cut surface was polished[9]. This polished half exhibited clearly visible laminae after polishing. In this study, only the topmost 26 mm of the stalagmite was analysed (Fig. 1b and Fig. 2).

Laminated stalagmite NJ1 was actively growing when it was sampled. In order to verify the continual deposition during study time period, stalagmite NJ was previously ^{230}Th-dated in a study by Cai et al[11]. Powdered samples were drilled for ^{230}Th dating and were centred at 3 mm and 24.5 mm (labelled NJ1-3 and NJ1-24.5, respectively, in Fig. 2) away from the top. The samples, which weighed approximately 100 mg, were drilled along their respective growth bands using a 0.9 mm in diameter carbide dental burr. The measurements were performed on a magnetic sector inductively coupled plasma mass spectrometer

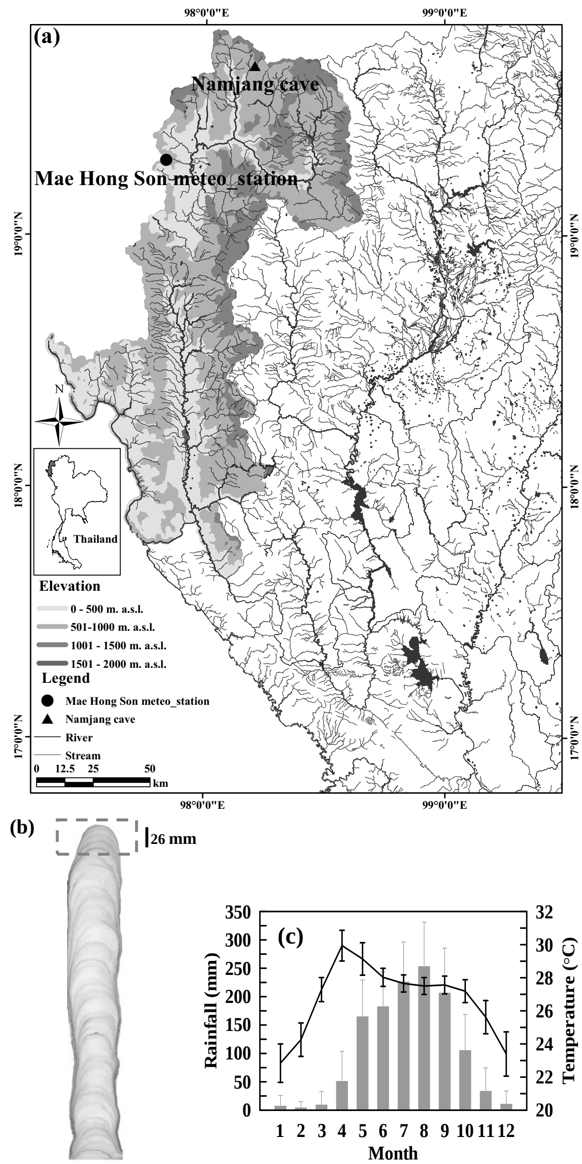

Fig. 1 (a) Map of the study region that shows Namjang cave (triangle) and the Mae Hong Son meteorological station (circle); (b) polished section of stalagmite NJ1 showing the topmost 26 mm (dashed rectangle); (c) the mean and standard deviation variability in monthly rainfall from 1911–2007 (grey bars with vertical bars) and temperature from 1951–2007 (black line with vertical bars) at the Mae Hong Son meteorological station.

(ICP-MS, Finnigan Element) at the Department of Geology and Geophysics, University of Minnesota, that procedure described by Shen et al[14]. The topmost 26 mm of the stalagmite accepted deposition from 1901 to 2005, and no growth hiatuses were observed.

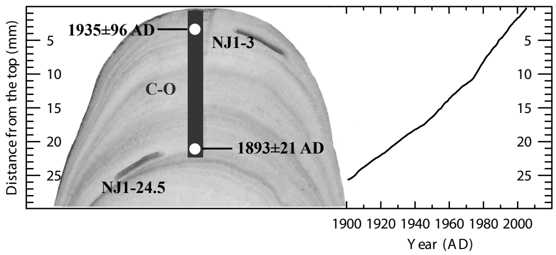

Fig. 2 Polished section of the topmost 26 mm of stalagmite NJ1 with ^{230}Th dating and lamina counting chronologies. Samples for ^{230}Th dating, which are centred at 3 and 24.5 mm (labelled NJ1-3 and NJ1-24.5, respectively), were horizontally drilled along their respective growth bands. White circles and black bar on the left-hand side indicate the ^{230}Th ages (details of the ^{230}Th ages are shown in Table 1) and the sampling location of stable isotopes (labelled C-O)[11], respectively. The bold black curve on the right-hand side represents the lamina counting chronology, which corroborates the ^{230}Th age at 24.5 mm.

