LETTERS

Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum

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Models and palaeoclimate data suggest that the tropical Pacific climate system plays a key part in the mechanisms underlying orbital-scale and abrupt climate change[1–7]. Atmospheric convection over the western tropical Pacific is a major source of heat and moisture to extratropical regions, and may therefore influence the global climate response to a variety of forcing factors. The response of tropical Pacific convection to changes in global climate boundary conditions, abrupt climate changes and radiative forcing remains uncertain, however. Here we present three absolutely dated oxygen isotope records from stalagmites in northern Borneo that reflect changes in west Pacific warm pool hydrology over the past 27,000 years. Our results suggest that convection over the western tropical Pacific weakened 18,000–20,000 years ago, as tropical Pacific[2,5,6,8] and Antarctic[9] temperatures began to rise during the early stages of deglaciation. Convective activity, as inferred from oxygen isotopes, reached a minimum during Heinrich event 1 (ref. 10), when the Atlantic meridional overturning circulation was weak[11], pointing to feedbacks between the strength of the overturning circulation and tropical Pacific hydrology. There is no evidence of the Younger Dryas event[12] in the stalagmite records, however, suggesting that different mechanisms operated during these two abrupt deglacial climate events. During the Holocene epoch, convective activity appears to track changes in spring and autumn insolation, highlighting the sensitivity of tropical Pacific convection to external radiative forcing. Together, these findings demonstrate that the tropical Pacific hydrological cycle is sensitive to high-latitude climate processes in both hemispheres, as well as to external radiative forcing, and that it may have a central role in abrupt climate change events.

Numerous palaeoclimatic studies have focused on changes in the tropical Pacific zonal sea surface temperature (SST) gradient and associated shifts in convection[2,4,5], extending an El Niño/Southern Oscillation (ENSO) framework to interpretations of millennial-scale climate variability. Recently, the potential for meridional changes in tropical Pacific temperatures has emerged as an important mechanism in shaping hydrological responses to abrupt climate change[7,13–15]. Indeed, new modelling and palaeoclimate results suggest that during Heinrich event 1 (H1), when a near-collapse of the Atlantic meridional overturning circulation[11] cooled most of the Northern Hemisphere, the Intertropical Convergence Zone (ITCZ) shifted southwards[7,13–15]. However, the extent to which tropical Pacific climate feedbacks were involved in deglacial abrupt climate events such as H1, the Antarctic Cold Reversal[9] and subsequent Younger Dryas[12] remains unclear. A combination of zonal and/or meridional changes in the distribution of tropical convection probably played a key part in shaping the global climate response to abrupt climate changes during the deglaciation. Uncovering the mechanisms and feedbacks that govern the response of the tropical Pacific climate system to both internal and external forcings requires well-dated, high-resolution records from climatic centres of action.

Here we present three absolutely dated stalagmite oxygen isotopic ($\delta^{18}O$) records from northern Borneo that document changes in western tropical Pacific atmospheric circulation and hydrology over the past 27,000 yr. Tropical stalagmite $\delta^{18}O$ records are particularly well-suited to the investigation of centennial-to-millennial hydrological change because tropical rainfall $\delta^{18}O$ is inversely correlated to precipitation amount and because U–Th dating provides excellent chronological control.

The research site is located in Gunung Buda National Park (4° N, 114° E) in the northwestern corner of Malaysian Borneo (see Methods for detailed site description). The ITCZ lies above northern Borneo year-round, delivering 5 m of rainfall with little seasonality (Supplementary Fig. 1). ENSO exerts a dominant control on northern Borneo precipitation, with anomalies as large as ±50% during ENSO extremes (Fig. 1). Interannual (2–7 yr) changes in rainfall account for ~20% of total precipitation variance in northern Borneo and are highly correlated to the Southern Oscillation Index ($R = -0.80$). Seasonal cycles in rainwater $\delta^{18}O$ (−10‰ during boreal autumn and −4‰ during boreal spring) probably reflect northern versus southern moisture trajectories[16]. ENSO-related interannual rainfall $\delta^{18}O$ variability is consistent with the 'amount effect'[17,18], whereby periods of increased precipitation are characterized by lighter rainfall $\delta^{18}O$ (ref. 16).

