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Thermoluminescence and radiocarbon dating of pre-colonial ceramics and organic midden material from the US Virgin Islands: outline for a revised chronology

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Abstract

A sample of 128 pottery shards curated by the National Museum of Denmark, from seven archaeological sites in the US Virgin Islands, has been dated using the thermoluminescence dating (TL) technique with the purpose of refining local pre-colonial pottery chronology. The results of the TL-dating generally confirm chronologies offered by Wild for St. John and there is considerable variation identified in traditional frameworks due to overlap in distributions of various pottery styles. The results of this study show that the Virgin Islands offer a viable space for the application of TL-dating, and that TL-dating offer a reliable addition to the traditional radiometric radiocarbon technique in pre-colonial midden contexts. Using the TL-technique for dating of pottery assemblages allows for a nuanced chronology and better understanding of settlement timing, socio-cultural interaction, and information transmission.

Keywords US Virgin Islands, Pre-contact ceramics, Thermoluminescence dating, Radiocarbon dating, Migration

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Graphical Abstract

Introduction

The pre-colonial colonization of the Lesser Antilles and Puerto Rico by ceramic bearing pre-colonial societies was traditionally viewed as a series of waves that originated near the Orinoco River in South America. In this model, populations travelled in a stepping-stone fashion north through the archipelago displacing or absorbing previous Amerindian cultures who settled the islands over the preceding millennia (see [1–3] for overview). Current evidence supports that some populations migrated directly from the South American mainland to the Greater Antilles and US Virgin Islands (USVI) [4]. These pottery bearing groups were the social and cultural progenitors of peoples living in the islands at the time of European conquest [1–3, 5]. Subsequent population movements and cultural interactions over the course of a millennia resulted in the development of regionally diverse socio-cultural groups throughout the islands [3].

A complicating factor in understating the timing of pre-colonial settlement of the region, and subsequent regional socio-cultural diversification, is the recognition that the chronological framework developed by Irving Rouse [5] is not as neatly organized as his model would indicate [6]. While pottery does not equate to culture, diagnostic techno-functional and design traits of pottery (and other aspects of material culture) can be useful for understanding the movement of people and the transmission of information and traditional knowledge through time and space. The patterns emergent from the distribution of shared material culture can be mapped and understood as social networks that have unique configurations [7, 8].

To understand this emergence of social networks, or communities (sensu Torres [9]), and cultural interactions through time, it is necessary to refine existing cultural historical frameworks. This is important because it offers an understanding of the central tendencies of traditional knowledge and practices that shape and transform culture. Pottery, one of the most durable and ubiquitous forms of material culture in the Caribbean, is of particular interest because of the information coded in its production and design, when examined within the contexts of localities or "micro-regions" (sensu Keegan [10]) and allows for the identification of and temporality of cultural networks at finer scales that may lose precision at broader scales of analysis.

In this study we present the results of 128 TL-dates performed on pottery from seven sites within the Virgin Islands. The samples were taken from the Gudmund Hatt Collection, curated at the National Museum of Denmark. These dates provide a finer resolution for local pottery traditions and advocate for the dating of co-occurring techno-functional and design traits. Through this the efficacy of TL as a dating technique of pottery in the Caribbean is promoted as a compliment to the traditional radiocarbon method.

Archaeological contexts

Around 500 BCE ceramic-bearing peoples migrated to the Lesser Antilles and Puerto Rico. These groups are defined as the Arawak-speaking Cedrosan Saladoid and the (linguistically undetermined) La Hueca pottery making groups [5]. Points of origin for Saladoid migration into the region are linked to north-eastern Venezuela and the Orinoco River basin [5]. The movement of these groups into the Caribbean has been, and continues to be, a subject of scholarly interest [11–13].

Rouse initially conceived migrations to the Virgin Islands and Greater Antilles as a stepping-stone model in which populations from South America moved into the region by successively following the intervisible island chain northward [5]. Current radiometric evidence suggests that some Saladoid groups also arrived to the Virgin Islands and Puerto Rico in a direct migration from the South American mainland [6, 12, 14, 15], [15]:61. Both Siegel [16] and Keegan [13] suggested that the process of migration was characterized by a series of "pulses" with scouting groups sent forth to found settlements, which subsequently saw continued interaction and further arrivals once they were established. Later settlement of the Windward Islands appears to reflect population expansion both north from South America and movement south from Puerto Rico and the Leeward Islands.

In addition to archaeological evidence of colonists from South America, pottery called La Hueca may indicate migrations of groups from the Isthmo-Columbian region [6]. Pottery of this style was first recognized at La Hueca-Sorcé by Chanlatte Baik [17] and later at Punta Candelero in eastern Puerto Rico [18]. Rouse originally envisioned La Hueca as diverging from a common Saladoid ancestry the Saladoid series [5]. This classification seemed to be supported by early pottery studies that did not see significant variation in paste and vessel form between Saladoid Hacienda Grande and La Hueca styles [19, 20] to substantiate a separate culture category or series. Rather, earlier perspectives saw Huecan and Saladoid pottery makers as two culturally similar but coexisting ethnic groups [20]. Thus, Rouse originally thought La Hueca style represented an offshoot of the Hacienda Grande style and not a separate cultural series [21]:48–49. Hope Estate and other sites in St. Martin [22, 23], and Morel I in Guadeloupe [24] suggested a distinct cultural group from the previously defined Saladoid series [25].

Saladoid and La Hueca pottery makers were horticulturalists and incipient agriculturalists who complemented their subsistence practices with fishing and collecting marine and terrestrial resources [26, 27]. It is generally agreed that Huecoid and Saladoid peoples displaced or "absorbed" pre-existing Archaic groups. However, evidence exists to indicate coterminous habitation and interaction with earlier Archaic groups for some time—these interactions are only recently being understood [6].

People during this period of settlement occupied large villages near coastal settings continuously for centuries in Puerto Rico and the Virgin Islands [9, 28–32] and practiced a mixed economy of root crop horticulture and incipient agriculture, hunting of land animals, fishing, and mollusc collecting [1]. As these groups settled into the islands, formed local and regional social networks, pottery traditions, and other forms of social expression, became more diverse across the region consisting of a variety of styles that constitute those of the Ostionoid Series [5]. This regional diversification was accompanied by a suite of other regional socio-cultural and material developments [1, 33, 34].

Socio-temporal framework

The socio-temporal framework for the Caribbean is largely based on pottery styles [5]. For Eastern Puerto Rico and the Virgin Islands, also referred to as the Vieques Sound Region (Fig. 1), Rouse identified one Archaic complex and nine ceramic styles (Table 1) which he categorized into four cultural periods (PI, PII, PIII, and PIV) each with an early and late (a, b) component ([5]:52 and 107). These periods are traditionally used to define the Archaic age (PI) (ca. 1000 BCE–300 BCE) and the ceramic sequences associated with the Saladoid (PII) series, which includes La Hueca pottery tradition in Rouse's framework (300 BCE–600 CE); the Elenan and Ostionan Ostionoid (PIII) subseries (600 CE–1200 CE); and finally, the Chican Ostionoid (PIV) subseries (1200 CE–1500 CE). Pottery styles within this framework were further identified, and their temporal distribution refined, in particular for the Virgin Islands, by the late Gary Vescelius [35].

Pottery chronology for St. Croix is rooted in the work of Hatt (1924) [36] and Irving Rouse (1992) [5], and was later modified locally by Morse [37, 38]. Later work by Sleight [39] built on these typologies. However, in more recent work, Morse [37, 38, 40] and Lundberg and Righter [41] observed similarities and changes in pottery styles throughout the Virgin Islands that indicated strong cultural connections with communities in eastern Puerto Rico [42, 43]. Despite these similarities between the northern Virgin Islands there were some minor variations identified for the island of St. Croix. The periods and styles for that island area as follows: Prosperity (ca. 200/100 BCE–400 CE) and Coral Bay —Longford (ca. 400–600 CE), representing styles of the Cedrosan Saladoid subseries and corresponding to Rouse's Periods IIa and IIb; Magens Bay—Salt River I (ca. 600–900 CE) and Magens Bay—Salt River II (ca. 900–1200 CE), representing styles of the Elenan Ostionoid subseries and corresponding to Rouse's Periods IIIa and IIIb; and Magens Bay—Salt River III (ca. 1200–1500 CE), representing Chican cultural influences, at the end of the Ostionoid period, and corresponding to Rouse's Period IV.

While there is some variation in the techno-functional and design elements of pottery from St. Croix, the styles in many instances are stylistically similar to those of the Vieques Sound area (Table 2). For the purposes of this study, and due to the general overlap in stylistic characteristics of the sample and overlap in temporality, we

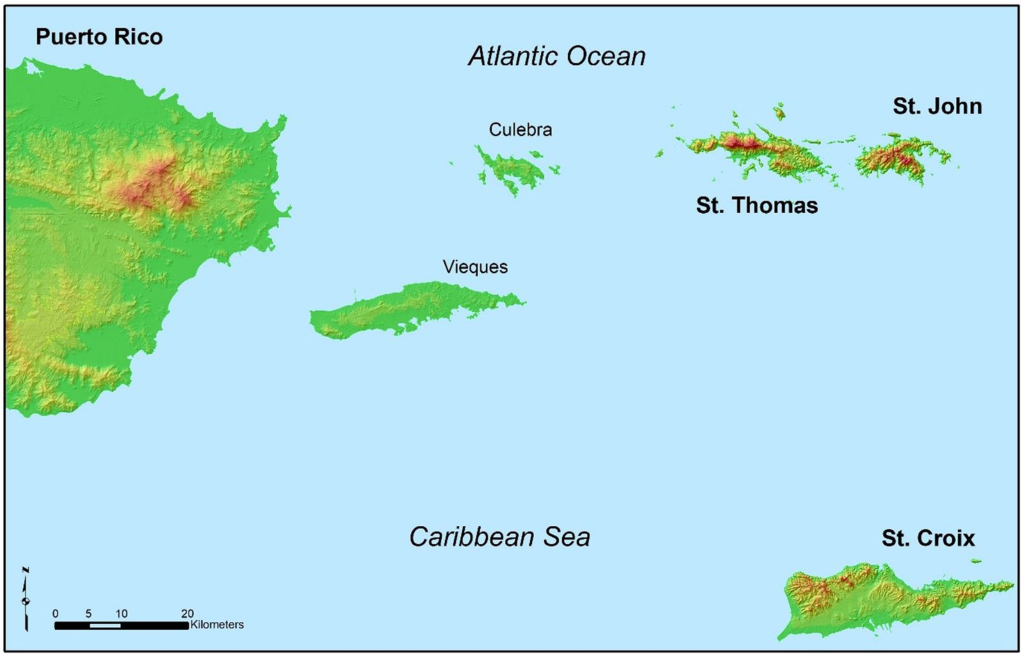

Fig. 1 The Vieques Sound Region and US Virgin Islands (map by Joshua Torres)

Table 1 Rouse's chronological framework for the Vieques Sound (modified from Rouse 1992:52, 53 [5])

Date	Period	Series	Subseries	Complex/Style
				Pottery styles vieques sound
1200–1500 CE	IVa	Ostionoid	Chican	Esperanza
900–1200 CE	IIIb		Elenan	Santa elena
600–900 CE	IIIa			Monserrate
400–600 CE	IIb	Late Saladoid	Cedrosan (for Saladoid only)	Cuevas
200 BCE–300 CE 200 BCE–400 CE	IIa	Saladoid		La Hueca Hacienda Grande
1000 BCE–300 BCE	Ib	Ortoroid		Coroso

default to use of the styles most commonly attributed to the Vieques Sound region.

Until the mid-1980's, pottery styles in Puerto Rico (Santa Elena, Early (Pure) Ostiones, Late (Modified) Ostiones, Capá, Esperanza and Boca Chica) were classified into three separate series: Ostionoid, Elenoid, and Chicoid ([21]; [44]:143). This categorization had the unintentional consequence of obfuscating variability in the material culture and the historical relationships among the three series. Based on research conducted in the Virgin Islands, Gary Vescelius [45] developed an intermediate taxonomical level between the style and series termed *subseries* which Rouse later adopted [5]:33.

Style, subseries, and series terms are all frequently used to denote cultural manifestations as well as the temporal

Table 2 Summary table of identified styles by site

Site	Boca chica	Capa	Cuevas	Esperanza	Hacienda grande	Huecoid	Monserrate	Ostiones	Santa elena	UID	Total
Coral bay			6	1	1		6	1			15
Krum bay			4								4
Lt Cruz bay			4	2	4		2	4	3	1	20
Magens bay				2			13	2	4	1	22
Prosperity		1					1	1			3
Richmond	1		5		3	2	3	3	2	1	20
Spratt hall 18			18				3	2	1		24
Spratt hall 30			1	3		2	6	5	2	1	20
Total	1	1	38	8	8	4	34	18	12	4	128

range in which a particular style, subseries or series is thought to have spanned (as noted by [46] and in [47]:14). In each case, these terms apply to different conceptual contexts that are often neither consistently maintained nor explicitly defined in archaeological studies of the Caribbean.

In his research, Reniel Rodríguez Ramos presented evidence showing that cultural development was neither unilineal nor sequential as predicated by Rouse's socio-temporal framework [6]. Using a suite of recalibrated radiocarbon dates from Puerto Rico, he demonstrated that many pottery styles used to define socio-temporal periods do not neatly conform to Rouse's framework. The temporal distribution of pottery based on the radiocarbon dates showed instances where more than one culture overlapped in time and space suggesting a more dynamic and plural landscape than previously conceived [48]. As a result, Rodríguez Ramos promoted a reticulate model of cultural development rather than one characterized by clear phylogenetic relationships.

Despite problems with the current cultural chronology, it is important to note that there are patterns in the temporal and spatial distribution of material culture throughout the region that promote the diachronic examination of local and regional social groups. Torres notes that "… the materiality of socially diverse groups is contingent upon particular local contexts and conditions that are not necessarily synchronized …" at broader scales ([9]:48). In this sense the varying temporal distributions of material culture reflect diverse and emergent interaction spheres that may lose interpretive precision over substantial geographical distances [49]. Therefore, cultural material must be socially and temporally contextualized at the regional and micro-regional levels [50]. This scale of analysis is tied to understanding social and cultural transformations, like the emergence of ancient social and political communities that, while linked at larger inclusive spatial scales, become more salient at smaller scales (as noted in [51]).

