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Late Pleistocene monsoon variability in northwest Thailand: an oxygen isotope sequence from the bivalve *Margaritanopsis laosensis* excavated in Mae Hong Son province

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A B S T R A C T

Long, continuous records of Late Quaternary environmental change are rare in Southeast Asia, yet they are crucial for understanding the nature of early human dispersal and occupation in the Australasian region. We present a new record of palaeomonsoon activity extending back to 35,000 BP (years before the present), based on the analysis of oxygen isotope ratios ($\delta^{18}O$) in the freshwater bivalve *Margaritanopsis laosensis* excavated from the Tham Lod and Ban Rai rockshelters in Mae Hong Son Province, northwest Thailand. Long-term changes in the *M. laosensis* $\delta^{18}O$ record reflect changes in the $\delta^{18}O$ of the river water in which these organisms grew, and correlate well with changes in speleothem $\delta^{18}O$ records of east Asian monsoon rainfall from Hulu Cave and Dongge Cave in China. The new northwest Thailand $\delta^{18}O$ sequence indicates wetter and relatively unstable climatic conditions from 35,000 to 20,000 BP, followed by drier conditions from 20,000 to 11,500 BP. A period of peak aridity occurred around 15,600 BP during Heinrich Event 1, suggesting that the intertropical convergence zone shifted southward when the North Atlantic region cooled. However, there is little evidence for the Younger Dryas event at ~12,800–11,500 BP. After 9,800 BP, precipitation increased substantially and climatic variability declined. Our findings provide an improved baseline against which to gauge interactions between early humans and climate change in Southeast Asia. For example, there was no significant change in the prehistoric flake stone technology used at Tham Lod and Ban Rai despite the bivalve $\delta^{18}O$ evidence for substantial climate change in the region. Also, the climatic impact of the Younger Dryas event appears to have been less intense in northwest Thailand compared to the cooling and drying observed in China, and may explain why agriculture made a relatively late appearance in Thailand, possibly involving migrants from China.

1. Introduction

A long continuous record of climate change for the mainland Southeast Asia region is essential for understanding past climatic and biogeographic change. Such a record is also necessary to explore the long-term relationship between hominins and their environment in this region. Recently, there has been a substantial increase in the resolution and length of terrestrial palaeoclimate records from the eastern hemisphere, but the lack of palaeoclimate data for the Indo-China region is especially notable compared to that available for nearby regions (Maloney, 1994; Penny, 2001). For example, considerable research has focussed on island regions such as Indonesia e.g. (e.g. Anshari et al., 2001; Dam et al., 2001; van der Kaars et al., 2001; Westaway et al., 2009; Wurster et al., 2010), Papua New Guinea (e.g. McGregor and Gagan, 2003a; Denham and Haberle, 2008) and the Pacific (e.g. Prebble and Dowe, 2008). In mainland Southeast Asia, the work of Hastings and Liengsakul (1983) is notable because it was the first broad overview of Late Quaternary climate change, based on radiocarbon dated sediments in Thailand. Maloney (1992) synthesized the results of pollen sequences from 33 locations in mainland and island Southeast Asia including pollen from deep-sea cores, archaeological sites and dry-land pollen cores. Recently described palaeoclimate proxies from Thailand and the wider region include pollen and phytolith records that give insights into local past vegetation histories but have limited chronological and geographical ranges, gaps and compressed parts of the records and

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ambiguities in interpreting taxonomic variation (e. g. Kealhofer, 1996; Kealhofer and Penny, 1998; Maloney, 1999; Penny, 1999; Maxwell, 2001; Penny, 2001; Maxwell and Liu, 2002; White et al., 2004). Most importantly, the records for mainland Southeast Asia show substantial differences and highlight the need for detailed site-specific records when attempting to describe relationships between human behaviour and climate change.

The recent development of high-resolution absolute-dated speleothem $\delta^{18}O$ records for cave sites in China has greatly improved our understanding of Late Quaternary climate change in the Asian monsoon domain (e.g. Wang et al., 2001; Yuan et al., 2004; Dykoski et al., 2005; Wang et al., 2008; Chen et al., 2010). These records have revealed strong correlations between east Asian monsoon rainfall and climate change in the North Atlantic region. The production of a similar style of speleothem $\delta^{18}O$ records is underway in Malaysian Borneo (Partin et al., 2007) and Indonesia (Griffiths et al., 2009; 2010a; 2010b; Lewis et al., 2011) to document the role of the entire Australasian monsoon system in global climate change.

Based on the success of the speleothem $\delta^{18}O$ studies, we were motivated to undertake similar $\delta^{18}O$ analysis of the freshwater bivalve *Margaritanopsis laosensis* excavated from the Tham Lod and Ban Rai rockshelters in northwest Thailand (Fig. 1) to produce a palaeomonsoon record for mainland Southeast Asia extending back to 35,000 BP. Recent work at Tham Lod and Ban Rai, in Mae Hong Son Province, has produced a ~40,000 year sequence of human activity (Treerayapiwat, 2005; Krajaejun, 2006; Shoocongdej, 2006; Marwick, 2007; 2008b). The excavation methods, sedimentology and stratigraphy have been described in detail by Shoocongdej (2006) and Marwick (2008a). Together, Tham Lod and Ban Rai have yielded one of the longest, densest and continuous archaeological sequences in mainland Southeast Asia. The continuity of the archaeological deposit, and abundance of *M. laosensis*, offers an excellent opportunity to obtain a palaeoclimate record the Late Pleistocene and Early Holocene.

Substantial research has been conducted on the $\delta^{18}O$ of marine bivalves as a proxy for temperature or salinity (e. g. Witbaard et al., 1994; Bice et al., 1996; Dutton et al., 2002; Schöne et al., 2003; Schöne et al., 2004; Carre et al., 2005; Chauvaud et al., 2005) and, more recently, similar work has been done with freshwater bivalves. In several studies, freshwater shell $\delta^{18}O$ values have been confirmed as a reliable proxy for changes in the $\delta^{18}O$ of river water and river flow conditions in different climate zones (Dettman et al., 1999; Rodrigues et al., 2000; Kaandorp et al., 2003; Ricked et al., 2003; Kaandorp et al., 2005; Gajurel et al., 2006; Goewert et al., 2007). Versteegh et al. (2009, 2010) have also shown that changes in river flow rates and river water sources can be identified in bivalve $\delta^{18}O$ values.

These studies, and the success of Davis and Muehlenbachs (2001) with $\delta^{18}O$ in freshwater bivalves, provide a sound basis for us to explore the applicability of the method as a proxy for past changes in monsoon rainfall in northwest Thailand. At sites like Tham Lod and Ban Rai, where monsoonal rainfall is highly variable, changes in the $\delta^{18}O$ of *M. laosensis* shells will reflect changes in the $\delta^{18}O$ of meteoric water, and rainfall amount (e.g. Dansgaard, 1964; Rozanski et al., 1993). The *M. laosensis* shells excavated from Tham Lod and Ban Rai were harvested by the prehistoric human occupants and discarded at the archaeological sites shortly after the shells died and stopped archiving climatic conditions. We show that the bivalve $\delta^{18}O$ sequence at Tham Lod and Ban Rai provides evidence of environmental change prior to and during the Last Glacial Maximum and the Pleistocene-Holocene transition that may have had implications for early human dispersal and occupation of the region.

