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Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies

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The tropics are the main source of the atmosphere's sensible and latent heat, and water vapour, and are therefore important for reconstructions of past climate[1]. But long, accurately dated records of southern tropical palaeoclimate, which would allow the establishment of climatic connections to distant regions, have not been available. Here we present a 210,000-year (210-kyr) record of wet periods in tropical northeastern Brazil—a region that is currently semi-arid. The record is obtained from speleothems and travertine deposits that are accurately dated using the U/Th method. We find wet periods that are synchronous with periods of weak East Asian summer monsoons[2], cold periods in Greenland[3], Heinrich events in the North Atlantic[4] and periods of decreased river runoff to the Cariaco basin[5]. We infer that the wet periods may be explained with a southward displacement of the Intertropical Convergence Zone. This widespread synchroneity of climate anomalies suggests a relatively rapid global reorganization of the ocean–atmosphere system. We conclude that the wet periods probably affected rainforest distribution, as plant fossils show that forest expansion occurred during these intermittent wet intervals, and opened a forest corridor[6–8] between the Amazonian and Atlantic rainforests.

The study area is in northern Bahia state (10° 10′ S, 40° 50′ W; 500 m above sea level), the centre of the drought-prone semi-arid region of northeastern Brazil, 500 km west of the tropical Atlantic (Fig. 1). Mean annual temperature is 28 °C with seasonal variations <2 °C. Average annual rainfall is $\sim$490 mm with high seasonality and a net moisture deficit caused by high potential evapotranspiration rates ($>$1,400 mm). Modern vegetation comprises shrub-like drought-resistant caatinga. The area is characterized by a well-developed underground karst containing some of the longest caves in the Southern Hemisphere, such as the 105-km-long Toca da Boa Vista (TBV).

Calcite speleothems were collected from TBV, Lapa dos Brejões (LBR) and Toca da Barriguda (TBR) caves (see Methods), and travertine deposits were collected from the surrounding Salitre and Jacaré river valleys. As in semi-arid southeastern Australia[9], low rainfall and high evapotranspiration in northeastern Brazil preclude speleothem and travertine deposition during dry intervals such as today. Therefore, speleothem and travertine formation unequivocally indicates wetter conditions in the past. Travertine surface deposits may be generated by relatively small increases in rainfall, as rainfall directly feeds bicarbonate-rich surface runoff. For speleothems to precipitate, however, soil and bedrock infiltration thresholds must be overcome; hence speleothem growth phases probably correspond to high rainfall periods. Wetter climates in the past were suggested by geological and geomorphological evidence from northeastern Brazil[10] and ocean sediment records off the continental margin of northeastern Brazil[11]. However, the chronological resolution of the data limited detailed correlation with climate elsewhere. Here, we further constrain the timing of past pluvial phases in northeastern Brazil by systematic sampling and high-precision mass spectrometric ^{230}Th dating of growth phases of multi- and single-phase speleothems and travertines (see Methods).

Fifty-four ^{230}Th ages from 11 speleothems and 55 U/Th analyses on travertines (Supplementary Tables S1 and S2, Supplementary Fig. S1) were obtained with thermal ionization[12] and inductively coupled plasma[13] mass spectroscopic techniques (see Methods). Most speleothem ages have 2σ analytical errors that correspond to $\sim$0.5–1% of the age. Ages are in correct stratigraphic order within quoted uncertainties and corrections for initial ^{230}Th are negligible.

Speleothem growth in northeastern Brazil was highly episodic. Growth phases were as short as several hundred years, with some lasting up to a few thousand years, typically separated in time by several thousands to several tens of thousands of years (Fig. 2), indicating extended intervals of dry conditions punctuated by short pluvial periods. Overall, periods of speleothem growth occupied only a small fraction ($\sim$8%) of the last 210 kyr, indicating that pluvial conditions were uncommon in the area.

Because of the high precision of our ages, we are able to correlate the pluvial periods to climate events recorded in other high-resolution records. The Hulu cave East Asian monsoon record[2], which covers most of the last glacial period, has comparable precision. Furthermore, the events at Hulu have been correlated with climate in Greenland[3], as have events recorded in the Cariaco basin[5], and Heinrich events in the North Atlantic[4]. To the extent that these correlations are accurate, we can compare the timing of our pluvial periods to climate at the other localities, relying on our temporal precision and that of the Hulu record.