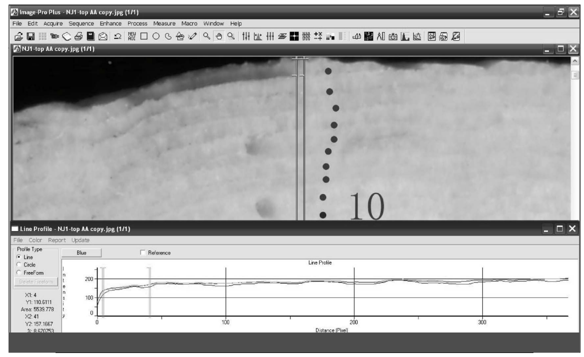

Fig. 3 Measured laminae grey levels using IMAGE-PRO PLUS 5.1 software.

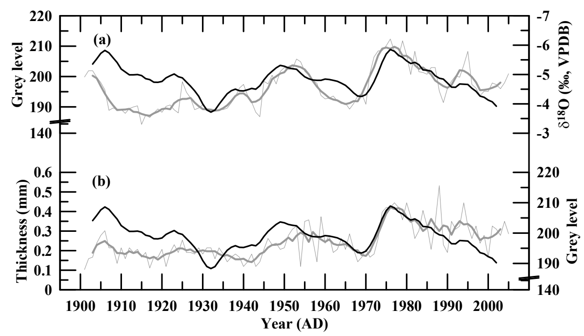

Fig. 4 Comparisons of NJ1 grey level record (black lines) to (a) δ^{18}O (grey lines) and (b) lamina thicknesses (grey lines) record of the same stalagmite from previously reported results[11]. Bold lines indicate five-years moving average trends.

Because of low ^{230}Th and high detrital mineral contents, the ^{230}Th dating results of the past 50 years were uncertain and exhibited a sizable error of ± 96 years (Fig. 2 and Table 1). Fortunately, stalagmite NJ1 was actively dripped upon when collected at the end of the dry season in April 2006. Furthermore, a glass plate, which was placed under the drip, received some modern carbonate deposition, which indicates that NJ1 was actively growing when it was collected. The topmost lamina can therefore be reasonably set to 2005, presumably forming during the rainy season of 2005 to the dry season of 2006. Therefore, only the ^{230}Th age at 24.5 mm was used in this study (Fig. 2 and Table 1). There are 105 laminae in the topmost 26 mm, which covers the time period of 1901–2005. This agrees well with the ^{230}Th dating result of 1893 ± 21, which is centred at 24.5 mm (24.0–25.0 mm) and covers the 98–104th laminae. This would indicate that the laminae in NJ1 occur annually and have a continual deposition from the dating point to the top[11] (Fig. 2 and Table 1).

The polished section of the stalagmite was scanned using a high-resolution scanner (Microtek) under RGB/3200 dpi conditions. The resultant digital image was marked and counted with ADOBE PHOTOSHOP software. Laminae grey levels were measured using IMAGE-PRO PLUS 5.1 software (Fig. 3). The grey values could be obtained from the average values within one lamina which were calculated using the intensities of red (R), green (G), and blue (B) light[17]. The grey level was set from 0 to 255. Larger numbers imply brighter colours, and vice versa. This work was done in Key Laboratory of Cenozoic Geology Environment, Institute of Geology and Geophysics, Chinese Academy of Science, China.

RESULTS AND DISCUSSION

Variation in grey level intensity

The observed grey level values varied between 149 (darker) and 211 (brighter). The grey level time series data exhibit a series of multi-decadal fluctuations (Fig. 4). Five distinct periods of higher (brighter) values occurred at approximately 1901–1917, 1921–1925, 1946–1956, 1958–1965, and 1972–1989. These were interrupted by four periods of lower (darker) values that were centred at approximately 1932, 1968, 1998, and 2003.

In a previous study of the same stalagmite, Cai et al[11] provided a proxy of rainfall in the late monsoon season using δ^{18}O and growth rate parameters. We compared these δ^{18}O and growth rate profiles to our

Table 1 ^{230}Th dating results of stalagmite NJ1 from Namjang Cave, Thailand [11].