Several tests confirm that the Gunung Buda stalagmites formed under oxygen isotopic equilibrium, allowing carbonate $\delta^{18}O$ changes

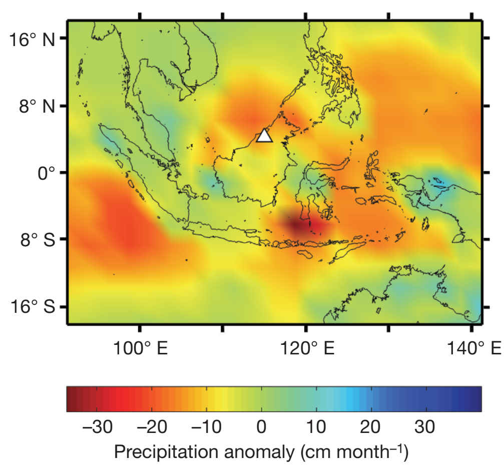

Figure 1 | Map of the west Pacific December-January-February precipitation anomaly during the 1997–98 El Niño event. Data are from ref. 31. A white triangle marks the approximate location of the research site.

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to be interpreted as rainwater $\delta^{18}O$ changes. First, the correlation between oxygen and carbon isotopic variability is low ($R<0.05$) after linearly detrending for glacial–interglacial isotopic changes. Second, all three samples pass the 'Hendy test'[19], exhibiting $\delta^{18}O$ variations of less than ~0.5‰ across the axial portion of a single growth layer (see Methods and Supplementary Figs 9 and 10). Third, the equilibrium calcite $\delta^{18}O$ value equals that measured for modern stalagmite calcite, given measured present-day rainwater $\delta^{18}O$ of −6.8‰ and 26 °C cave temperatures[16]. Last, the high degree of millennial-scale reproducibility of $\delta^{18}O$ in the three stalagmites from caves located ~5 km apart strongly suggests that the stalagmite $\delta^{18}O$ records regional climate changes associated with rainfall $\delta^{18}O$ variability (Fig. 2). Poor sub-millennial reproducibility between the three records can be attributed to dating uncertainties and/or site-specific stalagmite $\delta^{18}O$ variability. It is important to note that temperature changes could only account for ~0.7‰ of stalagmite $\delta^{18}O$ variability over the past 27,000 yr, given that warm pool temperatures were no more than 3.5 °C colder during the Last Glacial Maximum (LGM)[2,5,6,8].

A total of 75 U–Th dates and 11 isochrons provide excellent chronological control for the three stalagmite $\delta^{18}O$ records (see Methods and Supplementary Information). The age model for each record consists of 24–26 U–Th dates (Fig. 2) that were corrected for detrital thorium using stalagmite-specific detrital $^{230}Th/^{232}Th$ values calculated using isochrons. Age errors of up to 2% (2σ) represent a combination of analytical uncertainty and uncertainty in the detrital ^{232}Th correction. Slow growth rates and/or unresolved hiatuses represent the largest sources of chronological uncertainty, so we limit our climatic interpretations to portions of the records with growth rates higher than 10 μm yr^{-1}.

LGM stalagmite $\delta^{18}O$ values (averaged over the period 19–23 kyr ago) are 1.3 ± 0.3‰ heavier than modern values, and reflect a combination of global ice volume (+1‰)[20], LGM cooling of ~2–3.5 °C in the western tropical Pacific[2,5,6,8] (+0.4‰ to +0.7‰), and poorly constrained changes in LGM regional seawater $\delta^{18}O$ (−0.5‰ to +0.5‰)[2,5,6,21]. Thus, potentially small changes in northern Borneo rainfall $\delta^{18}O$ during the LGM are difficult to resolve. Possible controls on northern Borneo rainfall $\delta^{18}O$ over our whole 27-kyr record include: (1) changes in the tropical Pacific zonal SST gradient; (2) changes in the location and/or intensity of the ITCZ; and (3) changes in eustatic sea level, which determine the size of the emergent Sunda Shelf. Exposure of the Sunda Shelf undoubtedly altered atmospheric circulation in the west Pacific by increasing continentality and lengthening moisture trajectories, both of which deplete rainfall $\delta^{18}O$ (refs 17, 18). A complete understanding of warm pool hydrological changes during the LGM and deglaciation must account for the effect of the Sunda Shelf on the tropical Pacific coupled system.