Our last glacial period pluvial phases (~15 kyr ago, 39 kyr ago and 48 kyr ago, and six speleothem growth intervals between 60 and 74 kyr ago) correlate precisely with times of particularly high $\delta^{18}O$ values at Hulu cave[2], inferred to represent dry conditions associated with a weak summer East Asian monsoon (Fig. 2). The latter in turn correlates with Greenland ice-core cold events[3], largely associated with Heinrich events[4], and with times of high reflectance in Cariaco basin sediments that represent periods of low river runoff in northern South America[5]. Pluvial periods correlating with Heinrich events H1, H4, H5 and H6 are represented in our growth phases, but neither H2 nor H3, which occur at times of low austral autumn insolation, are represented. Dating of the pluvial phase correlated to H4 is precise enough to resolve its duration (700 ± 400 yr from 39.6 to 38.9 kyr ago, on the basis of top and bottom dates of a growth phase of stalagmite TBV 40, Supplementary Fig. S2).

Before ~75 kyr ago, correlations are more difficult as there are

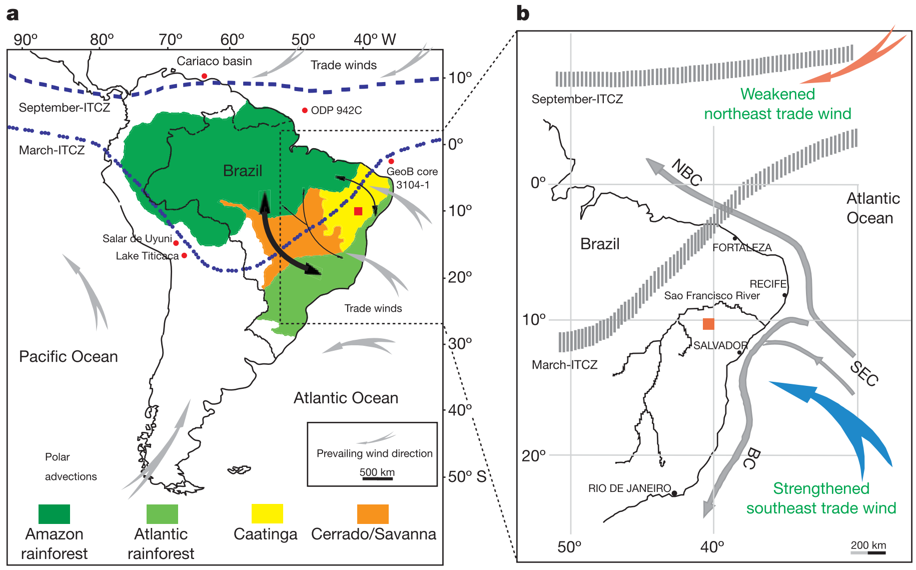

Figure 1 Location of study area, present ITCZ seasonal positions, dominant wind directions, ocean surface currents, and main vegetation distributions in Brazil (modified from ref. 8). Also shown is the Brazilian geographical boundary (black line). **a**, Red square indicates the study area. The 'pathways' connecting the Amazon and the Atlantic rainforest hypothesized by Por[6] are represented by double-headed arrows. The thickness of the arrows indicates the degree of past biogeographical connections. **b**, Grey arrows indicate dominant surface and near-surface ocean currents: NBC, North Brazil Current; BC, Brazil Current; SEC, South Equatorial Current. The blue arrow shows the current relatively strong southeast trade wind; the red arrow represents the currently relatively weak northeast trade wind.