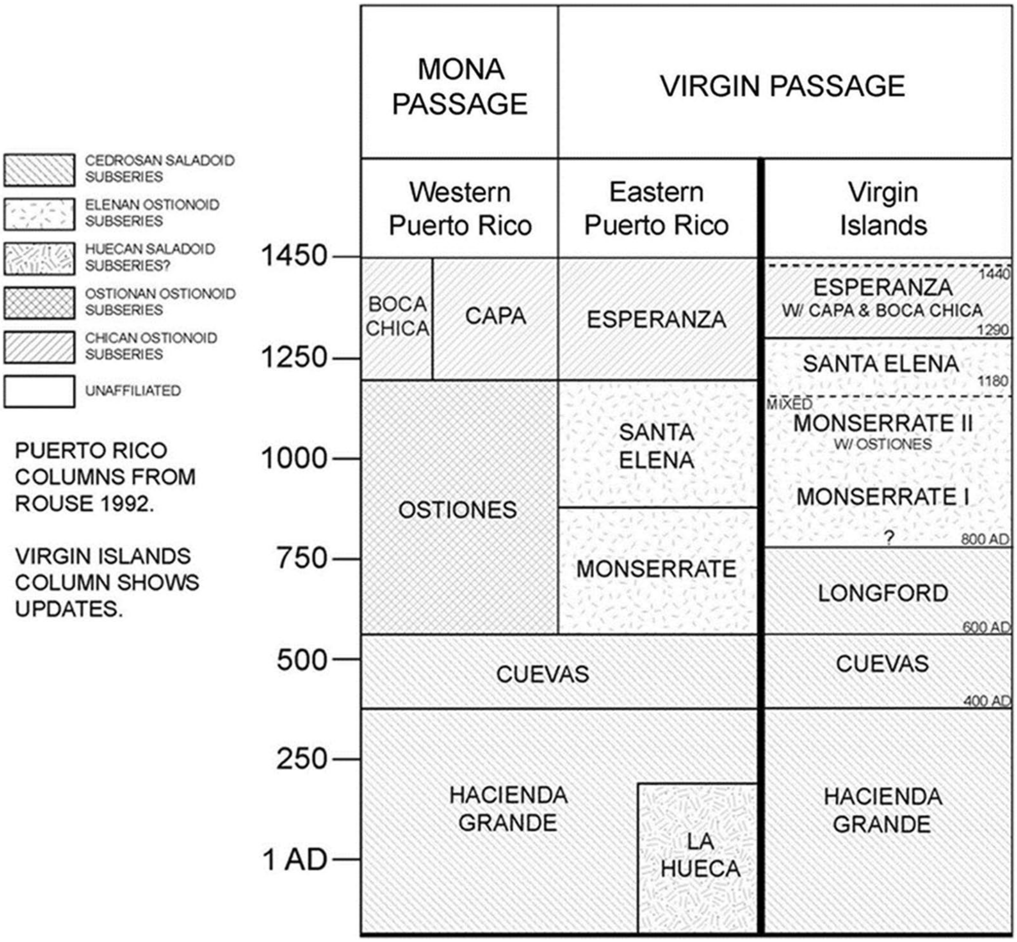

Fig. 2 Pottery chronology for the Vieques Sound Region (referred to in the graphic as the Virgin Passage) based on radiocarbon dates from Cinnamon Bay (from Wild 2013 [42]) Rouse's chronology for Puerto Rico left of the bold line

Focusing on the Vieques Sound Region, variation has already been documented in the temporal distribution of pottery styles as defined by Rouse. Figure 2 shows Rouse's typology and that developed for the Virgin Islands by Wild [42], based on his work at Cinnamon Bay on St. John. Wild's chronology is unique in that excavations at Cinnamon Bay yielded intact stratified deposits which detailed the ceramic history of the site and allowed for tight chronological control of the pottery assemblage there. While the Cinnamon Bay site is unique in many ways, the local chronological refinement of pottery styles indicate a more nuanced picture of the developmental trajectory of material culture.

Description of pottery styles for the vieques sound region

The following overview is based on Rouse's definitions of styles for the Vieques Sound region. While Vescelius identified nuances in regional practices of pottery production in St. Croix, the central tendency in styles from sites in St. John and St. Thomas typically align closely with those of Eastern Puerto Rico [43, 52] and for the sample in this study, largely equates to the pottery styles identified here. While the details and timing of these styles are variable and still a matter of refinement, the descriptions of these styles allow for a *lingua franca* for discussing pottery traits and central tendencies in attributes that can be attributed to specific pottery making traditions. Of particular importance here is recognition that the distinct social and temporal boundaries determined by Rouse's pottery styles should be viewed as dynamic overlapping periods of interaction and transformation rather than strict delimiters of them.

Saladoid pottery and La Hueca

Hacienda Grande style pottery is high quality, relatively thin walled (< 6 mm), well fired, and of fine paste with few aplastic inclusions. Surfaces are smooth, although somewhat uneven with light tan colouring varying slightly in darker and lighter degrees. Design elements mainly consist of bi-chromatic painting—particularly white-on-red ([53]:498). Incisions are common, especially zone-incised crosshatched designs (ZIC) which are sometimes filled with white paint on a red background.

Vessel walls are straight and sharply angled. Bowls, incense burners, bottles, jars, and plates are common vessel forms. Bottles and jars are typically circular or ovoid with annular bases. Unrestricted bowls in the form of inverted bells are common but in slightly less frequency than in the Cuevas style. Outward flaring rim shapes indicative of unrestricted vessel forms predominate over straight and restricted forms.

Pottery of the La Hueca (ca. 200 BCE–800 CE) style is quite different from the red-painted Hacienda Grande wares and is characterized by modelled elements and preponderance of zone-incised decoration (ZIC). The geographic distribution of this style is generally limited to the eastern edge of Puerto Rico and the northern Lesser Antilles. According to Rouse, "La Hueca assembleges do lack painted ware…but it's potters rubbed white or red paint into their ZIC incisions" ([5]:86).

Cuevas style pottery, considered a direct outgrowth from the Hacienda Grande pottery tradition, is more rounded than the Hacienda Grande style, contributing to its "graceful appearance" ([54]:336–338) and there is a general decrease in the use of polychrome painting and incision for decoration. White-on-red painting does continue; however, the frequency of occurrence diminishes through the duration of the style. Decorative elements are primarily restricted to red paint over the entire body of the vessel or as a single band along flattened, outflaring portions of the rim. Rouse and Rainey also noted the use of red paint to cover the interior base of shallow open bowls as common ([55]:44; [54]:442).

Non-painted vessel surfaces are light brown to ivory with a brownish or "chocolate tinge" ([54]:336). Cuevas pottery, like the Hacienda Grande style, is well-fired with fine paste and thin walls usually measuring around 6 mm in thickness. However, paste does become slightly coarser and walls thicker later in the development of the style. Diagnostic structural elements consist of D-shaped handles and tabular lugs. D-shaped handles extend from the shoulder to the top of the rim ([55]:51). Tabular lugs occur on opposing sides of oval and round vessels, slightly elevated above the edge of the rim, and are often "semi lunate" in shape ([55]:52). Tabular lugs can also be flat with simple edge points on rims.

Common among Cuevas vessel forms is the "inverted" bell shape. This form, while occurring in the earlier Hacienda Grande style, is at its highest frequency in Cuevas pottery assemblages. Plates and oval serving dishes are also frequent [56]. However, according to Rainey [55] boat-shaped or navicular bowls do not occur until the onset of the Ostiones style. Rims are often internally thickened and tend to be round rather than angular ([57]:114).

While it is generally accepted that the inception of the Cuevas style overlaps with Hacienda Grande, the style is also documented to overlap with later Elenan and Ostionan Ostionoid assemblages indicating a perpetuation of the style as a finely crafted serving ware [58]. However, documentation of the persistence of the style past 900 CE is primarily limited to the eastern parts of Puerto Rico.

Elenan ostionoid pottery

Monserrate style appears throughout eastern Puerto Rico and the Virgin Islands around 700 CE. Early manifestations of this style in the Virgin Islands are referred to as Longford and represent a transition period from Cuevas, whose defining traits for the later portion of the sequence persist in Eastern Puerto Rico past 900 CE and define aspects of the Monserrate style throughout the region. This style is the most poorly understood and difficult to identify. Since the style remains poorly defined, differences in reporting tend to emphasize traits associated with Cuevas or Santa Elena styles resulting in somewhat conflicting descriptions and documentation (compare [59]:10; [51]; and [60]:31–32). In general, Monserrate pottery lacks most of the decorative and morphological attributes present in Cuevas assemblages. However, some traits of Cuevas pottery are present, including tabular lugs, strap handles, and red painted and slipped ceramics. While sharing some similarities, Monserrate style has distinctive characteristics, albeit irregularly represented throughout eastern Puerto Rico [21, 44, 61] and persisting longer and more prevalent in the Virgin Islands [41, 42].

Monserrate style pottery is thicker, coarser, and rougher than pottery of the Hacienda Grande and Cuevas styles. Unlike Cuevas pottery, Monserrate pots lack definitive shoulders or carinas, vessels tend to have out rounded shoulders, although more vertical shapes increase in frequency. Rounded and internally thickened rims become common and secondary morphological features consist of loop handles.

Design elements consist of limited occurrences of "splotchy" red painting applied to buff backgrounds and areas of black smudging to create negative design patterns. Red painting has also been documented on vessel interiors, particularly in trays and open bowls. Vessels are often unpainted and have no incisions. A dichotomy between utilitarian and finer wares has been distinguished and painted wares are typically better fired and manufactured with slightly thinner walls and polished surface treatments are not present in the utilitarian wares [60]:47. Utilitarian wares typically lack any paint or slip. Brushing and scraping to form textured surfaces is also common later in the sequence [41, 42].

Santa Elena style pottery, commonly occurring in eastern Puerto Rico after 900 CE, are thick walled with average shard thickness around 8 mm. Paste is coarse and often contains an abundance of large (> 1.0 mm) aplastic inclusions. Vessels tend to be pale to medium brown or reddish brown in colour. Painting, evident in Cuevas and Monserrate assemblage, is rarely used; simple incision, modelling and appliqué become frequent [54]:344–347. Diagnostic design elements consist of crude vertical incisions on the exterior of the vessel running from the rim to just above the shoulder. Other design elements consist of incised interior horizontal lines just below the rim on unrestricted bowls and appliqué strips above the shoulder.

Vessels tend to be large, open, hemispherical bowls with roughly shaped rounded walls, restricted orifices, and round or flat bases. Vessel profiles are generally smooth, albeit crudely formed, and not angular. In Santa Elena pottery the coils used to construct the vessels are relatively thick, contributing to terminal coil breaks along rims which is characteristic for the style [30].

Chican ostionoid pottery

Esperanza style pottery, common to eastern Puerto Rico and the Virgin Islands after 1200 CE, is generally light brown to medium reddish brown in colour. Esperanza vessels are rarely red-slipped, and surface treatment mainly consists of smoothing. Like Santa Elena vessels, Esperanza vessel walls are thick ranging between 8 and 10 mm. Paste is medium coarse to coarse with aplastic inclusions ranging from c. 0.5 to 2 mm. Handles are absent from the style and globular vessel forms are most common.

Diagnostic design motifs for this style consist of double or triple sets of incised straight, curvilinear, or oblique parallel lines. Wide, downward curvilinear lines are reminiscent of the double rainbow mythological theme [62]. Incised lines are broad, deep, and widely spaced. Incision is restricted to the upper portion of the vessel between the rim and shoulder. Another common design element is an external singular horizontal line under the rim.

Capá style pottery is common to western Puerto Rico but also documented in the Vieques Sound region in low frequencies. It is more friable and elaborately decorated than Santa Elena style pottery [5]:111. Capá pottery is often sand tempered with vessel walls averaging around 7 mm in thickness. Painting is not a design element for this style and shards/vessels tend to be brown to very dark brown in colour. Burnishing is a common surface treatment and vessels often have a lustrous sheen. Decorative elements mainly consist of broad line incisions forming geometric patterns, punctations, zoomorphic lugs (but no true handles) and appliqué and modelling. Incisions are deep and extensive usually restricted to the shoulder areas of the vessel [54]:450. Vessels forms consist mainly of incurving or carinated (cazuela) bowls. Rims from this period are diagnostic and are predominately tapered and overturned with a narrow lip.

Boca Chica is the finest of the late-period styles, with hard and well-finished surfaces, complicated vessel forms, and intricate design motifs ([60]; [54]:348). This style has a relatively low distribution throughout Puerto Rico and the Virgin Islands and is commonly considered a trade ware from eastern Hispaniola. Burnishing is a common finishing technique that can occur on one or both surfaces of the vessel. Rouse [54]:347 described this ware as having a “soft sheen.” These ceramics are generally brown with thick walls (averaging 8 mm) and tapered rims. Boca Chica design elements include elaborate incision, punctation, and modelling. Rouse [54]:349 describes the common motifs as “circles, each with a dot in the centre and flanked with semi-circular lines; horizontal oblique, and vertical parallel lines; ovoid figures, each encircling a line or a series of dots; and a maze-like arrangement of curved lines.” Lines that end in dots are a defining characteristic of Boca Chica. Modelled plastic design elements include zoomorphic and anthropomorphic head lugs.

Sample and methods

This research focuses on the application of TL-dating from seven different sites on the three main islands of the US Virgin Islands (Fig. 3). The sites include Krum Bay and Magens Bay (St. Thomas), Little Cruz Bay and Coral Bay (St. John), and Prosperity, Spratt Hall, and Richmond (St. Croix). The sample materials were selected from collections recovered from twentieth century excavations conducted by Aage Gudmund Hatt, Emilie Demant Hatt, and J.P.B. de Josselin de Jong (1922–23), and by Gustav Nordby and Frieda Møller-Jørgensen (1903–1955). All the samples were selected for this study are curated at the National Museum of Denmark.

