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Stable isotope composition of cave guano from eastern Borneo reveals tropical environments over the past 15,000 cal yr BP

Christopher M. Wurster [a,*], Hamdi Rifai [b], Jordahna Haig [a], Jupiri Titin [c], Geraldine Jacobsen [d], Michael Bird [a]

[a] College of Science and Engineering, and Centre for Tropical Environmental and Sustainability Science, James Cook University, Cairns, QLD 4870, Australia
[b] Department of Physics Faculty of Mathematics and Natural Sciences, Padang State University, Padang 25131, Indonesia
[c] Forest Research Centre, Sabah Forestry Department, 90715 Sandakan, Sabah, Malaysia
[d] Australian Nuclear Science and Technology Organisation (ANSTO), Kirrawee DC, NSW 2232, Australia

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ABSTRACT

Insular southeast Asia is a key driver for global atmospheric and oceanic circulation, is a hotspot for biodiversity and conservation, and is likely to have played a unique and important role in early human dispersals. Despite this, partially due to its vast size and remote tropical location, very few continuous palaeoenvironmental records exist, especially in eastern Borneo. Therefore, we investigated $\delta^{13}C$ and $\delta^{15}N$ values, and geochemistry of two cave guano deposits to reconstruct palaeoenvironments in eastern Borneo. Firstly, a profile was recovered from Gomantong caves, Sabah, reflecting a continuous deposit over ~15 cal kyr BP. Secondly, a profile was recovered from Bau Bau cave, East Kalimantan, that ranged from ~15–5 cal kyr BP. The geochemical signature of each deposit confirmed the material to be ancient guano. $\delta^{13}C$ values revealed that a continuous dense rainforest persisted over at least the last 15 cal kyr BP around the Gomantong site that was relatively insensitive to regional climate change. By contrast, $\delta^{13}C$ values at Bau Bau indicate that, although rainforest remained dominant in the record, a significant drying occurred between 7.7 and 6.3 cal kyr BP, with up to 25% grasses present. Although most regional models suggest that sea-level rise and increased Holocene insolation led to an increase in monsoonal moisture, we find some evidence of more regional variability, and that a reduction in monsoonal precipitation could have occurred. However, we cannot discount the implementation of an anthropogenic fire regime that opened the canopy allowing more grasses to occur.

1. Introduction

In caves throughout the world, bats roosting in large numbers produce copious amounts of faecal material (guano) (e.g., Mizutani et al., 1992; McFarlane et al., 2002), that can accumulate over millennia (e.g., Wurster et al., 2010a; Wurster et al., 2010b). Throughout southeast Asia, swiftlets (*Aerodramus* sp.) also inhabit caves in large numbers and contribute substantially to cave guano accumulations (Bird et al., 2007). Faecal input is modified by bacteria and fungi, reactions with cave material and authigenic inputs, (Shahack-Gross et al., 2004; Wurster et al., 2015), while also supporting a guano-based fauna (e.g., Ferreira et al., 2007; Iskali and Zhang, 2015). After processing and removal of much of the organic component, residual 'rock' guano at depth consists largely of clay and phosphate minerals, as well as detrital material such as quartz, and a trace metal signature enriched in transition metals (Shahack-Gross et al., 2004; Onac and Forti, 2011; Wurster et al., 2015). These deposits are often located in regions where there is a general lack of complimentary palaeoclimate records, and elucidate past environmental conditions where there are few other proxy records (Wurster et al., 2008; Wurster et al., 2010b; Onac et al., 2014).

Although several new studies have demonstrated that guano is a valid and powerful palaeoenvironmental archive, it is still relatively unexploited. Recent work has shown its suitability to provide past environmental proxies to a range of broad environments including tropical (Bird et al., 2007; Wurster et al., 2010a), semi-arid (Wurster et al., 2008, 2010b) and temperate locations (Onac et al., 2014, 2015; Forray et al., 2015; Widga and Colburn, 2015). Pollen (Maher, 2006; Batina and Reese, 2011; Onac et al., 2015; Forray et al., 2015), geochemistry (Bird et al., 2007; Johnston et al., 2010; Wurster et al., 2015) and stable isotope ratios of carbon and hydrogen (Bird et al., 2007, Wurster et al., 2008, 2010b; Onac et al., 2014, 2015; Forray et al., 2015), have been successfully exploited. Moreover, archaeological evidence is often found in caves that contain considerable guano deposits (e.g., Karkanas et al.,

* Corresponding author.
E-mail address: Christopher.wurster@jcu.edu.au (C.M. Wurster).