2. Archaeological excavation of *M. laosensis*

The freshwater bivalve *M. laosensis* is the most abundant biogenic material at Tham Lod and Ben Rai and is present in nearly every excavation unit at both sites (Figs. 2 and 3). This bivalve provides 99% of the mass of all shell at Tham Lod and 96% of the mass of all shell at Ban Rai. Therefore, the bivalve $\delta^{18}O$ sequence has the advantage of providing a particularly long and complete record with high chronological resolution. This assertion is supported by the sequence of radiocarbon and thermoluminescence dates summarised in Table 1 and Fig. 4. For both sites *M. laosensis* specimens, and other organic materials, were dated directly using radiocarbon methods, while optically stimulated luminescence dating was

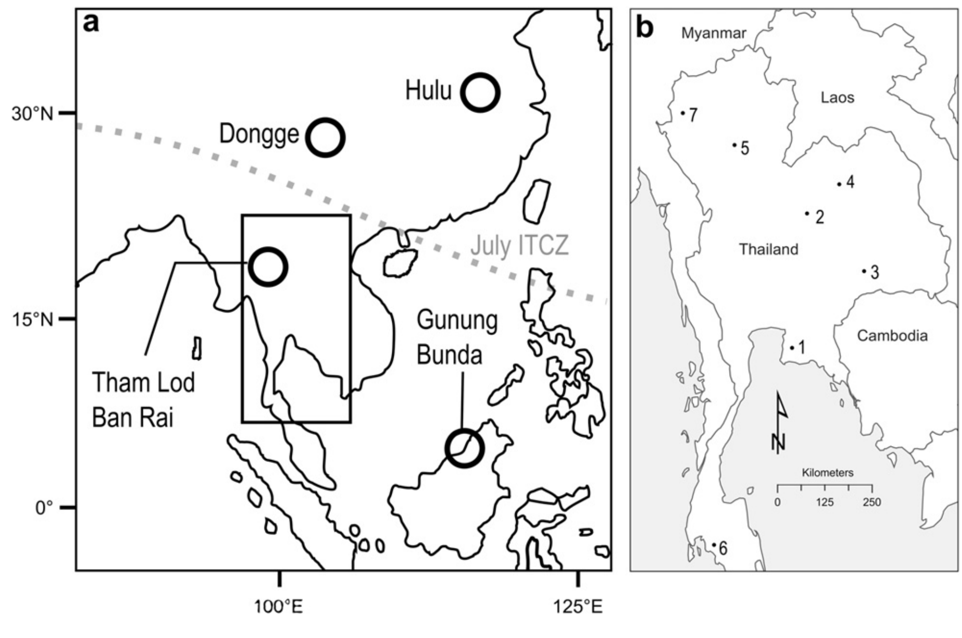

Fig. 1. (a) Map of Southeast Asia showing the location of the Tam Lod and Ban Rai rockshelters (circles) in northwest Thailand. The locations of speleothem records of monsoon rainfall mentioned in the text are also indicated. Dashed line indicates the average position of the intertropical convergence zone (ITCZ), and summer monsoon rainfall, in July. (b) Locations of palaeoclimate proxy records in Thailand: 1. Chanthaburi, 2. Nong Pa Kho, 3. Tung Kula Ronghai, 4. Nong Han Kumphawapi, 5. Kwan Phayao, 6. Nong Thale Song Hong.

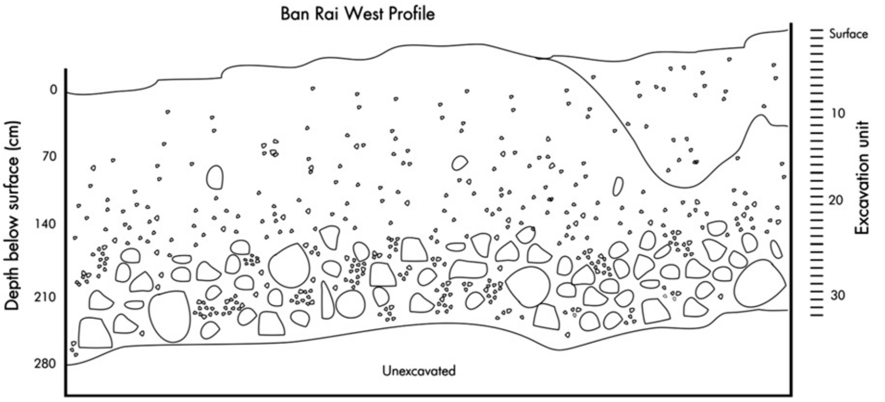

Fig. 2. Stratigraphic profile of Tham Lod showing depth of excavated deposit and frequency of rock in the deposit.

performed on the surrounding sediments. The radiocarbon dates are calibrated using the CALPAL2001 calibration curve in the CALPAL_A software (Weninger et al., 2007). The relatively high correlation coefficients for the depth-age relationships shown in Fig. 4 indicate that deposition of the dated *M. laosensis* shells was contemporaneous with the rest of the material in the strata.

We were particularly motivated to analyse *M. laosensis* for palaeoclimate reconstruction purposes because extracting a pollen sequence from Tham Lod and Ban Rai has met with limited success. The highly rugged topography of the study area combined with its highly seasonal climate means that there are no lakes or swamps to provide ideal coring conditions. Dan Penny (personal communication) has examined sediments from Ban Rai and Tham Lod and found pollen grains and fern spores typical of upland high altitude wind-pollinated plants, local grasses and ferns. However, preservation is generally poor, there are few taxa and many samples have no pollen. The incompleteness of the pollen record at the two sites means that it is not possible to discern change over time with any confidence.

Seven additional locations near these two archaeological sites have been sampled by Pumijumnon and Trikanchanawattana (2006) for ancient pollen. Two dates were obtained for the non-rockshelter locations, giving relatively young ages of 280 BP and 650 BP. Like Penny, they found that sediments from the nearby locations contained insufficient pollen to make conclusions about prehistoric climates (Trikanchanawattana, 2005).

Using a different approach, Wattanapituksakul (2006a) has identified environmental changes based on his analysis of mammalian teeth excavated from Tham Lod rockshelter. He identified 2300 mammal tooth specimens, representing a minimum number of 218 individuals classed into 31 taxa, mostly Cervidae, *Sus scrofa,* Bovinae and Pecora. Most mammals represented in the sequence have wide habitat ranges and are only diagnostic of extreme changes in local vegetation or climate. Notable taxa represented in the mammal teeth assemblage are *Ursus tibetanus,* Rhinocerotidae, both large-bodied mammals, and *Naemorhaedus*.

