Human adaptation strategies to abrupt climate change in Puerto Rico ca. 3.5 ka

Isabel Rivera-Collazo,1 Amos Winter,2 Denis Scholz,3 Augusto Mangini,4 Thomas Miller,5 Yochanan Kushnir6 and David Black7

Abstract
The connection between climatic change and social response is complex because change articulates a number of inter-related factors. Human decisions are filtered by social buffers – including social memory, risk perception, and cultural priorities – and the rate and scale of climate change is usually much larger than the scale of human decision-making. In this article, we provide information on climate change based on precisely dated speleothems with the response evident in archaeological sites that have radiocarbon date ranges within the same time frame. A stalagmite recovered from within the catchment area for aquifer recharge of the Pre-Arawak site of Angostura in Barceloneta, Puerto Rico, shows that a significant wet period occurred between 3.9 and 3.1 ka (primarily centered at 3.5 ka). We investigate the effect that this increase in precipitation had on the earliest occupations on the island in the context of palaeoenvironmental, geoarchaeological, and archaeological records from Angostura, Maruca, and Paso del Indio. Our analysis suggests the presence of two different adaptation strategies: settlement relocation and microlandscape modification. Our study concludes that the social response to change cannot be seen as monolithic given that human behavior, even within the same period, addresses the needs of individual groups with different priorities. This multiplicity of responses can indeed enhance resilience as social support can continue through alliances and exchanges, strengthening social bonds that can help buffer catastrophes. The results can help shed light on the range of adaptation strategies to change encompassed within the manifestations of social resilience or vulnerability.

Keywords
adaptation strategies, archaic period, Caribbean archaeology, climate change, Puerto Rico, speleothem

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Introduction
Human responses to climate change can be expected to reflect overall social resilience/vulnerability and risk perception. The articulation of climatic changes and social response is complex given that climate change triggers response in other environmental variables, and because human decisions are filtered by social buffers, including social memory, risk perception, and cultural priorities (Adger et al., 2013; Rosen and Rivera-Collazo, 2012). Research can be also complicated in that the rate and scale of climate change are usually much larger than the scale of human decision-making. This article discusses how people during the Archaic or Pre-Arawak period, the earliest human occupiers on the island of Puerto Rico, coped with an increase in precipitation around 3500 years ago (ka). Our results shed light on the range of human adaptive strategies to climate change.

General climate and environmental context for the Greater Antilles
The time period under study (i.e. the mid- to beginning of the late Holocene, 6–3 ka) coincided with the end of a period of intensified solar forcing (insolation) by the precession cycle, a process that peaked at ~9 ka. Northern Hemisphere (NH) climate characteristics of this high-insolation interval (termed the Holocene Climatic Optimum) were different than today owing to the overall higher sea-surface temperatures (SSTs) in summer and the larger land–sea contrast during winter. This influenced the Intertropical Convergence Zone (ITCZ) to migrate further north, reaching the Greater Antilles during summer (Braconnot et al., 2000; Gyllencreutz et al., 2010; Wanner et al., 2008). The convection band of the ITCZ also widened between 6 and 3 ka, affecting a larger area than at present and depositing a further 2–4 mm of rain per day.
compared with modern conditions (Braconnot et al., 2007). The northern sections of South America and the Greater Antilles therefore saw wetter wet seasons and drier dry seasons (Burney et al., 1994; Curtis et al., 1999; Greer and Swart, 2006; Higuera-Gundy et al., 1999; Hodell et al., 1991; Kennedy et al., 2006; Milne et al., 2005; Nyberg et al., 2001; Peros et al., 2007). These changes also led to the intensification of the African summer monsoon and a weakening of the El Niño Southern Oscillation (ENSO) variability (Clement et al., 2000; Moy et al., 2002), which in turn influenced the regular path and intensity of Atlantic tropical storms (Bertran et al., 2004; Donnelly and Woodruff, 2007; Haug et al., 2001; Malaizé et al., 2011; Woodruff et al., 2008a, 2008b).

Geologically, the north coast of Puerto Rico is characterized, from south to north, by a ridge of volcanic mountains (Central Cordillera) reaching a wide karstic region, which continues north into the Atlantic Ocean. These limestone deposits, accumulated between the Oligocene and the Pliocene, constitute the largest water reservoir of the island, consisting of confining and aquifer units that store precipitation and feed a vast underground drainage system (Renken et al., 2002). Further south in the karst, it is characterized by numerous caves and mogotes and increasing thickness of the unsaturated area. Precipitation influences groundwater recharge, which occurs by rapid infiltration with little evaporation (Jones and Banner, 2003; Taylor et al., 2013). Given the characteristics of the climate of the study area, aquifer recharge in the southern karst occurs mostly during the wet season of June–November.

Case study: Precipitation reconstruction from speleothems
Speleothems are increasingly used as terrestrial archives of past climate and environmental change because they provide long, continuous, high-resolution time series that can be precisely dated by uranium-series disequilibrium methods and are generally unaffected by post-depositional diagenetic alteration (Fairchil et al., 2006). The growth rates of speleothems are related to changes in climatic parameters (Lachniet et al., 2012). In the tropics, seasonal precipitation amounts (above individual cave-dependent thresholds) are most likely the primary variable affecting annual speleothem growth (Burns, 2002), but soil activity above the cave and temperature may also be important (Kaufmann, 2003; White, 2004). Hiatuses in speleothems are usually related to periods of climate change, primarily droughts, but may, on occasion, also be because of changes in cave morphology (earthquakes) or hydrologic patterns (Cruz et al., 2005; Van Beynen et al., 2007).

