A Chronology of Karstification In Puerto Rico Using Cosmogenic Dating Of Cave Sediments

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Abstract

The geomorphic history of cave development in Rio Camuy and Rio Tánamá agrees with cosmogenic dating of sediments in these two large cave systems. Local surveys of caves have shown that the present neighboring rivers of the Camuy and Tánamá were once united by large cave conduits down which the ancestral Camuy flowed east along the structural strike to the Tánamá. This combined flow [about 6 m s⁻¹] allowed the Tánamá River to maintain surface flow while down-cutting northward in a deep canyon, following the dip of the limestone to the Atlantic Ocean. Thick sediments in two large caves (close to sea level at the Tánamá outlets) were analyzed using in-situ-produced ⁶⁷Be and ⁶⁰⁰Al in river-borne quartz, and provided burial dates of 4.6 and 4.7 My (Million years old), a minimum age to begin karstification. Fossils found in young upper-Pliocene aged carbonates suggest an upper age for uplift of Puerto Rico of 5.5-6 My. The cave conduit that had channeled the Camuy discharge to the Tánamá was active until about 4.5 My, after which it was abandoned when the Camuy River developed its own route south following the dip. Over the following million years - to 3.6 My, new groups of conduits formed and were subsequently abandoned along upper reaches of the Camuy River; the currently active lower galleries of the Camuy Caves have developed since then. Deprived of the Camuy discharge, the Tánamá was also subsequently pirated underground through nine caves.

Keywords: cosmogenic dating, caves, karst, Puerto Rico

1. Introduction

Cave conduit formation and sequential abandonment influence the evolution of the surrounding drainage surfaces and the regional topography. The differential decay of the radioactive cosmogenic nuclides ⁶⁷Be and ⁶⁰⁰Al is now frequently used with other methods [e.g. speleothem U-Th, paleo-magnetic fields], or alone, to date the burial of sediments in caves, broadening the accuracy of biological ages for cave formation (Stock et al. 2005). Cosmogenic burial dating is typically best suited for dating sediments where depositional age ranges between a few hundreds of thousands of years to 6 My. Cave sediments experience less weathering and reworking than their surface equivalents stored in river terraces, and are also protected from erosion over much longer periods. Spatial correlations between deposits in cave systems and surface features are also aided by the preservation of geometrical and cross-cutting relationships between sequentially-abandoned cave conduit straths. With accurate cosmogenic dating, other useful geologic properties can also be extracted such as rates of denudation, and resistance of different rocks to erosion, as was determined in the recent study by Brocard et al. (2016) using caves in Puerto Rico. From this same set of caves data we chose two well surveyed caves systems in Puerto Rico exceeding 20 km in extent to test the degree of agreement between cave sediment burial dating and the timing of significant cave development previously-determined from the geomorphic relationships between conduits, and between conduits and surface valleys. This study represents the first cosmogenic dating of karst conduits in Puerto Rico and the Caribbean.

Deposition of reefal carbonates over the recently emerged Puerto Rico landmass ended in the Early Pliocene time with the deposition of the 5.6 My Quebradillas Limestone. Sedimentation ended due to rapid 4-5° northward tilting of the Puerto Rico-Virgin island tectonic block (van Gestel et al., 1999; ten Brink, 2005), which forced its crowning reef platform to sink 4.5 km into the Puerto Rico Trench, while the southern ledge of the platform emerged. Removal of these Miocene carbonates by shoreline and continental erosion exposed the underlying Tertiary shales and the Jurassic-Paleogene volcanic basement. Erosion has since restricted the E-W outcropping of the carbonate belt to a maximum 25 km N-S width along the northern coast, which rises inland with an average topographic slope of 2° up to an elevation of about 400-500 m.

The northern homoclinal 4° dip of its beds produces a series of landward-facing cuestas. Intense karstification since emergence has produced a dramatic epikarst, and the rivers that initially flowed across the emerged carbonates were soon diverted into it (Monroe, 1976; Moussa, 1987).

