Depositional History and Evolution of the Paso del Indio Site, Vega Baja, Puerto Rico

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Potsherds discovered during excavation of bridge pilasters for a major expressway over the Rio Indio floodplain, a stream incised within the karsts of north-central Puerto Rico, required large-scale archaeological excavation. Five-meter-deep bridge pilaster excavations in the alluvial valley provide a 4500-year history of deposition. Stratigraphic analysis of the exposed pilaster walls in combination with textural and organic carbon analyses of sediment cores obtained over a much broader area suggest a fluvial system dominated by overbank deposition. Six sequences of alternating light and dark layers of sediment were identified. The darker layers are largely composed of silts and clays, whereas the lighter layers are rich in sandsized sediment. Archaeological evidence indicates the organic-rich dark layers, believed to be buried A horizons, coincide with pre-historic occupation by Cedrosan Saladoid, Elenan Ostionoid, and Chican Ostionoid, extending from A.D. 450 to A.D. 1500. Lighter layers below the dark soil horizons are interpreted as overbank deposits from large magnitude flood events. The floodplain aggraded discontinuously with rapid deposition of sand followed by gradual accumulation of silt, clay, and organic material. An approximately 1-m-thick layer of coarse sand and gravel halfway up the stratigraphic column represents an episode of more frequent and severe floods. Based on radiocarbon ages, this layer aggraded between A.D. 1000 and A.D. 1100, which is well within the Elenan Ostionoid era (A.D. 900–1200). Rates of sedimentation during this period were approximately 8 mm per year, ten times greater than the estimates of sedimentation rates before and after this flood sequence. The cause for the change in deposition is unknown. Nonetheless the Elenan Ostionoid would have had to endure frequent loss of habitation structures and crops during these events. © 2001 Wiley Periodicals, Inc.

INTRODUCTION

The physical setting of an archaeological site provides important information about the site's depositional history and evolution. The environmental history, then, can provide archaeologists with clues about how the inhabitants lived, their environment, and ultimately what may have caused their demise. Moreover, because archaeological materials are recovered from sedimentary deposits, the geomorphic, and sedimentologic processes affect interpretation of the artifacts within them.
This paper describes sedimentological and stratigraphical observations of the Paso del Indio site at Vega Baja, Puerto Rico throughout three periods of occupation. These observations, in turn, are used to reconstruct the evolution of the floodplains and describe major changes to the environment during the latter part of the Elenan Ostionoid subseries Period IIIb (A.D. 900–1200; Rouse, 1992) and the effects of these changes on the inhabitants.

Background

The Paso del Indio site, located in north-central Puerto Rico (Figure 1), was first documented in 1979 as VB-4, but the full extent or content of the site was not truly realized for some 15 years (Puerto Rico State Historic Preservation Office, 1979). Construction of Route 22, a major highway in north-central Puerto Rico, required excavation and mitigation of the impacted portions of the site. Site evaluation using soil borings to determine the horizontal and vertical limits of prehistoric occupation was initiated in May of 1993. Some 450 borings, penetrating 4–5 m in depth on a 10-m grid, were analyzed in the field. That work was followed by large-scale data recovery excavations. During this phase, more than 10,000 m³ of the site were excavated by mechanical and manual means. The work described herein took place during that 18-month excavation and recovery operation.

Study Area

The study area is located in a relatively narrow (400-m-wide), north–south trending alluvial valley (Figure 2). The valley walls are steep Miocene limestone cliffs and hills that form a rugged, karstic landscape (Monroe, 1971). The Río Indio forms the eastern boundary of the site and has a drainage area of approximately 60.6 sq km (Johnson and Torres-Sierra, 1988). The Río Indio joins the Río Cibuco less than 2 km downstream, which in turn empties into mangrove swamps along the Atlantic Ocean about 5 km further downstream. The confluence of the Río Indio and the Río Cibuco is on the coastal plain, and the slope of these streams is very gentle (less than 0.01%). The area investigated here is limited to the walls of pilasters 6, 7, and 8 (Figure 2B), and we present sediment core data taken during the initial site assessment.

METHODS

Field Observations

Detailed stratigraphic columns were analyzed in Pilasters 6, 7, and 8 (P6, P7, and P8). The nine profile locations are shown in Figure 2. Individual strata were distinguished in the field by color (using the Munsell Soil chart), texture, structure, and cultural material (Clarke and Beckett, 1971; Birkeland, 1999). Contacts between strata, strata thickness, and elevation were also noted and described in the field. Samples taken from each strata were analyzed for texture and organic matter content in the laboratory.
Figure 1. Area map showing Puerto Rico with respect to the Caribbean. The small shaded box in north-central Puerto Rico (upper right) indicates the location of the study area.
Figure 2. A 1:12,000 scale topographic map (Figure 2A) showing study area (shaded box) set within the Rio Indio alluvial valley. Note the steep bedrock walls that bound the valley bottom and the concentric, closed contours characteristic of karst terrain. A detailed map of the study area (Figure 2B) shows pilaster and stratigraphic column locations. Sedimentologic and stratigraphic observations were taken at locations denoted by a boldfaced “X”. Labels of the columns indicate the pilaster (e.g., P6 denotes Pilaster 6), the wall (e.g., WW indicates west wall), and in P7, the distance in meters from an arbitrary datum located in the southwest corner of the pilaster.
Laboratory Analyses