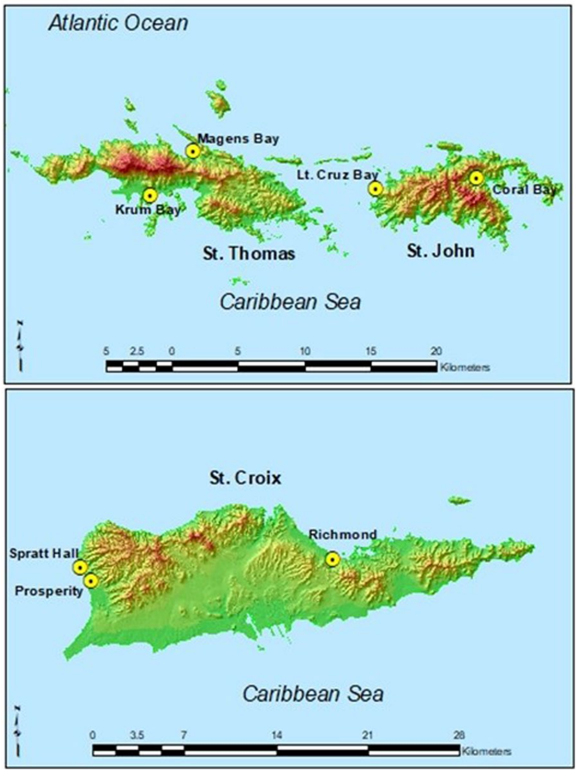

Fig. 3 Archaeological sites from which pottery samples for TL dating were acquired (map by Joshua Torres)

For this research, three types of materials were analysed: pottery and soil samples, and a suite of radiocarbon datable materials. The pottery shards were measured for Thermoluminescence (the TL dose equivalents), while the same shards and associated soil samples were analysed for uranium (U), thorium (Th), and potassium (K) making up for the construction of the radiation budget received by the sample, which is necessary for calculating the TL-date.

Pottery samples

One hundred and twenty-eight shards were first visually examined to determine style. The method normally utilized for characterizing pottery styles in Caribbean archaeology is based on identification of diagnostic techno-functional and design elements associated with accepted typologies discussed previously as described above [5, 54]. These traits are generally comprised of groups of specific morphological features and decorative motifs, and patterns, referred to Rouse as *modes*. These diagnostic attributes were originally defined by Rouse [54] and further documented for the Virgin Islands [35, 41, 43]. Diagnostic traits not only included design elements like painting, incisions, and *appliqué* or modelled elements, but also techno-functional attributes like surface treatment, paste characteristics, thickness, and colour of the paste. To provide the best resolution of the local pottery chronology, all samples were identified to the level of style.

As problems have been registered in the spatial and temporal distributions of Rouse’s styles [6, 34] one of the critical aspects of this study is to begin refining the pottery styles for the Virgin Islands based on the TL-dates. Importantly, we suggest here that the temporal range for traditional styles can be determined by examining the central tendencies in the data. Based on visual examination of the pottery the following style, sub-series, and series definition was determined (Table 2, Figs. 4 and 5). The Munsell colours of some of the shards depicted in Figs. 4 and 5 are listed in the Additional file 1.

The sites sampled are the following:

> Prosperity (St. Croix):
>
> The site has been investigated several times since the 1920s. Gudmond Hatt excavated Prosperity in 1923, and Herbert Krieger in 1937. Folmer Andersen collected from the site during the 1920s and 1930s, and collections of surface materials were made during the 1951 St. Croix Archaeology Pro-

Fig. 4 Pottery of the Huecoid and Saladoid Series. Top row (L-R) examples of La Hueca; the two middle rows (L-R) examples of Hacienda Grande; bottom row (L-R) examples of Cuevas

ject. Archaeological investigations were conducted at Prosperity from 1976 to 1979, by the then Territorial Archaeologist for the Virgin Islands, Gary Vescelius. Based on ceramic styles the site has been atrributed to the Early Saladoid and is regarded as the "type site" for this earliest phase on St. Croix (the equivalent of Hacienda Grande and La Hueca).

Richmond (St. Croix):

The Richmond site is located on the northern shore of St. Croix just west of Christiansted. The site is not well understood archaeologically. Gudmund Hatt visited the site in the 1920s and Vescelius investigated the site in 1951 during the St. Croix Archaeological Survey. Based on his examination, Vescelius attributed pottery from the site to the Cuevas style, followed by Ostiones and Santa Elena. One radiometric date has been obtained for the site and produced a date between 620 and 690 CE (2 sigma) [63].

Spratt Hall (St. Croix):

Sprat Hall is located on the western shore of St. Croix, roughly 1.2 km north of the Prosperity site. The site was investigated by Nordby, Andersen, Hatt (1924) [36], Vescelius (1951) [35] and Figueredo. The site is multicomponent, comprised of Late Saladoid through Ostionoid [28].

Fig. 5 Examples of pottery from the Ostionoid Series. Top row (L-R) Monserrate; second row (L-R) Ostiones; third row (L-R) Esperanza; bottom row left: Capa, right: Boca Chica

Magens Bay (St. Thomas):

Magens Bay, situated on the north side of the island, is a U-shaped bay oriented northwest to southeast and is protected by steep slopes and cliffs that bounds the windward side of the Bay. The site is the largest of all St. Thomas archaeological sites and deposits contain burials, pit features, pottery shard caches, and possible structure outlines. The site is a multi-component site with material ranging from Saladoid through Chican Ostionoid [39, 64].

Krum Bay (St. Tomas):

Large shell mound adjoining the hillside on the shore of Krum Bay. Most of the site has been destroyed through previous excavations and the construction of roads and other infrastructure. While the site is largely associated with early Archaic occupation of the Virgin Islands [65] Hatt investigated the site and recovered ceramics but details are lacking from his published accounts.

Cruz Bay (St. John):

Cruz Bay artifact assemblage predominantly exhibits Saladoid traits, as the majority of the diagnostic shards have White-On-Red (WOR) decoration, A minor number of diagnostic shards have ZIC decoration.

> Coral Bay (St. John):
>
> Coral Bay (St. John) is one of the largest prehistoric village sites on St. John. Coral Bay was excavated by Hatt in 1924 in 1922–23 and surveyed by Sleight in 1960 ([39]:23–24). Ceramic evidence from the site primarily indicates Saladoid and early Ostionoid pottery.

Soil samples

Soil samples (n = 22) from the 7 sites were acquired, either from samples extant in the Hatt-collection or compensatory modern samples taken in the field. While Hatt collected an excellent selection of surrounding soil, sadly, most of the soil samples were disposed of during efforts to save storage space at the National Museum of Denmark. Additional soil samples were later acquired in the field from the old excavation sites in cases where soils samples from those sites were not available in the collection (Table 3). Fieldwork for the compensatory soil samples was conducted in 2018 and 2020. New samples were acquired by digging ca. 10 cm below the topsoil, sampling ca. 100 g of soil which was later homogenized (Table 3).

Methods

Pottery sample processing

The pottery samples were crushed and sieved in the laboratory in darkened conditions, and the grain size fraction between 100 and 300 µm was used for analysis. The paleodoses of the samples were measured by a DA12 TL-reader built by Risø National Laboratory in Denmark. The equivalent doses were calculated using the Single Aliquot Regeneration (SAR-TL) method adapted from Hong et al. [66] with four sub-samples of each ceramic specimen being analysed and averaged. The calculation of the age from the dose rates required the determination of the annually received doses, which are assumed to originate from three sources: (1) the internal source from the four radioactive isotopes present in the samples, ^{40}K, ^{235}U, ^{238}U, and ^{232}Th; (2) the external source from the same four radioactive isotopes in the surrounding soil; and (3) the cosmic flux.

The radioactive isotopes from the samples and the surrounding sediment were measured using LA-ICP-MS (for Th and U) and XRF (for K). The cosmic flux was estimated regarding the localization of the site, its altitude, the depth at which the object was found, and the density of the overlying sediment. The calculation was performed using the "Luminescence" software package *R* [67]. Because of uncertainty in the depth of the object and the density of the overlying sediment, average values were calculated using a depth interval. The procedure required adjustment of factors affecting the irradiation dose rates received by the sample: (1) the self-shielding, which was calculated with a measured average density of 1.8 ± 0.3 g cm^{-3}; (2) the grain diameter after sieving was 200 ± 50 µm; (3) the alpha efficiency was assumed to be 0.08 ± 0.02; and (4) the sediment water content which was estimated to be 2% ± 0.2%. No HF etching was performed; thus, the alpha particle dose was included in the annual dose rate calculation. These parameters were computed and processed through the *AGE* software [68] to provide the dose rates and the TL-ages.

Table 3 Soil samples analyzed in the present work (n = 22)

Site name	Hatt collection No. of samples	New field collection No. of samples	Total no No. of samples
Magens Bay	7	–	7
Krum Bay	3	–	3
Spratt Hall	2	–	2
Richmond	–	1	1
Prosperity	–	2	2
Coral Bay	6	–	6
Lt Cruz Bay	1	–	1
Total	19	3	22

Sample preparation for chemical analysis

To calculate a TL-age from the paleo dose requires the determination of the U, Th, and K concentrations of the sample itself, together with that of its immediate surrounding soil. An aliquot of the ceramic samples and samples of the surrounding soil were either embedded in epoxy (Struers A/S) and polished down to 1 µm diamond finish or in the case of soil samples pressed into pellets using an in-house build pellet-presser utilizing a maximum pressure of 120 kN.

Micro-X-ray fluorescence (µ-XRF)

The embedded or pressed samples were subjected to analysis by µ-XRF (micro-X-ray Fluorescence) for the quantification of K, Si, and Ca. An ARTAX-800 µ-XRF manufactured by Bruker-Nano was used and operated with a high tension of 50 kV and a current 600 µA. Absolute calibration of the concentrations has been performed by the DCCR-method (Direct Calibration from Count Rates) provided by the Bruker software using the standard reference material NIST-2711.

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)

Laser ablation (LA) was performed with a CETAC LXS-213 G2 equipped with a NdYAG laser operating at a wavelength of 213 nm. A 25 µm circular aperture was used. The shot frequency was 20 Hz. A line scan was performed with a scan speed of 20 µm s^{-1} and was ca 300 s long following a 10 s gas blank. The helium flow was fixed at 600 mL m^{-1}. The laser operations were controlled by the DigiLaz G2 software provided by CETAC.

The inductively coupled plasma mass spectrometry (ICP-MS) analyses were carried out using a Bruker Aurora M90 equipped with a frequency matching RF-generator. The basic parameters were as follows: radiofrequency power 1.30 kW; plasma argon gas flow rate 16.5 L min^{-1}; auxiliary gas flow rate 1.65 L min^{-1}; sheath gas flow rate 0.18 L min^{-1}. The following isotopes were measured all without skimmer gas: ^{29}Si, ^{44}Ca, ^{232}Th, and ^{238}U. No interference corrections were applied to the selected isotopes. The analysis mode used was peak hopping with 3 points per peak, and the dwell time was 10 ms on ^{29}Si and ^{44}Ca, and 100 ms on ^{232}Th and ^{238}U. The data was subjected to a 5-point averaging filter.

The quantification was performed by first and last in a run of four samples to measure an in-house standard of approximately similar composition to the ceramic samples. For this sample the count rate ratios of U/Si and Th/Si were calculated adjusting the count rate for the isotopic abundance for each isotope analysed. The conversion from count rate to weight percent was done by multiplying by a fixed ratio, determined by the measurements of the standard sample, for which the Si, U, and Th concentration was known. In rare cases there were no Si detected in the sample (some soil samples only), but which had a high concentration of Ca. In these cases, Ca was used for standardization instead of Si.

Radiocarbon dating

A total of 37 radiocarbon dates were conducted on samples consisting of shell (n = 23), charcoal (n = 2), and animal bone (n = 12) from five of the sites (Coral Bay, Krum Bay, Magens Bay, Little Cruz Bay, and Spratt Hall). While the contexts for the radiocarbon dating samples are limited, they offer a rudimentary control for comparison with the TL-dates and potential range of occupation of the settlements discussed in this paper. Future refinement of the TL-method in the Caribbean will benefit from further comparing, side by side, TL-dates with radiocarbon dates from the same stratigraphic contexts.

Radiocarbon dating may yield dates which can be different from the true dates of the archaeological contexts in several ways. Even though Hatt and DeJong were excellent excavators for their time, their delineation of stratigraphic contexts was at best only divided into four layers, often with rather arbitrary limits such as feet of depth below the soil surface level, rather than clear delineations in strata and more precise quantifiable intervals within them. Hence, the contextual relations of the midden materials to the pottery were not recorded according to modern standards.

We also recognize that radiocarbon dated shells from the archaeological excavations can possibly represent dates older than the archaeological use as a result of ancient people re-using shell material of older development [69].

Diagenesis can also be a problem for the radiocarbon dating. This happens when a carbonate exchange has taken place between the environment and the outer layers of the shell or bone [70, 71]. In the case of bones, diagenetic changes can take place to a certain depth. In Danish medieval bones this altered zone can in some cases extend up to 0.5 mm into the outer cortical tissue of the bone, and furthermore into the cavities of the bone if water penetrates through the Haversian channels and other opening or postmortem cracks in the cortical bone [72]. The samples dated in this study have not had their surficial layers inspected or removed prior to dating, nor have the bone samples been cut and investigated in order to ascertain the degree of diagenesis, if any occurred.

However, the δ^{13}C values can sometimes give clues to the occurrence of contamination [73] or of deviating dietary habits, although it should be kept in mind that the δ^{13}C values reported by the radiocarbon laboratories are acquired in order to correct for isotope fractionation of the sample and of any fractionation imposed on the sample during the AAA-pre-treatment procedure, sample combustion, or graphite production; they are not always made on pristine sample material in order to provide the correct isotopic ratio of the ancient material. Even so, if deviations occur from the expected values these may reflect diagenesis. In this study it is particularly notable for three of the shell samples, reported with δ^{13}C values of + 6, + 6, and + 7 permille VPDB (AAR-26154, AAR-26157, and AAR-26159), which are significant deviations from the expected value of zero permille. In the other direction it is even more notable that shell sample AAR-26158 exhibits a δ^{13}C value of -11 permille VPDB. Taken together it is disturbing to have such large deviations from the zero permille characteristic of marine shells—both to the positive and the negative directions. As said, it is not possible to do more than raise a flag of suspicion of contamination for these four samples.

The other seashell samples are sufficiently close to the expected zero permille VPDB, making no cause to suspect isotope fractionation or contamination by diagenesis in these samples. Likewise, the bird bone sample of -21 permille is an expected value. The charcoal samples show δ^{13}C values of -24.4 and -26 permille VPDB, which is near the expected -25 permille. There is therefore no reason to suspect any isotope fractionation or contamination for these samples. The only caveat for the two charcoal samples is that the dated materials were not investigated by wood-anatomy prior to dating, which could have revealed the species of the tree and of the number of year rings in the samples. This imposes an uncertainty as to the possible internal age of the material. Even so, these two dates are probably more reliable than the seashells and the animal bones.