Stalagmite $\delta^{18}O$ values begin a protracted trend towards more positive values 18–20 kyr ago, as tropical Pacific SST[2,5,6,8] and Antarctic[9] temperatures began to rise during the early deglaciation. This stalagmite $\delta^{18}O$ excursion cannot be attributed to temperature or local seawater $\delta^{18}O$ changes, as recorded in nearby marine sediments[5,6,8,21], and is therefore interpreted as a positive rainfall $\delta^{18}O$ anomaly (dry conditions based on the amount effect). The inferred trend towards drier conditions in northern Borneo culminates in maximum stalagmite $\delta^{18}O$ values 16.3 ± 0.3 kyr ago, coincident with the timing of a $\delta^{18}O$ maximum in a Chinese stalagmite[22] attributed to H1 (Fig. 3). Conservative age error bars for specific features of the Borneo stalagmite $\delta^{18}O$ records take into account uncertainties associated with stalagmite $\delta^{18}O$ reproducibility, U-series dating errors, and the potential for nonlinear growth rates. Dry conditions in northern Borneo during H1 are consistent with model results[15] indicating a southward shift of the ITCZ in conjunction with a weakened Atlantic meridional overturning circulation inferred from proxy data[11]. Together with evidence for dry conditions in southeast

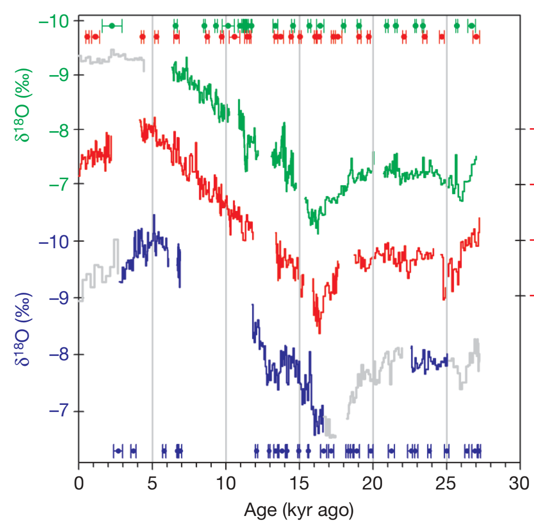

Figure 2 | Three absolutely dated stalagmite $\delta^{18}O$ records from northern Borneo. U–Th dates for each record are plotted in corresponding colours along the top and bottom; error bars represent 2σ analytical uncertainty plus uncertainty in the detrital thorium correction. The average $\delta^{18}O$ temporal resolution is 72, 56 and 60 yr per sample for SCH02, SSC01 and BA04, respectively, but varies from 1 to 100 yr per sample depending on growth rate. Data depicted in grey represent slow-growing (<10 μm yr^{-1}) portions of the records, and are considered untrustworthy for climatic interpretation owing to poor chronological control (up to ±1 kyr). Sample BA04 grew in Bukit Assam cave, while SSC01 and SCH02 grew ~20 m apart in Snail Shell cave, roughly 6 km from Bukit Assam (see Methods for more detailed cave and sample descriptions).