Texture

The relative proportion of sand, silt, and clay was determined in the laboratory using the hydrometer method (Day, 1965). Soil samples were pretreated with a dilute solution (5%) of sodium hexametaphosphate and placed into mechanical shaker for 10 minutes to disperse aggregates. The sediment was not visibly cemented so no other pretreatment was applied. After dispersal, the soil solution was placed into a 1-L graduated cylinder and floating debris were removed. The soil solution was again mixed, and hydrometer readings were taken at 0.5, 1, 3, 10, 30, 90, 270, and 540-minute intervals using an ASTM-152H hydrometer with a Bouyoucos (g/L) scale. A final reading was taken between 22 and 24 hours after the sample run began. The density of the fluid at the specified time interval was converted to a particle size distribution using the methodology outlined by Day (1965). Because fluid density is a function of temperature, a constant temperature water bath was used in most test runs to minimize temperature fluctuation. However, ambient temperature did fluctuate during some of the tests. In these cases, water temperature was recorded prior to each reading and a blank cylinder (water and dispersant only) at the same ambient temperature was used to calibrate the readings.

Organic Matter

Another soil property useful in differentiating strata is the amount of organic matter. Typically, soil horizons that were once at or near the surface (O and A horizons) have higher organic matter content. Lower soil horizons (B and C) have little or no organic matter. Organic matter (OM) content was determined using the following loss on ignition (LOI) test protocol as outlined by Rowell (1994). Samples were oven-dried for 24 hours at 105°C and then disaggregated by gently grinding with a mortar and pestle. Samples were then ashed in a temperature-regulated muffle furnace at 550°C overnight. After ashing, the samples cooled in a desiccation chamber and the post-ash weight was determined. The percentage mass change of each soil sample was calculated using the following formula: (change in soil mass/initial mass) × 100%. Because most organic matter is burned off at approximately 325°C, the change in mass is assumed to be primarily due to the loss of organic material.

The LOI method may overestimate the actual amount of organic material in the soil. Goldin (1987) noted that some clay minerals release water from their structures between 250°C and 400°C and may lead to positive errors in organic matter content. The amount of carbonate in the soil may also lead to overestimates, but the light-colored sand layers composed of quartz and calcium carbonate (CaCO3) sand scored consistently lower than the dark layers, suggesting that the presence of calcium carbonate does not affect OM content trends. Moreover, the organic matter content is used here simply as another diagnostic tool to differentiate layers.
The actual value of OM content is less important than the relative values between layers.

Radiocarbon Dating

A total of 22 samples were dated and calibrated to calendar years using conventional and mass-accelerated techniques by Beta Analytic, Inc. (Table I). Sixteen samples came from P6, four from P8, and two from P7. The two samples from P7 are essentially identical in age (approximately A.D. 1500) and are younger (outside the 2σ range) than those at the same elevation and from the same strata in P6. These P7 samples were taken near an intrusion and may be contaminated with younger sediment and debris from overlying strata. The samples from P8 were taken from units much lower in the profile than the other samples.

RESULTS AND INTERPRETATIONS

Stratigraphical and sedimentological observations made at nine locations throughout the site (Figure 2) are used to describe the physical setting. Stratigraphic column P7-SW is used to represent the typical vertical sequence (Figure 3 and Table II). An east-west transect (columns P6-WW, P6-EW, P7-WW.35, P7-EW, and P8-WW) shows how the different strata change laterally across the floodplain as one moves away from the Rio Indio (Figure 4).

Stratigraphy

Stratigraphic column P7-SW (Figure 3) was selected as the representative column because it covers the entire vertical sequence from the surface to the bottom-most strata and because several samples were taken in each stratum, allowing a detailed depiction of trends in texture and organic matter content. The descriptions and trends described below are indicative of all nine columns selected for study.

The vertical arrangement of strata can be simplified into a sequence of paleosols that are stacked on top of one another. The lower half of the stratigraphic column comprises eight alternating bands of light and dark sediment (Table II and Figure 3). The light bands (denoted as Roman numeral I) are typically more sandy and have less organic material than the dark bands (denoted as Roman numeral II; Table II and Figure 3). The relatively high organic matter and clay contents and the colors of the dark bands suggest that they are buried A horizons. The archaeological strata that correspond to the geomorphic units are listed in Table II.