The turtle bones constitute a problem of their own, as the there is no obvious way to ascertain the preferred diet of the turtles [74], which can include some terrestrial foodstuff, which in turn can lead to deviations in the stable isotope ratio and can impose reservoirs effects. In other words, it is not possible to assign a relevant correction for the isotope fractionation of each individual sample of turtle bone. The same goes for the manatee bone. In the present work we have opted for treating these samples as marine. If this assumption is not correct, the potential error can be several hundred years.

Both seashells and marine bones are collectively subject to the general marine reservoir effect, which has recently been established for the USVI [75]. The Marine offset value for St Croix was established by a single sample as $\Delta R = 32$, and a single sample from St Thomas $\Delta R = 25$. In the present study, the value for St Thomas was used also for the nearby island of St John.

TL-dating

Compounding issues noted in the previous section demonstrate the challenges of using radiocarbon dates in the Caribbean and the multiple ways in which shell and bone can yield skewed results. These challenges can be further compounded by midden formation processes combined with a sometimes very shallow burial depth that makes them prone to bioturbation and anthropogenic disturbance, as well as other natural processes including tidal action, seawater infiltration, and storm surges. The radiocarbon method is, as such, not more unreliable in the Caribbean than elsewhere, it is simply that archaeological middens and their formation processes, including their bioturbation history, a possible diagenetic effect on the seashells, as well as the unpredictability of the turtle and manatee diets, adds noise to radiocarbon dates and may also impose biases.

Thermoluminescence dating (TL-dating) is an alternative dating technique to radiocarbon dating but applied to pottery. TL-dating relies on isolators, in this case, quartz and feldspar mineral grains, to accumulate electrons in quantum state traps in the forbidden gap between the valence band and the free electrons in the conduction band. The quantum state traps, which should be prohibited—hence the name *the forbidden gap*—do exist due to the occurrence of occasional faults in the crystal lattice caused by mineral grain interfaces or the inclusion of a larger ions imperfectly fitting into the lattice. The TL-method works by heating the sample in the laboratory to a temperature of 400 °C, whereby the electrons in the traps are released to the ground state while the energy difference is emitted as a photon, which is detected in a photomultiplier. The TL-clock is reset at the time of firing the ceramic sample in antiquity. The more time that has elapsed since the firing, the more electrons have been lifted to the traps, and the more light is eventually detected in the laboratory. Hence, the TL-method dates the last time of firing of pottery, ostensibly the time of their production or the last incident of heating the vessels to above ca. 400 °C, whereas the radiocarbon method dates the time of death of a living creature.

Potential biases of the TL-dates

The TL-dates are also prone to added noise in the case of the Caribbean pre-colonial cultural midden sites. Bioturbation and the frequently shallow burial depth make it a possibility that some ceramic shards can have been re-heated by campfire in later periods or reused as a cultural process of heirloom curation. One should therefore occasionally expect a TL-date to be later than the archaeological context. The likelihood of a TL-date to be older than its true age by exposure to *e.g.*, hard rock or other materials exceptionally high in U, Th, or K is, however, very small for the sites in the US Virgin Islands investigated in the present study. The U and Th concentrations encountered in this study are generally very low and homogenous compared to more terrestrial settings in South America or Europe (see *e.g.*, [76, 77]). This fact makes is quite unlikely that the TL-dates could occasionally be too old, and it also makes the estimation of the radiation budget from the surrounding soil more robust than usual.

In this study there are minor sources of possible bias in the dates. One uncertainty that could add to the noise, both older and younger, is that it is now impossible to get access to precise information about the context. This was problematized by a previous decision by the National Museum to discard the large contextual soil samples which were actually brought home by Hatt. The chemistry of the contexts has instead been ascertained by analysing a few samples that were left behind in the boxes, and in two cases by procuring new soil samples on site. The estimation of the cosmic flux is based, amongst other parameters, on the depth at which ceramics was found and the density of overburden. In this work, these factors are largely unknowns. The calculated estimate of the cosmic flux is based on a range of possible depths and densities (*i.e.,* types of sediment) and these can potentially be a source of

Table 4 Results of the radiocarbon dating

Lab. code	Arch. site	Catalog number	Type of sample	Date BP	1 STD	δ13C (o/oo)	D R	2 s Low calib CE	2 s high calib CE	Square & layer
AAR-21198	Coral Bay	O.5.31	Charcoal	1322	25	− 26 ± 1	0	653	773	Sq. IV–L2
Beta-502579	Coral Bay	O.5.52	Shell	1700	30	− 0.1	25	733	1022	Sq. IV–L2
Beta-5022579	Coral Bay	O.5.52	Shell	1700	30	− 0.1	25	733	1022	
Poz-60114	Coral Bay	O.5.55	Bone	1775	30	− 7.2 ± 0.1	25	671	946	Sq. V-L1
Beta-502580	Coral Bay	O.5.71	Shell	1670	30	3.7	25	771	1051	Sq. V–L2
AAR-21201	Coral Bay	O.5.96a	Shell	1570	25	2 ± 1	25	884	1166	Sq. IIc–L1
Beta-455038	Krum Bay	O.2.172	Shell	2830	30	2.6	25	− 599	− 232	Sq. B IV
Beta-455039	Krum Bay	O.2.141	Shell	2760	30	1.6	25	− 484	− 161	Sq. B II
Beta-455040	Krum Bay	O.2.147	Shell	2650	30	3.9	25	− 354	− 39	Sq. BI
Beta-455041	Krum Bay	O.2.154	Shell	2470	30	2.8	25	− 123	201	Sq. B III
Beta-455042	Krum Bay	O.2.70/72	Shell	2170	30	1.6	25	251	548	Sq. A V
Beta-455861	Krum Bay	O.2.58	Shell	1980	30	2.1	25	449	717	Sq. A I
Beta-455862	Krum Bay	O.2.44	Shell	2620	30	3.2	25	− 336	0	Sq. A III
Beta-455863	Krum Bay	O.2.36	Shell	2470	30	1.1	25	− 123	201	Sq. A I
Beta-5022566	Magens Bay	O.1.172	Bone	1870	30	− 12.8	25	587	847	
Beta-5022567	Magens Bay	O.1.804	Bone	1910	30	− 12.2	25	547	807	
Beta-5022568	Magens Bay	O.1.809	Bone	1500	30	− 10	25	960	1238	
Beta-5022569	Magens Bay	O.1.814	Bone	1460	30	− 12.8	25	1009	1268	
Beta-5022570	Magens Bay	O.1.828	Shell	1130	30	3.9	25	1302	1523	
Beta-5022571	Magens Bay	O.1.829	Shell	1280	30	1.2	25	1181	1420	
Beta-5022572	Magens Bay	O.1.840	Shell	1580	30	2.4	25	867	1162	
Beta-5022573	Magens Bay	O.1.862	Bone	1130	30	− 11.3	25	1302	1523	
Beta-5022574	Magens Bay	O.1.886	Bone	1470	30	− 11.5	25	998	1261	
Beta-5022575	Magens Bay	O.1.952a	Bone	1380	30	− 12.1	25	1061	1319	
Beta-5022577	Magens Bay	O.1.952c	Bone	1660	30	− 13.3	25	777	1055	
Beta-5022578	Magens Bay	O.1.953	Bone	1300	30	− 11.8	25	1162	1410	
AAR-26153	Lt. Cruz Bay	O.8.12	Shell	1934	32	4 ± 1	25	508	784	Sq. IV–L1
AAR-26154	Lt. Cruz Bay	O.8.17	Shell	445	27	6 ± 1	25	Modern		Sq. IV–L2
AAR-26155	Lt. Cruz Bay	O.8.49	Shell	1835	28	1 ± 1	25	628	884	Sq. XII–L?
Beta-502581	Lt. Cruz Bay	O.8.54	Turtle bone	2720	30	− 15.1	25	− 408	− 109	Sq. I–L2
Beta-502582	Lt. Cruz Bay	O.8.60	Turtle bone	2210	30	− 12.5	25	205	509	Sq. L2–
AAR-26156	Lt. Cruz Bay	O.8.63	Shell	1884	26	4 ± 1	25	577	828	Sq. VIII–L?
Beta-502583	Spratt Hall	O.18.20	Charcoal	1250	30	− 24.4	0	674	877	Sq. III–L3
AAR-26157	Spratt Hall	O.18.23	Shell	1694	26	6 ± 1	32	756	1035	Sq. III–L3
AAR-26158	Spratt Hall	O.18.24	Shell	932	26	− 11 ± 1	32	1458	1708	Sq. III–L3

Table 4 (continued)

Lab. code	Arch. site	Catalog number	Type of sample	Date BP	1 STD	δ13C (o/oo)	D R	2 s Low calib CE	2 s high calib CE	Square & layer
AAR-26159	Spratt Hall	O.18.29	Shell	1599	29	7 ± 1	32	849	1146	Sq. V–L3
AAR-26160	Spratt Hall	O.18.33	Shell	2728	35	3 ± 1	32	− 418	− 101	Sq. II–L2

The calibrations are performed using the Calib 8.1 program and the Marine20 and IntCal20 curves (Reimer et al. 2020 [78] and Heaton et al. 2020 [79]). The last column reports Hatt's excavation designations referring to the squares and layers minor errors in the TL-dates, although the ages provided are quite robust to moderate changes in the cosmic dose rate. We estimate that the upper limit of the error caused by variations in the cosmic flux is probably less than ± 5 years. The assumption on the water content of the surrounding sediment has a more important influence on the age calculation since some of the external dose can be absorbed by the water. We assume that the sediment water content is 2% on average. An increase of 5% sediment water saturation (to 7 wt%) for a 1000-year-old sample will make the TL-date 40 years older. All in all, the biases for the TL-dates are therefore relatively small compared with the quoted uncertainties.

Results

The radiocarbon dates of the charcoal samples are presented as the interval covering ± 2 standard deviations, and the central point plotted in the figures below and in Table 4 is the calibrated range at ± 2 standard deviations using the Calib 8.1 Groningen calibration program and the atmospheric curve IntCal20 [78]. The radiocarbon dates of the marine samples are presented in Table 4 in the same way, but now obtained by using the Marine20 calibration curve [79].

The average compositions of the soil samples of the sites investigated are listed in Table 5, and the U, Th, K, and TL-dates of the ceramic samples are listed in Table 6.

To visualize the qualitative difference between the TL-dates and the radiocarbon dates, a comparison of the results at two of the investigated sites can be seen in Fig. 6. The uncertainties of the single dates are comparable, but it is apparent that the archaeological material selected for radiocarbon dating from the Hatt Collection are less suited to reflect occupational aspects of the two sites shown in Fig. 6. This underlines the principal difference of the two types of material used for radiocarbon- and TL-dating, as discussed in detail above.

It is evident that radiocarbon dates are not well suited to chronologically contextualize by association the ceramic assemblages recovered and analysed in this study. Below the results of the TL datings will be viewed and interpreted on a statistical basis, where the central tendency of the data—with outliers excluded—is the decisive parameter. We will also discuss singular typological ceramic styles, such as shards with La Hueca diagnostic elements, White-On-Red paint, complex incisions, and other morphological characteristics typically associated with styles developed by Irving Rouse. The perspective here is to definitively attribute particular designs and morphological elements, commonly referred to as *modes* to particular temporal contexts. Thus, Tl-dates performed directly on a wide set of ceramic shards will contribute to clarify and complement the style chronology derived from the previous studies in the area.

Discussion

Settlement implications based on TL-dates

Based on the dates for the pottery from the sample sites it is possible to offer some summary comments regarding the pottery and settlement of the Virgin Islands. The TL-datings offer the opportunity to show a chronology between the sites under analyses. The TL-dates and the timing/duration of settlement should be viewed as a heuristic and not absolute as the TL-dates for the pottery samples represent a non-systematic selection of pottery whose stratigraphic context is not as refined as material collected from modern excavations. Nonetheless the material allows for some interesting observations.

The TL-dates show that the earliest date documented comes from a La Hueca shard from the site of Richmond on the island of St. Croix indicating very early settlement of the Virgin Islands (234 BCE). This date is in line with other early La Hueca/Saladoid dates from sites in Puerto Rico and Vieques (*e.g.*, Tecla, La Hueca/Sorce). This early settled site, with an apparent long continuous range of occupation, may have been part of a dispersed network of early Heucan settlements throughout the region.

The site with the next-earliest dates is Little Cruz Bay (171 CE). The earliest and latest dates of all the seven sites are listed in Table 7. It is evident from Table 7 that generally the radiocarbon dates exhibit larger a variance than the TL-dates in each individual site.

Saladoid communities are known to have maintained wide interaction networks (*e.g.*, [28]). The similarities seen in Saladoid pottery throughout the Lesser Antilles and into Puerto Rico attest to that interaction. Symbolic imagery maintained throughout the interaction sphere, and expressed through similar manufacture and decorative techniques, reflects a relatively cohesive region of shared practices and traditional knowledge. Nonetheless regional linkages seen in prestige goods, imagery, raw materials, and so forth should not obscure the complexity that surely existed within the Saladoid culture and social groups during the millennium of Saladoid occupation in the eastern Caribbean. There were distinct social groups and communities with stronger ties than those identifying an entire zone of trade or cultural identity. Such local differences should be distinguishable, in part, through study of local artifact assemblages which we advocate for here both in terms of techno-functional and design analysis and through the use of TL-dating.

Table 5 Results of the soil analyses

Site name	No. of samples	U µg g^{-1}	Th µg g^{-1}	K wt %
Magens Bay	7	0.73	0.25	0.85
Krum Bay	3	0.20	0.03	0.31
Spratt Hall	2	0.87	1.60	1.48
Richmond	1	0.64	0.90	1.14
Prosperity	2	0.84	0.93	1.86
Coral Bay	6	0.77	0.94	1.15
Lt Cruz Bay	1	0.37	0.88	1.33

"n" is the number of analyses included in the average. One relative standard deviation uncertainty is estimated to be ca 5%, mostly resulting from sample inhomogeneity

Ceramic classification and the relation to the TL-dates

When the TL-dates are ordered with respect to the ceramic classification of the shards, an interesting picture appears (Fig. 7).