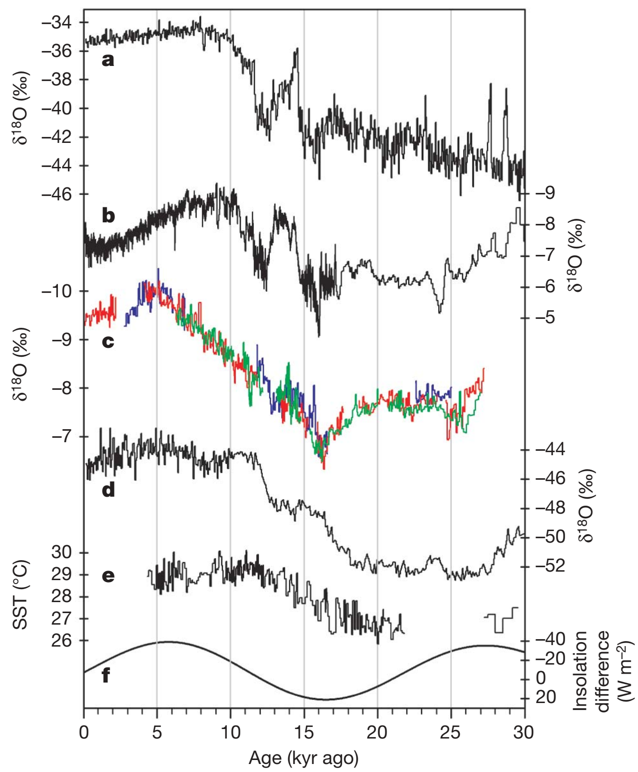

Figure 3 | Comparison of the Borneo stalagmite $\delta^{18}O$ records with other palaeoclimate records. Records plotted are as follows. **a**, Greenland (NGRIP) ice core $\delta^{18}O$ (ref. 12). **b**, Hulu/Dongge caves stalagmite $\delta^{18}O$ records (ref. 22 and R. L. Edwards, personal communication). **c**, Borneo stalagmite $\delta^{18}O$ records (SCH02, blue; SSC01, red; BA04, green). Slow-growing (<10 μm yr^{-1}) portions of the records are excluded. Note that BA04 $\delta^{18}O$ values have been shifted by +0.4‰. **d**, EPICA Dronning Maud Land ice core $\delta^{18}O$ (ref. 9). **e**, Sediment core reconstruction of SST from the Sulu Sea[6]. **f**, March minus September insolation at the Equator.

Asia[22] and enhanced wind-driven upwelling in the eastern equatorial Pacific[7] during H1, the new stalagmite data strongly suggest that a meridional ITCZ shift may have characterized the tropical Pacific hydrological response during H1.

However, the new stalagmite data suggest that the relationship between North Atlantic and Pacific climate is more complex than unidirectional forcing and associated response. For example, the onset of dry conditions in northern Borneo lies between 18 and 20 kyr ago, before the beginning of H1 in North Atlantic sediments[10]. Interestingly, this early onset of dry conditions in northern Borneo occurs during a transition to relatively wet conditions recorded in the Chinese stalagmites[22], before the strong drying observed ~16.5 kyr ago in both stalagmite reconstructions. Furthermore, while sediment reconstructions of the strength of the Atlantic meridional overturning circulation suggest that a rapid resumption of overturning occurred 14.7 kyr ago[11], coincident with the onset of the Bølling–Allerød, the Borneo stalagmite $\delta^{18}O$ records exhibit a more gradual recovery that began as early as 15.5 kyr ago. Therefore, climatic feedbacks in the tropical Pacific may have played a part in driving the variability of the North Atlantic meridional overturning circulation across H1, which in turn affected tropical Pacific hydrology.

Following H1, the deglaciation follows a relatively smooth trend towards more negative Holocene values, interrupted by a millennium-long $\delta^{18}O$ plateau centred at 13.2 ± 0.2 kyr ago that coincides with the Antarctic Cold Reversal[9] (Fig. 3). A western tropical Pacific expression of the Antarctic Cold Reversal is somewhat surprising, given that a prominent Younger Dryas event is present in a Chinese stalagmite record[22]. Oxygen isotopic records from several western tropical Pacific sediment cores north of the Equator exhibit a muted Greenland-like sequence of late deglacial events[6,23], including the Younger Dryas, consistent with Northern Hemisphere influence on the southeast Asian monsoon during the deglaciation. However, with one exception[23], temperature proxy records from northern west Pacific sediment cores do not contain the Younger Dryas[6,24], raising the prospect that the hydrological signature of the Younger Dryas in these cores is associated with runoff from the southeast Asian landmass rather than equatorial rainfall. Indeed, $\delta^{18}O$ and temperature proxy records from cores south of the Equator depict a smooth, uninterrupted deglaciation[8,24], reminiscent of Southern Hemisphere ice cores and the Borneo stalagmite $\delta^{18}O$ data. The similarity between the Antarctic ice core record and the western tropical Pacific stalagmite record during the late deglacial strengthens the view that Southern Hemisphere forcing dominated tropical Pacific climate during this period[2,4,8].