The light-colored sediments gradually grade into the overlying dark sediments. Stratigraphic column P7-SW shown in Figure 3, for example, shows that the light layers fine upwards into the overlying A horizons. The gradual contact between the fine units and the underlying coarse units is partially due to hydraulic sorting during deposition, but also likely a result of translocation of some clay particles from the A horizon downward. The underlying coarse units are the parent material from which and upon which the A horizon forms. During extreme floods, the A horizons may be buried by coarse sediment, thus preserving the older soils. These buried...
<table>
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<th>Sample No.a</th>
<th>Calendar Age Intercepts b</th>
<th>2σ Calendar Minimum and Maximum Ages</th>
<th>Stratum Pilaster c</th>
<th>Modified Elevation (m)d</th>
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<td>1595 to 1905</td>
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<td>10.70</td>
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<td>77175</td>
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<td>77174</td>
<td>1105</td>
<td>995 to 1235</td>
<td>8</td>
<td>10.27</td>
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<td>81840</td>
<td>860</td>
<td>660 to 1065</td>
<td>6</td>
<td>10.17</td>
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<td>81843</td>
<td>995</td>
<td>880 to 1115</td>
<td>9</td>
<td>10.03</td>
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<td>1035</td>
<td>990 to 1195</td>
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</tr>
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<td>985 to 1180</td>
<td>16</td>
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<td>10a</td>
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<td>2580</td>
<td>2870 to 2460</td>
<td>30</td>
<td>7.21</td>
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*a Boldface samples indicate mass accelerated dates.
*b Radiocarbon ages were converted to calendar age and calibrated by Beta Analytic.
*c The locations of pilarer sample sites are shown in Figure 1.
*d Elevation of each age-dated stratum has been modified to match the vertical sequences observed in column P7-WW35.
Figure 3. Stratigraphic column P7-SW representing typical vertical sedimentary sequence. Strata were distinguished based on texture, organic matter content, and color and are indicated by alphanumeric labels. Relative amounts of sand, silt, clay, and organic matter are plotted with depth and correspond to the soil stratigraphy visible in the photograph of the column. Important strata, including cultural horizons, are noted to the right of the photograph. The location of column is shown in Figure 1.
soils and their underlying sandy parent material become the strata that make up
the floodplain fill observed today.

A light layer (parent material) and its overlying dark layer (A horizon) can be
considered as a single paleosol. Each paleosol is considered a geomorphic unit and
is labeled alphabetically from bottom to top (Table II and Figure 3). Geomorphic
units SI and SII show few if any signs of soil development. Therefore, they are not
paleosols, but simply flood deposits.

**Interpretation of Depositional Environment**

The bottom-most paleosol (AI and AII) is sterile, but some scattered cultural
debris was noted in the overlying paleosol sequence (BI and BII). Abundant but
scattered cultural debris was observed in unit CI with a concentration of shells,
pottery, and charcoal observed throughout unit CII. This unit has been interpreted
by the archaeologists as the Cedrosan Saladoid (Cuevas style) Period IIb occupa-
tional horizon (Rouse, 1992). Units DI and DII also exhibit cultural debris, again
with a large concentration located within the finer, darker DII unit, but to a lesser
degree than the C sequence.

Unit DII is truncated by a coarse layer of sand and gravel (Unit SI) that forms
an abrupt, often irregular contact with underlying unit DII (Figure 5). The gravel
layer itself is only 1–2 grains thick. This particular gravel layer is found in most
columns throughout the site.

The coarseness of the gravel (maximum intermediate diameter = 31 mm), the
irregular lower contact, and the relatively small thickness of unit DII strongly sug-

### Table II. Sedimentologic, pedologic, and general characteristics of stratigraphic units.

<table>
<thead>
<tr>
<th>Geomorphic Unit</th>
<th>Archaelogical Strata</th>
<th>Soil Horizon</th>
<th>Color (Munsell)</th>
<th>Texture (USDA)</th>
<th>Cultural Material</th>
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<td>10YR1/2</td>
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<td>10YR3/3</td>
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<tr>
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<td>10YR3/3</td>
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</tr>
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<td>Variable</td>
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<tr>
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<td>Sandy loam and gravel</td>
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<tr>
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<td>Sandy loam</td>
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<td>Sterile</td>
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<tr>
<td>SII PH1–PH2</td>
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<td>10YR5/4</td>
<td>Loamy sand</td>
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Figure 4. East-West transect of stratigraphic columns. Individual layers have been grouped into paleosols and correlated across the transect. Distance between the columns is proportional to the true ground distance. Solid lines represent contacts that could easily be followed. Dashed lines are inferred contact boundaries. Locations of columns that make up the transect are shown in Figure 1.
Figure 5. Photograph of imbricated gravel layer in P6-EW that forms an abrupt, erosional contact with the underlying dark, clay-rich unit DII. The sediments are clast-supported and exhibit imbrication, suggesting downstream flow. Location of imbricated gravel layer is denoted as P6-EW in Figure 1.

Figure 8. Photograph of imbricated layer in P6-EW that forms an abrupt, erosional contact with the underlying dark, clay-rich unit DII. The sediments are clast-supported and exhibit imbrication, suggesting downstream flow. Location of imbricated gravel layer is denoted as P6-EW in Figure 1.

gest that erosional stripping of the floodplain took place before the coarse layer was deposited. The velocity of water required to entrain sediment particles 20–30 mm in diameter is in excess of 1 m/s (Hjulstrom, 1939). This flow velocity is also capable of eroding clay-sized sediment despite its cohesive strength. It is, therefore, likely that some erosion of the floodplain surface took place during the flood event that left the gravel material behind. The gravel layer exhibits imbrication (Figure 5) suggesting strong flows over the floodplain.