Depth (mm)	^{238}U (ppb)	^{232}Th (ppt)	^{230}Th/^{232}Th (ppm)	δ^{234}U (measured)	^{230}Th/^{238}U (activity)	^{230}Th age (yr) (uncorrected)	^{230}Th age (yr BP) (corrected)	^{230}Th age (AD) (corrected)	δ^{234}U$_{initial}$ (corrected)
3	1450 ± 3	17 980 ± 180	6.7 ± 0.1	1664 ± 4	0.00504 ± 0.00004	206 ± 2	15 ± 96	1935 ± 96	1664 ± 4
24.5	1018 ± 2	3737 ± 16	17 ± 1	1743 ± 4	0.00383 ± 0.00018	152 ± 7	57 ± 21	1893 ± 21	1744 ± 4

The errors are 2σ errors. Decay constant values are: $\lambda_{230} = 9.1577 \times 10^{-6}$ y^{-1}, $\lambda_{234} = 2.8263 \times 10^{-6}$ y^{-1} [15], and $\lambda_{238} = 1.55125 \times 10^{-10}$ y^{-1} [16]. Corrected ^{230}Th ages assume the initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Depths along the growth axis are relative to the top of the stalagmite. Year BP: year before present (1950).

grey level values. Generally, they exhibit similar variability (Fig. 4). The lighter colours coincide with wider laminae and more negative δ^{18}O values, particularly in 1926–1944, 1966–1972, and 1988–1991. The good agreement between grey level and other parameters is supported by a significantly negative correlation between grey level and δ^{18}O ($r = -0.26$, $p < 0.01$), as well as a significantly positive correlation between grey level and growth rate ($r = 0.21$, $p < 0.05$), indicating that grey level variation may be controlled by the same climatic condition. However, significant differences were observed in these profiles in some time periods, which suggests that other factors might impact the grey level changes.

Comparisons of grey level to instrumental data

In order to understand the palaeo-climatic signal preserved in stalagmite NJ1, the measured stalagmite grey level was first compared to the annual, monthly, and seasonal rainfall totals obtained from the local meteorology station (Mae Hong Son) over a 91-year period (1911–2002). The monthly data were used only from April through November because the other months had no rainfall for 50% of the years. The seasonal rainfall was divided into the early monsoon season, which is from May to July (MJJ), and the late monsoon season, which is from August to October (ASO). Unfortunately, these yearly correlations were weak and statistically insignificant (Table 2). Considering that groundwater could blur seasonal rainfall signals due to fluid passing through the vadose zone, we plotted the annual-scale grey level profile against the five-year moving averages of the rainfall data, including the ratio of ASO rainfall to MJJ rainfall. This five-year averaged value was averaged at the midpoint by taking into account the average values between the two previous years and the two following years. The strongest correlations were found when using five-years running averages of the rainfall data. There were negative correlations with monthly rainfall in May ($r = -0.24$, $p < 0.05$), July ($r = -0.25$, $p < 0.05$) and total rainfall in May, June, and July ($r = -0.32$, $p < 0.01$) and positive correlations with monthly rainfall in October ($r = 0.22$, $p < 0.05$), the ratio of ASO to MJJ ($r = 0.38$, $p < 0.01$), and the ratio of ASO to total rainfall from May through October (M–O) ($r = 0.35$, $p < 0.01$) (Table 2 and Fig. 5). Taking the effective sample size of smoothed rainfall time series into account, statistically significant relationships were found between the NJ1 grey level and the ratio of ASO to MJJ ($p < 0.05$) and the ratio of ASO to M–O ($p < 0.01$), based on adjusted degrees of freedom (Table 2). These correlations confirm that the monsoon rainfall, especially during the late rainy season (ASO), likely affected the grey level of NJ1, as well as other parameters.

Table 2 Pearson's correlations (r values) between Mae Hong Son rainfall data (1911–2002) and stalagmite grey level values. Statistically significant values are shown in bold print.

Month or season	Yearly averaged rainfall	Five-year running averaged rainfall
Apr	−0.01	−0.02
May	−0.16	**−0.24**[b]
Jun	−0.08	−0.15
Jul	−0.05	**−0.25**[b]
Aug	−0.02	−0.03
Sep	0.09	0.17
Oct	0.15	**0.22**[b]
Nov	0.04	0.04
Annual	0.005	−0.04
May–Oct	−0.02	−0.08
MJJ	−0.15	**−0.32**[a]
ASO	0.12	0.17
ASO/MJJ	0.16	**0.38**[ac]
ASO/M–O	0.15	**0.35**[ad]

[a] Statistically significant at the 0.01 level.
[b] Statistically significant at the 0.05 level.
[c] Statistically significant at the 0.05 level based on adjusted degrees of freedom of smoothed rainfall series.
[d] Statistically significant at the 0.01 level based on adjusted degrees of freedom of smoothed rainfall series.