Our data derive from a stalagmite (PA 2b) collected in 2005, 100 m inside the cavern of Palco located in the Lares Limestone rock formation in the Ciales municipality of Puerto Rico (Figure 1, ~N18.35°/W66.5°). The in-cave elevation is 250 m a.s.l., with a mean annual cave temperature of 23°C. No formal monitoring has been undertaken, although temperatures, atmospheric CO₂, and ¹⁸O isotopes have been collected on several occasions. Entry to the cave is via a restricted series of rooms (requiring crawling at one point) that insulate the large interior chambers from outside atmospheric influences. This together with its active dripping at the time of collection and candle-shape were factors in choosing PA 2b for analysis. The stalagmite is 29.25 cm long, with a rounded top and does not show a ‘cup’ that could imply drip erosion. The thickness of the rock overburden at the cave is 50–70 m, tending to increase the lag between rainfall and drip response in the cave (Miller, 2004, 2009).

Methods
For ²³⁰Th/U-dating, 12 powder samples, each weighing approximately 200 mg, were extracted with a hand-held dental drill along growth layers from a polished slab section of PA 2b. Two ages (PA 2b-3 and PA 2b-8) were determined using a thermal ionization mass spectrometer (TIMS) Finnigan MAT 262 RPQ housed at the Heidelberg Academy of Sciences. The other 10 samples were analyzed with a multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) located at the Max Planck Institute for Chemistry (MPIC), Mainz. The samples were prepared similarly as described in Frank et al. (2000) for TIMS and Hoffmann et al. (2007) for MC-ICPMS. The calibration of the mixed ²³⁵U–²³⁴U spike used at MPIC is described in Zak et al. (2012) and Scholz et al. (2014). Analytical MC-ICPMS techniques involved a standard-sample bracketing procedure to derive correction factors for mass fractionation and Faraday cup to ion counter gain, as described in Hoffmann et al. (2007), Jochum et al. (2011), and Scholz et al. (2014). All activity ratios reported for both laboratories were calculated using the decay constants from Cheng et al. (2000).

For stable isotope analysis, PA 2b was continuously milled at 0.3-mm intervals using a SHERLINE 5410 milling machine. The samples were analyzed using a continuous flow IsoPrime Multiflow System at the Geology Department at the University of Puerto Rico. Samples were transferred into 10-ml borosilicate vials and sealed with Butyl rubber septa (Labco, High Wycombe, UK). Subsequently, 61 samples and 18 internal standards were heated in the Gasbench tray to 72 ± 0.1°C, and analyzed on a Gasbench II carbonate periphery. For analysis, the carbonate samples were dissolved in 3–5 drops of orthophosphoric acid under helium (grade 5) atmosphere. Four sample gas aliquots were carried through a Nafion trap to remove residual water before entering the Valco multi-injection loop. The gas mixture (CO₂ and He) was introduced into a gas chromatographic column (Poraplot Q) and the CO₂ separated from other gases. After passing a second water trap, the analyte was introduced into the mass spectrometer. NBS 19 was used as in-house reference material, with isotopic ratios (¹⁸O/¹⁶O and ¹³C/¹²C) reported in standard delta notation relative to the Vienna Pee Dee Belemnit standard (% VPDB). The external analytical precision for both δ¹³C and δ¹⁸O is better than 0.06‰.

Results and discussion
The results of ²³⁰Th/U-dating for PA 2b are shown in Table 1 and Figure 2. The ²³⁵U content ranges from 0.197 to ca. 0.578 µg/g, and the ages range from 0.2535 ± 0.0095 to 6.987 ± 0.067 ka. The stalagmite exhibits three growth phases (Figure 2): 7–5.5 ka (bottom), 3.9–3.1 ka (middle), and the last 200 years (top). The age determined at the top of PA 2b-1 (i.e. at 10.4 mm distance from top (dtf)) is significantly older than the age at 21.8 mm df and consequently represents an age inversion (Figure 2). Since this sample has the lowest ²³⁰Th/²³²Th ratio of all samples (Table 1), the age inversion is probably because of contamination with detrital ²³⁰Th.

Application of the ‘standard’ correction for detrital contamination, assuming a bulk Earth ²³²Th/²³⁵U weight ratio of 3.8 and ²³⁰Th, ²³⁴U, and ²³⁸U in secular equilibrium, results in insignificant age changes for all samples. However, several speleothem studies, in particular from the Caribbean, have shown that a much lower ²³²Th/²³⁴U weight ratio of the detrital component may be required for appropriate correction for detrital contamination (Beck et al., 2001; Fensterer et al., 2010, 2012; Hellstrom, 2006; Hoffmann et al., 2010; Richards and Dorale, 2003).

Using the stratigraphic constraint that the age of the speleothem must increase with increasing df, the ²³²Th/²³⁴U weight ratio of the detritus can be estimated (Hellstrom, 2006). Sample PA 2b-1 is ideal for this purpose because it (1) is very young and (2) has a very low (²³⁰Th/²³²Th) ratio (Table 1) and is thus largely affected by the correction. Its age must be younger than the age of the sample below (PA 2b-2), but older than AD 2005 (i.e. the year of the collection of the stalagmite). This tightly constrains
the age and consequently the $^{232}\text{Th}/^{238}\text{U}$ weight ratio of the detritus. The resulting $^{232}\text{Th}/^{238}\text{U}$ weight ratio of the detritus is $0.35 \pm 50\%$, which is of the same magnitude as reported in other speleothem studies from the Caribbean (Beck et al., 2001; Fensterer et al., 2010, 2012; Hoffmann et al., 2010). Application of this value to the whole data set resolves all age inversions and results in generally younger ages (Figure 2). However, despite of the lower $^{232}\text{Th}/^{238}\text{U}$ value compared with the ‘standard’ approach, the correction is only significant for two samples (PA 2b-1 and 2b-4, Figure 2, Table 1). Because of the correction, the uncertainty of all ages increases, which is particularly important for the samples with a low $^{230}\text{Th}/^{232}\text{Th}$ ratio (Table 1, Figure 2).