The coarse sediments fine upwards into medium sands and, in some columns, a thin (5 cm) clay lens (Figure 3). The contact between the gravel and overlying fining-upwards sequence is well illustrated by the spike in sand content around 1.7 m deep and the subsequent drop in sand content over the next 20 cm from 1.7 to 1.5 m deep (Figure 3). The presence of the clay lens suggests that the flow strength...
waned enough for fine sediment to fall out of suspension. Moreover, it suggests that the thick (20–40 cm) layer of sand above the clay lens was deposited in a later flood event. The sand (SII) overlying the clay is interbedded with laterally discontinuous pebble lenses. In most of the columns, this sand layer is sterile, but some dispersed cultural debris was observed in other locations. These coarse, relatively sterile layers (SI and SII) are referred to as the flood sequence.

Overlying and grading into the massive sand is another sequence of alternating dark and light layers. Unlike the lower paleosols, these layers contain much more cultural debris. A dark, loamy layer with abundant cultural material and correspondingly large amount of organic matter (Figure 3) is interpreted as another occupational horizon, the Elenan Ostionoid (A.D. 900–1200, unit EII). Overlying the Elenan Ostionoid layer is a massive, sandy loam deposit (FI). The sandy loam deposit grades into another dark, loamy soil horizon (FII) with an exceptionally high organic matter content as well as observed high concentrations of cultural debris. This cultural horizon corresponds to the Chican Ostionoid (A.D. 1200 to approximately A.D. 1500, period IV; Rouse, 1992) occupational period. In some pilasters, the Chican Ostionoid layer and its underlying parent material are difficult to distinguish because of similarities in color, texture, and abundance of cultural debris.

The two top strata are another sequence of light (GI) and dark (GII) layers. These layers are not very distinct and show only a slight color difference (Munsell colors 10 YR 3/2 for GII vs. 10 YR 3/4 for GI), nearly the same percentage of organic matter, and little difference in texture (Table II and Figure 3). These units both exhibit scattered cultural debris, and the contact between them is indistinct. They represent the modern A-soil (GII) and its underlying parent material (GI). The soils seem very similar because the A horizon has not had enough time to fully develop and because it has been well mixed due to cultivation of sugar cane during the late 19th and early 20th centuries.

The vertical distribution of strata can be simplified into a sequence of paleosols that are stacked on top of one another. The sequence is interrupted and somewhat complicated by the coarse sand and gravel layers, but then the pattern continues with the Elenan Ostionoid, Chican Ostionoid, and modern soil horizons. This same pattern can be observed across the floodplain (Figure 4).

East–West Transect

As with the representative stratigraphic column described above, the stratigraphic sequence will be described from bottom to top, such that we are moving forward in time and following the order in which the sediment was deposited.

The lower three paleosols (A–C; Table II, Figure 4), including the Cedrosan Saladoid (period IIb) occupational horizon, are laterally continuous and generally reflect the surface topography. In most columns, cultural material was found throughout the CII horizon. An exception to this trend is column PT-EW where the lower 20 cm of the CII horizon was sterile.
Unlike the underlying strata, unit DII is not continuous across the transect; it is missing in the P7-EW column. The absence of DII is probably due to local scour. As seen in Figure 4, P7-EW is a local topographic low that may have been the site of concentrated overbank flow. Once flood waters breach a levee, they tend to rush down the levee and concentrate at the low point in the floodplain. The distinct contact between DII and the gravel layer in other columns along the E–W transect suggests that this flood was capable not only of suspending gravel and carrying it out of the channel, but also of eroding the floodplain surface. If an area of concentrated flow exists, as it does near P7-EW, then it is reasonable that the flow would have had the velocity necessary to entirely remove unit DII, leaving a relatively thick package of coarse material behind.

The flood sequence above paleosol D (SI and SII; Figure 3) introduces a great deal of lateral complexity. Not only is the continuity of the paleosols interrupted by erosion, but also the gravel layer itself is not laterally continuous; it is absent at the western-most end point of the transect. The absence of the gravel layer in P6-WW is indicative of a reduction in flow velocity as one moves away from the channel. Vegetation and habitation structures found on the floodplain, but not in the channel, would provide resistance to the flowing water, further reducing its velocity. Instead of gravel, massive clean sand was deposited at P6-WW. Despite the discontinuous nature of the gravel lenses, the flood sequence itself is remarkably consistent across the site.

The contact between the flood sequence and the parent material for layer EII (Elenan Ostionoid) is arbitrary and represented by the dashed line in Figure 4. Physically, there is no distinction between the upper-most flood sequence and the parent material for EII. They are one and the same and separated only for the purpose of discussion. The Elenan Ostionoid occupational horizon is thick and well developed in the eastern portion of the site, but tends to thin towards the west. This may reflect a settlement pattern where the population center was closer to the stream. A thin layer of gravel overlies the Elenan Ostionoid horizon near the river’s edge at P8-WW. As with other gravel deposits described above, this probably represents material carried overbank by the mainstream once it breached the levee.

The thickness of the Chican Ostionoid horizon (Figures 2 and 3) varies across the site and does not exhibit any consistent trends. The parent material in the eastern-most column P8-WW is anomalously thick and may be a reflection of levee building close to the water’s edge.