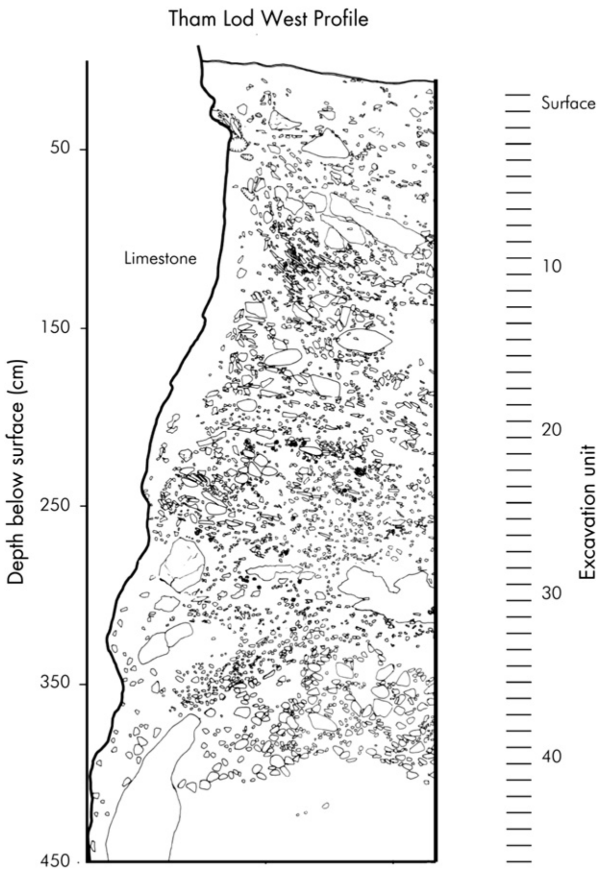

Fig. 3. Stratigraphic profile of Ban Rai showing depth of excavated deposit and frequency of rock in the deposit.

Table 1
Radiocarbon (^{14}C) and thermoluminescence (TL) age determinations for the Tham Lod and Ban Rai excavation sites. All ^{14}C ages are calibrated ($\pm 1\sigma$ error) in years before the present (BP) notation, where present is 1950 AD.

Site name/ Excavation unit	Dated material	Lab code	Age (yr $\pm$ 1σ)	Calibrated ^{14}C age (yr BP $\pm$ 1σ)
Tham Lod				
TL4	Organic sediment	Beta-168223	12,100 ± 60	14,070 ± 140
TL7	Organic sediment	Beta-168224	13,640 ± 80	14,764 ± 60
TL9	Calcrete	Akita-TL7	13,422 ± 541	
TL17	Charred material	Beta 194122	24,920 ± 200	29,910 ± 270
TL18	*M. laosensis*	Wk-20398	20,000 ± 117	23,900 ± 180
TL24	Sedimentary quartz	Akita-TL12	22,257 ± 154	
TL27	*M. laosensis*	Wk-20399	29,318 ± 336	34,500 ± 500
TL28	Shell (unspecified)	Beta-172226	22,190 ± 160	26,740 ± 400
TL31	Organic sediment	Akita-TL10	32,380 ± 292	
TL32	*M. laosensis*	Wk-20400	34,029 ± 598	39,960 ± 1050
Ban Rai				
BR3	*M. laosensis*	OZJ686	7040 ± 60	7870 ± 60
BR10	*M. laosensis*	OZJ687	6600 ± 70	7500 ± 50
BR12	*M. laosensis*	OZJ688	6850 ± 70	7700 ± 70
BR17	*M. laosensis*	OZJ689	7950 ± 70	8820 ± 130
BR18	Charred material	Beta-168220	7250 ± 40	8080 ± 60
BR22	Charred material	Beta-168221	8850 ± 50	9970 ± 140
BR23	Charred material	Beta-168222	8190 ± 50	9150 ± 90

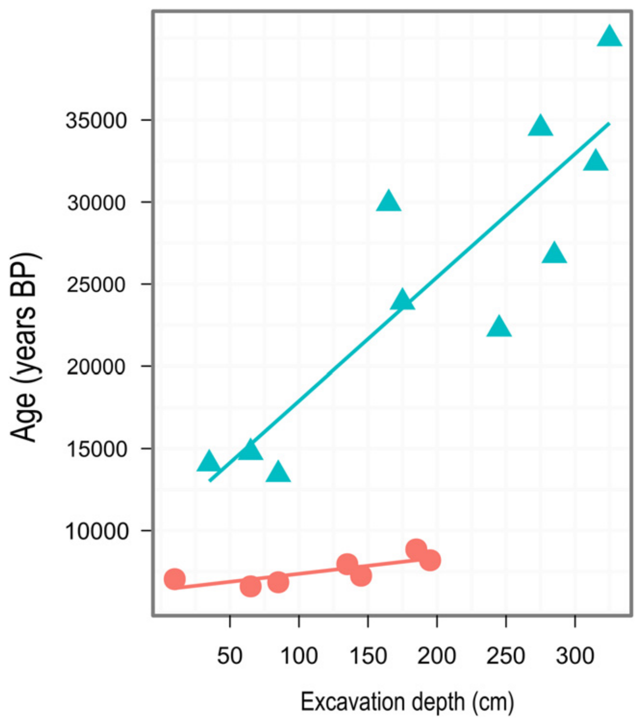

Fig. 4. Age-depth plots based on radiocarbon and optically stimulated luminescence dates for the Tham Lod (blue triangles) and Ban Rai (red circles) excavation sites. Symbols represent each date, the 1σ uncertainty ranges are too small to be displayed. The calculated lines of best fit (and corresponding regression equations) were calculated from the data in Table 1 and used to interpolate the ages presented in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Curiously, the habitat of Rhinocerotidae is dense forest and swamp, while *Ursus tibetanus* and *Naemorhaedus* typically prefer open montane habitats. All three of these taxa occur in Pleistocene and Holocene archaeological units, suggesting that taxonomic representation may be more indicative of human foraging ranges and strategies rather than changes in mammalian habitat ranges related to climate change.

Wattanapituksakul notes a gradual reduction in the width of the first and second upper molars of *Naemorhaedus* from the Pleistocene to the Holocene. This reduction in molar width is argued by Wattanapituksakul (2006b) to reflect a reduction in body size of *Naemorhaedus*, possibly in response to a decrease in the quality of food, the seasonal availability of food, or a warmer climate. This supports the general observation that the Holocene was significantly warmer than the Pleistocene in Thailand (Hastings and Liengsakul, 1983), but adds little in terms of specific magnitudes or chronological resolution.

3. Environmental control of $\delta^{18}O$ in *M. laosensis*

The theory behind shell stable oxygen isotope ratios as a palaeoenvironmental proxy is that during the life of the organism the $\delta^{18}O$ values of the growing shell will reflect the properties of the water in which it lives. Under isotopic equilibrium conditions, the $\delta^{18}O$ in a *M. laosensis* shell will be a function of river water temperature and the $\delta^{18}O$ of the water. Several studies have empirically quantified the contribution of these parameters to shell material (Epstein et al., 1953; Grossman and Ku, 1986; Dettman and Lohmann, 1993; Wanamaker et al., 2006; Wanamaker et al., 2007). Fortunately, the oxygen isotope fractionation between water and shell carbonate minerals is opposite in sign to the relationship between air temperature and the $\delta^{18}O$ of rainfall, so the potential impact of the two temperature effects on the resulting shell $\delta^{18}O$ tend to cancel out. This is particularly the case for subtropical latitudes like northern Thailand where the relationship between air temperature and $\delta^{18}O$ of rainfall (ca. +0.25‰/ degree C, Dansgaard, 1964) is nearly equal to the opposing temperature-dependent water-carbonate relationship (−0.23‰/C, Epstein et al., 1953). Therefore, in environmental settings like Tham Lod and Ban Rai, where changes in monsoon intensity and the $\delta^{18}O$ of rainfall are large, the impact of changing temperature on *M. laosensis* shell $\delta^{18}O$ will be relatively small.