The chronology of PA 2b is constrained by 12 $^{230}\text{Th}/\text{U}$-ages. In addition, we assume an age of AD 2005 for the top of PA 2b because it was actively dripping at the time of collection. The age model was constructed using StalAge (Scholz and Hoffmann, 2011), a software specifically developed for construction of speleothem age models. Because of the relatively large effect of detrital contamination on samples PA 2b-3 and 2b-4 (Figure 2), the age uncertainty of the younger part of the middle section, as estimated by StalAge, is relatively large. Nevertheless, the growth rate of the middle section is between 100 and 200 $\mu$m/a and thus relatively large.

It is possible that the middle section of PA 2b grew during a shorter interval of time than the 800 years estimated by the (relatively uncertain) age model. In this case, the growth rate would be similar as for the bottom section that grew during 7 and 6 ka (Figure 2). Fast growth during only relatively short intervals in Caribbean speleothems has been observed for several other stalagmites during the Holocene (Winter et al., 2014). The period of relatively fast growth observed here between 4 and 3 ka for PA 2b has yet to be found in other speleothems. Although we cannot exclude local features, such as a change in aquifer characteristics causing the increase in growth, the most likely explanation given for fast tropical speleothem growth is high precipitation (Kaufmann, 2003; Proctor et al., 2000). Supporting the connection between precipitation and speleothem growth is the fact that stalagmite PA 2b has been growing for the last 200 years, a time when precipitation increased after the pervasive droughts of the ‘Little Ice Age’ (Kennett et al., 2012).

The $\delta^{18}O$ values of speleothem calcite precipitated at constant temperature deep within the cave are sensitive recorders of varying rainfall amounts that accumulated in the overlying aquifer in Puerto Rico. This is because there is a large negative isotope fractionation in the tropics that accompanies the distillation of rainwater from clouds (Dansgaard, 1964; Winter et al., 2011). $\delta^{18}O$ values during 3.9–3.1 ka growth phase and for the recent period
The Holocene

Table 1. $^{230}$Th dating results. The error is 2σ error. Corrected ages were calculated assuming a bulk earth $^{232}$Th/$^{238}$U value of 3.8±0.5% and secular equilibrium between $^{230}$Th, $^{234}$U, and $^{238}$U. Corrected age represents calendar years, before year of analysis (2013).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{238}$U (µg/g)</th>
<th>$^{234}$U/$^{238}$U</th>
<th>$^{230}$Th/$^{238}$U</th>
<th>$^{230}$Th/$^{232}$Th</th>
<th>Age uncorrected (ka)</th>
<th>Age corrected ± 50% (ka)</th>
<th>Age corrected ± 2σ 95.4% (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA 2b-1</td>
<td>0.197 ± 0.001</td>
<td>2.6159 ± 0.0053</td>
<td>0.01656 ± 0.00033</td>
<td>14.3 ± 0.2</td>
<td>0.6930 ± 0.0140</td>
<td>0.2697 ± 0.0506</td>
<td></td>
</tr>
<tr>
<td>PA 2b-2</td>
<td>0.262 ± 0.002</td>
<td>2.630 ± 0.015</td>
<td>0.00610 ± 0.00022</td>
<td>47.4 ± 2.1</td>
<td>0.2535 ± 0.0095</td>
<td>0.2069 ± 0.0248</td>
<td></td>
</tr>
<tr>
<td>PA 2b-3</td>
<td>0.2233 ± 0.004</td>
<td>2.599 ± 0.013</td>
<td>0.0794 ± 0.0077</td>
<td>122.4 ± 11.9</td>
<td>3.38 ± 0.34</td>
<td>3.142 ± 0.352</td>
<td></td>
</tr>
<tr>
<td>PA 2b-4</td>
<td>0.216 ± 0.001</td>
<td>2.6041 ± 0.0042</td>
<td>0.08627 ± 0.00083</td>
<td>62.34 ± 0.78</td>
<td>3.667 ± 0.037</td>
<td>3.162 ± 0.240</td>
<td></td>
</tr>
<tr>
<td>PA 2b-5</td>
<td>0.225 ± 0.001</td>
<td>2.5907 ± 0.0051</td>
<td>0.08897 ± 0.00090</td>
<td>477.4 ± 7.4</td>
<td>3.803 ± 0.040</td>
<td>3.735 ± 0.050</td>
<td></td>
</tr>
<tr>
<td>PA 2b-6</td>
<td>0.254 ± 0.002</td>
<td>2.582 ± 0.012</td>
<td>0.0915 ± 0.0013</td>
<td>1388.1 ± 92.1</td>
<td>5.78 ± 0.36</td>
<td>5.57 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>PA 2b-7</td>
<td>0.2025 ± 0.006</td>
<td>2.578 ± 0.010</td>
<td>0.1335 ± 0.0083</td>
<td>1852.1 ± 123.8</td>
<td>5.78 ± 0.36</td>
<td>5.57 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>PA 2b-8</td>
<td>0.295 ± 0.002</td>
<td>2.5508 ± 0.0048</td>
<td>0.12626 ± 0.00098</td>
<td>1994.4 ± 29.5</td>
<td>5.508 ± 0.045</td>
<td>5.484 ± 0.045</td>
<td></td>
</tr>
<tr>
<td>PA 2b-9</td>
<td>0.295 ± 0.002</td>
<td>2.5530 ± 0.0067</td>
<td>0.1500 ± 0.0012</td>
<td>1724.7 ± 272.4</td>
<td>5.78 ± 0.36</td>
<td>5.57 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>PA 2b-10</td>
<td>0.263 ± 0.002</td>
<td>2.5509 ± 0.0059</td>
<td>0.1479 ± 0.0014</td>
<td>636.34 ± 808.0</td>
<td>6.485 ± 0.063</td>
<td>6.477 ± 0.063</td>
<td></td>
</tr>
<tr>
<td>PA 2b-11</td>
<td>0.369 ± 0.002</td>
<td>2.5530 ± 0.0067</td>
<td>0.1500 ± 0.0012</td>
<td>1724.7 ± 38.4</td>
<td>5.676 ± 0.058</td>
<td>5.654 ± 0.062</td>
<td></td>
</tr>
<tr>
<td>PA 2b-12</td>
<td>0.389 ± 0.002</td>
<td>2.5493 ± 0.0044</td>
<td>0.1511 ± 0.0013</td>
<td>6846.5 ± 255.9</td>
<td>6.634 ± 0.061</td>
<td>6.626 ± 0.061</td>
<td></td>
</tr>
<tr>
<td>PA 2b-13</td>
<td>0.578 ± 0.004</td>
<td>2.5438 ± 0.0039</td>
<td>0.1586 ± 0.0015</td>
<td>6039.6 ± 159.6</td>
<td>6.987 ± 0.067</td>
<td>6.977 ± 0.068</td>
<td></td>
</tr>
</tbody>
</table>