The ground surface and most underlying units slope downward away from the channel along the East–West transect (Figure 4). This trend is not unusual as alluvial streams commonly build levees along their channel margins. That the underlying units also tend to exhibit an increase in elevation towards the channel indicates that the Río Indio had built natural levees in the prehistoric past as well. These levees would serve as minor protection against lesser flood events but would also inhibit floodplain drainage and tend to hold water on the floodplain for long periods in the event of over bank flow.
Rates of Deposition

Radiometrically dated features of individual strata were used to create a composite of age vs. elevation above mean sea level (MSL) (Figure 6). The elevation of individual layers varies across the site (Figure 4), making direct age correlation of strata between pilasters problematic. For example, layer DII (archaeological strata 16, sample 77168) in P6 is located 20 cm below layer DI (archaeological strata 17, sample 77164) of P8. Stratigraphy of individual columns (Figures 2 and 3) show, however, that unit DII should be above, not below DI. Moreover, radiometric ages indicate that the DII stratum is approximately 400 years younger than DI. To address this issue, radiocarbon ages and stratigraphic position were used to establish a relative cross-correlation between strata that were given the same geomorphic designation across the pilasters. In practice, true elevation above MSL (shown in Figure 4) was modified such that strata from P6 and P8 had the same elevation as the same strata in P7-WW35. This process effectively masks the influence of subsurface topography and allows a direct comparison of the apparent radiocarbon ages between different strata. Once modified, the elevation data can be used in conjunction with the radiocarbon data to estimate rates of sediment accumulation across the entire site.

When viewed as a composite, three distinct trends are observed (Figure 6). From the oldest date of 2580 B.C., at the base of P8 (Elev. 7.21 m) to approximately A.D. 1027 from layer DII of P6 (Elev. 9.05 m), there apparently is a gradual accumulation of sediment with time (0.5 mm/yr). This trend increases more than tenfold to 8.4 mm/yr between DII (stratum 16) at 9.05 m and unit FI (stratum 8) at 10.3 m (Table II). Even more striking is the nearly vertical trend between 9 m and 10 m in elevation (strata SI–EI, the flood sequence). The radiocarbon ages from these layers are statistically similar, suggesting that nearly a meter of sediment was deposited within a very short time. From 10.3 m to the uppermost sample at 10.7 m the rate of deposition line has a similar slope to the lower series, suggesting a return to more gradual sedimentation (0.8 mm/yr). A definitive cause for the substantial increase in sedimentation rate during the flood sequence is unclear at this time, but a few possibilities are discussed below.

DISCUSSION

Agents of Change in Rates of Deposition

To increase the rate of floodplain sedimentation, either the river must overflow its bank more often or it must deposit more sediment when it floods. There are three ways to increase the frequency of overbank flow: (1) Increase base level through either subsidence of the island or increasing sea level; (2) increase the frequency or magnitude of storms; and (3) change vegetation (land cover) such that more water and sediment run off. The latter factor is particularly important because it results not only in an increase in flow frequency, but also higher sediment yield.

Dates on marine terraces in northwestern Puerto Rico suggest that sea level was...
Figure 6. Plot of radiocarbon age in calendar years vs. elevation. Samples are grouped by pilaster. Nearly horizontal trend lines indicate very low rates of sedimentation, whereas nearly vertical trend lines indicate high rates of sedimentation. A transition between low and high rates of sedimentation occurred at ca. A.D. 1500 and corresponds to deposition associated with the storm sequence.
as much as 2 m higher 3300 years before present (Seiders, 1971). An inland paleo-
shoreline that formed between 4000 and 2000 yr B.P. also was observed on the
island of Barbuda in the Lesser Antilles, further indicating a higher-than-present
sea level stand in the prehistoric past (Watters et al., 1992). Increasing sea level by
2 m would inundate the existing coastal plain and effectively move the ocean 2–3
km closer to the study site. Consider also that the flood plain elevation, as inferred
from Figure 6, would have been at approximately 8 m. These two factors could
combine to increase the frequency and magnitude of flooding at the site. The flood
deposits, however, aggraded only 1000 years ago, when sea level was lower than
present in Jamaica (Digerfeldt and Enell, 1984). The timing of the events therefore
makes the change in sea level an unlikely cause. Subsidence of the island is also
unlikely because no accounts of such tectonic activity during the last 1000 years
have been reported.

The frequency of occurrence of large magnitude storm events is not evenly dis-
tributed in time. Reading (1990), for example, documented clustering in hurricane
occurrence, with increased frequency observed during the decades following A.D.
1770, 1780, 1810, 1830, and 1890. Therefore, it is possible that the flood sequence
as interpreted in the stratigraphy is simply a result of several storms occurring
within a relatively short time.

Field and laboratory observations support the idea of a short period of rapid
deposition. The near absence of cultural horizons and poor or incomplete soil de-
velopment within this storm sequence indicate that soils did not have much time
to develop and that occupation of the site was minimal. Alternatively, floods may
have removed soil horizons or portions of soil horizons. Stratigraphy shows that
there were at least two and perhaps many more distinct flood events, each of which
may have erased evidence of prior floods. Regardless of what deposits may have
been lost to erosion, the clustering of radiocarbon dates within approximately 100
years of each other (Table I and Figure 6) strongly indicates that these deposits
were laid down in a very short time.

