Chemical Geology 357 (2013) 8–17

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Multi-proxy evidence for human-induced deforestation and cultivation from a late Holocene stalagmite from middle Java, Indonesia

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ARTICLE INFO

Article history:
Received 22 December 2012
Received in revised form 13 August 2013
Accepted 14 August 2013
Available online 20 August 2013

Editor: U. Brand

Keywords:
Speleothems
Stable isotopes
Trace elements
PCP
Anthropogenic impact
Late Holocene

ABSTRACT

Speleothem multi-proxy records have proved highly useful in reconstructing past changes in climatic and environmental conditions as well as karst processes, and in distinguishing between the numerous potential driving forces that influence these proxies. There is lack of such terrestrial proxies from the tropical Indo-Pacific. For the first time, we present an annual- to decadal-scale multi-proxy record of 377 samples including stable isotopes ($\delta^{18}O$, $\delta^{13}C$) and trace elements (Mg/Ca, Sr/Ca) from a Holocene calcite stalagmite from Bribin Cave, Gunung Kidul regency, middle Java, Indonesia that has grown over the last 4000 years (11 ^{230}Th dates). $\delta^{18}O$ values average −7‰ with high-frequency variability of up to 1‰, and hint at relatively stable overall climatic conditions in the tropical Indo-Pacific region during the late Holocene. The $\delta^{13}C$ values of stalagmite JB2 are low (~−13‰) at the beginning of the record suggesting a C3-dominated rainforest cover. Strong positive covariation with Mg/Ca and Sr/Ca ratios is a stringent indication of a dominant natural control by prior calcite precipitation and water–rock interaction. However, $\delta^{13}C$ values increase dramatically by ~4‰ from ~1.1 ka to ~0.5 ka, clear evidence of an anthropogenic influence through deforestation and cultivation.

1. Introduction

Although studies of past climatic and environmental conditions based on speleothems have already added substantially to our understanding of the environmental system, there is still a gap in terrestrial proxy records from the tropics (McDermott, 2004). This applies in particular to proxies other than $\delta^{18}O$, and this study will add further important information to help close these gaps by providing the first multi-proxy stalagmite (JB2) record ($\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Sr/Ca) on middle Java, Indonesia.

Palaeoenvironmental research already conducted in this region of Indonesia is not very extensive. With their oxygen isotope studies on stalagmites from Flores (Fig. 1), Griffiths et al. (2009) have established a basis for a reconstruction of Holocene regional rainfall in response to changes in monsoon intensity and meridional shifts of the ITCZ.

On the contrary, most information available on the evolution of the terrestrial environment of Java Island stems from studies on lacustrine sediments that include analyses of diatoms, pollen, micro-charcoal, phytoliths and sediment lamination and mineralogy (Sémah et al., 1992; van der Kaars et al., 2000; Pudjoarinto and Cushing, 2001; Chacornac-Rault, 2005; Purnomo, 2007; Robles, 2007). These studies draw a rather complex picture of late Holocene variation in vegetational composition on Java resulting from natural processes and anthropogenic impact. In many cases, uncertainty remains whether changes in vegetation cover have been natural or human induced, which makes it impossible to confidently assess the onset and extent of human intervention.

Stalagmite records are suited to help solve these problems and to complement the sedimentological findings for several reasons. Age reversals do not occur and age uncertainties are usually low so that a wide variety of geochemical variables can be tied to a robust and highly resolved chronology (Fairchild I.J. et al., 2006). The analysis of speleothem carbon isotopes may yield information on past variations in vegetation density within the surface catchment of the drip site, which adds to data on vegetation composition deduced from sedimentological research. As pollen-rich deposits (lacustrine and peat) are relatively rare on Indonesian islands (Pudjoarinto and Cushing, 2001), speleothem data are all the more valuable to complete the environmental record. Finally, multi-proxy speleothem records in particular can help distinguish between natural and anthropogenic processes, simply by following the principle of exclusion. The proxy indicators used in this study ($\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Sr/Ca) are discussed in the following.

Speleothem carbon isotope composition depends on the relative contributions of the two main carbon sources, i.e. soil gas CO_2 and

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http://dx.doi.org/10.1016/j.chemgeo.2013.08.026