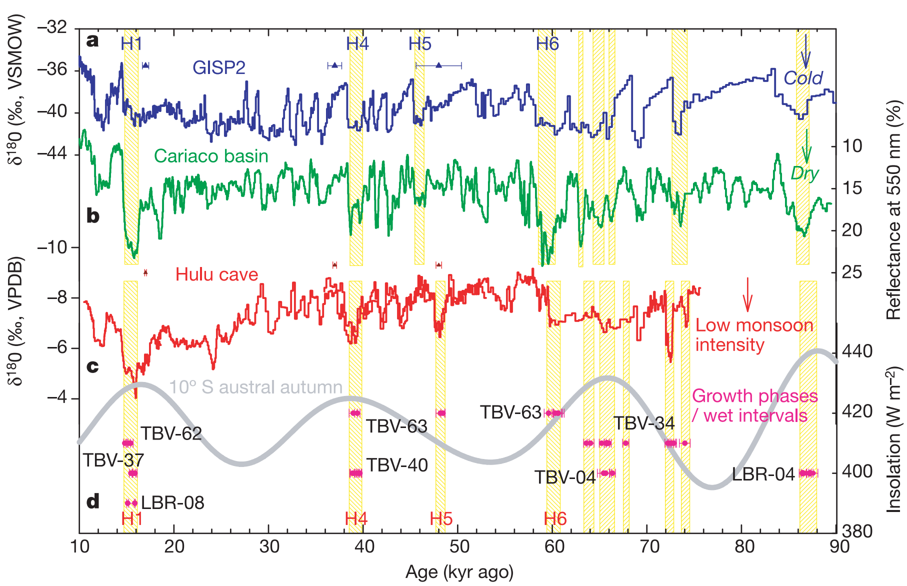

Figure 2 Comparison of the growth patterns of speleothems from northeastern Brazil with events recorded in several Northern Hemisphere palaeoclimate archives. **a**, $\delta^{18}O$ values of Greenland ice[3]. **b**, Light colour reflectance (greyscale) of the Cariaco basin sediments from ODP Hole 1002C[5]. **c**, $\delta^{18}O$ values of Hulu cave stalagmites[2]. **d**, Speleothem growth patterns in northeastern Brazil. Growth intervals are shown by separated pink dots or connections between dots if they are within the same phase. 2σ dating errors (error bars) are typically 0.5–1%. Yellow vertical bars indicate possible correlations between four records. Also shown are dating errors for the GISP2 ice core[29] (blue bars) and Hulu cave speleothems[2] (red bars), and 10° S austral autumn insolation[30] (grey line). VSMOW, Vienna standard mean ocean water. VPDB, Vienna PeeDee Belemnite. H1, H4, H5, H6, Heinrich events.

fewer comparable high-resolution records. Nevertheless, the growth phase between 86.5 ± 0.4 and 87.2 ± 0.3 kyr ago probably correlates with a cold period in Greenland between Greenland interstadials (GIS) 21 and 22[3] (Fig. 2), and an associated dry period recorded in the Cariaco basin[5]. Growth phases between ~130 and 134 kyr ago (Fig. 3) corresponded to a period of weak Asian monsoon just before an abrupt increase (at 129.3 ± 0.9 kyr ago) in monsoon intensity that marks monsoon termination II[14] and with H11[15]. Growth phases from 178 to 182, 205 to 206, and 207 to 209 kyr ago correlate broadly with events within marine isotope stages (MIS) 6.6 and 7.2[16].

The travertine record extends and complements the speleothem record because it probably includes periods of growth at times not wet enough to promote speleothem growth. Represented in the travertine (Fig. 3), but not the speleothem, record are times within the Younger Dryas (ages between 11.7 and 12.1 kyr ago) and the Last Glacial Maximum (ages between 16.7 and 21.7 kyr ago). Some ages fall between 350 and 450 kyr ago. A large number of sub-samples have ages greater than the ^{230}Th dating limit (Supplementary Fig. S1); on the basis of their measured δ^{234}U values (~450) and the initial δ^{234}U values (~6,000) of neighbouring younger travertines, the ages of these old travertines are about 0.9 to 1.0 million years, indicating pluvial periods as old as the mid-Pleistocene.

Because modern rainfall to the north is largely associated with the Intertropical Convergence Zone (ITCZ)[1], our pluvial periods probably represent times when the southerly limit of the ITCZ was in (or south of) our field area, more than several hundred kilometres south of its present southern limit. If so, a southward shift in the southern limit of the ITCZ occurs when Greenland air temperature is low, the East Asian monsoon is weak, and the northern limit of the ITCZ is to the south. As the monsoon front is related to the ITCZ[17], these observations can be summarized in terms of a southward shift of various manifestations and geographical limits of the ITCZ, at times of cold temperature in Greenland.

In recent decades, the Atlantic 'meridional mode' may have played a role in controlling the position of the Atlantic portion of the ITCZ[18]. Dry anomalies in northeastern Brazil correlate with negative sea surface temperature (SST) anomalies in the southern tropical Atlantic and positive anomalies in the northern tropical Atlantic[19,20]. This SST pattern strengthens the southeast trade winds, displacing the ITCZ to the north (Fig. 1). Conversely, temperature anomalies in the opposite sense strengthen the northeast trade winds, causing a southward shift in the ITCZ, as observed in our study.

