Earth and Planetary Science Letters 275 (2008) 54–60

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in Amazonia

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ARTICLE INFO

Article history:
Received 21 May 2008
Received in revised form 30 July 2008
Accepted 31 July 2008
Available online 20 September 2008

Editor: P. DeMenocal

Keywords:
speleothem
fluid inclusions
stable isotope
South America

ABSTRACT

Most proxy records used for reconstruction of Holocene climate of Amazonia are unable to quantitatively distinguish between the effect of temperature and rainfall amounts.

We present a new isotope technique applied to a ~13,500 yr stalagmite archive from Peruvian Amazonia. By analysing the coupled isotope composition of fossil dripwater trapped in stalagmite fluid inclusions, and that of the calcite hosting the fluid inclusions, we were able to calculate independent paleotemperatures and rainfall amounts.

This stalagmite record shows that Holocene climate variation was controlled by orbitally-forced Southward migration of the Inter Tropical Convergence Zone. While temperature remained constant, isotope variation of rainwater, reflected in fluid inclusion water $\delta^{18}O$ composition, suggests a ~15–30% increase in convective rainfall through the Holocene.

A comparison of the low-land Peruvian fluid inclusion record with the high Andean Huascaran ice core record shows a constant ~12‰ offset of $\delta^{18}O$ curves for the Holocene, suggesting that Andean vertical temperature gradients (lapse rates) did not vary much over the last 9000 years. During the Younger Dryas interval, however, the offset of $\delta^{18}O$ values was much higher than in the Holocene. This may be attributed to a relative drop in air temperatures in the highlands (higher lapse rate), caused by long distance teleconnections to climate perturbations in the North Atlantic.

In a wider perspective, fluid inclusion isotope analysis drastically improves paleotemperature reconstructions based on speleothem calcite $\delta^{18}O$ data, because it provides the $\delta^{18}O$ value of drip water through time, which is usually the most important unknown in paleotemperature equations.

1. Introduction

The climate history of the Amazon Basin has been studied intensively over the last decades, with particular focus on Glacial-Interglacial variability, and its effect on biodiversity in Amazonia (Hooghiemstra and van der Hammen, 1998). Of crucial importance for our understanding of the relation between climate and biodiversity is our ability to quantitatively determine temperature and rainfall variation in space and time. However, nearly all currently applied climate proxy records in Amazonia are affected by temperature as well as rainfall amounts (Hooghiemstra and van der Hammen, 1998; Thompson et al., 2000). This is particularly limiting for the interpretation of high-resolution stable isotope climate records, like ice cores (Thompson et al., 1995, 2000; Ramirez et al., 2003), lacustrine calcite (Seltzer et al., 2000) and speleothems (Cruz et al., 2005). While these isotope records are highly valuable for our understanding of high resolution Holocene climate variation, quantification of the variation of temperature relative to rainfall amounts remains problematic.

Here, we present new speleothem-based isotope records from Peruvian Amazonia, which allow quantification of the effect of temperature and rainfall amounts on isotope signals in Amazonia. Of pivotal importance in the present study is the application of a technique to analyze the stable isotope composition of fossil dripwater trapped as fluid inclusions in speleothem calcite (Vonhof et al., 2006, 2007).

Speleothems (stalagmites) commonly contain microscopic water-filled cavities. These so-called fluid inclusions are filled with cave drip water from the time of formation of the relevant speleothem growth increment (Schwarcz et al., 1976; Harmon et al., 1979). It has been established that cave drip water, and thus fluid inclusion water, is isotopically identical to local rainwater (for δ^2H and $\delta^{18}O$; Caballero et al., 1996; McDermott et al., 2006). In arid regions cave drip water may deviate from rainwater due to evaporation. However, this is not likely to be the case in the humid tropical climate of our study area.

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doi:10.1016/j.epsl.2008.07.060

Speleothem calcite hosting the fluid inclusions can be dated at high precision by Uranium-series chronology (Richards and Dorale, 2003; McDermott et al., 2006).

Stable isotope records from speleothem calcite are commonly used as paleoclimate proxy (Bar-Matthews et al., 1999; Wang et al., 2001; Fleitmann et al., 2003; Genty et al., 2003; Yuan et al., 2004; Cruz et al., 2005; Wang et al., 2005). It is a powerful tool, because a wide variety of climate phenomena like El Niño events (Frappier et al., 2002), the Little Ice Age (Holmgren et al., 1999), the Younger Dryas (Bar-Matthews et al., 1999; Yuan et al., 2004; Vacco et al., 2005; Genty et al., 2006) and Dansgaard Oeschger events (Wang et al., 2001; Genty et al., 2003) are recognised in these isotope records. Oxygen isotope records of carbonates are commonly used as a direct paleotemperature proxy, because at known $\delta^{18}O$ values of formation water and calcite that forms from it, the temperature of calcite formation can be calculated (Epstein et al., 1953; Craig, 1965; Kim and O'Neil, 1997). This proxy system is based on the known temperature dependency of oxygen isotope fractionation between calcite and the water in which the calcite precipitates. The most important limitation for the application of this proxy to calculate paleotemperatures concerns the uncertainty on the assumed $\delta^{18}O$ value of past formation water. For marine records, this is not too much of a problem because past $\delta^{18}O$ variation in the oceans is limited, and relatively well understood (Shackleton and Opdyke, 1973). However, for continental records like speleothems, climate change affects drip water isotope composition in a less predictable way. Therefore, quantification of the contribution of temperature to speleothem $\delta^{18}O$ records is impossible based on the $\delta^{18}O$ value of the speleothem calcite alone (Hendy and Wilson, 1968; Harmon et al., 1978; Schwarcz and Yonge, 1983; Fairchild et al., 2006).