*Corrected ages were calculated using a $^{232}$Th/$^{238}$U weight ratio of the detritus of 0.35 (see main text for details).

*Samples dated by TIMS.

Figure 2. Age model of Palco 2b based on StalAge (Scholz and Hoffmann, 2011), showing that the stalagmite grew rapidly (8 cm) around 3.5 ka.

Social context of Puerto Rico at the end of the mid-Holocene

It has been previously thought that the earliest occupations of Puerto Rico, collectively referred to as Pre-Arawak or Archaic Period, comprised small bands of mobile hunter-gatherers. However, recent research has led to the re-evaluation of this characterization (Rivera-Collazo, 2011b, 2011c; Rodríguez Ramos, 2008, 2010). Sites such as Maruca, Paso del Indio (PDI), and Angostura indicate the presence of permanent settlements on open-air areas near rivers or coasts, providing easy access to the sea (Rivera-Collazo, 2011b). The material culture assemblage of the period suggests long-distance webs of interaction with other islands and the Caribbean coasts of South and Central America, particularly the Isthmo/Colombian area (Págán Jiménez, 2007, 2011; Rodríguez Ramos, 2010).

Exchange and long-distance webs of interaction during the Archaic Period were significant drivers of social dynamics and settlement patterns, including sedentism or permanent settlement within hunter-gatherer socioeconomic contexts (Rivera-Collazo, 2011b; Rodríguez Ramos, 2010). Radiocarbon dates from archaeological studies (Rodríguez Ramos, 2010: 44) indicate that Puerto Rico was initially occupied ca. 4.8 ka (4713 cal. BP (intercept, 2σ 95.4%) from Maruca; Puerto Rico). The archaeological record during the Archaic Period suggests cultural continuity without significant social change until after the beginning of the Ceramic Age/Saladoid Period (ca. 2.0–1.9 ka). No change in social parameters of the Archaic Period is evidenced in the archaeological record that could explain adaptive responses as discussed in this paper.

Case study: Archaeology

In order to evaluate what effect, if any, the 3.5 ka wet period had over the social groups living in Puerto Rico, we selected Angostura, Maruca, and Paso del Indio (PDI; Figure 1). These three sites are archaeological deposits where permanent settlement occurred during the Archaic Period, with radiocarbon dates overlapping the 3.5 ka wet period.

The data on Maruca and PDI discussed here are based on the stratigraphic, chronostatigraphic, and archaeological records included in published and unpublished reports (Clark et al., 2003; García Goyco, 1998; García Goyco and Maurás Casillas, 1993; Pantel, 1994; Rodríguez, 1997, 2004; Rodríguez Ramos, 2010; Walker, 2005) and reexamined within the context of the new palaeoclimate data discussed above.
Geoarchaeological methods for Angostura

Accelerator mass spectrometry (AMS) radiocarbon dates were obtained from mounds B and C, and from the anthrosol area adjacent to mound B (Beta Analytic Laboratories). Other radiocarbon dates (AMS and conventional) were reported in previous excavations (Ayés, 1988; Vega, 2000). All were calibrated with OxCal09 or IntCal09 as appropriate (Table 2). The occupational history of the rest of the site was reconstructed through stratigraphic analysis, which included a detailed geoarchaeological evaluation of the deposits: grain size, organic and carbonate content (OM and CaCO3), phosphates, magnetic susceptibility (Table 3), and microartifact analysis (Tables 4 and 5). Grain size analysis combined dry sieving method for the coarse fraction and hydrometer method for the fine fraction (Goldberg and Macphail, 2006). The coarse fraction (>1 mm) was removed from the sample through wet sieving after disaggregating the mineralogical components using a sodium hexametaphosphate solution (Calgon 5%). The finer fraction (including fine sand) was collected in a 1000 mL cylinder where the density of the sediment suspended in the water column was measured in g/L using a hydrometer. Readings were taken at set intervals between 30 s and 24 h. Corrected readings were calculated after deducting the reading obtained from a control cylinder containing distilled water and Calgon.

The coarse fraction was weighed and sieved using nested sieves separating them into different Φ sizes.

After dry sieving, all the coarser fractions were retained for multifraction microartifact analysis (4, 2, 1, 0.5, 0.25, 0.125, and 0.063 mm fractions). Samples were inspected under an incident-light microscope and percentages of artifact content per fraction were estimated visually using the chart from Bullock et al. (1985: 24–25). In addition, the contents of the field-collected 3 mm-mesh sieves were sorted and analyzed for size-specific microartifact analysis. A statistical random sample of 1.15 L was selected for study.

Loss on ignition (LOI) was used for determining the organic (OM LOI) and carbonate (CaCO3 LOI) contents of the samples. OM LOI samples, consisting of approximately 10 g of sediment, were fired in a furnace at 550°C for 1.5 h and allowed to cool in a desiccator to room temperature. For calculating the CaCO3, the samples were returned to the furnace and fired at 1000°C for 1 h after reaching peak temperature. The samples were left to cool in the furnace overnight.