We have studied the timing of sinking and integration of two of the most extensive cave systems of Puerto Rico, those of Rio Camuy and of Rio Tánamá. Although both streams have similar elevations, discharges, catchment areas, and climate, their geomorphology and cavernous development are quite different due to distinct geology and chronology of development. Both cave systems, however, have been valuable in their ability to provide information concerning the age of karstification of the Camuy Karst Block, and the uplift of Puerto Rico and its erosional history (Miller, 2009). Both streams initiated side by side over the volcaniclastic rocks of the Central Cordillera before flowing north, towards the Atlantic Ocean, across the Oligocene-Miocene sedimentary cover. They first encountered the Oligocene San Sebastian Shales and then the Miocene Lares Limestone, into which they sank within two 2 km after contact. The subterranean Rio Camuy has produced more than 20 km of surveyed cave passages grouped into conspicuous levels (straths) of galleries that exhibit lateral and vertical offsets. Rio Camuy meanders underground over a surface straight
distance of 11 km before reappearing at a series of baselaw and wet season resurgences hosted within the chalky Cibao Formation. Rio Tanamá flows within a deep gorge through Tertiary limestones and across exhumed hills of Cretaceous volcanlastic rocks before joining Rio Grande de Arecibo, 16 km farther downstream in a straight line. The river successively passes beneath three travertine bridges and six bedrock caves of variable length, which altogether have a cumulative length of about two kilometers (Miller, 2004; 2010).

2. Cosmogenic Dating And Methods
Terrestrial cosmogenic $^{10}$Be and $^{26}$Al are produced in the O and Si atoms in quartz crystals in the uppermost few meters beneath the Earth’s surface by high energy cosmic rays. Cosmogenic production during subsequent downslope transport, fluvial transport, and transitory storage in floodplains is generally regarded as minimal compared to the initial exhumation in mountainous settings. Once buried in a cave, the grains are shielded from further production and the original $^{26}$Al/$^{10}$Be ratio of ~7 then decreases predictably with time due to faster decay of $^{26}$Al compared to $^{10}$Be (half-lives of 0.71 and 1.4 My, respectively). The concentration of these isotopes in buried quartz grains can thus be used to retrieve the minimal burial age of the sediments (Lal, 1991; Granger and Mazarik, 2001).

We sampled former sandy and gravelly underground deposits to insure proximity to the former river channels, and minimize the uncertainties typically associated with overbank deposits that may have been deposited in abandoned galleries during exceptional floods or following lower-conduit choking long after gallery abandonment. We therefore assume that the range of deposits only slightly postdate cave formation, and immediately predate cave abandonment and river rerouting towards lower elevation conduits. Quartz grains were extracted from the sandy matrix of sandy-gravelly alluvium and from igneous gravel of diorite, quartz diorite and granodiorite from outcropping plutonic bodies located in the headwaters. Quartz isolation, purification, and dissolution; ion exchange extraction; and precipitation of beryllium were performed at the University of Pennsylvania Cosmogenic Isotope Laboratory (PennCIL) following an adaptation of the technique of Kohl and Nishizumi (1992). Inductively coupled plasma optical emission spectroscopy (ICP-OES) measurements indicated elevated total Al concentration in quartz after etching, higher in the standard fraction (0.25–0.5 mm) than in the 0.5–1.0 mm and 1–2 mm fractions, which were used to gain dating precision. Selected fractions had Al concentration ranging from 25 to 90 ppm that did not require $^{26}$Al carrier addition. About 220 μg of $^{10}$Be carrier (Scharlaau BE03450100 carrier batch 2Q2P—14 October 2010) with a measured $^{10}$Be/$^{14}$Be ratio of 1.5 × 10$^{-10}$ was added to each sample during quartz dissolution. $^{10}$Be and $^{14}$Be were precipitated at pH 13 and removed prior to the ion exchange chromatography separation of Be and Al. Be and Al hydroxides were precipitated at pH 6–9, oxidized to BeO and Al$_2$O$_3$, and separated by column chromatography (AMS) at P.R.I.M.E. Laboratory, Purdue University. Results were normalized to standard 07KNSTD for $^{10}$Be and 31950KKNSTD for $^{24}$Al (Nishizumi et al., 2007, Balco et al., 2008) with an assumed $^{10}$Be/$^{14}$Be ratio of 2.79 × 10$^{-10}$.