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2002; Shahack-Gross et al., 2004; Campbell et al., 2017) potentially enabling a direct comparison between environmental change and human adaptation. Arguably, $\delta^{13}C$ values are the most powerful proxy for past environments that can be obtained from tropical guano records.

In tropical environments, grasses dominantly utilise Hatch-Slack (C4) photosynthesis; whereas trees and woody vegetation exclusively utilise the Calvin cycle (C3) photosynthesis (Bird and Pousai, 1997; Ehleringer et al., 1997). These different enzymatic pathways of carbon fixation result in $\delta^{13}C$ values of C4 plants (−9 to −16‰) that are distinct when compared with C3 plants (−19 to −34‰) (Ehleringer and Cerling, 2002). Moreover, significant variability in individual plant $\delta^{13}C$ values are considerably reduced at the regional level (Randerson et al., 2005). Insect abundance is largely determined by available vegetation (Pinder and Kroh, 1987; Warren and Gaston, 1992), and insect $\delta^{13}C$ values are determined by diet with little fractionation (Webb et al., 1998; Gratton and Forbes, 2006). An integrated measure of insect cuticle, $\delta^{13}C$ value is therefore a strong indicator of vegetation type at the regional level. It has further been demonstrated that the $\delta^{13}C$ values of guano from insectivorous bats largely consists of insect cuticles and directly reflect the relative abundance of C4 vegetation in a region via $\delta^{13}C$ values (Sullivan et al., 2006; Wurster et al., 2007). Communities of bats and swiftlets generally forage within a 15 km range of the roost (e.g., Zahn et al., 2005), although long-range foragers including wrinkle-lipped bats (*Chaerephon plicatus*) may travel as long as 80 km (Stimpson, 2012), ensuring that a local to regional signal is captured in the guano deposit. Guano deposits from insular Southeast Asia have been demonstrated to provide important records of vegetation change via $\delta^{13}C$ profiles in a region where few additional records currently exist (Bird et al., 2007; Wurster et al., 2010b; Wurster and Bird, 2016).

The nature of glacial to interglacial climate and vegetation change experienced in insular southeast Asia is currently a topic of debate, and not even the general vegetation type present during the Last Glacial Maximum (LGM, 23-19 cal kyr BP) are known unequivocally (Wurster and Bird, 2016). During the Last Glacial Period (LGP, 110-11.7 cal kyr BP), reduced global sea level exposed the continental shelf from south of Thailand to Sumatra, Java, and Borneo, revealing the contiguous continent 'Sundaland' (Bird et al., 2005), and some of these land connections remained until well into the Holocene (Bird et al., 2010). Forest reduction during the LGM has been demonstrated for Palawan and Peninsular Malaysia (Wurster et al., 2010a) in the north, and similarly drier conditions have been reported in the south during the LGM and Antarctic Cold Reversal (ACR, 15-12.9 cal kyr BP) (Dubois et al., 2014; Wurster and Bird, 2016). However, climate modelling (Cannon et al., 2009) and dipterocarp species distribution models (Raes et al., 2014) along with offshore pollen (Wang et al., 2009) have suggested that much of Sundaland remained tropical rainforest and humid during the LGM.

Eastern Borneo has relatively little environmental information over the Late Pleistocene and Holocene, despite it being reputed as a possible refuge for rainforest specialists (Wurster and Bird, 2016), and despite having a unique and rich archaeological context including prehistoric paintings dating to the upper Pleistocene (Plagnes et al., 2003; Grenet et al., 2016). The environment surrounding Niah Cave is thought to have remained forested throughout the LGP and beyond, and has been inferred to be a rainforest refugium, however the extent of this refugium is not known (Bird et al., 2005; Wurster et al., 2010a; Wurster and Bird, 2016). Archaeological work in East Kalimantan showed that lithic industries changed little over the Pleistocene/Holocene transition; one interpretation of this stability is that climate and environments remained stable in the region (Grenet et al., 2016). However, there are no well-dated and unambiguous environmental records of past environments during the Pleistocene/Holocene transition in eastern Borneo (Wurster and Bird, 2016), the nearest being in northern Borneo to the north (Wurster et al., 2010a; Dubois et al., 2014), or Sulawesi to the east (Russell et al., 2014).