The monsoonal rainfall season begins in May and continues through October, wherein its major and minor peaks occur during August-September-

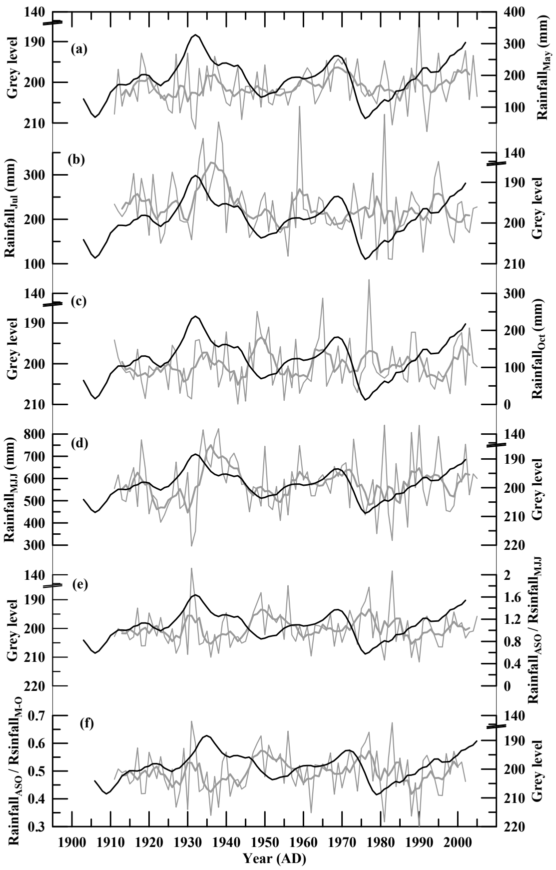

Fig. 5 Comparisons of stalagmite NJ1 grey levels (black lines) to Mae Hong Son instrumental records (grey lines) based on the most significant correlations. The total rainfall in (a) May, (b) July, (c) October, (d) the MJJ; (e) the ASO/MJJ; and (f) the ASO/M–O. Bold lines indicate five-years moving average trends.

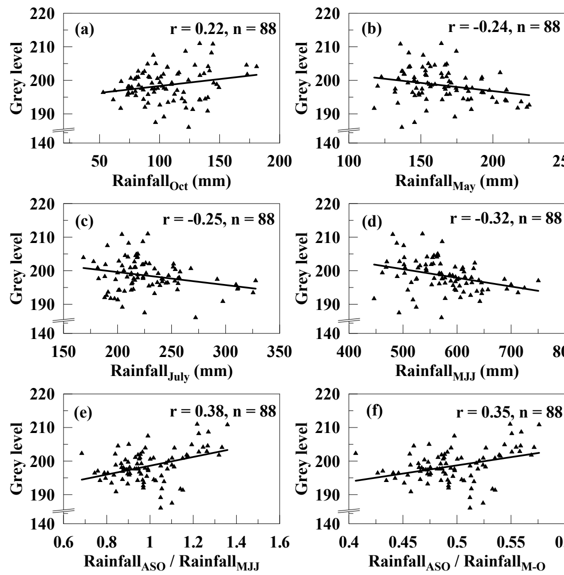

Fig. 6 Correlational analyses of stalagmite grey level and Mae Hong Son instrumental record data. Grey level versus total rainfall in (a) October, (b) May, (c) July, (d) the MJJ; (e) the ASO/MJJ; and (f) the ASO/M–O. Linear regressions are shown with black lines, r represents Pearson's correlation coefficient, and n is the number of data points.

October (ASO) and May-June-July (MJJ), respectively[18]. Grey level is possibly influenced by the drip water supply during the strong monsoon rainfall season because more discharge water in the cave could result in a higher moisture level and reduced dust emissions. The strong relationship between stalagmite growth rate and grey level indicates that increasing stalagmite growth rates may decrease detrital particle contents per unit volume of carbonate deposition. Furthermore, the high drip rate does not provide sufficient time for the detrital particles to become trapped, these particles are removed by the splashing of the next drip, which, in turn, results in high grey levels (whitish in colour)[19]. The grey level of stalagmite NJ1 closely correlates with the October rainfall amount (Table 2 and Fig. 6a), which is at the major peak of seasonal rainfall distribution in this area[18]. This significantly positive correlation between grey level and rainfall in the late monsoon season (Fig. 6a) suggests that the grey level of stalagmite NJ1 may provide a proxy of rainfall in the late monsoon season. However, the reason for the observed negative correlations between stalagmite grey level and rainfall in the early rainy season is still unclear (Fig. 6b–d). Overall, these findings indicate that the climatic response of the grey level is complex. Hence, cave monitoring should be carried out in future studies in order to better understand the relationship between stalagmites and climate change.

CONCLUSIONS

The variation in grey level of stalagmite NJ1 from Namjang cave in Mae Hong Son province, Thailand, was qualitatively validated with growth rate and $\delta^{18}O$ values. Higher grey levels were observed to coincide with wider laminae and more negative $\delta^{18}O$ values, indicating that grey level may have similar climatic signals to those indicated by lamina thickness and $\delta^{18}O$. Variations in grey level were primary a function of rainfall in the late monsoon season. Increased rainfall in the late rainy season could decrease detrital deposition in the stalagmite, resulting in a whiter aragonite in colour. Therefore, the grey level of stalagmite NJ1 can be used as a palaeoclimate proxy of rainfall in the late monsoon season.

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