(Balco, 2009). $^{10}$Be/$^{14}$Be and $^{26}$Al/$^{28}$Al ratios of the procedural blanks were 2.8 ± 0.8–3.4 ± 0.7 × 10$^{-10}$ and 2 ± 6 × 10$^{-12}$, respectively. Reported 1 sigma uncertainties (Table 1) encompass uncertainties on Purdue accelerator mass spectrometry measurement, uncertainties on the primary standard, an estimated 2% uncertainty on the Be concentration of the carrier solution, and uncertainties on the procedural blanks. The production ratio of $^{26}$Al/$^{10}$Be and the decay constants are those used in the CHRONUS online calculator (Balco et al., 2008) version 2.2.0.1 (Balco, 2009).

3. Collection
The framework of the Rio Tanamá and Rio Camuy caves is well known, and most of the significant conduits were surveyed decades ago. However, a noteworthy finding of the recent decade was the Dugón System, a dissected series of three large, previously-connected cave conduits lying at higher elevation (which are therefore older) than the oldest known Camuy cave headwater fragments. Their elevation declines from west to east, indicating a flow gradient directly towards the Tanamá catchment. We therefore surmise that these caves once routed water from the Rio Camuy watershed to the Rio Tanamá along a generally-strike-oriented path (Miller, 2009, 2010). They augmented the discharge of Rio Tanamá to 6 m$^3$ s$^{-1}$, allowing that river to armor its bed with clastic sediment and maintain a surface flow probably all the way to Rio Grande de Arecibo, following the structural dip and the trend of a large surface lineation. Each of these segments, namely the ancient Tanamá, the Dugón System, and the recent Camuy, contains dateable sediments that record important events of their evolution (Fig. 1).

We sampled two large, filled, ancient cave conduits near the mouth of Rio Tanamá [Group RT]. They are exposed in the walls of crosscutting younger conduits and preserve 10 to 15 m-thick deposits of sand and rounded stream gravel and cobbles. One of these is crosscut by Cueva Sorbetos, which is accessed through a cliff wall above the Rio Tanamá (at 90 m asl), while the other is exposed in Cueva Jaguar just above the post-glacial coastal filling of the Rio Grande de Arecibo valley (20 m asl), and interpreted as a likely former outlet of the Tanamá to that river. These passages may continue farther downstream below current sea level, onshore below the coastal plain, and/or offshore, as caves or alluviated river valleys, due to post-emergence tilting of the carbonates (Meyerhoff, 1927). Thick (>10 m) accumulations of river sediments farther upstream in one of the caves of the Dugón System.

![Figure 1. Puerto Rico and location of the sample sites. The shaded arrow is the karst area bordering the Atlantic Coast and rising inland; these Tertiary rocks comprise 90% of the Island's karst.](image-url)
[DS] record the approximate time of separation and diversion of the Camuy River to its present northward course.

The uppermost Camuy passages [RC] postdate the abandonment of the Dugón conduits and are organized in several segmented sections on both sides of the present Rio Camuy above the poron that marks the current entrance to its subterranean course. Presumably, other passages used to exist farther upstream and have been eroded away by incision and enlargement of the Rio Camuy gorge. The RC fossil conduits all head north down the structural dip and are younger, or contemporary to the Dugón conduits; several contain clastic sediments of high elevation and great age.

Results And Discussion

We sampled eight deposits in six caves for $^{10}$Be/$^{26}$Al dating (Fig. 1). Three geomorphic events of known relative age are expected to closely agree with ages provided by these measurements (Table 1), namely: 1, the initiation of the karst cave systems, which most closely follows the emergence of the carbonate platform, and therefore most closely follows the deposition of the Quebradillas Limestone (post-5.6 My), 2, the diversion of the Camuy River from its combined flow of Rios Camuy and Tanamá, and the abandonment of the Dugón system, and 3, the development of the younger, modern set of vertically-tiered Camuy cave conduit straths.