There is a general large-scale correlation between the TL-dates and the progressing order of the traditional ceramic classification from Early Saladoid staring at 500 CE to Late Ostionoid ending at 1550 CE. Therefore, on a large scale, the classification system of Rouse [5] is somewhat supported by the present data. However, there are also deviations from this general pattern. The most prominent deviation is that in Hacienda Grande, Cuevas, and La Hueca styles there are an appreciable fraction which are older than the expected upper limit of 600 CE documented in traditional models for the Saladoid series. There are also three Early Ostionoid shards with ages younger than expected. These, together with the single Late Ostionoid shard from Prosperity on St. Croix with an age of 1674 ± 15, could be due to later re-heating events (campfires, wildfires, lightning etc.). Finally, all the groupings contain shards with appreciably older ages than expected from the ceramic classification. It is not possible to put forward an explanation for these seemingly old dates, mainly because of lack of (U, Th)-rich granite types rocks on the islands – they likely reflect the correct time of firing.

Looking at greater detail into each class by itself, the results for the Early Saladoid shards are shown in Fig. 7. Most of the shards are from Richmond and Spratt Hall O13 both on St. Croix, and Little Cruz Bay on St. John, while only two shards are from Coral Bay on St. John. The rest of the sites are not represented in this group.

The dating of five shards with bi-chromatic white on red, characteristic of the Cuevas style, show a continuous distribution in time from 522 ± 84 CE to 990 ± 47 CE, fitting closely with expected Cuevas dates from Lower Camp and other work in eastern Puerto Rico [6, 34, 56, 80].

In general, the sample of material examined as a part of this study resembles material from Vieques and Eastern Puerto Rico and is congruent to other well documented assemblages in the Virgin Islands such as Tutu and Kongens Gade in St. Thomas [43, 52, 81].

Hacienda grande (n = 7)

Inasmuch as Hacienda Grande is commonly dated from c. 200 BCE to 400 CE, the sample examined in this study indicates temporal congruence with the style in general terms. However, there is one outlier that may indicate an error in original identification of the shard (*i.e.*, Cuevas and not Hacienda Grande) or less likely an issue with the TL-date (Fig. 8).

La Hueca (n = 4)

Ceramics classified as belonging to the Huecoid Culture, falls in three distinct and time-separated groupings which in some respects concur with the much-discussed results Narganes Storde and Chanlatte Baik obtained from the type site of La Hueca on Vieques—the USVI nearest neighbour island to the west [82, 83].

The TL-dates of the shards classified as La Hueca pottery varying from 234 BCE (not shown in Fig. 7) to 701 CE. This speaks in favour for a large time window for La Hueca ceramic production, or of different events of production or import. However, it should be kept in mind that the number of samples is very low.

Cuevas (n = 37)

Pottery identified as Cuevas in this study vary from 337 to 1251 CE (Fig. 9), the range from the 1st to the 3rd quartile here from 689 to 1001 CE and varies from Rouse's framework—with the majority of samples extending beyond the expected date range for the style. Some evidence from eastern Puerto Rico also demonstrates this trend [56, 80, 84]. While not surprising, based on the previous research, some of the surface colour, red slipping and vessel forms from Cuevas do not indicate a clear transition to later Ostionoid styles in the area and appear to be perpetuated in Monserrate, with some noticeable variation. Originally identified by Gary Vescelius [35] it appears that the Longford style could be a local transitional style between Cuevas and later Monserrate which combines various techno-functional elements of both and early Ostiones that make formal identification of style challenging. Importantly, it demonstrates the blurred transitions between styles

Table 6 The results of the stylistic observations and chemical analyses of the samples and the calculated TL-dates. Lab No.; Name of Site; Abr: Abbreviation of site name used in the figures; Style; Pr: problematic samples, *i.e.*, those difficult to classify; Period; Hatt Collection context designations unit/square/layer where applicable; U and Th are given in $\mu g\ g^{-1}$ and K in wt%. The relative standard deviation of the U, Th, and K concentrations are estimated to be ca. 5 %, mainly arising from sample inhomogeneity the analytical uncertainty is less; TL-date before current era; one standard deviation of the date estimation

Lab-no	Site	Abr	Style	Pr	Period	Context	U	Th	K	TL Date	STD
KLR-11973	Magens Bay O1	MB	Santa Elena		O	1/XXI/3	2.200	3.750	1.920	1000	92
KLR-11974	Magens Bay O1	MB	Hacienda Grande	*	LS	1/XXI/4	0.095	0.248	0.282	1315	43
KLR-11975	Magens Bay O1	MB	Monseratte		EO	1/LVI/2	0.549	0.914	0.733	1244	39
KLR-11976	Magens Bay O1	MB	Monseratte		EO	1/XXXI/1	0.497	0.783	0.315	1202	40
KLR-11977	Magens Bay O1	MB	Ostiones		O	1/VI/3	0.721	1.405	0.670	1204	43
KLR-11978	Magens Bay O1	MB	Monseratte		EO	1/VI/4	0.715	1.270	1.029	860	60
KLR-11978b	Magens Bay O1	MB	Monseratte		EO	1/VI/4	0.548	0.902	0.786	1068	46
KLR-11979	Magens Bay O1	MB	Monseratte		LS/EO	1/VII/4	0.056	2.272	0.780	967	48
KLR-11980	Magens Bay O1	MB	Esperanza	*	LO	1/VIII/4	0.724	1.255	1.498	952	57
KLR-11981	Magens Bay O1	MB	Esperanza	*	LO	1/XII/1	0.121	0.678	0.884	1308	31
KLR-11982	Magens Bay O1	MB	Santa Elena	*	LO	1/XII/2	1.163	1.691	1.508	915	69
KLR-11983	Magens Bay O1	MB	Monseratte		LS/EO	1/XII/3	1.414	1.758	1.346	1194	55
KLR-11984	Magens Bay O1	MB	Ostiones		O	1/XII/4	0.127	6.550	0.824	1113	39
KLR-11985	Magens Bay O1	MB	Santa Elena	*	LO	1/XVI/3	0.423	0.733	0.800	1179	38
KLR-11986	Magens Bay O1	MB	Monseratte		LS/EO	1/XXIII/2	1.341	1.752	1.174	1110	59
KLR-11987	Magens Bay O1	MB	Monseratte		LS/EO	1/LI/1	0.334	0.644	0.427	1135	40
KLR-11988	Magens Bay O1	MB	Monseratte	*	O	1/LIV/3	0.590	1.049	0.943	1013	49
KLR-11989	Magens Bay O1	MB	Monseratte		LS/EO	1/LX/1	0.474	0.909	0.836	1078	44
KLR-11990	Magens Bay O1	MB	Santa Elena		LO	1/LX/2	0.398	0.839	0.634	1355	30
KLR-11991a	Magens Bay O1	MB	Monseratte		LS/EO	1/LX/3	0.720	0.980	0.940	1111	46
KLR-11991b	Magens Bay O1	MB	Monseratte		LS/EO	1/LX/3	0.697	1.068	1.290	1067	49
KLR-11992	Magens Bay O1	MB	Monseratte		LS/EO	1/VIII/4	0.603	0.780	0.236	1441	29
KLR-11993	Krum Bay O2	KB	Cuevas		EO	B/I/1	0.211	0.339	0.652	497	92
KLR-11995	Krum Bay O2	KB	Cuevas		LS	B/IV/1	0.240	0.610	0.707	337	106
KLR-11996	Krum Bay O2	KB	Cuevas	*	LS/EO	B/V/1	0.173	0.410	0.739	433	96
KLR-11997	Krum Bay O2	KB	Cuevas	*	LS/EO	B/VII/1	0.270	0.620	0.720	-1233	208
KLR-11998	Coral Bay O5	CB	Cuevas		LS/EO	A/III/1	0.389	6.153	0.523	1146	55
KLR-11999	Coral Bay O5	CB	Cuevas		LS/EO	A/IV/1	0.763	2.310	1.284	490	77
KLR-12000	Coral Bay O5	CB	Monseratte		LS	A/IV/2	0.607	0.458	1.076	822	52
KLR-12001	Coral Bay O5	CB	Monseratte	*	O	A/V/1	0.321	0.809	1.100	886	44
KLR-12002	Coral Bay O5	CB	Monseratte		LS/EO	A/IV/2	1.062	2.168	0.852	734	71
KLR-12003a	Coral Bay O5	CB	Monseratte		EO	A/VII/2	0.558	1.016	1.120	840	52
KLR-12003b	Coral Bay O5	CB	Cuevas		LS	A/VII/2	0.256	0.545	0.672	1100	38
KLR-12003c	Coral Bay O5	CB	Cuevas		S	A/VII/2	0.488	1.532	0.539	1177	39
KLR-12004a	Coral Bay O5	CB	Esperanza		LO	A/IIc	0.276	0.701	0.581	1306	30
KLR-12004b	Coral Bay O5	CB	Monseratte		LS	A/IIc	0.406	0.859	1.381	787	52
KLR-12005	Coral Bay O5	CB	Monseratte		O	A/IId/1	0.188	0.435	0.549	1098	39
KLR-12006	Coral Bay O5	CB	Cuevas		LS	A/IX/1	0.489	0.850	0.422	855	89
KLR-12007	Coral Bay O5	CB	Cuevas		LS/EO	A/IX/1	0.617	1.110	0.416	856	55
KLR-12008	Coral Bay O5	CB	Hacienda Grande		ES	A/IIc	0.492	1.190	0.953	982	46
KLR-12009	Coral Bay O5	CB	Ostiones		EO	A/IId	0.389	1.091	0.801	830	52
KLR-12010a	Lt Cruz Bay O8	LtCB	Hacienda Grande		S	A/III/2	1.800	3.960	1.570	288	124
KLR-12010b	Lt Cruz Bay O8	LtCB	Esperanza		LO	A/III/2	0.275	0.537	0.954	946	45
KLR-12012	Lt Cruz Bay O8	LtCB	Monseratte		EO	A/I/2	0.496	1.137	1.010	1039	44
KLR-12014	Lt Cruz Bay O8	LtCB	Ostiones		O	A/IV/2	0.677	1.170	1.177	1030	45
KLR-12015a	Lt Cruz Bay O8	LtCB	Santa Elena		O	A/IV/2	1.050	2.650	1.441	713	76

Table 6 (continued)

Lab-no	Site	Abr	Style	Pr	Period	Context	U	Th	K	TL Date	STD
KLR-12015b	Lt Cruz Bay O8	LtCB	Cuevas		S	A/IV/2	0.565	1.562	1.352	816	55
KLR-12016	Lt Cruz Bay O8	LtCB	Ostiones		EO	A/VI	2.868	2.511	0.553	1048	77
KLR-12018a	Lt Cruz Bay O8	LtCB	Hacienda Grande		ES	A/XII	0.717	1.480	1.174	373	78
KLR-12018b	Lt Cruz Bay O8	LtCB	Esperanza		LO	A/XII	0.340	0.589	0.811	1003	46
KLR-12018c	Lt Cruz Bay O8	LtCB	Ostiones	*	O	A/XII	1.010	3.560	1.341	703	76
KLR-12018d	Lt Cruz Bay O8	LtCB	Hacienda Grande	*	ES	A/XII	2.131	5.740	1.612	196	148
KLR-12019a	Lt Cruz Bay O8	LtCB	Ostiones		O	A/XII	0.384	0.484	1.344	767	53
KLR-12019b	Lt Cruz Bay O8	LtCB	UID	*	S	A/XII	0.081	0.212	1.152	920	46
KLR-12020	Lt Cruz Bay O8	LtCB	Hacienda Grande		ES	A/V/2	2.389	1.685	0.908	171	129
KLR-12021a	Lt Cruz Bay O8	LtCB	Cuevas	*	LS	A/VII	0.348	1.150	0.707	1227	50
KLR-12021b	Lt Cruz Bay O8	LtCB	Cuevas		LS	A/VII	0.253	0.526	0.926	875	51
KLR-12021c	Lt Cruz Bay O8	LtCB	Santa Elena		O	A/VII	0.359	0.812	1.153	811	52
KLR-12021d	Lt Cruz Bay O8	LtCB	Monseratte	*	S	A/VII	0.647	1.450	1.341	767	59
KLR-12022a	Lt Cruz Bay O8	LtCB	Cuevas	*	O	A/VIII	1.740	3.720	1.530	437	109
KLR-12022b	Lt Cruz Bay O8	LtCB	Santa Elena	*	LS	A/VIII	1.171	2.420	1.565	877	66
KLR-12024a	Spratt Hall O18	SH18	Cuevas		LS	A/II/2	0.660	0.996	0.892	994	46
KLR-12024b	Spratt Hall O18	SH18	Cuevas		LS	A/II/2	0.828	1.160	0.956	1007	46
KLR-12025a	Spratt Hall O18	SH18	Cuevas		LS	A/II/3	0.579	0.923	1.030	940	45
KLR-12025b	Spratt Hall O18	SH18	Cuevas		LS	A/II/3	0.179	0.518	0.649	721	105
KLR-12025c	Spratt Hall O18	SH18	Ostiones		EO	A/II/3	0.193	0.919	0.708	902	48
KLR-12026	Spratt Hall O18	SH18	Cuevas		LS	A/III/1	0.395	0.877	1.056	1234	34
KLR-12027a	Spratt Hall O18	SH18	Ostiones		EO	A/III/2	0.361	1.950	1.355	925	48
KLR-12027b	Spratt Hall O18	SH18	Cuevas		LS	A/III/2	0.582	1.220	0.865	1240	34
KLR-12028	Spratt Hall O18	SH18	Monseratte		EO	A/III/3	0.299	1.090	0.527	756	55
KLR-12029a	Spratt Hall O18	SH18	Cuevas		EO	A/IV/2	0.145	0.287	0.926	521	68
KLR-12029b	Spratt Hall O18	SH18	Cuevas		S/LS	A/IV/2	0.457	0.757	0.526	960	51
KLR-12029c	Spratt Hall O18	SH18	Cuevas	*	LS	A/IV/2	0.560	0.920	1.040	1071	45
KLR-12029d	Spratt Hall O18	SH18	Cuevas		LS	A/IV/2	2.395	7.404	1.796	689	107
KLR-12030a	Spratt Hall O18	SH18	Santa Elena		O	A/IV/3	0.604	1.220	1.435	709	56
KLR-12030b	Spratt Hall O18	SH18	Cuevas		LS	A/IV/3	0.469	0.983	1.100	918	46
KLR-12031a	Spratt Hall O18	SH18	Monseratte		LS	A/V/2	0.224	0.845	1.027	919	46
KLR-12031b	Spratt Hall O18	SH18	Cuevas		LS	A/V/2	0.248	0.787	1.112	719	55
KLR-12031c	Spratt Hall O18	SH18	Cuevas		LS	A/V/2	2.230	1.340	0.540	757	77
KLR-12031d	Spratt Hall O18	SH18	Cuevas		??	A/V/2	0.701	1.035	0.964	1001	45
KLR-12032a	Spratt Hall O18	SH18	Cuevas		LS	A/V/3	0.555	0.881	1.040	985	44
KLR-12032b	Spratt Hall O18	SH18	Cuevas		LS	A/V/3	1.280	1.980	1.944	557	76
KLR-12032c	Spratt Hall O18	SH18	Cuevas		LS	A/V/3	0.826	1.737	0.463	898	54
KLR-12032d	Spratt Hall O18	SH18	Cuevas		LS	A/V/3	0.310	0.488	1.092	934	46
KLR-12032e	Spratt Hall O18	SH18	Monseratte		LS/EO	A/V/3	0.501	0.813	0.320	1074	43
KLR-12033	Prosperity O20	PRO	Ostiones		O	–/–/–	0.230	0.428	0.708	743	54
KLR-12034	Prosperity O20	PRO	Capa		LO	–/–/–	0.357	0.737	0.331	1674	15
KLR-12035	Prosperity O20	PRO	Monseratte		LS	–/–/–	0.420	0.770	1.360	779	51
KLR-12037	Spratt Hall O30	SH30	Monseratte		LS/EO	–/–/–	0.657	1.014	0.907	1013	44
KLR-12038	Spratt Hall O30	SH30	Monseratte		EO	–/–/–	0.388	0.941	1.221	1007	42
KLR-12039	Spratt Hall O30	SH30	Monseratte		LS	–/–/–	0.572	2.059	2.167	840	53
KLR-12040	Spratt Hall O30	SH30	Ostiones	*	O	–/–/–	1.088	2.990	0.994	681	71
KLR-12041	Spratt Hall O30	SH30	La Hueca		S	–/–/–	0.356	1.051	0.512	668	57
KLR-12042	Spratt Hall O30	SH30	Esperanza		LO	–/–/–	0.129	0.540	0.951	1410	26
KLR-12043	Spratt Hall O30	SH30	Esperanza	*	O	–/–/–	0.245	0.670	0.130	1495	26