Our data confirm model predictions that southward expansion of Northern Hemisphere ice sheets and northern sea-ice cover caused a southward shift in the ITCZ position—in part, by establishing meridional mode SST patterns[21]. It is also possible that millennial-scale changes in ocean heat circulation related to the bipolar see-saw mechanism[22] could change meridional Atlantic SST gradients, shifting the ITCZ. In a broader sense, it has been argued that the position of the ITCZ is controlled by the relative pole-to-Equator temperature gradients between hemispheres, with the ITCZ offset to the hemisphere with the lower temperature gradient[23]. If cold Greenland temperatures correspond to times of high Northern Hemisphere latitudinal temperature gradient, this would explain the broad link between ITCZ position and Greenland temperature.

Feedbacks between the tropics and high northern latitude climate may also be important in establishing the observed climate patterns. For example, southward displacement of the ITCZ may change the flow pattern and intensity of the North Brazil Current (NBC)[11], which could directly affect heat and salt transport into the Caribbean and ultimately to portions of the North Atlantic. Alternatively[5], the ITCZ position could modulate water vapour export from the Atlantic to the Pacific. Such changes could also shift Caribbean salinity and affect northward heat transport. Another possible feedback related to ITCZ position could be changes in low-to-high latitude moisture transport associated with changes in the Asian monsoon[14].

Furthermore, over the period 10–210 kyr ago there is a striking correlation between speleothem growth phases and times of high insolation at 10 °S during austral autumn (Fig. 3). Modern rainfall in this area occurs mainly during austral autumn (February to May)[1], when the ITCZ is close to its southernmost position. Our data thus confirm the strong dependency of the ITCZ position and associated tropical precipitation on precessional forcing demonstrated in modelling[24] and field studies in South America[25]. Increased continental heating and land/sea thermal contrast could

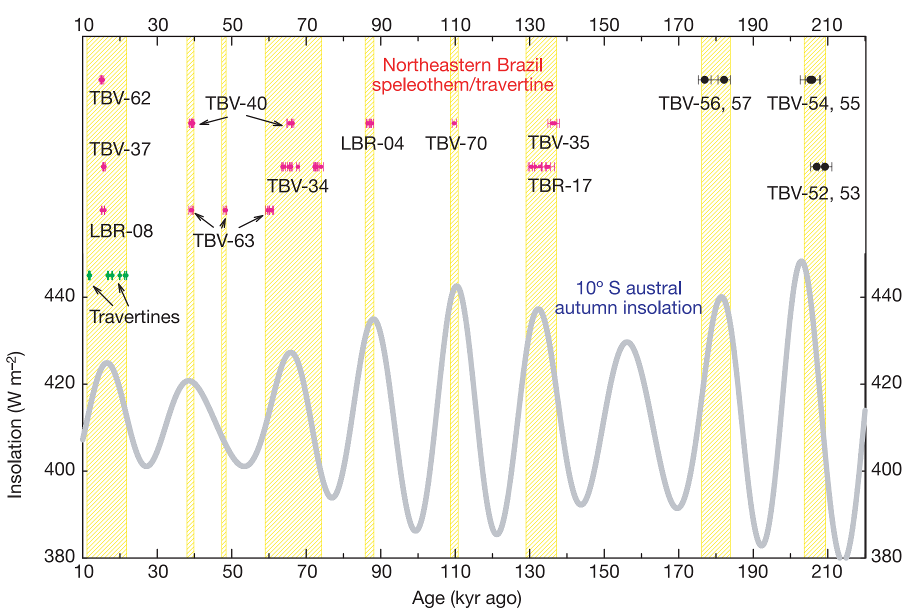

Figure 3 Comparison of growth intervals of speleothem and young travertine from northeastern Brazil, and insolation variation at 10° S over the austral autumn[30]. Pink, black and green dots represent respectively stalagmite, flowstone (a type of speleothem) and travertine.

shift the ITCZ to the south and enhance landward water vapour transport[1,25].