Phosphorous content was calculated using the Gundlach Method, where presence of phosphorous is revealed by a blue color and is expressed in terms of a subjective relative visual scale from 0 to 3, where 0 is no blue tint and 3 is strong blue radiating bands. For this test, 50 mg of sample was placed on the center of an ash free filter paper. Two drops of acid ammonium molybdate solution were added to the sample, followed, 30 s later, by two drops of ascorbic acid. Given that blue color even in weak samples continues to develop with time, readings were taken at a standardized time of 2 min.

Magnetic susceptibility (χ) was measured using a Bartington MS2 meter with a MS2B sensor. For each sample, 10 g of sediment was placed in diamagnetic containers. Readings of all samples were first made in low frequency followed by high frequency (0.46 and 4.6 kHz). In order to determine maximum potential, the samples were submitted to an oxidation and reduction cycle in the furnace: 10 g of dry sample was mixed with 1 g of plain flour and placed in 25 mL porcelain crucibles. The
Table 2. Radiocarbon dates from Angostura, calibrated with OxCal4.1 using Marine09 for shell samples and IntCal09 for all others. AMS samples are marked * and conventional, +. Samples collected by the author (Rivera-Collazo) are marked ^. All the other radiocarbon dates were published by Ayes (1988) or Vega (2000).

| Lab no. | Material | Locus – context | Depth (cm below surface) | 
|---------|----------|-----------------|-------------------------|------------------|
| GX-28808 | Charcoal* | Mound B – midden | ca. 7–39 | 3670 ± 40 | 4144–4121; 4094–3888 | 4003 |
| GX-28806 | Charcoal* | Mound B – midden | ca. 7–39 | 3570 ± 40 | 3979–3816; 3797–3723 | 3870 |
| GX-28805 | Charcoal* | Mound B – habitation surface | ca. 39–63 | 3700 ± 30 | 4147–4115; 4100–3967; 3944–3930 | 4037 |
| GX-28807 | Charcoal* | Mound B – forest soil/first habitation surface | >99 | 3920 ± 40 | 4511–4484; 4442–4239 | 4354 |
| Beta-29778 | Charcoal+ | Mound B – unknown | Unknown | 5960 ± 250 | 7414–7392; 7371–7356; 7330–6300 | 6820 |
| GX-28809 | Charcoal* | Mound B – midden | ca. 39–63 | 3470 ± 40 | 3840–3638 | 3749 |
| GX-28810 | Shell+ | Mound B – shell layer | ca. 63–99 | 3980 ± 80 | 4226–3761; 3986–3899 | 3986 |
| GX-28813 | Shell+ | Mound B – shell layer | ca. 63–99 | 4010 ± 70 | 4229–3829 | 4024 |
| GX-28814 | Charcoal+ | Mound B – shell layer | ca. 63–99 | 3740 ± 100 | 4413–3860 | 4108 |
| GX-28811 | Shell+ | Mound B – shell layer | ca. 63–99 | 3830 ± 90 | 3932–3419 | 3672 |
| GX-28812 | Shell+ | Mound B – forest soil/first habitation surface | >99 | 4120 ± 80 | 4048–3556 | 3784 |
| Beta-294435^ | Charred material* | Unit 3 – Shell layer/Anthrosol | 74–80 | 2120 ± 30 | 2295–2270; 2155–1998 | 2093 |
| Beta-294434^ | Charred material* | Mound C – midden/shell layer | 12–14 | 3680 ± 40 | 4146–4118; 4096–3898 | 4019 |
| Beta-294440^ | Plant material* | Offsite Core 2 | 538 | 3740 ± 30 | 4224–4205; 4158–3985 | 4096 |
| Beta-294438^ | Organic sediment* | Offsite Core 1 | 353 | 178 ± 30 | 1938–1732 | 1839 |
| Beta-294437^ | Wood* | Offsite Core 1 | 439 | 660 ± 30 | 673–628; 603–558 | 611 |
| Beta-294437^ | Charred material* | Offsite Core 3 | 439 | 660 ± 30 | 673–628; 603–558 | 611 |

AMS: accelerator mass spectrometry.

Table 3. Summary of main results of the geoarchaeological analyses of onsite samples. Grain size is presented as cumulative percentages of gravel (■), sand (■), silt (■), and clay (■).

<table>
<thead>
<tr>
<th>Locus</th>
<th>Stratum</th>
<th>Grain size</th>
<th>P</th>
<th>χ_LF</th>
<th>χ_conv</th>
<th>OM LOI (%)</th>
<th>CaCO_3 LOI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mound C</td>
<td>A</td>
<td>3</td>
<td>4.4</td>
<td>0.10</td>
<td>18.12</td>
<td>6.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>3</td>
<td>4.1</td>
<td>0.13</td>
<td>11.40</td>
<td>10.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3</td>
<td>1.6</td>
<td>0.03</td>
<td>12.06</td>
<td>2.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
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<td>0.19</td>
<td>7.12</td>
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</table>

LOI: loss on ignition.
Table 4. Artifact (A) and microartifact (M) content per volume of sampled sediment.

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<tr>
<th>Locus</th>
<th>Stratum</th>
<th>Sample weight (g)</th>
<th>Artifact content (%)</th>
<th>Microartifact content (%)</th>
<th>M/A ratio</th>
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<td>100.103</td>
<td>17.6</td>
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(Continued)

Table 5. Percentage of microartifact content per size fraction of studied sample. Identified microartifacts include shell (burnt and unburnt), bone (burnt, unburnt, chewed, and digested), charred organics (including wood, twigs, leaves, and seeds), lithic flakes, burnt limestone, and burnt clay. The table also shows the non-artifactual sediment content of the sample.