The Holocene portions of the records are characterized by broad $\delta^{18}O$ minima 5 kyr ago, indicating the sensitivity of the western tropical Pacific to spring/autumn precessional insolation forcing (Fig. 3). The stalagmite $\delta^{18}O$ minimum is interpreted as a negative rainfall $\delta^{18}O$ anomaly (wet conditions), as it cannot be explained by regional temperature and/or seawater $\delta^{18}O$ changes[5,8,21,24]. Most tropical palaeo-precipitation records from north of the Equator contain maxima in the range 10 to 8 kyr ago[24–26], while those from south of the Equator exhibit late Holocene maxima[27], presumably linked to boreal and austral summer insolation, respectively. When combined with the new data from the Borneo stalagmites, these records strongly suggest that the mean position of the ITCZ migrated southwards over the course of the Holocene in response to precessional forcing, crossing the equatorial west Pacific ~5 kyr ago. However, relatively wet conditions in northern Borneo during the mid-Holocene could also reflect an increase in the tropical Pacific's zonal SST gradient driven by spring/autumn insolation, a prospect that finds qualitative support in coupled model simulations[28]. Indeed, an observed minimum ~5 kyr ago in eastern equatorial Pacific temperatures[4] lends further support to a zonally mediated insolation response, whereby an increased tropical Pacific zonal SST gradient led to enhanced warm pool convection. A minimum in atmospheric CH_4 5 kyr ago[29] may provide further clues—precipitation anomalies associated with ITCZ variability versus Walker circulation changes probably have different consequences for global methane production. Increased methane production during modern-day El Niño events[30] suggests that a mid-Holocene increase in the tropical Pacific zonal SST gradient may have contributed to the mid-Holocene minimum in atmospheric methane. However, an ITCZ-related mechanism for atmospheric methane control during the Holocene cannot be ruled out, and warrants further investigation.

This study demonstrates that the tropical Pacific hydrological cycle is sensitive to high-latitude climate processes in both hemispheres as well as to external radiative forcing. However, the relatively smooth character of the warm pool's hydrological variability over the past 27,000 yr suggests a limited potential for large, abrupt changes in the character of tropical Pacific variability. Nonetheless, by gradually altering the heat and salt budgets of the global oceans, the tropical Pacific may have a pivotal role in driving thermohaline circulation changes associated with abrupt climate change events. Whether the tropical Pacific coupled system acts as an amplifier or a trigger of internal global climate variability, its feedbacks on the global climate system must be an integral part of any climate change mechanism, natural or anthropogenic.

METHODS SUMMARY

U-series samples weighing 100–500 mg were drilled with a 1.6 mm drill bit parallel to growth banding. Each sample was dissolved and spiked with a mixed ^{236}U–^{229}Th solution before the separation of U and Th using standard techniques. The isotopic compositions of the U and Th fractions were measured using a Finnigan 'Neptune' MC-ICPMS at Caltech (see Methods and Supplementary Information). Relatively low ^{238}U concentrations (0.1–0.5 p.p.m.) combined with low $\delta^{234}U$ values (−100‰ to −600‰) and high detrital ^{232}Th concentrations result in U–Th age uncertainties of 0.3–2% (2σ) (see Supplementary Information). We account for initial ^{230}Th using the measured ^{232}Th content and estimates of detrital $^{230}Th/^{232}Th$ ratios ($\sim(60–120) \times 10^{-6}$ atomic ratio) obtained from 11 isochrons. All three stalagmites contain multiple hiatuses that are associated with visible bands and high ^{232}Th concentrations. Larger hiatuses are closely bracketed by U-series dates, but shorter and/or adjacent hiatuses can not be accurately resolved with U-series sampling. Slow-growing ($<10\ \mu m\ yr^{-1}$) portions of the stalagmites probably contain unresolved hiatuses (supported by high ^{232}Th concentrations measured in these regions), and reflect large chronological uncertainties (up to 1,000 yr in the case that a hiatus is poorly constrained by high-^{232}Th dates). Stalagmite $\delta^{18}O$ data were assigned calendar ages based on a linear interpolation between each pair of U-series dates.