The patterns of latitudinal migration of the ITCZ and rainfall inferred here imply geographical shifts in rainforest boundaries that, in turn, influenced rainforest biodiversity and evolution. Analysis of widespread vegetal remains associated with the travertines (Supplementary Fig. S3) has allowed the identification of plant species not adapted to the present semi-arid climate, with less than 5% coriaceous leaves (predominant in modern caatinga vegetation). Many specimens show brochidodromous venation, common in the modern Atlantic rainforest but not in the caatinga. The travertine palaeobotanical remains indicate a dense mesophilic semi-deciduous forest that could have replaced, or mixed with, the caatinga. The wide occurrence of vegetation-rich fossil travertines in northeastern Brazil indicates that the expansion of forest was a regional phenomenon during wet phases.

Historically, the existence of 'refugia' was proposed as a critical factor in development of tropical rainforest biodiversity[26]. Central to this idea is the large-scale drying of the tropical forest lowlands during glacial times, leaving 'refuges' of rainforests at wetter higher elevations. However, some pollen studies suggest that Amazonian lowland vegetation may not have changed significantly during the late Pleistocene[27]. An alternative explanation supported by botanical and genetic studies[6–8,28] is that the high biodiversity resulted from periodic exchanges between the Amazonian and Atlantic rainforests. Our data show that the currently semi-arid southeastern border of the Amazonian rainforest experienced relatively frequent, dramatic and abrupt changes in available moisture during the Pleistocene. These intermittent wetter conditions allowed the expansion and extension of gallery forest, and floristic exchange between the two forest areas. The precise timing, frequency and mechanism for such connections were previously unknown. Our data indicate that relatively frequent intermittent connection (on average one pluvial event every ~20,000 yr for the past 210 kyr) through ITCZ migration has been possible since at least the mid Pleistocene, a process which probably affected rainforest species dynamics and biodiversity. □

Methods

Sample description

Calcite speleothems were collected from deep caves in the Precambrian Una carbonates, northeastern Brazil. Conservation ethics (and permit restrictions) limited sample collection, and only 11 speleothems could be analysed. We systematically sampled the oldest and youngest suitable calcite from each sample, and also collected sub-samples bracketing hiatuses to constrain speleothem growth intervals by high-precision mass spectrometric ^{230}Th dating (see Supplementary Fig. S2 for an example). Some duplicates and sub-samples in the middle of growth phases were also collected to check analytical precision and growth rate.

Travertine deposits were collected from the surrounding Salitre and Jacaré river valleys. Travertine sites are underlain by the thin impermeable Caatinga limestone. Rapid rainfall infiltration towards the limestone causes seepage to concentrate in shallow streams that cascade steeply into the main river valley, causing travertine deposition via degassing and/or evaporation. It was necessary to establish strict age reliability criteria because of the friable and porous nature of travertines. Two main criteria were adopted for travertine sample selection: (1) coeval sub-samples (that is, different samples from the same growth layer) were analysed for all samples. Because post-depositional isotopic migration is unlikely to affect different portions of the same layer in exactly the same way, a comparison of isotopic ratios and age provided a reliable check on age accuracy. (2) Top and bottom sub-samples were analysed whenever possible in order to check for stratigraphic order. Some larger travertine outcrops contain shallow caves. Calcite deposits within these caves were sheltered from weathering and mixing with terrigenous sediment, and tended to yield calcite samples that were free of impurities and less likely to be altered (see Supplementary Table S2).

U-series experimental methods

Speleothem sub-samples (~0.1–0.3 g) for dating were extracted by milling from flat, polished surfaces using a hand-held dental drill. For travertines, small pieces (0.1–0.4 g) were cleaned using an ultrasonic cleaner and rinsed with deionized water to remove surface contamination. Procedures for chemical separation and purification of uranium and thorium are similar to those described in ref. 12. Some travertine samples carried a HNO_3-insoluble residue. In these cases, we completely dissolved the detritus with a concentrated HF–$HClO_4$ mixture.

A few U and Th measurements were made at the Minnesota Isotope Laboratory by thermal ionization mass spectrometry. Following instrumental procedures similar to those of ref. 12, measurements were made separately on two Finnigan MAT-262-RPQ instruments, using the multiplier behind the retarding potential quadrupole. The majority of the measurements were made by magnet-sector inductively coupled plasma mass spectrometry, following procedures modified from ref. 13. Measurements were performed on a Finnigan ELEMENT, equipped with a double-focusing sector magnet in reversed Nier-Johnson geometry using a single MasCom multiplier.

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