<table>
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<th>Locus</th>
<th>Stratum</th>
<th>Fraction size</th>
<th>Shell</th>
<th>Bone</th>
<th>Charred organics</th>
<th>Lithics</th>
<th>Burnt limestone</th>
<th>Burnt clay</th>
<th>Sediment</th>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>60</td>
</tr>
</tbody>
</table>

(Continued)
samples were placed in the furnace covered with lids, and fired at 650°C for 1 h (Clark, 1996). After the first firing stage, the furnace was switched off and left closed for 20 min. After this, the lids were removed from the crucibles, and the furnace was run for another 45 min after reaching optimal temperature. The furnace was then switched off, and the door was opened briefly to ensure it contained atmospheric oxygen. Samples were allowed to cool in the oven, weighed, placed in diamagnetic containers, and measured in low and high frequencies. Mass specific magnetic susceptibility, presented in units of 10−6 m3/kg, was calculated using the following formula: χ = κ/mass/10. Mass specific frequency dependence is presented as a percentage of χL max and is calculated as (χL − χH)/χL max. Fractional conversion (χconv) is also presented as a percentage, calculated using the following formula: χconv = χL/χL max (Dearing, 1999; Goldberg and Macphail, 2006).

**Results for Angostura**

The surface before occupation is identified as a soil that formed under forested conditions. After the initial forest clearing, which was dated to ca. 4.4 ka on mound B layer 5 (see Table 2), the site presents layers of tightly packed shells (Stratum J, ca. 30–50 cm on mounds B and D) with little or no other food remains, with dates between 4.1 and 3.6 ka. The geoarchaeological analysis of the sample from mound B suggests this layer is the product of anthropic activity. Low OM and fine sediment content suggests it was accumulated rapidly. The lower phosphate levels, sediment composition comprising mostly of three mollusk species (*Crassostrea rhizophorae*, *Phacoides pectinatus*, and *Anomalocardia brasiliana*), and low microartifact content (Table 4) and diversity (Table 5) suggest that these layers were deliberately created and were not just a random accumulation of food refuse. The bones within the deposit could have been the main source of phosphates.

These shell layers are covered with a 5- to 8-cm-thick loamy deposit (dates between 4 and 3.8 ka) with very high microartifact content – particularly tiny bones and shell fragments at 0.125 mm fraction and coarser (see Table 5) – but with few or no large artifacts. This loamy layer seems to have been created by intentionally covering the shell layers (Stratum J) with locally sourced fine-grained sediments, producing a surface similar in texture to the originally cleared forest floor. The geoarchaeological characteristics suggest that this loamy layer was used as a habitation surface. The shells over the forest floor would have given better drainage capacity than the clay-over-limestone surface.

Analysis of the radiocarbon dates from Angostura suggests that the site was occupied before the 3.5 ka wet period and that it continued being occupied after it (see Figure 4 and Table 2). Radiocarbon dates for the black anthropo deposits suggest a much later phase of microlandscape use within the site, ca. 2.1 ka for the deeper section of the deposit. Therefore, the area in between the mounds seems to have been clear of anthropic activity at the time the mounds were being actively modified. The deepest sediments at the site (Unit 2), underlying the anthrosols, indicate the area was flooded, at least intermittently, with common changes in water table levels, as suggested by the presence of ferrous nodules and iron staining of the matrix.

The earliest date reported for the growth phase in the speleothem is 3903 corrected ka (see Table 1). The earliest date reported for the shell layers in Angostura is 4.1 ka (GX-28814, 4413–3860 cal. BP, median 4108 cal. BP, 3740 ± 100, calibrated 95.4%, 2σ probability). The time discrepancy between the earliest shell layer and the earliest date of the speleothem could be an artifact of the low precision of the radiocarbon date compared with the U/Th date of the speleothem and the palinspest effect of archaeological sites. The median for the other two dates for this layer correspond to 3.6 and 4.0 ka (Table 2). The average of the date falls at about 3.8 ka, within the 3.9–3.1 ka wet period. The deposition of shell layers at Angostura could be seen as an immediate response to the 3.5 ka wet period.
Figure 4. Calibrated radiocarbon dates (median marked) from the sites of Maruca, Paso del Indio (PDI), and Angostura (ANG). The Angostura dates are identified by locus (Mound B = U4, Mound C = U1, and Unit 3/Anthropic soil = U3), and layer/stratum. The lab number for all the Angostura dates plotted in this table can be found in Table 2. The light gray area (red online) marks the time frame of the 3.5 ka growth period. The darker colored areas (blue online) highlight the dates from Angostura. The table shows that all three sites were inhabited before and after the 3.5 ka growth period. While Angostura continued to be inhabited throughout. Reoccupation at Maruca coincides with the end of the wet period as registered in the Palco speleothem. The stratigraphic correlation of this information is summarized in Table 6.

Table 6. Chronological depiction of the archaeological records of Angostura, Maruca, and Paso del Indio (PDI) in relation to the Palco PA 2b speleothem. Dashed lines mark changes with broad beginning or ending date ranges.

<table>
<thead>
<tr>
<th>Chronology (ka)</th>
<th>Angostura</th>
<th>Maruca</th>
<th>PDI</th>
<th>PA 2b Speleothem</th>
</tr>
</thead>
<tbody>
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<td>?</td>
<td>?</td>
<td>Abandonment: river flooding</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Anthroposols/middens</td>
<td>Midden/habitation (burials)</td>
<td>Habitation</td>
<td>No growth</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td></td>
<td>Abandonment</td>
<td>Growth: wet period</td>
</tr>
<tr>
<td>3.5</td>
<td>Habituation surface</td>
<td>Shell layer/midden</td>
<td>Midden/habitation (no burials)</td>
<td>Habitation</td>
</tr>
<tr>
<td>4.0</td>
<td>Burnt surface</td>
<td>Forest soil</td>
<td>Forest soil/swamp</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td></td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
undated archaeological deposits indicate that surface use within the
site changed, with the formation of different shell deposits and
the beginning of anthropic soils, which were already formed by
2.1 ka.