The question then becomes one of how to interpret the *M. laosensis* shell $\delta^{18}O$ record in terms of changes in monsoon rainfall. The hydrological regime of northern Thailand is a result of distinct wet and dry monsoon seasons. The northeast winter monsoon brings cool and dry air from the Siberian anti-cyclone over major parts of Thailand from November to February. In contrast, the southwest monsoon, which begins in mid-May and ends by mid-October, brings 90% of the annual rainfall and air of high humidity originating from the Indian Ocean (Khedari et al., 2002). Previous studies of the $\delta^{18}O$ of monsoon rainfall in the seasonally dry regions of China (Wang et al., 2001) and southern Indonesia (Griffiths et al., 2009) have shown that the $\delta^{18}O$ values for summer monsoon rainfall are substantially lower than those for winter rainfall, primarily due to the "amount effect" (Rozanski et al., 1993). Given the large seasonal difference in rainfall amount in northern Thailand, we interpret changes in the *M. laosensis* shell $\delta^{18}O$ record primarily in terms of changes in the ratio of summer and winter rainfall.

Ideally, samples of live *M. laosensis* specimens and river water would have been collected as a control to establish that seasonal changes in monsoon rainfall actually do drive changes in the $\delta^{18}O$ of *M. laosensis* (Mannino et al., 2003). However, despite intensive searching and shovel-pit sampling over several kilometres of river banks, we were unable to locate specimens of *M. laosensis*, and it is believed that the species is locally extinct due to pollution of the river from recent intensive agricultural activity. Interviews of people living near the river revealed that they had never encountered *Margaritanopsis* when foraging for shellfish to sell at local markets.

4. Materials and methods

4.1. Mineralogical assessment of *M. laosensis*

The primary goal of this study was to produce a long and accurate record of palaeomonsoon variability based on bulk $\delta^{18}O$ analysis of *M. laosensis*. However, the significance of any long-term changes in the $\delta^{18}O$ record provided by bulk analysis of individual *M. laosensis* specimens depends on the signal being larger than the potential uncertainties in the bulk $\delta^{18}O$ value produced by $\delta^{18}O$ heterogeneity within an individual shell. Therefore, in any analysis of $\delta^{18}O$ in freshwater bivalves, it is critical to document the proportions of the carbonate minerals calcite and aragonite in the shell. Shells can grow aragonite, calcite or both in alternating layers (Falini et al., 1996; Thompson et al., 2000) with the carbonate being derived from dissolved inorganic carbon in the ambient water (McConnaughey and Gillikin, 2008). The key point is that aragonite and calcite are chemically identical forms of calcium carbonate, but with different structures, symmetry and crystal shapes, and thus they fractionate oxygen isotopes differently. The difference in $\delta^{18}O$ between aragonite and calcite precipitated in isotopic equilibrium with ambient water is only 0.7‰ (Grossman and Ku, 1986). Nevertheless, large differences in the proportions of aragonite and calcite for individual shells could potentially have a measureable impact on the long-term $\delta^{18}O$ record.

The other possibility is that the shells of *M. laosensis* have been affected by dissolution and meteoric diagenesis during their burial history at Tham Lod and Ban Rai. For shells in shallow vadose-zone environments, diagenesis involves the precipitation of secondary aragonite or calcite in skeletal voids, or the replacement of skeletal aragonite with calcite (Bathurst, 1975). Isotopes are exchanged during these transformations, thus altering the geochemistry of arogonitic shells, such as corals (e. g. Bar-Matthews et al., 1993; McGregor and Gagan, 2003b). At Tham Lod and Ban Rai, the δ^{18}O of diagenetic calcite would be determined by the ratio of moles of oxygen derived from dissolving limestone formations in the area and from the meteoric water (Gross, 1964; Allan and Matthews, 1982). However, water flow rates in tropical regions are generally much greater than the rate of limestone dissolution, so the δ^{18}O of calcite precipitated in vadose environments reflects the δ^{18}O of the meteoric water. As a result, the δ^{18}O value of any diagenetic calcite in the shells of *M. laosensis* should be similar to the δ^{18}O value of the original shell. Therefore, it is likely that substantial (and obvious) amounts of diagentic calcite would be required to significantly distort the *M. laosensis* δ^{18}O record.

As a preliminary qualitative mineralogical test, four shell specimens from Tham Lod and four from Ban Rai (from the upper, middle and lower excavation units of each site) were sawn in half from margin to umbo and stained with Feigl's solution which turns black in the presence of aragonite (Friedman, 1959; Lewis and McConchie, 1994). This confirmed that *M. laosensis* secreted aragonite but did not indicate if diagenetic processes had altered the shell.

To investigate diagenetic alternation, X-ray diffraction (XRD) analysis was undertaken to quantitatively determine the shell mineralogy (Stephens et al., 2008). We hypothesised that diagenetic processes might differentially alter the shell, with the best preservation of the original shell mineral at the thickest area near the umbo. Therefore, 13 shells from Ban Rai and nine from Tham Lod were sampled in four locations per shell using a 3 mm or 5 mm diameter drill bit. Prior to sampling, any contaminants were removed by cleaning the shells with a wire brush and an abrasive disk attached to an electric rotary tool. The sample powder was then ground finely in acetone using an agate mortar and pestle for three minutes and transferred by pipette to a quartz sample plate and mounted in the XRD instrument. The samples were analysed at the ANU Department of Earth and Marine Sciences using a Siemens D501 Diffractometer (Copper target) and interpreted using computer software (database: PDF-2, search/match: DiffracPlusEva 10.0, quantitative analysis: Siroquant V3).

4.2. δ^{18}O analysis of *M. laosensis*

An important protocol for producing accurate bulk measurements of δ^{18}O in *M. laosensis* is to choose similar-sized specimens with typical lifespans of two to three years to minimise differences in ontogenetic effects and limit the number of seasonal cycles of δ^{18}O in each analysis. To determine the magnitude of variation in δ^{18}O that should be expected between individual bulk measurements we analysed the seasonal range of δ^{18}O within two specimens, one from Ban Rai and one from Tham Lod. Thirty isotope samples were taken along the profile of the shell from Ban Rai and 22 samples from the Tham Lod shell, following cleaning and cutting of the shells longitudinally along the growth profile. The samples were evenly spaced from umbo to margin, although the margins of both shells were damaged so the sequence does not include the most recently deposited layers. If the δ^{18}O variation between specimens is greater than most of the seasonal δ^{18}O variation within a single specimen, then a reliable long-term climatic signal can be obtained.

For the bulk δ^{18}O measurements, three shells from each excavation unit at Tham Lod and Ban Rai where *M. laosensis* was present were selected for analysis. Three was chosen as the baseline number of specimens because it was the maximum number of intact specimens of similar size that were found in most of the excavation units. Twenty-six excavation units were sampled at Tham Lod and 14 at Ban Rai. This gives a relatively detailed sequence of climate change spanning about 35,000 BP to 6000 BP.