The ability to analyse stalagmite fluid inclusion $\delta^{18}O$ values eliminates the uncertainty associated with reconstruction of drip water $\delta^{18}O$ values back in time, and thus allows for the reconstruction of independent speleothem growth temperatures based on paired fluid inclusion and host $CaCO_3$ $\delta^{18}O$ values. Since drip water isotope composition is believed to reflect that of rainfall recharging the cave aquifer, fluid inclusion isotope values in stalagmites furthermore provide temporal records of rainfall isotope variation which can be related to changing rainfall patterns through time (McDermott et al., 2006; Vonhof et al., 2006).

2. Results

We analysed $\delta^{18}O$ values of fluid inclusions and host calcite of speleothems collected in the Cueva del Tigre Perdido near the town of Nueva Cajamarca in the Peruvian district San Martín (Fig. 1). This cave lies in a densely vegetated area in the foothills of the Andes, at ~1000 meter above sealevel. The composite record consists of two stalagmites, with an age model based on 15 TIMS U-series ages from the lab of VU University Amsterdam, and 5 additional MC-ICP-MS ages from the lab of Melbourne University (Fig. 2, Table 1; see also the additional material). A high-resolution $\delta^{18}O$ record of speleothem calcite shows a long cycle through the Holocene (Fig. 3), with an amplitude of ~2‰.

Petrographic analysis of both speleothems studied, reveals the presence of abundant fluid inclusions in speleothem calcite (Fig. 4). Speleothem mineralogy and fluid inclusions are interpreted to be primary, which leads us to conclude that fluid inclusion isotope composition is undisturbed since the time of formation.

A total of 18 cubes of speleothem calcite, weighing ~0.3 g each, were cut from a central slab of the stalagmites, crushed, and the liberated inclusion water analyzed for δ^2H and $\delta^{18}O$, applying the technique described by Vonhof et al. (2006, 2007).

Results show ~15‰ variation in δ^2H values and ~2‰ in $\delta^{18}O$ values. δ^2H values of the youngest part of the stalagmite record plot at approximately −42‰ (SMOW) which is in reasonably good agreement with the −46‰ value analysed for some local rain-showers and from the river that runs through the cave. $\delta^{18}O$ and δ^2H values combined plot on the Global Meteoric Water Line (GMWL; Fig. 5). Since modern rainwater isotope data for Amazonia generally plot on the GMWL (Gat and Matsui, 1991), this observation provides further support for the excellent preservation of the original isotope composition of fluid inclusion water in these speleothems, P post-depositional changes in the fluid inclusion water isotope composition would have driven the water away from the GMWL. Three cubes, however, gave isotope values that plotted away from the GMWL. These were samples with a low water yield (<0.1 µl), resulting in erroneous $\delta^{18}O$ values, as was confirmed by

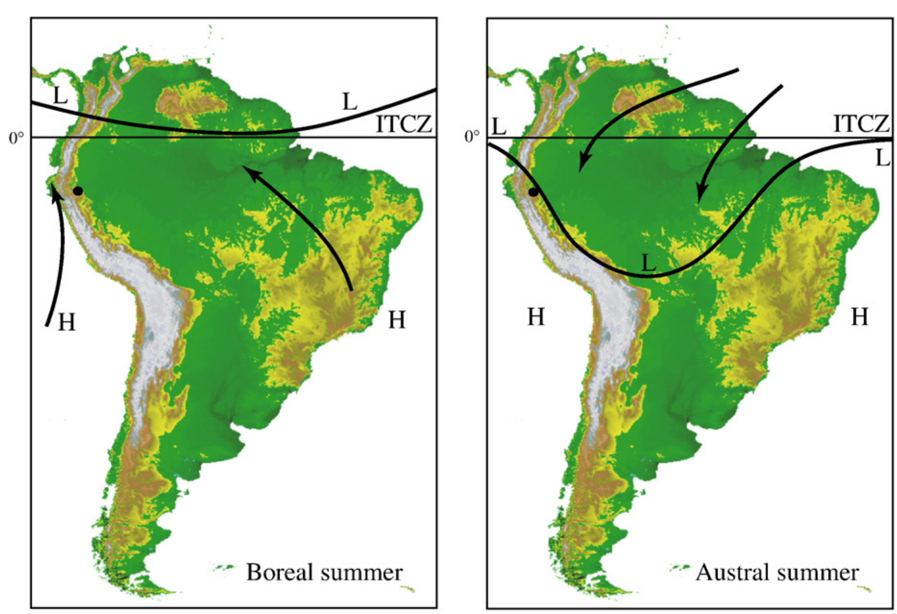

Fig. 1. Map of South America showing the generalized position of the Inter Tropical Convergence Zone (ITCZ; black line) during Boreal summer (July) and Austral summer (January). The black dot marks the position of Cueva del Tigre Perdido, which lies under the ITCZ in Austral summer. Arrows indicate the prevailing wind direction, during the season. "H"and "L indicate the position of high- and low pressure areas.