The geoarchaeological analysis suggests that deposition and
site formation occurred continuously. Field sieved samples were
recovered every 10 cm and bulk samples were collected for all
strata. Given the low energy of the depositional environment
where Angostura is located, the coarse fraction of the granulom-
etry analysis (Table 2) can be assumed to be anthropogenic. This
was corroborated by the artifact/microartifact ratio (Table 4)
observed for each strata per volume. High phosphorous and mag-
netic susceptibility ratios also correlate to anthropogenic strata
(Table 2). Sedimentologically, no interruption of deposition was
identified, and all levels with lower coarse content in the granu-
ometry analysis contained high microartifact content in multiple
fractions down to 0.25 mm (Table 5), emphasizing the relevance of
in situ human activity over site formation processes. All these
characteristics support the interpretation of Angostura as a perma-
nently occupied, sedentary settlement.

Comparison of Angostura, Maruca, and PDI

The pattern of continued occupation identified in Angostura is not
evident at the other two contemporaneous archaeological sites:
Maruca and PDI (see Figure 1 and Table 6). Maruca is located
directly south of the cave sampled for climate reconstruction,
south–southwest of Angostura, on the opposite coast of the island.
The area is drier, mostly because of the rainshadow caused by
the Central Cordillera. Even though today the site is away from
the shoreline, at the time of occupation, the site was located on the
coast, within mangrove forests (Rodríguez, 1997, 2004). No geo-
archaeological analysis was conducted at Maruca, but the stratig-
ographic and technological analyses of the site suggest that there
were two distinct occupation events (Rodríguez, 2004). The earli-
est one presents dates from 4.5 to 3.9 ka (4568–3905 cal. BP), and
the later from 3.2 to 2.1 ka (3280–2060 cal. BP). These two occup-
cations are separated by a sediment layer identified as an aban-
donment phase. Human burials are found in association to the
later phase of occupation (Rodríguez, 2004).

PDI is located east of Angostura, on the west bank of the
Cibuco River on the narrow (ca. 400 m wide) floodplain within
the boundaries of cliffs eroded by the river on the limestone bed-
rock. The site contains occupation layers starting at the Pre-
Arawak period continuing to the present. Distinct occupations
are separated by river flood events. The analysis of the rich
assemblage recovered has not been completed yet, but brief
accounts of the excavation (Rodríguez Ramos, 2010; Walker,
2005) and a report on the geoarchaeological analysis of the site
and its surroundings (grain size analysis and OM content, Clark
et al., 2003) allow evaluation of the site. PDI presents three dis-
tinct Archaic occupation phases: the first one is dated to ca.
4.6 ka, the second one between 2.6 and 2.3 ka (2610 and 2400 cal.
BP), and the last one ca. 1.8 ka (1860 cal. BP, AD 90; Rodriguez
Ramos, 2010: 46). These occupations are separated by inundation
events that left a distinct, coarser grained, lighter colored
sediment deposit caused by overbank flow and periodic river
flooding (Clark et al., 2003).

Discussion: Human adaptation
strategies

We posit that people at Angostura responded rapidly to
increased moisture by creating better draining shell deposits
over the limestone outcrops and designed habitation spaces
raising the living surfaces from the periodically flooding forest
floor because of groundwater surfacing. This is an exciting
indication of adaptation to climate variability among early
Caribbean populations.

Onsite and offsite landforms at and around Angostura suggest
that the climatic parameters of the period under study prompted
aquifer recharge and intense spring and river activity (Rivera-
Collazo, 2011a, 2011b). Coring of coastal plain north of Angos-
tura (Rivera-Collazo, 2011b) suggests that 4.1 ka the area was
flooded, with sediments evidencing the existence of a palaeo-
agoon with marine to brackish environmental conditions and active
biotic activity on the muddy bottom (Rivera-Collazo, 2011a, see
Table 2 for radiocarbon dates). The 3.5 ka wet period intensified
the mid-Holocene wet conditions, prompting lowland flooding.

The PDI context supports this observation, as the Cibuco River
turned from a stable to a depositional environment at some point
after 4.6 ka (Clark et al. 2003). Wetter conditions and higher river
discharge with more common overbank flow would have nega-
tively affected the desirability of previously stable locations. Closer
to Angostura, the environmental conditions observed in the palaeo-
agoon changed gradually as salinity in the lagoon decreased, it
became shallower, and there was increased mixing of the water
column. Dry-land conditions are evident in some areas of the
coastal plain by 1.3 ka (Rivera-Collazo, 2011a: 118–123).

Facing these changing environmental conditions, the archaeo-
logical record shows two different types of social response or
adaptation strategies to the wetter conditions ca. 3.5 ka. The
inhabitants of Maruca and PDI seem to have relocated. Both sites
present habitation hiatus correlating to the 3.5 ka wet period (Fig-
ure 4). In the case of Maruca, even though precipitation param-
ters can be expected to be lower on the south of the island, the
elevation gradient of the area is very low – at sea level today – and
minute changes in river discharge or spring activity can be
expected to have had drastic effects over the coastline and flood-
plain. It is possible that flooding reduced dry-land area and other
coastal zones were easier to access, but sedimentary analysis of
the coastal plain would have to be conducted to evaluate this pos-
sibility. So far, the sediments within the site identified as the aban-
donment layer are reported to be the product of flooding
(Rodríguez, 1997, 2004). Reoccupation of Maruca occurred just
at the end of the precipitation period, around 3.3 ka (Figure 4),
possibly because of the drier conditions south of the Central Cor-
dillera and the local microclimate, but additional research is mer-
ited. Sadly, the site was destroyed during construction of a
megastore and its parking lot.

PDI shows increased river instability and absence of settle-
mament (Clark et al., 2003). Given that only two radiocarbon sam-
ple analyses were done from the Archaic context at PDI, it is not
possible to pin down precisely when the Cibuco River flooding
regime started, except from ascertaining that it occurred at some
point between 4.6 and 2.6 ka. The correlation between the aban-
donment of the earliest occupation event at PDI and the increased
precipitation period registered in the speleothem is not completely
clear because of a 600 a difference between one and the other.