A total of 105 bulk carbonate samples were extracted from the *M. laosensis* specimens by sawing each shell in half from margin to umbo and then drilling into the thickest part of the profile near the umbo. Multiple powder samples from single shells were obtained with a 3 mm or 5 mm diameter drill bit and combined to measure the average δ^{18}O value for the life of each shell. Shells were rinsed in de-ionized water prior to drilling. XRD analysis was performed on 22 of the specimens to determine if there is any relationship between sample depth, mineralogy and δ^{18}O.

4.3. Oxygen isotope mass spectrometry

Sample powders were combined and homogenised and subsamples of 180–200 μg were weighed for delivery to the mass spectrometer. The samples were analysed at the ANU Research School of Earth Sciences on a Finnigan MAT 251 using a Kiel microcarbonate preparation device, both computer-controlled with ISODAT software. The carbonate samples were reacted with two drops of 105% phosphoric acid at 90 °C over a reaction time of 13 min. Water was removed from the H_2O–CO_2 gas evolved from this reaction by freezing and then vaporising CO_2 in a double trap system using liquid nitrogen. The pure CO_2 then entered the inlet system of the mass spectrometer for measurement.

Following convention, the results are reported as delta (δ) values in units of per mil (‰). The delta value is an expression of the difference between the raw δ^{18}O value of the shell and a standard, in this case Vienna Peedee Belemenite (VPDB). National Bureau of Standards NBS-19 was used to normalise the data to the VPDB scale. The working gas (KAZZA) was composed of $\delta^{18}O_{VPDB} = -1.88$‰ and $\delta^{13}C_{VPDB} = 2.39$‰. The data were corrected for ^{17}O interference using the method of Santrock et al. (1985) and normalised so that a sample of solid NBS-19 analysed by this method would yielded $\delta^{18}O_{VPDB} = -2.20$‰. The working gas values and ion correction methods are reported here to allow comparison with data produced in different laboratories. Analytical precision for replicate measurements ($n = 36$) of δ^{18}O in NBS-19 was ±0.06‰ (2SD).

5. Results

5.1. *M. laosensis* shell mineralogy and δ^{18}O

The results of the XRD analysis showed that the shells of *M. laosensis* are mostly aragonite with consistently small amounts of calcite (Table 2). The amount of aragonite in the shells ranged from 100% to 88.4% (mean 95.9%, SD 3.7%), with relatively low percentages found in samples taken from the umbo. The average percentage of calcite was 2.0% at Ban Rai and 7.3% at Tham Lod. The shell that returned the highest calcite value of 11.6% is notable because it had a different colour and texture. This specimen was selected because it was thought to have been cooked or burnt, given that the shell was much denser than the others and had a blue-grey exterior. The anomalously high percentage of calcite supports the claim that it was burnt, which could convert aragonite to calcite (Epstein et al., 1953).

Comparison of shell mineralogy, δ^{18}O and depth in the excavation shows no significant correlation between mineralogy and δ^{18}O or mineralogy and age of a specimen (Fig. 5). The correlation

Table 2
Summary of excavation depth and sample age compared with percentage calcite and $\delta^{18}O$ in *M. laosensis*. Depths are from the ground surface and ages are interpolated from data in Table 1.

Sample ID	Depth (cm)	Age (yr BP)	Calcite (%)	$\delta^{18}O$ VPDB
BR1a	5–10	5970	5.1	−7.95
BR3a	15–20	6290	0.7	−8.37
BR5a	25–30	6610	2.1	−9.06
BR7a	40–45	6930		−8.72
BR7b				−7.65
BR9a	50–60	7250	2.8	−7.8
BR9b			5.9	−9.22
BR11a	70–80	7570	1.5	−8.62
BR11b				−8.58
BR11c				−8.42
BR11d				−8.5
BR13a	90–100	7890	1.4	−9.16
BR13b				−8.47
BR13c				−8.33
BR15a	110–120	8220	2.3	−8.43
BR15b				−8.62
BR15c				−8.66
BR17a	130–140	8540	2	−7.95
BR17b				−8.98
BR17c				−9.06
BR19a	150–160	8860	0.2	−8.48
BR19b				−8.43
BR19c				−8.8
BR21a	170–180	9180	0	−8.98
BR22a	180–190	9340		−8.98
BR22b				−8.76
BR22c				−8.5
BR23a	190–200	9500	1.3	−8.92
BR25a	210–220	9820	0.7	−8.45
TL2a	5–20	11,180		−5.69
TL2b				−5.28
TL2c			9.5	−5.92
TL4a	30–40	12,770		−6.25
TL4b			5.4	−5.46
TL5a	40–50	13,560		−6.17
TL5b				−5.25
TL5c				−6.34
TL6a	50–60	14,350		−5.91
TL6b				−6.27
TL6c			11.6	−5.55
TL6d			0.6	−5.41
TL7a	60–70	15,140		−5.67
TL7b				−5.4
TL8a	70–80	15,930		−5.54
TL8b				−5.74
TL8c			6.4	−7.23
TL10a	90–100	17,510		−6.47
TL10b				−5.35
TL10c			9.1	−5.75
TL11a	100–110	18,310		−6.79
TL11b				−6.45
TL11c			6.6	−6.39
TL12a	110–120	19,100		−6.27
TL12b				−7.09
TL12c			6.6	−6.35
TL13a	120–130	19,890		−5.53
TL13b				−6.09
TL13c				−6.33
TL14a	130–140	20,680	10.6	−6.5
TL16a		22,260		−7.03
TL16b				−6.79
TL16c	150–160			−7.1
TL17a	160–170	23,050		−7.78
TL17b				−7.17
TL17c				−7.93
TL18a	170–180	23,840		−6.47
TL18b				−7.81
TL18c				−6.45
TL19a	180–190	24,640		−6.81
TL19b				−6.36
TL19c				−6.6
TL20a	190–200	25,430		−7.28
TL21a	200–210	26,220		−6.5
TL21b				−6.1
TL21c				−6.51
TL22a	220–230	27,010		−7.9
TL22b				−6.36
TL22c				−7.59
TL23a	230–240	27,800		−8.71
TL23b				−7.38
TL23c				−6.75
TL24a	240–251	28,590		−6.94
TL24b				−6.04
TL24c				−7.06
TL25a	250–261	29,380		−7.61
TL25b				−6.94
TL25c				−7.72
TL26a	260–270	30,180		−6.51
TL26b				−7.67
TL26c				−7.57
TL27a	270–282	30,970		−6.67
TL27b				−6.52
TL27c				−7.22
TL28a	280–293	31,760		−6.55
TL28b				−6.77
TL28c				−6.51
TL29a	290–303	32,550		−6.61
TL29b				−7.85
TL29c				−7.43
TL30a	304–310	33,340		−6.3
TL30b				−6.09
TL30c				−6.03
TL31a	310–320	34,130		−7.23
TL31b				−7.79
TL31c				−6.8

between percentage calcite and excavation depth (as a proxy for time of exposure to diagenesis) is weak (Tham Lod: $r = -0.17$ Ban Rai: $r = -0.47$). Surprisingly, the amount of shell calcite appears to decrease with increasing excavation depth. This suggests that the calcite may be related to meteoric waters percolating downward through the deposit, with diagenesis occurring mainly near the ground surface. Whatever the cause, there is no significant correlation between percentage calcite and $\delta^{18}O$ in the shells (Tham Lod: $r = -0.11$, Ban Rai: $r = -0.04$).