Table 6 (continued)

Lab-no	Site	Abr	Style	Pr	Period	Context	U	Th	K	TL Date	STD
KLR-12044	Spratt Hall O30	SH30	Cuevas		LS/EO	–/–/–	0.501	0.868	0.993	1048	41
KLR-12045	Spratt Hall O30	SH30	Ostiones	*	O	–/–/–	0.202	0.318	0.638	785	56
KLR-12046	Spratt Hall O30	SH30	Monseratte		O	–/–/–	0.146	1.066	1.260	1405	25
KLR-12047	Sprat Hall O30	SH30	Esperanza		LO	–/–/–	0.156	0.643	0.647	1603	17
KLR-12048	Spart Hall O30	SH30	Monseratte		O	–/–/–	0.145	1.001	2.121	1244	29
KLR-12049	Spratt Hall O30	SH30	Santa Elena		LO	–/–/–	0.371	1.028	1.229	1534	19
KLR-12051	Spratt Hall O30	SH30	Santa Elena		EO	–/–/–	0.342	0.890	1.274	1085	39
KLR-12054	Spratt Hall O30	SH30	Monseratte		O	–/–/–	0.606	1.060	0.675	1111	39
KLR-12056	Sprat Hall O30	SH30	Ostiones		O	–/–/–	0.222	0.853	1.225	1532	19
KLR-12058	Spratt Hall O30	SH30	Ostiones		O	–/–/–	0.268	1.127	1.740	911	46
KLR-12059	Spratt Hall O30	SH30	UID		?	–/–/–	0.291	1.210	1.623	853	46
KLR-12060	Spratt Hall O30	SH30	La Hueca		S	–/–/–	0.665	1.278	1.135	701	56
KLR-12061	Spratt Hall O30	SH30	Ostiones		O	–/–/–	0.207	1.660	1.886	1208	34
KLR-12062	Richmond 033	RIC	Hacienda Grande		S	–/–/–	0.200	0.419	0.570	262	97
KLR-12063	Richmond 033	RIC	Boca Chica		LO	–/–/–	0.403	0.696	0.705	1506	23
KLR-12064	Richmond 033	RIC	Santa Elena		LO	–/–/–	0.219	1.120	2.009	1335	28
KLR-12065	Richmond 033	RIC	La Hueca	*	ES	–/–/–	0.688	1.550	1.358	− 234	107
KLR-12066	Richmond 033	RIC	Monseratte		EO	–/–/–	0.369	0.714	1.013	632	38
KLR-12067	Richmond 033	RIC	UID		EO	–/–/–	0.522	1.490	1.045	838	53
KLR-12068	Richmond 033	RIC	Monseratte		EO	–/–/–	0.512	1.450	0.698	605	65
KLR-12069	Richmond 033	RIC	Monseratte		O	–/–/–	0.298	0.862	1.290	1087	39
KLR-12070	Richmond 033	RIC	Ostiones		O	–/–/–	0.497	0.685	2.097	1014	43
KLR-12071	Richmond 033	RIC	Santa Elena		O	–/–/–	0.202	0.400	1.410	1036	39
KLR-12072	Richmond 033	RIC	Ostiones		O	–/–/–	0.271	0.504	0.806	1307	30
KLR-12073	Richmond 033	RIC	Hacienda Grande		ES	–/–/–	3.010	6.470	2.966	436	158
KLR-12075	Richmond 033	RIC	Ostiones		O	–/–/–	0.632	1.525	1.504	853	54
KLR-12076	Richmond 033	RIC	La Hueca		ES	–/–/–	0.323	0.622	0.864	398	70
KLR-12077	Richmond 033	RIC	Cuevas		LS/EO	–/–/–	0.567	2.160	1.576	903	53
KLR-12078	Richmond 033	RIC	Cuevas		S	–/–/–	0.980	1.730	1.050	522	84
KLR-12079	Richmond 033	RIC	Cuevas		ES	–/–/–	0.618	0.988	1.034	660	61
KLR-12080	Richmond 033	RIC	Cuevas	*	LS	–/–/–	0.194	0.270	0.452	770	58
KLR-12081	Richmond 033	RIC	Cuevas		S	–/–/–	0.176	0.408	0.440	990	47
KLR-12082	Richmond 033	RIC	Hacienda Grande		S	–/–/–	0.173	0.389	0.423	931	62

over time that may indicate gradual transformation of localized traditional knowledge practices through time. The Cuevas style in Wild's chronology from Cinnamon Bay was ca. 400–600 CE, a range that is embedded in the first quartile of samples of the date ranges in the present study.

Monserrate (n = 34)

The Cuevas/Monserrate transition is a blur. Certain elements of the Cuevas style/tradition continued for a prolonged period of time in eastern Puerto Rico. While not readily evident in the morphology and surface treatment of Santa Elena pottery, Cuevas style elements persisted in the eastern portion of Puerto Rico and in the Virgin Islands from 640 CE through at least 1000 CE [58, 80]. With this caveat in mind, the shards classified as Monserrate in this work show TL-dates vary from 632 to 1441 CE, while the 1st to the 3rd quartile range from 840 to 1111 CE, which is in complete accordance with Wild's chronology from Cinnamon Bay on St. John [42] (Fig. 10).

Ostiones (n = 17)

Although found throughout Puerto Rico between ca. 600 and 1200 CE, this style is typically associated with the western side of Puerto Rico. The majority of dates for this style tend to date post-800 CE (see Fig. 11).

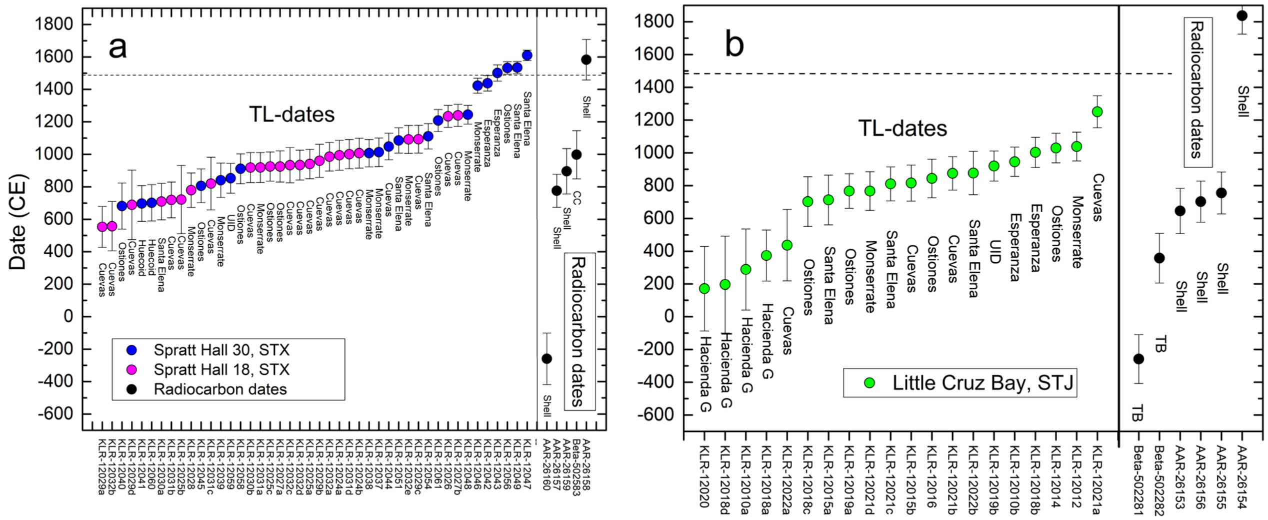

Fig. 6 Two examples of a comparison of the TL-dates with the radiocarbon dates from the same location. a: Spratt Hall (both O18 and O30) on St Croix, and b: Little Cruz Bay on St John. Scale bars are 2 standard deviations for the TL-dates and 95% probability for the calibrated dates of the radiocarbon dates. The year 1492 is marked by a dashed line. TL-dates are shown to the left and radiocarbon dates to the right in both plots. The error bars of the TL-dates are 2 standard deviations

Table 7 Early and late dates for sites based on TL and radiocarbon dates

	No. TL-dates	Early date	Late date	No. RC dates	Early date	Late date
Magens Bay	22	860 CE	1441 CE	12	508 CE	1523 CE
Krum Bay	15	337 CE	497 CE	8	599 BCE	717 CE
Spratt Hall	44	553 CE	1534 CE	5	418 BCE	1708 CE
Richmond	20	234 BCE	1506 CE	0	N/A	N/A
Prosperity	3	764 CE	1679 CE	0	N/A	N/A
Coral Bay	15	490 CE	1337 CE	6	653 CE	1166 CE
Lt Cruz Bay	20	171 CE	1251 CE	6	408 BCE	884 CE

Two outliers are not included in this list, KLR-11997 from Krum Bay and KLR-12047 from Spratt Hall. No radiocarbon dates were collected or sampled from Richmond and Prosperity

Diagnostic elements of the samples indicate modified Ostiones style which is more prevalent during later in the temporal sequence. Samples were identified at sites on all three islands. Due to its identification outside the normal zone of highest distribution (*i.e.*, western Puerto Rico), the presence of this style may indicate an import/trade ware or that local potters may have immigrated into the region.

Santa Elena (n = 12)

Based on the Cinnamon Bay stratigraphy, Wild [42] re-defined the Santa Elena culture from Rouse's original 900–1200 CE to a range from 1180 to 1290 CE. In the present study the 1st to the 3rd quartile ranges from 844 to 1257 CE, which is in good agreement the terminus, while the beginning is marginally older, ca. 50 years, than that of Rouse [5] (Fig. 12).

Chican ostionoid: Boca Chica (n = 1), Capa (n = 1), Esperanza (n = 8)

This is the latest of the pottery production within Eastern Puerto Rico. Boca Chica is also identified in St. John. This style originates from Hispaniola but is also present in small quantities in southern Puerto Rico [29] indicating potential trade routes. The dates are largely congruent with typical dates associated with these styles, although the number of samples of these materials is small. The Esperanza shards dated to between 946 and 1603 CE, while the single Boca Chica shard dated to 1506 ± 23 CE, and the single Capa shard dated to 1674 ± 15 CE.