Changes in vegetation affect both the runoff and sediment supplied to a stream.
Vegetation may change due to natural influences like climate or due to anthropo-
genic influence (e.g., deforestation). It is unlikely that the pre-Columbian human
population would have been large enough to significantly alter watershed vegeta-
tion, especially considering that the surrounding hillsides are very steep and have
only a thin covering of soil, thereby making them unattractive for agriculture on a
large scale.

Changes in climate, however, could lead to changes in vegetative cover. A pa-
leoenvironmental reconstruction based on oxygen isotope measurements from os-
tracods and lake level indicators from Lake Miragoane, near the north shore on the
southern peninsula of Haiti, suggests that the Caribbean experienced a dry period
from 250 B.C. to A.D. 1050 (Hodell et al., 1991; Higuera-Gundy et al., 1999). During
this time, there was a loss of mesic forest species, and dry-forest taxa and weeds
dominated. However, during the last 300 years of the dry period, there was a de-
crease in the evaporation-precipitation ratio. This suggests that the climate was
getting wetter by the end of the dry period. In a relative sense, the period A.D. 750–
1050 was relatively wet as compared to the previous millennium.

An increase in rainfall coupled with a xeric (dry) forest composition would likely
result not only in enhanced runoff, but also in large contributions of sediment to
the streams (Langbein and Schumm, 1958). Dry forests are more susceptible to
erosion by running water and rain splash because their sparse canopy coverage
and lack of a litter layer leave much of the ground exposed. As vegetation adjusts
to the new climate, the soil yield will eventually decrease. This pattern is very
similar to the one recorded in the sediments (Figure 3). Moreover, the timing of
the climate shift and the resultant increase in sediment yield places it well within
the period in which the flood sequence was deposited.

Floodplain Formational Processes

Two common models of floodplain formation are those of overbank deposition
and lateral migration (Mackin, 1937; Wolman and Leopold, 1957). Lateral migration
is the most common form, especially in meandering streams (Leopold et al., 1964).
Overbank deposition also operates in meandering systems but becomes dominant
in aggrading streams. Natural stream channels often fit somewhere between these
two models. Overbank deposition tends to dominate in aggradational streams be-
cause as the river bed accumulates sediment (aggrades), the bed elevation will
increase, and so too will the frequency of overbank flows.

The Río Indio is classified as a meandering stream based on its planform ge-
ometry. However, stratigraphic and sedimentologic evidence indicate only limited
lateral migration of the Río Indio in the vicinity of the Paso del Indio study site
over the past several thousand years.

The first piece of evidence comes from the coring conducted during an initial
site survey. If the stream had migrated westward into the site, gravelly channel
deposits would be observed in the cores. The coarsest material observed in the
cores, however, was coarse sand, adjacent to the present channel and in a narrow
band running northeast–southwest across the site. The latter band is aligned di-
rectly with a small abandoned tributary, which runs off the adjacent hillsides, sug-
gesting that this sand is from a side-channel, not derived from the main channel.

Whereas the core data suggest no large-scale channel migration, the absence of
paleosols in the eastern 20 m of P8 indicates some migration westward. The north
wall of P8 clearly exhibits an erosional contact between the expected sequence of
paleosols (described above) and relatively new sand lens deposits set in loam. The
erosional contact suggests that the river must have moved westward, erasing the
entire stratigraphic sequence. The river then migrated eastward leaving younger
sediment behind. Because only two cores were taken on the eastern side of the
channel, the extent of channel migration to the east is unknown. Nonetheless, it
appears that the Río Indio was relatively stable in the vicinity of the Paso del Indio
site. This stability could be one of the reasons the site was occupied for hundreds
of years. Lateral migration would not have been extensive, and therefore, these
floodplains must have been built primarily through vertical accretion of overbank deposits.

Overbank flow is a prerequisite for floodplain sedimentation in a vertically accreting system. Flooding is exacerbated for extreme storms (e.g., 100 year events) because the Río Indio valley is relatively narrow (approximately 400 m wide) in the vicinity of the Paso del Indio site, and because the outlet to the ocean is constricted. On a greater scale, the Río Cibuco, to which the Río Indio is a tributary, meets the ocean through a 50-m-wide channel that is bounded by 20 m high cliffs of eolianite to the east and sand dunes several meters high to the west (Monroe, 1971). The narrow outlet causes water to back up and become stagnant. Mangrove swamps, which fill the lowland coastal areas, further impede river flow and enhance the backwater effect. During the 1965 flood, for example, the Paso del Indio site was under approximately 3 m of water (Hickenlooper, 1968). According to Johnson and Torres-Sierra (1988), this particular storm had an estimated discharge of 510 m³/s and a recurrence interval of 18 years at Paso del Indio. Although the 1965 flood is one of the most severe on record for the area, larger events, like the 100-year flood (estimated at 1100 m³/s), would inundate the valley under an additional meter of water (Johnson and Torres-Sierra, 1988). Given the long period over which the site was occupied, there were many opportunities for these rare, yet powerful, floods.