Taken together, the results confirm that *M. laosensis* is an aragonite producing species and that diagenetic processes have not substantially altered the mineralogy of the archaeological specimens. Based on these findings, it appears that *M. laosensis* specimens recovered from the archaeological excavations at Ban Rai and Tham Lod are suitable for the style of palaeoclimate study described herein.

5.2. *Seasonal and long-term variations in shell $\delta^{18}O$*

Before discussing the palaeoclimate implications of the *M. laosensis* $\delta^{18}O$ record, we must confirm that millennial-scale changes in the shell $\delta^{18}O$ values exceed the uncertainty in bulk $\delta^{18}O$ values measured by sampling multiple spots within an individual shell. Our high-resolution analysis of $\delta^{18}O$ in *M. laosensis* showed an average seasonal range of 0.74‰ for the Tham Lod specimen and 0.59‰ for the Ban Rai specimen. It follows, therefore, that the uncertainty associated with a bulk $\delta^{18}O$ value based on the average of samples from multiple spots within a shell will be much smaller than the seasonal range in $\delta^{18}O$.

By way of comparison, the bulk $\delta^{18}O$ values for all the *M. laosensis* specimens contributing to the palaeoclimate record have a range of 4.0‰. The $\delta^{18}O$ values of *M. laosensis* shells excavated at Tham Lod ($n = 76$) have a 3.4‰ range and those from Ban Rai

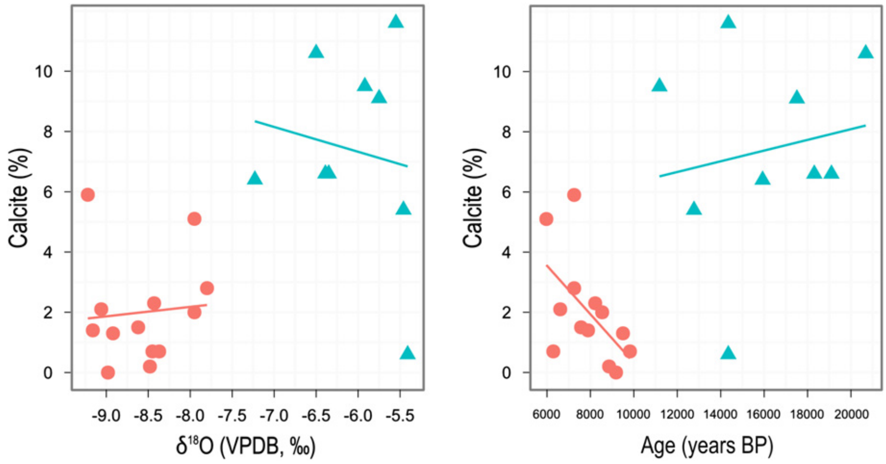

Fig. 5. Cross-plots of calcite percentage versus age of deposit (right) and calcite percentage versus $\delta^{18}O$ in *M. laosensis* (left). Tham Lod is represented by blue triangles and Ban Rai by red cirlces. There is no significant relationship thus the impact of meteoric diagenesis on the $\delta^{18}O$ of *M. laosensis* is negligible. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

($n = 29$) have a range of 1.6‰. The results show that the differences in $\delta^{18}O$ between specimens are much larger than the uncertainties associated with bulk $\delta^{18}O$ values within a single specimen. Based on this outcome, we conclude that the millennial-scale changes observed in the shell $\delta^{18}O$ record can be interpreted in terms of changes in past climate.

6. Discussion

6.1. Assessment of the Tham Lod and Ban Rai $\delta^{18}O$ records

Before examining the Tham Load and Ban Rai $\delta^{18}O$ record in detail, it is important to establish the reliability of the climate signal provided by *M. laosensis* by comparing the record to reliable, well-dated palaeoclimate records from the Southeast Asian region. This is important for two reasons. First, for some shell species there is not always a clear and predictable relationship between the environmental conditions of a shell's habitat and the measured $\delta^{18}O$ values in the shell carbonate (e. g. Shanahan et al., 2005). In the absence of modern test specimens, a key question is whether *M. laosensis* precipitates oxygen isotopes in equilibrium with the ambient water, thus allowing the record to be interpreted in terms of changes in the $\delta^{18}O$ of meteoric water. Second, because the Holocene data are from Ban Rai and the Pleistocene data from Tham Lod, with no overlap, it is necessary to investigate the possibility that that localised environmental variations along the river may have influenced the $\delta^{18}O$ of different cohorts of *M. laosensis*, thus distorting the record.

No comparable $\delta^{18}O$ records are currently available for mainland Southeast Asia. However, further north in China there are well-dated Late Pleistocene-Holocene speleothem $\delta^{18}O$ records from two cave sites that together record regional changes in East Asian summer monsoon rainfall (Wang et al., 2001; Zhao et al., 2003; Yuan et al., 2004). Detailed chronological and oxygen isotopic data from these two locations were downloaded from internet archives at the World Data Centre for Palaeoclimatology, Boulder, Colorado, USA (http://www.ncdc.noaa.gov/paleo/). Carbon isotope data were not available. These records are significant because the speleothems grew in isotopic equilibrium with ambient waters at relatively constant temperatures (near mean annual air temperature), so the speleothem $\delta^{18}O$ is primarily a function of the $\delta^{18}O$ of cave drip water, which is closely related to mean local precipitation. (Schwarcz, 1986; McDermott, 2004). This sensitivity to precipitation makes the speleothem records from China ideal to test the model of $\delta^{18}O$ variation in *M. laosensis* as a function of monsoon precipitation amount.

Wang et al. (2001) described a high resolution sequence of $\delta^{18}O$ based on five stalagmites in Hulu Cave (also known as Tangshan Cave), 28 km east of Nanjing (Fig 1, Fig 6). The record was dated with 59 ^{230}Th dates with analytical errors of 150–400 years, spanning 75,000 BP to 11,000 BP. These data are useful for verifying the range and variation in the $\delta^{18}O$ of *M. laosensis* from Tham Lod, given that the records overlap from 33,600 BP to 11,600 BP. Another well-dated speleothem $\delta^{18}O$ record is available from Dongge Cave, 18 km Southeast of Libo, Guizhou Province (Yuan et al., 2004), for verification of the $\delta^{18}O$ record for Ban Rai spanning 9,800 BP to 5,700 BP. A very high-resolution sequence of $\delta^{18}O$ values spanning 15,600 BP to recent times was obtained from Dongge stalagmite D4, dated with 28 ^{230}Th dates.