Oxygen isotopic analyses were conducted on powders drilled every 1 mm along the central growth axis of the stalagmites with a 1.6 mm drill bit. The $\delta^{18}O$ of BA04 and SSC01 powders were measured using a GV Isoprime-Multiprep located at Georgia Tech (long-term reproducibility of ±0.05‰). SCH02 $\delta^{18}O$ profiles were analysed on a Finnigan 253 equipped with a Kiel device located at Wood's Hole Oceanographic Institute (long-term reproducibility of ±0.08‰). All $\delta^{18}O$ data are reported with respect to VPDB.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Information The stalagmite $\delta^{18}O$ data can be downloaded at http://www.ncdc.noaa.gov/paleo/pubs/partin2007/partin2007.html. Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to J.W.P. (jpartin@eas.gatech.edu).

METHODS

U-series dating. U-series dating of carbonates has been an important part of constraining past climate for decades. With the advance of U and Th isotope detection by mass spectrometry instead of alpha particle counting, sample sizes were shrunk while also improving precision[32]. Stalagmites tend to have lower ^{238}U concentrations than corals but higher ^{234}U/^{238}U ratios[33]. Our tropical stalagmites have low ^{238}U, low ^{234}U/^{238}U ratios and relatively high detrital ^{232}Th. These features make radiogenic age constraints especially challenging in our samples. Sample BA04 has 1–2 p.p.m. ^{238}U, about −600‰ δ^{234}U, and 1–100 pmol g^{-1} ^{232}Th. Sample SCH02 has 0.3–0.9 p.p.m. ^{238}U, about −350‰ δ^{234}U, and 1–15 pmol g^{-1} ^{232}Th. Sample SSC01 has 0.1–0.3 p.p.m. ^{238}U, about −100‰ δ^{234}U, and 0.3–3 pmol g^{-1} ^{232}Th.

We drilled 100–500 mg samples from time synchronous bands along the growth axis of all three stalagmites. Samples were dissolved and spiked with a mixed ^{236}U and ^{229}Th solution[34]. U and Th isotopes were separated and purified by traditional methods[35] and measured on a Finnigan 'Neptune' MC-ICP-MS at Caltech. The U fraction was tested for the U concentration and diluted to match intensities of all samples. ^{234}U was measured on the centre SEM with ^{235}U and ^{238}U on separate Faraday cups. ^{229}Th and ^{230}Th were measured on the MICs attached to Faraday cup L4 and ^{232}Th was measured in this cup. For both U and Th, samples were bracketed with known ratio standards, CRM-145 for U and an in-house spiked gravimetric standard for Th. With samples of ~100 ng ^{238}U we can measure the ^{229}Th/^{230}Th ratio to 1–2‰ (2σ) and the ^{234}U/^{238}U ratio to better than 0.5‰.

Hendy tests. Powders were drilled along a single growth layer to measure the δ^{18}O and δ^{13}C variability as a function of distance from the stalagmites' central growth axes, in order to quantify potential effects of kinetic fractionation[19]. Isotopic values are plotted as departures from central axes values in Supplementary Fig. 9. Negative distances correspond to samples drilled to the left of the central axis, and positive distances represent samples drilled to the right of the central axis. Non-equilibrium CO_2 degassing on the surface of the stalagmite would result in kinetic fractionation of oxygen and carbon isotopes and isotopic enrichments off-axis. Such kinetic fractionation might explain the weak correlation between δ^{18}O and δ^{13}C variability across single growth layers of the Borneo stalagmites (Supplementary Fig. 10). However, our Hendy analyses suggest that kinetic fractionation accounts for no more than ~0.5‰ of the δ^{18}O variability observed in the down-core stalagmite δ^{18}O records. Furthermore, the fact that the three Borneo stalagmite δ^{18}O records exhibit strong millennial-scale reproducibility confirms that rainfall δ^{18}O variations are the likely source of their shared millennial-scale δ^{18}O variability.

Cave locations. Samples SSC01 and SCH02 originate from Snail Shell cave (4° 12′ 20.8″ N, 114° 56′ 26.9″ E). They formed ~250 m from the cave entrance and ~20 m from each other. Sample BA04 originates from Bukit Assam (4° 15′ 18″ N, 114° 57′ 34″ E), which lies ~6 km NNE from Snail Shell Cave. BA04 formed >500 m from the cave entrance.

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