Analysis of lagoon sediments from the coastal plain just north of
PDI suggests that during the abandonment of PDI – and during
the 3.5 ka wet period – people could have turned to use coastal
zones more intensively. According to Burney et al., 1994), the
area surrounding the Tortuguero Lagoon (immediately east of
Angostura, Figure 1) began to be affected by human activity pos-
sibly as early as 5.9 ka, as suggested by micro-charcoal presence
in cored sediments. However, the study reports the highest
micro-charcoal values precisely between 4.0 and 3.5 ka, with
a distinct peak at 3.2 ka (Burney et al., 1994). The geological
and topographic conditions surrounding Tortuguero Lagoon suggest
that the area was prone to flooding even during mid- to early
late-Holocene conditions. Even though Angostura is near Tortu-
guero (Figure 1), it is outside Tortuguero’s catchment area
for charcoal particles, as it lies downwind from it. The observed
micro-charcoal must have been produced close to the lagoon or east of it, where the wind could have picked up and transported the particles. It is possible that groups affected by flooding upriver, such as those living at PDI, relocated to the coastal dry land around Tortuguero. Taking into consideration that social ties acquire more relevance under stressful periods (Adger et al., 2013; Curet, 2005; Curet and Oliver, 1998), proximity to the coast and easier access to the maritime networks could have been an attractive option for Archaic groups at that time.

The archaeological record for the Archaic period supports social continuity and strong bonds between islands and continent throughout the period, starting at least ca. 4.8ka (Rodríguez Ramos, 2008, 2010: 75–87). Even though abandonment of colonization efforts is a possibility, the cultural continuity before and after the 3.5ka wet period suggests that people could have moved from PDI or Maruca to other areas while onsite conditions were not favorable, and returned later once conditions improved. Additional research in the area surrounding these sites, including a solid radiocarbon dating program, is needed to understand these coastal landscapes during the Archaic period.

Angostura presents a different adaptation strategy. Instead of site abandonment, the settlement shows the development or implementation of already known technology to improve living conditions, as well as the intensification of micro-surface modification as part of landscape formation (sensu Terrell et al., 2003 and the ‘domesticated landscape’ concept). Angostura was located at the dry land closest to the shoreline of the palaeolagoon. The aeolianite ridges at the coast today would have provided a smaller range of resources and would have been far from access to – and control of – the resource diversity available at the ecotonal area between forest, estuary, and river. Relocating to the aeolianite ridges – or further into the forest – would increase distance to resources from the diverse habitats available from the ecotone, increasing energy investment for resource procurement, making relocation a less profitable option than adaptation.

It is possible that Angostura also played an important role within a maritime network of social interaction and exchange, where settlement abandonment and relocation would have been counterproductive for the group’s priorities. The presence of burials – at least one in primary context and additional remains in possible secondary contexts – within the earlier deposits at Angostura suggests that social ancestry was tied to location (Curet, 2005; Curet and Oliver, 1998), a phenomenon seen in Maruca only after resettling occurred. In the case of Maruca, settlement reshuffling in response to higher precipitation regimes could have affected territorial perception in the later phase of occupation, triggering more intense social identification with a particular location.

**Conclusion**

General climatic patterns might have different effects on the landscapes comprised within broad regions, therefore influencing the perception of magnitude, scale, and rate of change for the people living on those landscapes. Broad patterns of climatic change and variability for the mid-Holocene in the Caribbean Region suggest that the Greater Antilles were subject to higher precipitation, lower sea levels, and higher seasonality. Even though these patterns help to frame general processes, their wide scale makes it hard to correlate them to the small-scale data of human responses that can be obtained from archaeological sites. In this work, we compare variations in the archaeological record with scale-compatible climate data by considering climatic records close to the location where human activity occurred and not just broad patterns that might not coincide with people’s experiences in the past.

The local palaeoclimatic record presented here suggests that precipitation rates fluctuated during the early stages of island colonization in Puerto Rico (near the end of the mid-Holocene). The speleothem record at Palco2 presents an 800-year wet period that spanned from 3.9 to 3.1ka. The archaeological record corresponding to this period suggests that people living in Puerto Rico at this time perceived this change and responded to it in different ways. Human responses to change are complex and can vary drastically depending on the social priorities at the time when change is perceived. In the case of Angostura, location was a cultural priority and technology was implemented as an adaptation strategy in response to change. In Maruca and PDI, location was considered less of a priority, and therefore, settlement was abandoned or relocated until favorable conditions returned. The archaeological record of PDI and the Tortuguero Lagoon suggests that access to the coast – and possibly to long-distance networks – played an important role in ensuring social continuation and support. Abandonment of Maruca and PDI, as individual sites, could be interpreted as evidence of vulnerability, as the settlement did not continue through the environmental change. However, we argue that vulnerability or resilience of particular groups needs to be contextualized within broader social processes. Flexibility in the perception of location and the identification of relocation as an acceptable adaptation strategy are resilient social responses, as there is evidence of cultural continuation after the end of the environmental instability. In addition, social response to change cannot be seen as monolithic. Even within single cultural periods, response in different locations can be varied, as human behavior addresses the needs of individual groups with different priorities.

This multiplicity of responses can indeed enhance resilience as social support can continue through alliances and exchanges that enhance social bonds that can help buffer catastrophes. Resilience and vulnerability, therefore, have to be qualified in terms of scale of observation and goals of adaptation. This conclusion agrees with Adger et al. (2013) who emphasize the importance of the goals of adaptation in the definition of vulnerability and sustainability.

In conclusion, people respond to the environmental and climatic changes they perceive based on their lived or learned experiences. Therefore, broad palaeoclimatic parameters have to be scaled-down to regions and territories when attempting to articulate climate change and cultural response. In addition, different social groups have different priorities, even within the same culture. As a response to climate or environmental change, people will develop adaptation strategies that fit their own needs, allowing for groups to respond differently to the same environmental phenomenon.

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**References**


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