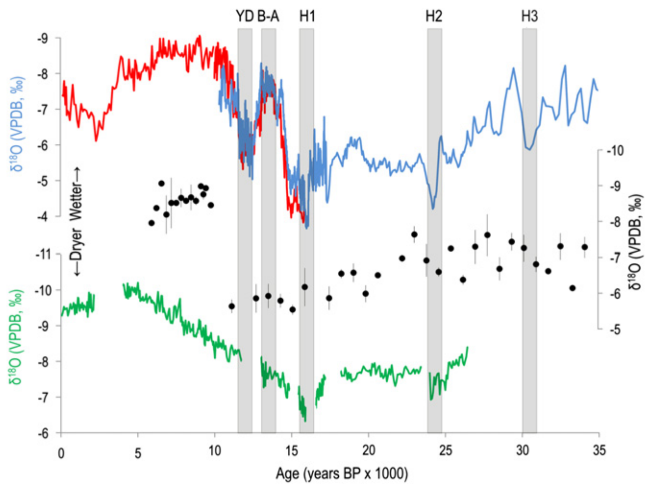

Fig. 6. Comparison of the Tham Lod and Ban Rai $\delta^{18}O$ records with speleothem $\delta^{18}O$ records of Southeast Asian monsoon rainfall. The Tham Lod and Ban Rai $\delta^{18}O$ sequence (black circles with standard error bars) is superimposed on the Hulu Cave (blue, Wang et al., 2001) and Dongge Cave (red, Yuan et al., 2004) from China, and the Gunung Buda Cave record from Malaysian Borneo (green, Partin et al., 2007). The synchronized changes in monsoon rainfall demonstrate the critical role of the ITCZ in transmitting climate change across the Southeast Asian monsoon domain. Climate events discussed in the text are highlighted by grey vertical bars, YD – Younger Dryas, B–A – Bølling-Allerød, H1 – Heinrich event 1, etc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Dongge Cave is located relatively close to northwest Thailand so the early Holocene section of the speleothem $\delta^{18}O$ record (9,000 BP to 6,000 BP) provides a good benchmark against which to test for equilibrium precipitation of oxygen isotopes in the Ban Rai *M. laosensis* record. The environmental settings for both sites are similar with elevations of 680 masl and mean $\delta^{18}O$ of rainfall of ~ -6.5 to $-7.0‰_{SMOW}$ (Aggarwal et al., 2004). As a result, the average $\delta^{18}O$ value for the Dongge Cave speleothem $\delta^{18}O$ record, with calcite precipitated close to isotopic equilibrium, is $-8.7‰_{VPDB}$ over the 9,000–6,000 BP interval (Yuan et al., 2004). By comparison, the average $\delta^{18}O$ value for the Ban Rai *M. laosensis* $\delta^{18}O$ record is $-8.6‰_{VPDB}$ (Fig. 4, Table 2). The remarkable agreement strongly indicates that the aragonitic shell of *M. laosensis* precipitates oxygen isotopes in equilibrium. Strictly speaking, however, an aragonite shell precipitated in equilibrium should have a $\delta^{18}O$ value that is 0.7‰ higher than that for calcite precipitated under the same conditions (Grossman and Ku, 1986). Nevertheless, the agreement between the two $\delta^{18}O$ records is still surprisingly good, particularly given that the $\delta^{18}O$ of rainfall at Ban Rai is likely to be slightly higher than that at Dongge Cave (Aggarwal et al., 2004).

The Tham Lod *M. laosensis* and Hulu Cave speleothem $\delta^{18}O$ records can be compared further back in time over the interval of overlap from 33,600 BP to 11,600 BP (Fig. 4). Hulu Cave is only 100 masl (Yuan et al., 2004), whereas Tham Lod is $\sim$640 masl so, in theory, the $\delta^{18}O$ of rainfall at Hulu should be slightly higher ($<1‰$) than at Tham Lod. However, the regional decrease in the $\delta^{18}O$ of rainfall towards higher, generally cooler latitudes around Hulu Cave means that the two effects (latitude vs elevation) would tend to cancel, and that the Tham Lod and Hulu records should be comparable. This appears to be the case because the average $\delta^{18}O$ value of the Hulu record over the 33,600–11,600 BP interval is $\sim -7‰$, while the average for Tham Lod is $-6.6‰$. Again, the agreement is excellent when the 0.7‰ offset in $\delta^{18}O$ between biogenic aragonite and calcite precipitated in equilibrium is taken into account. There is also good overall agreement between the Late Pleistocene trends evident in the $\delta^{18}O$ records for Tham Lod and Hulu Cave (Fig. 4). Both records show a long-term 1.5‰ increase in $\delta^{18}O$ during the Late Pleistocene. The $\delta^{18}O$ minima are not synchronous, $\sim$33,000 BP at Hulu and $\sim$28,000 BP at Tham Lod, but their maxima are reasonably well aligned at $\sim$16,000 BP for Hulu and $\sim$15,000 BP for Tham Lod.

6.2. The history of Southeast Asian monsoon variability

The close correspondence between the $\delta^{18}O$ records from Thailand and China shows that the *M. laosensis* records from Tham Lod and Ban Rai can be interpreted in terms of changes in monsoon precipitation, given that $\delta^{18}O$ variability in the speleothem records from China is almost entirely explained by monsoon variability (e.g. Wang et al., 2001; Zhao et al., 2003; Wang et al., 2008). Variations in surface seawater $\delta^{18}O$ in the South China Sea, where the summer monsoon draws its moisture, are well known for this period (Wang et al., 1999) and are small relative to the changes observed in the $\delta^{18}O$ records from Thailand and China. The summer monsoon in Southeast China contributes 80% of annual precipitation, with $\delta^{18}O$ of the summer rainfall being $\sim$10‰ lower than the winter rainfall (Zheng et al., 1983). Equivalent data are not available for Thailand, but because the Thai climate is similarly dominated by summer monsoon rain (Khedari et al., 2002), it is reasonable to explain $\delta^{18}O$ in the Thai records in terms of changes in the ratio of summer to winter precipitation (Wang et al., 2001; Zhao et al., 2003).

On the basis of this scenario, the Tham Lod $\delta^{18}O$ sequence for the period $\sim$33,000 BP to $\sim$20,000 BP indicates a period of relatively wet and unstable climate during the transition from Marine Isotope Stage 3 to the Last Glacial Maximum. Climatic instability is indicated by the high variability of the $\delta^{18}O$ values, relative to the Holocene portion of the record. From $\sim$20,000 BP to $\sim$11,500 BP conditions are at their driest, including Heinrich Event 1 with maximum dryness at $\sim$15,600 BP. The early stage of this period probably reflects the climatic impact of the Last Glacial Maximum, when local conditions were drier and cooler in response to the global increase in ice sheet area.

Wang et al. (2001) have shown that a sharp increase in $\delta^{18}O$ centred on $\sim$16,000 BP in the Hulu Cave record is related to a reduction in monsoon rainfall intensity at the time of Heinrich Event 1, one of six extremely cold periods documented in the North Atlantic region (Grootes et al., 1993; Meese et al., 1997; Hemming, 2004; Steffensen et al., 2008) Zhao et al. (2003) have also observed this event in another speleothem record from Hulu, and it has been reported elsewhere in China (Zhou et al., 2008). A similar reduction in rainfall is evident in a high-resolution speleothem $\delta^{18}O$ record from Malaysian Borneo (Partin et al., 2007), well to the south of Thailand (Figs. 1 and 6). A subtle increase in $\delta^{18}O$ occurs in the Tham Lod record during Heinrich Event 1, however, the relatively low resolution of the sequence means that further work is required to determine if had a measureable impact on Thailand.