An estimate of the recurrence interval of these rare paleo-floods can be made using the radiocarbon ages from strata AII (Table I: archaeological strata 23; sample 87611) and DI (Table I: archaeological strata 17; samples 87610 and 77164). Between these units there are three sandy, light layers BI, CI, and DI. The two radiocarbon dates from DI are different, so the average of 605 years is used. Given the age difference between AII (A.D. 90) and DI (A.D. 605) of 515 years, the average interval between floods is about 170 years. This figure is in contrast to the recurrence interval for the storm sequence floods, which was estimated to be less than 100 years.

Model of Floodplain Development

The alluvial stratigraphy and trends in deposition described above can be explained using a simple conceptual model of floodplain development. This model will be used to determine the environmental context of the site including changes in depositional rates. Implications of these changes in environmental conditions on the inhabitants also will be discussed.

Figure 7 is a schematic diagram showing five phases of floodplain development at the Paso del Indio site. Phase A is the assumed initial starting condition of the river and floodplain. The flood plain is composed of a fining upwards sequence of sand to clay and represents the light to dark layer gradational contact observed in the field (Figure 3).

Deposition following a large, approximately 200-year recurrence interval (RI) flood is depicted in phase B. The lateral continuity of the light, coarse deposits...
Figure 7. Conceptual model showing five stages of channel and floodplain development. "a" is the initial condition. Deposition of coarse- to medium-grained overbank sediments due to a large magnitude flood is shown in b. Subsequent annual or biannual overbank deposition of fine-grained sediment, accumulation of organic material, and the development of soil horizons is depicted in c. Frequent, large-magnitude flows caused erosional stripping of the floodplain and deposited sand and gravel. Deposition was frequent enough that soils did not develop, or erosion removed soils prior to deposition (d). Flood frequency returns to normal and soil development and yearly deposition of fines takes place on flood deposits (e). The composition of floodplain sediment below the channel bed elevation is unknown and represented by question marks.
(Figure 4) suggests that during their deposition, the entire alluvial valley was subject to overbank flow and sedimentation. Large storm events would probably cause upstream flooding and could generate overbank flow velocities capable of stripping away floodplain sediment. The combination of floodplain stripping and subsequent valley sedimentation would create the distinct contact between overlying light, coarse sediment and underlying dark, clay-rich sediments shown in phase B and observed in the field (Figures 2 and 7b).

During these events, most crops and vegetation would likely be removed and what remained would be covered in 20–30 cm of fresh sand and silt. Habitation structures would also likely be destroyed or severely damaged. Cultural material in the upper soil horizon would be removed, mixed, and redeposited downstream. The scattered bits of charcoal and shell found in some of these light layers (CI and DI for example) probably resulted from removal and subsequent deposition of cultural material. Whether this material came from the Paso del Indio site itself or an upstream source is unknown. As the water receded, a new floodplain surface of nutrient-rich silt and clay underlain by sand would emerge. This surface would be ideal for cultivation and vegetation quickly would become established.

Between large events like those depicted in Figure 7b, several small (annual or biannual) overbank flows would add fine sediment to the top of the floodplain (Figure 7c). Most rivers experience minor floods (those just overtopping their banks) approximately every year (Langbein, 1949; Leopold, 1994). However, these floods are minor and leave only a light dusting of silt and clay on the floodplain. Over time, decaying organic matter and fine-grained sediment would accumulate and form relatively thin, dark A-horizons. Water percolating through the soil column would move some of the clay particles and organic matter into the underlying parent material. The diffuse contact between the dark layers and their underlying light layers (Figures 2 and 7c) suggests that leaching of fines and organics has taken place. Surfaces such as these would be particularly attractive for agriculture and are well represented by stratum CII.

Channel deposits would also accumulate and raise the channel bed, thereby allowing overbank deposition to continue. Without an aggrading stream bed, the stream banks and floodplains would continue to accumulate sediment and increase in elevation until they became too high for flooding to occur (Wolman and Leopold, 1957). Aggradation of the bed probably took place between the large flood events.

Taken together, Figures 7a–c illustrate vertical accretion of the floodplains. The light layers were deposited by large (ca. 200 year RI) floods that likely eroded parts of the floodplain and deposited fining upwards sequences of sand to silt and clay. Over time, minor overbank flows would deposit more fine sediment and organic material on this surface making the fine, dark layers observed today. Subsequent soil formation would tend to further blur the contact between the upper soil horizon (A horizon) and the underlying parent material. Gradual accumulation of fines, accumulation of organic debris, and the formation of soil horizons would continue until another large flood filled the valley with a new layer of coarse, light-colored sediment burying and preserving the underlying soil. From here, the process re-
peats itself. On average, this accumulation process is slow—about a half-millimeter per year—based on radiocarbon dating (Figure 6). The cycle of deposition described above was abruptly interrupted by the “flood sequence” (Figure 7d). Several very large magnitude events occurred in rapid succession, depositing interbedded layers of gravel and sand with clay lenses (Figures 2 and 3). The floods in this sequence differ from those described above in both their frequency and magnitude. We believe the magnitude of these events was greater than those that deposited sediment composing AI, BI, CI, etc., because it would take a very large flood to carry gravel-sized sediment in suspension and out of the channel. Moreover, extreme floodplain stripping, like that inferred from the partial absence of stratum DII (Figure 4), also suggests a very large event. Extreme erosional stripping is depicted on the right side of Figure 7d, where the coarse material has replaced the A horizon. Typically, erosion of the floodplain would take place during the rising and peak portions of the flood, whereas deposition occurs as the flood wanes and velocities drop.