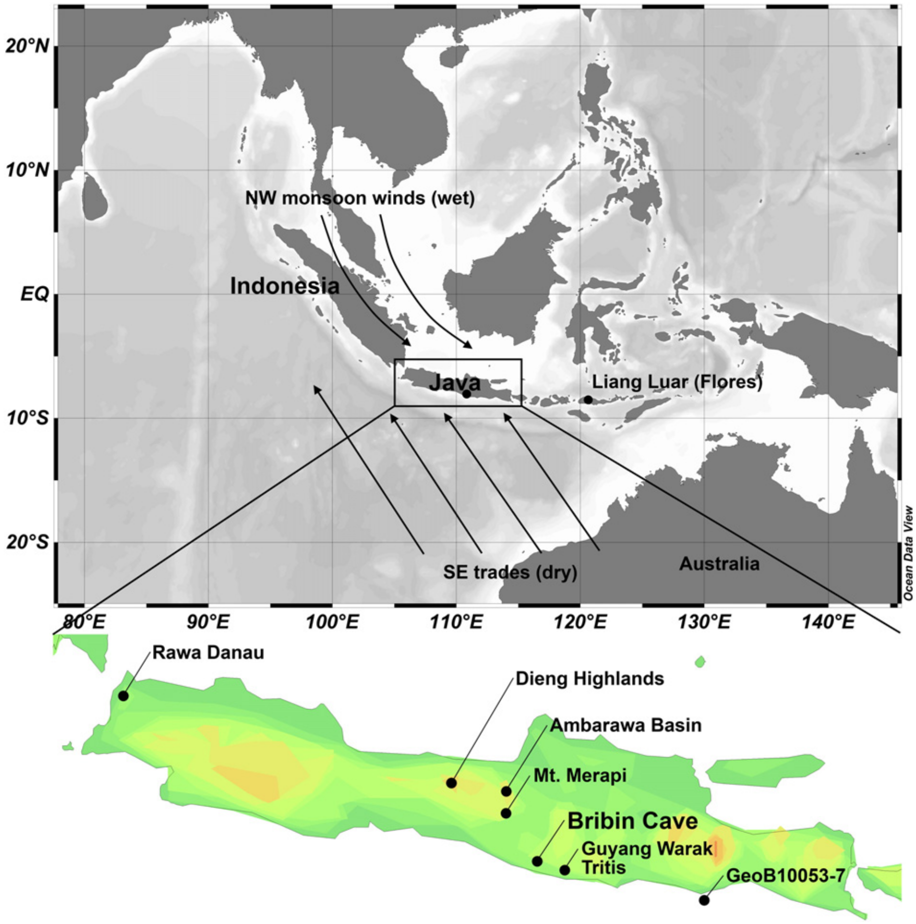

Fig. 1. Location of Java and Bribin Cave. Bribin Cave lies ~500 m above sea level on the southern coast of middle Java. Also indicated are sites studied by other authors: Cave Liang Luar on Flores Island (Griffiths et al., 2009), Rawa Danau (van der Kaars et al., 2000), Dieng Highlands (Pudjoarinto and Cushing, 2001), lake Tritis (Chacornac-Rault, 2005), lake Guyang Warak (Purnomo, 2007) and sediment core GeoB 10053-7 (Mohtadi et al., 2011). Arrows schematically illustrate the main wind direction during wet and dry seasons of the AISM.

bedrock carbonate (Hendy, 1971), on conditions that alter these contributions, such as open versus closed system dissolution of carbonate bedrock (Hendy, 1971) and isotopic disequilibrium between soil water and soil CO_2, and on local inorganic processes, such as prior calcite precipitation (PCP) in the karst system above the cave (Baker et al., 1997), evaporation in the cave, and CO_2 degassing from drip water depending on drip rate or ambient cave air pCO_2 (Spötl et al., 2005; Mattey et al., 2008).

Whereas atmospheric CO_2 ($\delta^{13}C$ ~ −8‰; all values indicated relative to the Pee Dee Belemnite standard — PDB) and bedrock carbonate ($\delta^{13}C$ ~0‰ on average for those of marine origin) are isotopically relatively heavy and quasi-constant (Darling et al., 2006), soil CO_2 is isotopically light due to discrimination of ^{13}C during photosynthesis, and its mean $\delta^{13}C$ value varies with vegetation type.

Whereas the organic matter of C3 plants (most trees; Darling et al., 2006) features $\delta^{13}C$ values between −20‰ and −34‰ with an average of −26‰ (Schwarcz, 1986; Cerling et al., 1991), the biomass of C4 plants (mostly tropical and savannah grasses) exhibits $\delta^{13}C$ values between −9‰ and −16‰ (PDB) with an average of −13‰ (Schwarcz, 1986; Cerling et al., 1991). Speleothems associated with these different plant assemblages show $\delta^{13}C$ values from −14‰ to −6‰, and from −6‰ to +2‰ (McDermott, 2004), respectively. Because of these large differences related to the dominating photosynthetic pathway, speleothem $\delta^{13}C$ values are suitable to indicate past variations in vegetation composition above the cave (e.g. Dorale et al., 1992; Bar-Matthews et al., 1996).

As the contribution of atmospheric CO_2 to groundwater is often negligible, speleothem carbon isotopes reflect a mass balance between soil and bedrock carbon sources. Genty and Massault (1999) and Genty et al. (2001) have demonstrated that 80 to 90% of the carbon in the carbonate of most temperate speleothems originates from soil CO_2 which explains the sensitiveness of speleothem $\delta^{13}C$ to changes in surface vegetation. Therefore, speleothem $\delta^{13}C$ also depends on vegetation density and the productivity of the soil microbial communities that transform organic matter to CO_2 by decomposition, as both factors influence the available amount of soil carbon.

As vegetation type, density and soil microbial productivity depend on climate, particularly on temperature and precipitation, climate is an important driver of speleothem $\delta^{13}C$ values. In general terms, warm and wet conditions enhance ecosystem productivity, which results in an increased contribution of isotopically light soil CO_2 and, thus, in decreased $\delta^{13}C$ values in speleothems (e.g. Hellstrom et al., 1998; Genty et al., 2010).

Degassing of CO_2 from groundwater can happen before drip water emergence in the cave leading to PCP along the flow path within the vadose zone above the cave. As ^{13}C is discriminated during degassing, the percolating water becomes progressively enriched in heavy isotopes and corresponding speleothem carbonate $\delta^{13}C$ values are increased (Baker et al., 1997). As PCP requires aerated zones in the aquifer with lower pCO_2 for degassing of descending karst waters, it can be associated with periods of reduced meteoric infiltration along the flow paths and/or enhanced ventilation of the cave and aquifer cavities (Mattey