$^{26}$Al/$^{10}$Be burial ages (Table 1) are in broad agreement with the relative time scale of known geomorphic events, although some measurements carry large uncertainties. These uncertainties result from the fact that the measured quartz grains have a naturally elevated $^{26}$Al content, and that the caves are quite old enough to result in a decay of $^{26}$Al so great that it brings the $^{39}$Al/$^{26}$Al ratio close to the threshold of detection. First, the absolute ages of the ancient, united lower Tanamá conduits (Cuevas Sorbetos and Jaguar), are, at 4.6 My, 4.7 My, and 4.4 My, consistently younger than the age of emergence of the carbonate platform (after 5.6 My). Second, these ages are, as expected, at or older than that of the pre-piracy Dugón System (4.5 My). Third, the ages of the post-piracy conduits of the Camuy System are the same, at 4.5 My for Cueva Oscura (the highest of these caves), or less (3.6 and 4.0 My) for the nearby, lower elevation Cueva Ensuene, and finally 4.0 My for the extensive Cueva Humo level which is about 40 m above the modern underground water course of Río Camuy.

A likely history for the major conduits draining the Camuy Karst Block is therefore uplift beginning about 5.5 My ago, and commencement of epikarst erosion shortly thereafter. Within a few hundreds of thousands of years, rivers had established allogenic catchments on non-soluble rocks, flowing down dip to the Atlantic Ocean. The largest rivers were able to maintain surface courses by cutting canyons entrenched 200 m or more into the uplifting limestone, while smaller streams that did not meet the minimum flow threshold (6 m$^3$ s$^{-1}$) to armor their beds were diverted underground.

The combined eastward-flowing Rio Camuy and northward-flowing Rio Tanamá were thus able to maintain surface flow across the karst platform, perhaps for several hundreds of thousands of years, cutting a deep, narrow canyon. Once the Camuy River split off to flow north approximately 4.5 My ago, both the Tanamá and Camuy rivers became unable to maintain surface discharge. The Tanamá then cut half a dozen caves down to a new base level, leaving eroded stream-cut notches on top of all the new bedrock cave bridges.

The Camuy's path to the Atlantic today is more direct and efficient than was its shorter and lower gradient underground to the Tanamá, however its redirection may have been the ultimate result of the large combined stream incising deeply enough to encounter and exhum older volcanlastic rocks. That these rocks (at least in this area) are more resistant to erosion than limestone is shown by the abandonment of a large valley of the Tanamá stream incised into one of these exhumed hills, and its subsequent down-cutting > 40 m alongside the contact of the limestone and the volcanastics, forming a large cave. The difficulty and delay in increasing the gradient would have made the Rio Camuy's route north increasingly attractive, to the point of diversion.

Table 1. $^{10}$Be and $^{26}$Al Concentrations and Burial Age of Quartz in the Caves