Herein we present the stable isotope composition and geochemistry from two new cave guano profiles sampled in eastern Borneo: Gomantong in Sabah, Malaysia (5°32′60″N, 118° 5′60″E) and Bau Bau (0°55′0″S, 117°13′11″E) along the Bungalun River in East Kalimantan, Indonesia (Fig. 1). Both records have higher deposition rates than previously reported for insular Southeast Asian tropical guano (Wurster et al., 2010a), and provide a ~15 cal kyr BP history of tropical environments in these regions over the Pleistocene/Holocene transition.

2. Methods

2.1. Study area and sampling

Surface and ancient 'rock guano' (at depth) were collected from three sites along the eastern edge of Borneo (Fig. 1). From Sabah, Malaysia, a 1.8-m-deep guano profile derived from both insectivorous bats and *Aerodramus* sp. was collected from *Simud Puteh* Cave in the centre of Pandandanan Chamber (GOM-SP-P) (5°32′60″N, 118° 5′60″E) in Gomantong Forest Reserve. Gomantong caves are located on Gomantong Hill, an isolated limestone outcrop on the flood plain of the Menugai River (Lundberg and McFarlane, 2012). Gomantong consists of two caves systems that also separate the major species of swiftlet present. *Simud hitam* houses the black-nest swiftlet (*Aerodramus maximus*), and *Simud puteh*, where the guano was collected for this study, houses the white-nest swiftlet (*Aerodramus fuciphagus*). The total population of bats is estimated at one million, with a similar sized population of swiftlets. The wrinkle lipped bat (*Chaerephon plicata*) is the dominant bat species, but *Hipposideros cervinus, Rhinonolophus philippinensis, Rhinolphus boneeis*, and *R. creaghi*, and *Myotis gomantongensis* are present (Lundberg and McFarlane, 2012 and references therein). Further south, in East Kalimantan, Indonesia, we collected two profiles, 0.9 m (BBA) and 2.6 m (BBB), from Bau Bau Cave (0°55′0″S, 117°13′11″E) that contained unidentified insectivorous bats (Fig. 1). Bau Bau Cave is located along the Bungalun river in the mountainous Mangkalihat Peninsula. Here, limestone outcrops are generally located between 300 and 700 m above sea level (Plagnes et al., 2003).

Both sites were located in limestone caves, and were sampled from pits excavated through the accumulated guano to bedrock in each case except Bau Bau B, where time permitted excavation only to the depth presented. At each deposit, exposed sediments were sampled at 3–5 cm intervals, adjusted where necessary to ensure that sample intervals did not cross stratigraphic boundaries. Samples were kept in a cold store at 4 °C until freeze-dried.

2.2. Geochemical analysis

A distribution of selected elements for samples taken at Gomantong was generated using a Spectro X-Lab EDP X-ray Fluorescence (XRF) using polarised X-rays on pulverised and pelletized samples, and calibrated using a mix of NIST, USGS, ANRT-CRPG and BCS standards, and a selection of these have been previously described (Wurster et al., 2015). This technique has been applied for the rapid and non-destructive analysis of 30 elements in organic-rich substrates (Stephens and Calder, 2004). A similar distribution of elements were measured on a selection of samples from Bau Bau using a Bruker-AXS S4 Pioneer XRF on pulverised and pelletised samples using semi- quantitative approach at the Advanced Analytical Centre, James Cook University, with error estimated at ±5% of the value.

Principal Component Analysis (PCA) was performed on normalized data using Gigawiz Aabel 3.0 software. The PCA enabled the identification of the samples that are most similar and dissimilar, and components responsible for most of the observed variation.