The Tham Lod record also spans the Bølling-Allerød Interstadial (14,600–12,800 BP), a widespread warm period probably triggered by exceptionally large melting of continental ice sheets, causing an increase in sea levels and altering ocean circulation patterns in the North Atlantic (e.g. Weaver et al., 2003). The Younger Dryas cold interval (12,800–11,500 BP), recorded in Greenland ice cores, is also spanned by the Tham Lod record. The climatic impacts of these distant events are clearly evident in speleothem $\delta^{18}O$ records from China (e. g. Wang et al., 2001) but, interestingly, they are not apparent in the speleothem $\delta^{18}O$ record from Malaysian Borneo (Fig. 6), despite clear evidence for drying there during Heinrich Event 1 (Partin et al., 2007). The relatively low chronological resolution of the Tham Lod excavation units means that there are limited data available to investigate the climatic impact of the Bølling-Allerød and Younger Dryas in Thailand, and the *M. laosensis* $\delta^{18}O$ record shows no clear signal. However, the Younger Dryas does not seem to be evident in any pollen cores from Thailand, or elsewhere in mainland or island Southeast Asia e.g. (Maloney, 1995; Kealhofer, 1996; Kealhofer and Penny, 1998; Maloney, 1999; Penny, 2001), so the result may have some validity.

The Ban Rai $\delta^{18}O$ sequence for the early Holocene, starting at $\sim$9,800 BP, shows consistently higher and less variable monsoon precipitation compared with the Late Pleistocene, in good agreement with the speleothem $\delta^{18}O$ records from China (Fig. 6). Increased precipitation during the Holocene is also evident in speleothem $\delta^{18}O$ records from Malaysian Borneo (Partin et al., 2007) and Indonesia (Griffiths et al., 2009) and in pollen cores and other records for island Southeast Asia (Stephens et al., 2008). There is a subtle trend towards increasing dryness in the Ban Rai $\delta^{18}O$ sequence from $\sim$9,800 BP to 5,900 BP, which also occurs at the same time in China (e. g. Yuan et al., 2004) but does not begin in Malaysian Borneo until $\sim$5,000 BP during the middle Holocene. In China and Thailand, this transition may reflect the end of the Early Holocene Climatic Optimum, a warm-moist period with stronger East Asian monsoon rainfall in response to stronger insolation during boreal summer brought about by changes in the Earth's orbit (Zhou et al., 2001). A similar drying trend has been described in pollen sequences elsewhere in China (Zhuo et al., 1998; An et al., 2000; Liew et al., 2006; Wang et al., 2007).

6.3. Archaeological implications

Early work on mainland Southeast Asian palaeolithic archaeology claimed that Late Pleistocene climates were similar to modern climates. van Heekeren and Knuth's (1967) pioneering excavations at Sai Yok in Kanchanaburi Province in western central Thailand uncovered faunal remains and about 1,500 flaked stone artefacts. No radiometric age determinations are available but van Heekeren suggests a maximum age of about 10,000 BP. He describes the flaked stone artefact assemblage as simple and unchanging, and links the result to 'a tropical climate with heavy rainfall and […] perhaps no major climatic and faunistic changes at the termination of the Pleistocene period' (1967:111). Gorman's (1972) excavations at Spirit Cave in Mae Hong Son Province in northwest Thailand recovered an archaeological deposit with radiocarbon dates to 12,000 BP. Like van Heekeren, Gorman described a flaked stone artefact sequence from Spirit Cave with no substantial changes over time. Gorman similarly concluded that absence of any significant changes in stone artefact technology probably resulted from the apparent continuity of environmental conditions from the terminal Pleistocene to the Holocene.

A revision of these views was presented by Anderson (1990) in his report of excavations at Lang Rongrien in Krabi Province, southern Thailand. In the 38,000 year long archaeological sequence, Anderson described Holocene stone artefacts as large flaked cobbles and Pleistocene artefacts as small stone flakes. Anderson suggests that the Pleistocene flake assemblage was used by hunters who exploited open savannahs and animal movement patterns that were made predictable by the use of valleys as refuges from cool Pleistocene temperatures. During the Holocene the increased precipitation caused the open savannahs to disappear and the warmer temperatures reduced the need for biogeographical refuges. He proposes that the cobble assemblages may be related to agricultural tasks such as forest-clearing, ground-breaking or shellfish procurement.

The data presented here give some support to Anderson's interpretation of a cooler and drier Pleistocene and a wetter and warmer Holocene in mainland Southeast Asia. Claims by van Heekeren and Gorman appear no longer reliable given the clear shift from Late Pleistocene to Holocene climates in the *M. laosensis* $\delta^{18}O$ sequence from Tham Lod and Ban Rai. This implies either that prehistoric flaked stone technology did not need to change much to be useful in substantially different environments, or that the methods used by van Heekeren and Gorman were not sensitive to changes in flaked stone artefacts that related to climate change. We expect that both implications are relevant, but the insensitivity of the analytical methods was probably more important (Marwick, 2007). Forthcoming results on the analysis of flaked stone artefacts from Tham Lod and Ban Rai will explore this issue in more detail.

A final archaeological implication relates to the Younger Dryas. The Tham Lod $\delta^{18}O$ sequence and speleothem $\delta^{18}O$ records from Malaysin Borneo presented here are notable for the absence of a Younger Dryas signal. The archaeological implications of the Younger Dryas are controversial as it has been proposed to be the cause of shifts from hunter-gatherer to agricultural economies in west Asia (Moore and Hillman, 1992; Richerson et al., 2001; Bar-Yosef, 2002; Willcox et al., 2007). With the limited data available for mainland Southeast Asia, it may be premature to declare that the Younger Dryas had no impact on past climates in this region. However, if the Younger Dryas was absent from or less intense in mainland Southeast Asia compared to further north in China, then this may in part explain why agriculture appears not to have independently emerged here and instead made a relatively late appearance, possibly involving migrants from China (Higham, 1996).

7. Conclusions

Our new northwest Thailand $\delta^{18}O$ sequence indicates wetter and relatively unstable climatic conditions from 33,000 to 20,000 BP, followed by drier conditions from 20,000 to 11,500 BP. A period of peak aridity occurred around 15,600 BP during Heinrich Event 1, suggesting that the intertropical convergence zone shifted southward when the North Atlantic region cooled. We found little evidence for the Younger Dryas event at ~12,800–11,500 BP. After 9,800 BP, precipitation increased substantially and climatic variability declined. We conclude that statements claiming that Pleistocene climates of mainland Southeast Asia were unchanging and similar to modern climates are unreliable and we encourage recognition of the diverse past climates and exploration of their implications for the prehistoric occupants of the region. Our findings provide an improved baseline against which to gauge interactions between early humans and climate change in Southeast Asia. For example, there was no significant change in the prehistoric flaked stone technology used at Tham Lod and Ban Rai despite the bivalve $\delta^{18}O$ evidence for substantial climate change in the region. Also, the climatic impact of the Younger Dryas event appears to have been less intense in northwest Thailand compared to the cooling and drying observed in China, and may explain why agriculture made a relatively late appearance in Thailand, possibly involving migrants from China. Although this study has some substantial limitations, we hope that it has demonstrated the value of oxygen isotope sequences in palaeoclimate reconstruction in mainland Southeast Asia, and that future work will refine the broad sequence presented here.

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