<table>
<thead>
<tr>
<th>Cave</th>
<th>Grain Size (Φ)</th>
<th>East (deg)</th>
<th>North (deg)</th>
<th>Elev (m)</th>
<th>$[^{10}$Be] *10$^6$ at g$^{-1}$</th>
<th>$[^{26}$Al] *10$^6$ at g$^{-1}$</th>
<th>$^{39}$Al/$^{26}$Al</th>
<th>Burial Age (My)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Tanamá Group</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>SOR</td>
<td>4-2</td>
<td>-66.72</td>
<td>18.40</td>
<td>90</td>
<td>3.91 ± 0.30</td>
<td>2.86 ± 0.28</td>
<td>0.73 ± 0.09</td>
<td>4.6 ± 0.6</td>
</tr>
<tr>
<td>JAG</td>
<td>-3-4</td>
<td>-66.69</td>
<td>18.39</td>
<td>20</td>
<td>3.82 ± 0.19</td>
<td>2.52 ± 0.36</td>
<td>0.71 ± 0.2</td>
<td>4.7 ± 1.0</td>
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<tr>
<td></td>
<td>4-2</td>
<td>4.43 ± 0.38</td>
<td>3.56 ± 0.37</td>
<td>0.80 ± 0.11</td>
<td>4.4 ± 0.6</td>
<td></td>
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<tr>
<td>Cueva Larga (Dugón System)</td>
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<td></td>
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<td></td>
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<tr>
<td>LAR</td>
<td>1-0</td>
<td>-66.81</td>
<td>18.32</td>
<td>330</td>
<td>3.40 ± 0.21</td>
<td>2.50 ± 0.32</td>
<td>0.74 ± 0.10</td>
<td>4.5 ± 0.6</td>
</tr>
<tr>
<td>HUM</td>
<td>-3-4</td>
<td>-66.83</td>
<td>18.31</td>
<td>290</td>
<td>5.89 ± 0.22</td>
<td>5.57 ± 2.68</td>
<td>0.9 ± 0.5</td>
<td>4.0 ± 4.0</td>
</tr>
<tr>
<td>ENS</td>
<td>0-1</td>
<td>-66.8</td>
<td>18.32</td>
<td>310</td>
<td>6.46 ± 0.45</td>
<td>7.76 ± 0.54</td>
<td>1.20 ± 0.12</td>
<td>3.6 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>4-2</td>
<td>7.44 ± 0.40</td>
<td>6.96 ± 0.47</td>
<td>0.94 ± 0.08</td>
<td>4.0 ± 4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSC</td>
<td>1-0</td>
<td>-66.82</td>
<td>18.32</td>
<td>340</td>
<td>5.45 ± 0.29</td>
<td>4.11 ± 0.36</td>
<td>0.75 ± 0.08</td>
<td>4.5 ± 0.5</td>
</tr>
</tbody>
</table>

*Cave Names: JAG = Jaguar, SOR = Sorbetos, LAR = Larga, HUM = Humo, ENS = Ensuene, OSC = Oscura
1Location of cave entrances (purposely imprecise for the sake of cave preservation).
2The Larga deposit was sampled along the descending conduit about 30 m below the highest entrance. Analyzed sediment grain size fraction given in phi scale with particle diameter $D = D'$*2$^{-n}$ with $D' = 1$ mm.
The rest of the Camuy caverns' history is that of successive northward development, with vertical abandonment of lower gradient passages and galleries, occurring over the next million years (3.6 My). More sampling of large burial deposits, and locating new sites, is needed to expose the details of each level's development.

4. Conclusions
The results of the $^{10}$Be/$^{26}$Al dating process (Table 1) are in broad agreement with the relative time scale of known geomorphic events:

1. The times of cave sediment burial in Cuevas Sorbetos and Jaguar (4.4 My, 4.6 My, 4.7 My) are more recent than those of the Pliocene Quebradillas Fm. (5-6 My), yet
2. Older than that of pre-piracy Dugón System (4.5 My).
3. For post-piracy conduits of the Camuy System, the dates are the same 4.5 My for Cueva Oscura (the highest of these caves), but are 3.6 and 4 My for the nearby but lower elevation Cueva Ensueno, and finally 4 My for the extensive Cueva Humo strath which is about 40 m above the modern underground flow of the Río Camuy.

The study shows that information can be obtained from cosmogetic dating of cave-buried sediments in terms of absolute dates that can be used to apply temporal limits to important geologic events.

Future work can be broadened to aid in determining rates of denudation, aggradation, uplift, etc. by distinguishing between the several straths within the Río Camuy caves. Other cave data from elsewhere on the island can also be added to that of local speleothem data to combine their regional stories with that of the Camuy Karst Block.

Numerous surface stream terraces and straths of the karst areas also need to be examined to see how they relate to the cave data. Abundant instances of catchment piracy exist in the volcaniclastic areas that can probably explain some of the migration history of the subterranean straths. Finally, the hundred-vertical-meters of offshore karst presently drowned and alluviated by sea level rise can to some extent be understood by analyzing the cosmogenic data associated with the mobile knickpoints and stream gradients common in the mountains of Puerto Rico.

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References