Not only were these flood events of greater magnitude, but they also occurred more frequently than the floods that deposited sediment composing layers AI, BI, CI, etc. The clustering of radiocarbon ages (Table I and Figure 6) and the absence of A horizons in the flood sequence (Figures 2 and 3) both indicate that these events occurred very frequently, possibly within the same decade and almost certainly within the same century.

Eventually the environmental perturbation that caused the flood sequence must have passed, for on top of the coarse deposits rests another paleosol, EII (Figures 2 and 7e). Fines would again accumulate from yearly floods, and an A horizon would develop until another flood came along to cover the valley in fresh sediment.

CONCLUSIONS

The information gathered in the previous phases of this investigation allows us to partially reconstruct the environmental setting of the site. Settlers were probably attracted to the area because it offered many practical advantages. First, the alluvial valley is ideal for agriculture and habitation. Annual floods that deposited silt, clay, and organic debris would act as natural fertilizers and irrigators of the floodplain. Second, the Río Indio is large enough to offer easy transportation to the coast for fishing and perhaps trade. Third, the Río Indio has been shown to be relatively stable such that stream migration would not compromise the site. Finally the Paso del Indio site is in close proximity to karstic terrain, which includes many caves. These caves may have been used for storage of food stuffs, religious purposes, or shelter during floods.

The floodplains that the Archaic inhabitants encountered were probably very similar to the modern day surface, albeit lower in elevation. Based on the drainage area (60.6 km²), we can estimate that the floodplain was probably 1.5–2.0 m above the channel bottom (Dunne and Leopold, 1978). From the Archaic to the Cedrosan Saladoid occupations, the channel and floodplains aggraded through a combination of large infrequent events and smaller yearly events (Figures 7a–c).
The inhabitants of the site would have welcomed small yearly floods that helped to enrich the soil (Figure 7c). Every few centuries or so, however, they would have had to endure larger floods (Figures 7b and 7d). These events would have required evacuation of the area for several days or weeks. The velocities associated with onset of floods likely exceeded 1 m/s and were capable of removing floodplain vegetation, crops, habitation structures, and soil layers. In the aftermath of a large flood, about 0.5 m of sand and silt would be left behind, covering most of the valley bottom. The inhabitants may have had difficulty finding their former settlement with only major local landmarks to guide them. Nonetheless, this site was resettled after every large event. It appears that advantages of the site outweighed the negative consequences of frequent flooding.

That tradeoff may have not been as attractive during the Elenan Ostionoid occupation, however. The Elenan Ostionoid period (A.D. 900–1200; Rouse, 1992) is coincident with a period of frequent disturbance by large magnitude flows (ca. A.D. 1000–1100). These events are represented by deposition of the storm sequence (SI–SII) and resulted in a drastic increase in the rate of deposition (Figure 6). A burnt floor observed in P7-WW.35 suggests that the Paso del Indio site was occupied during the storm sequence period. In addition, some of the storm layers included mixed cultural material indicating that material was removed, mixed, and redeposited. Because these events were of large magnitude and occurred frequently, the effects on the inhabitants were probably severe.

Mortality resulting directly from the flooding was probably rare because there likely would have been sufficient warning (e.g., heavy rain for hours or days) and plenty of time to evacuate to the karstic highlands. However, the loss of or damage to habitation structures and crops would have had longer-lasting effects. Habitation structures could be rebuilt quickly, albeit at a cost of time and energy. However, crops would need to be replanted and would require time to grow. Moreover, if food and seeds were stored in the village, these too could have been lost, further exacerbating the food shortage. The frequency of flooding is also a problem. If these events occurred within a single decade, for example, the inhabitants would have had little time to recover (rebuild and replant) before the next event. If the events were spread over the course of a century, however, there would be enough time to rebuild and reestablish crops. Nonetheless, mortality due to starvation or malnutrition would likely be higher during and shortly after the flood sequence, and the diet of the inhabitants may have switched from cultivated crops to more fish, shellfish, and indigenous plants.

Despite the hardship caused by frequent and severe flooding, people persisted in the area, and the Elenan Ostionoid gave way to the Chican Ostionoid. From this transition through modern times, the river has returned to a cycle of flooding similar to the Archaic and Cedrosan Saladoid times. Presently the river flows overbank every 3–5 years, with severe flooding occurring much less frequently (Hickenlooper, 1966; Johnson and Torres-Sierra, 1998). By the time Europeans arrived on the island, the area had returned to one that was well suited to habitation and agriculture.
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