Preliminary thoughts on ceramic chronology

We advance the following preliminary chronology for the Virgin Islands (Fig. 13, Table 8). While this framework is tentative, it provides additional baseline information

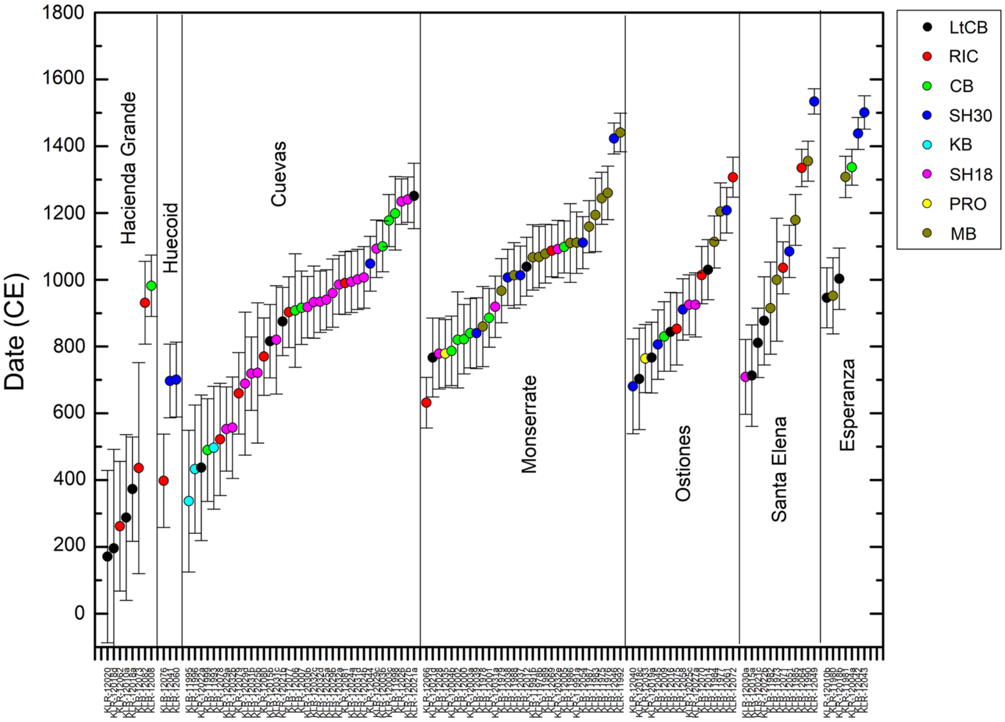

Fig. 7 TL-dates per style (coloured dots indicate site location according to legend to the right). Error bars are 2 standard deviations

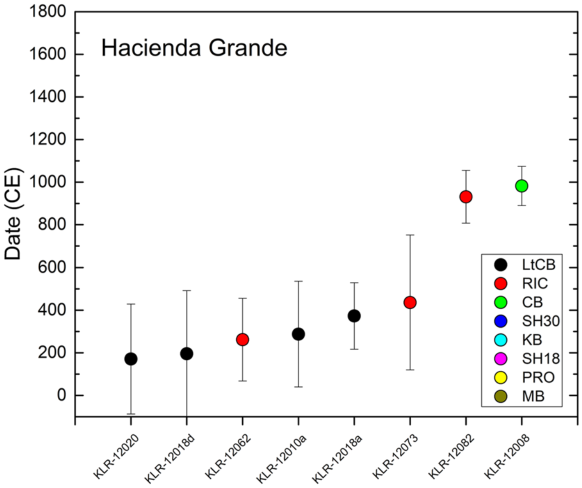

Fig. 8 TL-dates of the Hacienda Grande style. Error bars are 2 standard deviations

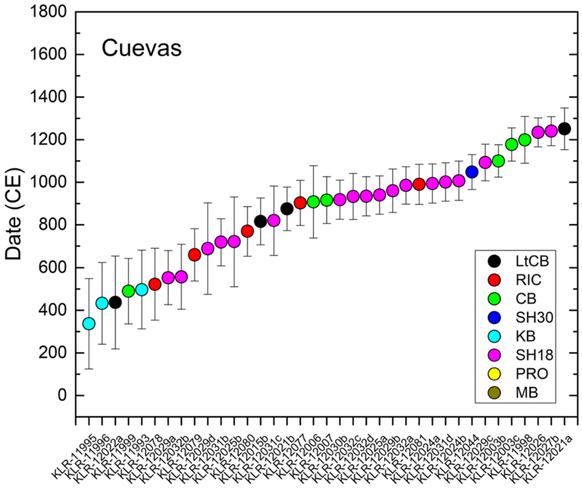

Fig. 9 TL-dates of the Cuevas pottery in the present study. Error bars are 2 standard deviations

for the refinement of pottery chronologies in the region and points of comparison for other previously developed frameworks (*e.g.*, [5, 42]).

The data indicate relatively early settlement of the US Virgin Islands. This, combined with previous research, supports the indication of early ceramic migration to the Vieques sound region [4, 14, 15, 85]. It can be said that the present dataset of TL-dates are more overlapping in the temporal distribution of pottery styles when compared to the earlier interpretations based on an over-reliance on relative dating techniques and models that tended to be more sequential.

The boundaries between styles can be blurred and multiple styles can appear contemporaneously. In our model

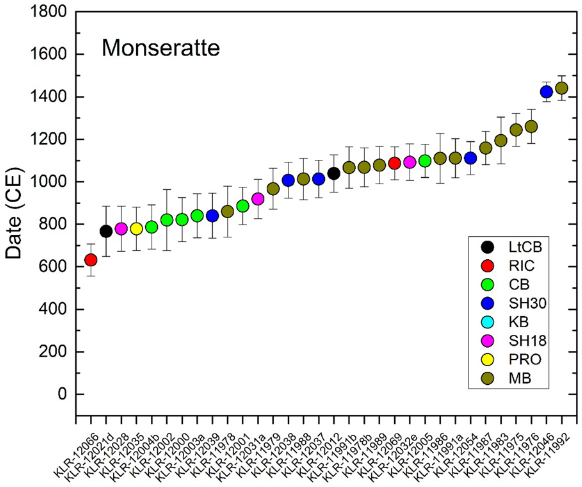

Fig. 10 TL-dates of the pottery classified as Monserrate in the present study. Error bars are 2 standard deviations

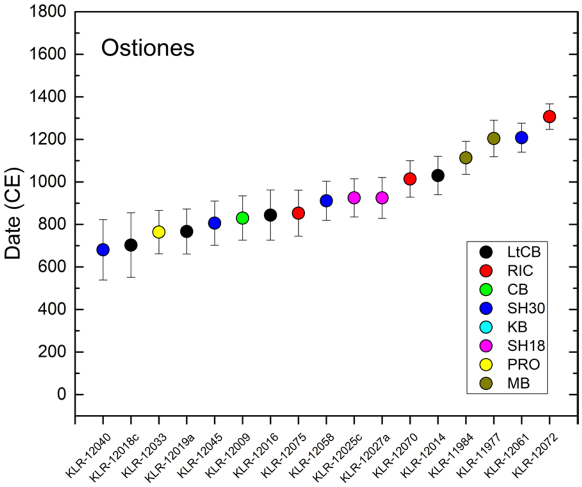

Fig. 11 TL-dates of the pottery classified as Ostiones in the present study. Error bars are 2 standard deviations

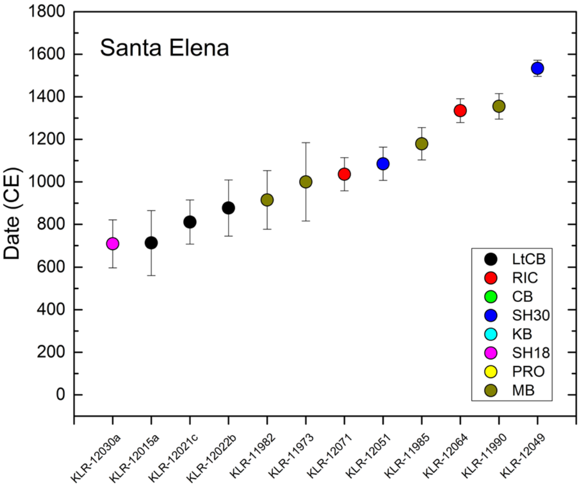

Fig. 12 TL-dates of the Santa Elena pottery in the present study. Error bars are 2 standard deviations

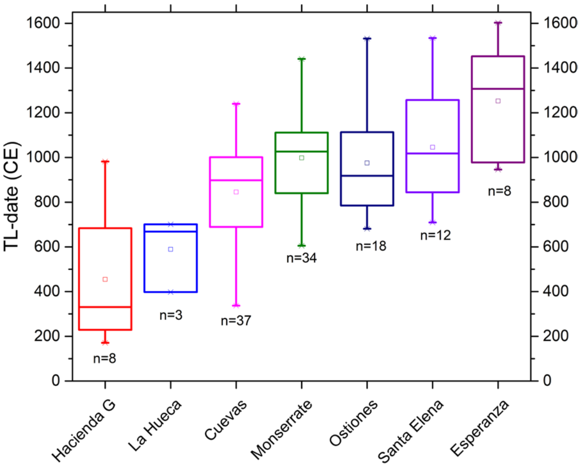

Fig. 13 Boxplots for pottery styles from the Virgin Islands based on the TL-dates of the present study. Three outliers are not included in this plot (KLR-11997, KLR-12065, and KLR-11974)

we have taken the median TL-date and used the first and third quartiles for the beginning or early occurrence of the style and the third quartile for an approximate terminus or late date for the style as this represents the central tendency of the data which accounts for the preponderance of solid information and the potential peak when this practice of pottery production was occurring at a given site. We also do this to avoid potential problems in the way that a single outlier date may skew the approximate beginning and end dates. While this may bias the data due to the limited number of shards for some of the styles, we feel it removes some of the potential noise. While limited, this information can hopefully be elaborated on to understand in more specificity the sites from which the samples were collected. Future work will examine variability between and amongst the sites themselves to further address the more detailed examination of data presented here. Further the framework here allows for future comparison with eastern Puerto Rico and much needed refinement of US Virgin Islands archaeological record.

Based on our analysis and the work of others (*e.g.*, [41, 43, 86]) we find that changes in pottery assemblages throughout the US Virgin Islands indicate close cultural affinities with peripheral communities in eastern Puerto Rico [80]. Many of the style attributes demonstrate

Table 8 Pottery chronology based on TL-dates from this study compared to Wild (2013) [42] and Rouse (1992) [5]

Style	TL-dates this study		Wild 2013		Rouse 1992 (Eastern PR)	
	Early date (1st quartile)	Late date (3rd quartile)	Beginning	Terminus	Beginning	Terminus
La Hueca (n = 3)	398 CE	701 CE	N/A			
Hacienda Grande (n = 8)	229 CE	684 CE	ca. 300 BCE	ca. 400 CE	ca. 300 BCE	ca. 400 CE
Cuevas (n = 37)	689 CE	1001 CE	ca. 400 CE	ca. 600 CE		
Monserrate (n = 34)	840 CE	1111 CE	ca. 800 CE	ca. 1180 CE	ca. 600 CE	ca. 900 CE
Santa Elena (n = 12)	844 CE	1257 CE	ca. 1180 CE	ca. 1290 CE	ca. 900 CE	ca. 1200 CE
Ostiones (n = 18)	785 CE	1113 CE				
Esperanza (n = 8)	978 CE	1453 CE	ca. 1290 CE	ca. 1440 CE	ca. 1200 CE	ca. 1450 CE
Capa (n = 1)	N/A	N/A			ca. 1200 CE	ca. 1450 CE
Boca Chica (n = 1)	N/A	N/A			ca. 1200 CE	ca. 1450 CE

Three outlier dates are not included in the calculations (KLR-11997, KLR-12065, and KLR-11974)

continued contact with the developing Ostionoid sociopolitical units in the Greater Antilles. It is proposed that these relations were established during the Saladoid settlement of the region and persisted through time.

Summary and conclusions

There is a tendency to use radiocarbon as the first choice of dating method in any archaeological excavation. Only occasionally will TL be used. The archaeology of the US Virgin Islands, however, presents an unusual set of circumstances that allow for the efficient use of the TL-method. Firstly, the primary and ubiquitous form of material culture on the US Virgin Islands consists of pottery – proportionately the amount of surviving material made from materials datable by radiocarbon are scarcer. This constitutes an advantage for the TL-method. Secondly, the sediments in the US Virgin Islands generally exhibit very low levels of U and Th compared to many sites in Europe and South America. This makes the TL-dates more robust in the US Virgin Islands as compared to the several other regions. Thirdly, most samples datable by radiocarbon in a typical US Virgin Island excavation site are present mainly as stratigraphic indicators, like *e.g.*, a hacked conch shell, which does not necessarily relate directly to the ceramic found in the context. There is furthermore a chance that the shells and bones are only naturally occurring without a solid connection to the cultural layers. Fourthly, in the US Virgin Islands there can be a problem with the reservoir effect. At present the marine reservoir effect is based on a single sample from St Croix and one from St Thomas. Finally, the food choice between terrestrial and marine food chains of turtles and manatees can vary to a large degree making the assessment of a reservoir effect quite difficult. As the majority of the datable samples are marine, the reservoir effects and the marine calibration curve add to the inherent uncertainty of the radiocarbon results. Combined, these four factors further push the balance towards the TL-dating technique in this particular area.

Critically, and an important aspect to benefit the Caribbean archaeology, is that the dating of shards themselves allows for more precise dating of the time the pottery was actually produced, or used on a campfire, and provides a basis for understanding regional and local information exchanges through chronological control of the object itself. With the development of the present data set, and potential future ones, it will be possible to continue to refine the spatio-temporal distribution of pottery to better understand the rhythm and tempo of innovation, symbolic iconography, communities of practice, and information transmission in the region.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-00936-1.

Additional file 1: The Munsell colours of some of the shards depicted in Figs. 4 and 5.

Acknowledgements

We are most grateful to Sean L. Krieger, director of the State Historic Preservation Office, USVI for permission to take soil samples and for support of the present work, and to Mille Gabriel from the National Museum of Denmark for permission to sample the USVI collections curated there. Pia Klingenberg Haussmann and Emma Simonsen are thanked for technical help in the laboratory. We are also grateful to the four anonymous reviewers for their constructive comments that helped us improve this paper.

Author contributions

Conceived and designed the experiments: CJT, TD, KLR. Performed the experiments: TD, KLR. Analysed the data: TD, KLR, JT, GF. Contributed with field work: DB, JF, KLR. Wrote the paper: JT, KLR. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

All relevant data are included in the paper. Other information can be retrieved by addressing the authors.

Declarations

Ethics approval and consent to participate

There are no special ethical issues involved in this work.

Competing interests

It is declared that we have no competing interests.

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Received: 6 December 2022 Accepted: 18 April 2023

References

1. Keegan W, Hofman C. The caribbean before columbus oxford university press. New York: Oxford University Press; 2017.
2. Keegan WF, Hofman CL, Ramos RR. The oxford handbook of caribbean archaeology. Oxford: Oxford University Press; 2013.
3. Wilson SM. The archaeology of the Caribbean. Cambridge: Cambridge University Press; 2007.
4. Napolitano MF, DiNapoli RJ, Stone JH, Levin MJ, Jew NP, Lane BG, et al. Reevaluating human colonization of the Caribbean using chronometric hygiene and Bayesian modeling. Sci Adv. 2019;5(12):7806.
5. Rouse I. The tainos: rise and decline of the people who greeted Columbus. London: Yale University Press; 1992.
6. Ramos RR. Rethinking puerto rican precolonial history. Tuscaloosa: University of Alabama Press; 2010.
7. Mol AA. Studying pre-Columbian interaction networks: mobility and exchange. 2013.
8. Mol AA, Mans JLJA. Old boy networks in the indigenous Caribbean. Network analysis in archaeology: New approaches to regional interaction. 2013:307-33.
9. Torres JM. The social construction of community, polity, and place in ancient Puerto Rico (AD 600–AD 1200). Gainesville: University of Florida; 2012.
10. Keegan WF. Central plaza burials in Saladoid Puerto Rico: an alternative perspective. Latin Amer Antiq. 2009;20(2):375–85.
11. Heckenberger MJ. Rethinking the Arawakan diaspora: hierarchy, regionality, and the Amazonian formative. Comparative Arawakan histories: rethinking language family and culture area in Amazonia. 2002:99–122.
12. Keegan WF. Islands of chaos. Bar international series. 2004:33–46.
13. Keegan WF. Continent of Islands: New Perspectives on the Pre- Columbian Colonization of the Insular Caribbean. 16th Annual Symposium of the PreColumbian Society of Washington DC; 2009.
14. Torres JM, Ramos RR. The Caribbean: a continent divided by water. Archaeology and geoinformatics: Case studies from the Caribbean. 2008:13–29.
15. Haviser JB. Settlement strategies in the early ceramic age. The indigenous people of the Caribbean. 1997:57–69.
16. Siegel PE. Continuity and change in the evolution of religion and political organization on pre-Columbian Puerto Rico. J Anthropol Archaeol. 2010;29(3):302–26.
17. La Chanlatte Baik, Naganes Storde Y. La nueva Arqueología de Puerto Rico (su proyección en las Antillas). Boletin del Museo del Hombre Dominicano. 1989;16(22):9–49.
18. Rodríguez López M, editor Arqueología de Punta Candelero, Puerto Rico. XIIIe Congreso Internacional del Caribe; 1991.
19. Carini SP. Compositional analysis of West Indian Saladoid ceramics and their relevance to Puerto Rican prehistory: University of Connecticut; 1991.
20. Roe PG. A grammatical analysis of Cedrosan Saladoid vessel form categories and surface decoration: Aesthetic and technical styles in early Antillean ceramics. Early ceramic population lifeways and adaptive strategies in the Caribbean. 1989: 267–382.
21. Rouse I. Ceramic and religious development in the Greater Antilles. J New World Archaeol. 1982;5(2):45–56.
22. Haviser JB. Development of a prehistoric interaction sphere in the northern lesser antilles. New West Indian Guide. 1991;65(3–4):129–51.
23. Hoogland M, Hofman C. Taino expansion towards the lesser antilles. the case of Saba. J Soc Am. 1999;85:93–113.
24. Delpuech A, Hofman CL, Hoogland ML, editors. Excavations at the site of Anse à la Gourde, Guadeloupe. Organisation, history and environmental setting. Proceedings of the XVIIIth International Congress for Caribbean Archaeology; 1999.
25. Oliver J. The la hueca complex in puerto rico and the caribbean: old problems, new perspectives, possible solutions. In: Hofman CL, Hoogland MLP, editors. Archaeological investigations on st martin, (lesser antilles): the sites of norman estate, hope estate & anse des Peres. Leiden Holland: Archaeological Studies Leiden University; 1999. p. 253–97.
26. Susan D, Newsom LA. The status of paleoethnobiological research on Puerto Rico and adjacent islands ancient borinquen: archaeology and ethnohistory of native Puerto Rico. Tuscaloosa: The University of Alabama Press; 2005.
27. Newsom LA, Wing ES. On land and sea: Native American uses of biological resources in the West Indies. Tuscaloosa: University of Alabama Press; 2004.
28. Hardy MD. Saladoid economy and complexity on the Arawakan frontier. 2008.
29. Lundberg ER. Settlement Pattern Analysis for South-central Puerto Rico. 1985.
30. Rodríguez-López M. Prehistoria de Collores: Centro de Estudios Avanzados de Puerto Rico y el Caribe; 1983.
31. Torres JM. Settlement Patterns and Political Geography of the Saladoid and Ostionoid Peoples of South-Central Puerto Rico. Unpublished Master's thesis, Department of An-thropology, University of Colorado, Denver; 2001.
32. Torres JM. Deconstructing the polity: communities and social landscapes of the Ceramic-Age peoples of South Central Puerto Rico. Ancient Borinquen: Archaeology and Ethnohistory of Native Puerto Rico. 2005:202–29.
33. Ramos RR, Jiménez JP. Interacciones multivectoriales en el Circum-Caribe precolonial: Un vistazo desde las Antillas. Caribbean Studies; 2006:99–139.
34. Rodríguez Ramos R, Joshua M. Torres JM, Pestle LWJ, Curet A, J. O, Rodríguez López M. Hacia una periodización para la historia precolonial de Puerto Rico International Congress for Caribbean Archaeology; San Juan; 2013.
35. Vescelius GS. The Cultural Chronology of St. Croix; 1952.
36. Hatt G. Archaeology of the Virgin Islands: na; 1924.
37. Morse BF. At the Onset of Complexity: Late Ceramic Developments in St. Croix. In: Delbuech AH, C.L., editor. Late Ceramic Age Societies in the Eastern Caribbean. Oxford: BAR International Series 1273. 2004: 183–93.
38. Morse B, editor The sequence of occupations at the Salt River site, St. Croix. Proceedings of the XV International Congress for Caribbean Archaeology, Centro de Estudios Avanzados de Puerto Rico y el Caribe, San Juan; 1995.
39. Sleight FW, Bullen RP. Archaeological Reconnaissance of the Island of St. John, United States Virgin Islands: Central Florida Museum; 1962.

40. Faber Morse B. Saladoid remains and adaptive strategies in St. Croix, Virgin Islands. Early Ceramic population lifeways and adaptive strategies in the Caribbean. 1989:29–41.
41. Lundberg ER, Righter E, editors. Ceramic Style Definition and Refinement: Late Saladoid Changes in the Virgin Passage Area. Seventeenth Congress of the International Association for Caribbean Archaeology. NY: Molloy College; 1999.
42. Wild KS, editor A timeline of Taíno development in the Virgin Islands. 25th International Association for Caribbean Archaeology Conference; 2013.
43. Lundberg ER. Pottery Analysis. 2014.
44. Rouse I. Migrations in prehistory: inferring population movement from cultural remains. New Haven: Yale University Press; 1986.
45. Vescelius GS. A cultural taxonomy for West Indian archaeology. J Virgin Islands Archaeol Soc. 1980;10:36–9.
46. Petersen JB, Hofman CL, Curet LA. Time and culture: chronology and taxonomy in the eastern Caribbean and the Guianas. Bar international series. 2004:17–32.
47. Weaver GG, Garrow PH,´R. OJ. Phase II Archaeological Data Recovery at PO-38 El Parking Site, Barrio Maraguez, Ponce, Puerto Rico: Garrow & Associates; 1992.
48. Rodríguez Ramos R, Rodríguez López M, Pestle WJ. Revision of the cultural chronology of precolonial Puerto Rico: a bayesian approach. PLoS ONE. 2023;18(2): e0282052.
49. Thomas HL, Ehrich RW. Some problems in chronology. World Archaeol. 1969;1(2):143–56.
50. Keegan WF. Archaeological investigations on Ile à Rat, Haiti: Avoid the–OID. Proceedings of the XVIII International Congress for Caribbean Archaeology: International Association for Caribbean Archaeology Guadeloupe; 2001.
51. Curet LA. Issues on the diversity and emergence of middle-range societies of the ancient Caribbean: a critique. J Archaeol Res. 2003;11(1):1–42.
52. Righter E. The Tutu archaeological village site: a multidisciplinary case study in human adaptation. London: Psychology Press; 2002.
53. Curet LA. Technological changes in prehistoric ceramics from Eastern Puerto Rico: an exploratory study. J Archaeol Sci. 1997;24(6):497–504.
54. Rouse I. Porto Rican Prehistory: The Academy; 1952.
55. Rainey FG. Porto rican archaeology. New York: New York Academy of Sciences; 1940.
56. Torres JR, Carlson LA. Torres and Carlson 2011 Phase II Evaluations of Three Archaeological Sites (CE-34, CE-35, and RR-10) Located on Punta Medio Mundo, Naval Activity Puerto Rico. By Joshua M. Torres and Lisabeth A. Carlson, Ph.D. Prepared for Naval Facilities Engineering Command Southeast. Jacksonville, Florida; 2011.
57. Siegel PE. Ideology, power, and social complexity in prehistoric Puerto Rico. Binghamton: State University of New York at Binghamton; 1992.
58. Carlson LA, Torres JR. Significance Evaluations of Eight Archaeological Sites at the Naval Facility Formerly Known as Roosevelt Roads, Ceiba, Puerto Rico. Prepared for Naval Facilities Engineering Command; 2009.
59. Carlson LA. Significance Evaluations of Eight Archaeological Sites at the Naval Facility Formerly Known as Roosevelt Roads, Ceiba, Puerto Rico; 2009.
60. Garrow PH, C McNutt J, Weaver GG, Oliver JR. La Iglesia de Maragüéz (PO-39): Investigation of a Local Ceremonial Center in the Cerrillos River Valley, Ponce, Puerto Rico; 1995.
61. Rouse I. Prehistory of the West Indies: the Indians Columbus encountered when he discovered the new World were moving up from South America. Science. 1964;144(3618):499–513.
62. Arroyo AMS. Cave of the Jagua: the mythological world of the Taínos. Scranton: University of Scranton Press; 2006.
63. Wentz R. Inventory and Analysis of Human Skeletal Remains from St. Croix, U.S. Virgin Islands. Manuscript on file, Christiansted National Historic Site, Christiansted, St. Croix, U.S. Virgin Islands; 2007.
64. Bullen RP. @ Ceramic Periods of St. Thomas and St. John Islands, Virgin Islands: Verlag nicht ermittelbar; 1962.
65. Gross JM. The Archaic period of the Virgin Islands: new investigations: Island Resources Foundation; 1975.
66. Hong D, Kim M, Choi J, El-Faramawy N, Göksu H. Equivalent dose determination of single aliquot regenerative-dose (SAR) protocol using thermoluminescence on heated quartz. Nucl Instrum Methods Phys Res Sect B. 2006;243(1):174–8.
67. Kreutzer S, Schmidt C, Fuchs MC, Dietze M, Fischer M, Fuchs M. Introducing an R package for luminescence dating analysis. Ancient TL. 2012;30(1):1–8.
68. Grün R. The DATA program for the calculation of ESR age estimates on tooth enamel. Quat Geochronol. 2009;4(3):231–2.
69. Rick TC, Vellanoweth RL, Erlandson JM. Radiocarbon dating and the "old shell" problem: direct dating of artifacts and cultural chronologies in coastal and other aquatic regions. J Archaeol Sci. 2005;32(11):1641–8.
70. Cooper J, Thomas K. Constructing caribbean chronologies: comparative radiocarbon dating of shell and wood artefacts from pre-columbian sites in cuba. Archaeometry. 2012;54(2):401–25.
71. Petchey F, Piper PJ, Dabell K, Brock F, Turner H, Lam TMD. Dating thach lac: cryptic CaCO3 diagenesis in archaeological food shells and implications for 14c. Radiocarbon. 2022;64(5):1093–107.
72. Rasmussen K, Milner G, Skytte L, Lynnerup N, Thomsen P, Boldsen J. Mapping diagenesis in archaeological human bones. Herit Sci. 2019. https://doi.org/10.1186/s40494-019-0285-7.
73. Van der Plicht J, Rasmussen KL. Radiocarbon dating and qumran. Holist Qumran Brill. 2010. https://doi.org/10.1163/ej.9789004181526.i-210.62.
74. Godley B, Thompson D, Waldron S, Furness R. The trophic status of marine turtles as determined by stable isotope analysis. Mar Ecol Prog Ser. 1998;166:277–84.
75. DiNapoli RJ, Fitzpatrick SM, Napolitano MF, Rick TC, Stone JH, Jew NP. Marine reservoir corrections for the Caribbean demonstrate high intra- and inter-island variability in local reservoir offsets. Quat Geochronol. 2021;61:101126.
76. Vera SD, Guillermo A, Rasmussen KL. Prácticas alfareras, tecnología y cronología durante los períodos Tardío e Inca en el sector meridional del Valle de Abaucán Tradiciones y rupturas: el caso de Costa de Reyes N° 5 (Tinogasta, Catamarca, Argentina). Latin Amer Antiq. 2019;30(1):70–90.
77. Rasmussen KL, editor Termoluminiscensdatering af mursten fra Nyborg Slot. Bygningsarkæologiske Studier 2006–2008: Tværvidenskabeligt seminar på Nyborg Slot 30 marts; 2010: Bygningsarkæologiske Studier; 2006.
78. Reimer PJ, Austin WE, Bard E, Bayliss A, Blackwell PG, Ramsey CB, et al. The IntCal20 Northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon. 2020;62(4):725–57.
79. Heaton TJ, Köhler P, Butzin M, Bard E, Reimer RW, Austin WE, et al. Marine20—the marine radiocarbon age calibration curve (0–55,000 cal BP). Radiocarbon. 2020;62(4):779–820.
80. Oliver J. Archaeology of Lower Camp, Culebra Island. IACA; San Juan, Puerto Rico; 1993.
81. Lundberg ER. Tutu pottery and ceramic chronology. In: Righter E, editor. The tutu archaeological village site: a multidisciplinary case study in human adaptation. London: Routledge; 2002. p. 166.
82. Chanlatte Baik LA. Cultura Ostionoide: Un Desarrollo Algroalfarero Antillano. Proceedings of the Eleventh International Congress for Caribbean Archaeology: La Fundación Arqueológica, Antropológica e Histórica de Puerto Rico: San Juan; 1990
83. Chanlatte L, Narganes I, editors. La Hueca, Vieques: nuevo complejo cultural agroalfarero en la Arqueologia Antillana. Proceedings of the 8th International Congress for Caribbean Archaeology; 1980.
84. Pestle WJ, Curet LA, Ramos RR, López MR. New questions and old paradigms: reexamining Caribbean culture history. Latin Amer Antiq. 2013;24(3):243–61.
85. Fitzpatrick SM, Kappers M, Giovas CM. The southward route hypothesis: examining Carriacou's chronological position in Antillean prehistory. In: Fitzpatrick SM, Ross AH, editors. Island shores, distant pasts: archaeological and biological approaches to the pre-Columbian settlement of the Caribbean. Bioarchaeological interpretations of the human past. Gainesville: University Press of Florida; 2010.
86. Lundberg ER, Righter E. Ceramic Style Definition and Refinement: Late Saladoid Changes in the Virgin Passage Area. Seventeenth Congress of the International Association for Caribbean Archaeology. NY: Molloy College; 1999.

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