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HOLOCENE TUFA-COATED SERPULID MOUNDS FROM THE DOMINICAN REPUBLIC: DEPOSITIONAL AND DIAGENETIC HISTORY, WITH COMPARISON TO MODERN SERPULID AGGREGATES FROM BAFFIN BAY, TEXAS

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ABSTRACT

Late mid-Holocene calcareous serpulid worm-tube aggregates form mounds of up to 2 m in height along the paleo-shoreline of Lago Enriquillo in southwestern Dominican Republic. This hypersaline lake was formed by the cutoff of a reentrant from the Caribbean Sea and its evaporation to a position of about 40 meters below present sea level. Many of the serpulid mounds are coated with a layer of porous carbonate tufa up to 20 cm thick.

Examination of modern serpulid reefs from Baffin Bay, a hypersaline lagoon on the southern coast of Texas, suggests that serpulid aggregates form under extremely variable environmental conditions, which eliminate competing species and allow the euryhaline serpulids to flourish. Stable isotope results indicate that serpulids secrete tubes from waters of variable salinity, but most of the aggregates form under more narrowly defined, optimal (hyposaline?) conditions. In the Dominican example, such conditions may have been established by freshwater input into Lago Enriquillo. The distribution and morphology of serpulid mounds were controlled by lake bathymetry and water depth. The development of tall mounds was precluded on the gentle slopes of shallow nearshore environments, where low-relief aggregates formed instead.

Well-preserved cyanobacterial filaments indicate a microbial influence on the precipitation of tufa coatings on the serpulid mounds. Stable isotopes suggest that tufa precipitation and serpulid aggregate formation occurred under similar conditions. With decreasing lake levels serpulid mounds provided suitable substrates for tufa precipitation near the water surface. Evaporation of Lago Enriquillo ended tufa precipitation and exposed the tufa-coated serpulid mounds. Localized dissolution produced truncational surfaces on the tufa precipitates. Thin iron-oxide rims coat these surfaces and hematitic micrite is found inside dissolution-enlarged void spaces. The remaining porosity is partially infilled with peloidal and skeletal sediment produced by the breakdown of tufa and associated gastropods.

In the 16th century, Taino Indians carved petroglyphs in the porous tufa substrate. Preservation of the tufa substrate and these unique and well-preserved petroglyphs is enhanced by the semi-arid climate in the area today.

INTRODUCTION

Serpulids are sessile polychaete annelids that secrete tubes made of calcium carbonate. Serpulids are very common as encrusters in a variety of marine and marginal marine environments. Large aggregates of serpulid tubes, on the other hand, are quite rare (Ten Hove and Van den Hurk, 1993). To better understand the conditions under which such serpulid aggregates form, this study focused on the large and exceptionally well-developed late mid-Holocene serpulid mounds from the Enriquillo Valley in the southwestern Dominican Republic. The exteriors of these mounds are coated with calcareous tufa precipitate that Taino Indians used as a substrate to carve petroglyphys. To gain additional insights into the origin and history of these unusual serpulid structures, we also examined modern counterparts from Baffin Bay, Texas.

This paper presents a brief overview of the geographic and geological settings of serpulid aggregates in the Dominican Republic and Baffin Bay. The origin of serpulid aggregates in Baffin Bay is discussed and a comparison is made to the Dominican examples. This comparison, in conjunction with the field, petrographic, and stable isotope evidence is used to interpret the depositional and diagenetic history of serpulid mounds and tufa coatings in the Dominican Republic. The results provide unique insights into the formation of these exceptional structures and contribute to our understanding of the dynamic environmental changes that this area underwent during mid- to late-Holocene time.

STUDY SITES AND SERPULID AGGREGATE DESCRIPTIONS

The Dominican Republic

The Dominican Republic is located on the Caribbean island of Hispaniola that hosts two countries: Haiti to the west and the Dominican Republic to the east (Figure 1A). The study area is located around Lago Enriquillo in the Enriquillo Valley of the southwestern part of the Dominican Republic (Figure 1B). Lago (Lake) Enriquillo is in the northwestern part of the Enriquillo Valley, which is a fault-bound valley surrounded by Cenozoic sedimentary rocks (Lewis et al., 1990). Additional information about the geographic and geologic history of this area can be found in Guerard et al. (this volume).

The present-day Lago Enriquillo is a hypersaline lake that formed when a seaway that extended northwestwards from Bahia de Neiba was cutoff from the Caribbean Sea and evaporated to a position of about 40 meters below present sea level (Figure 1). This cutoff was caused by the accumulation of large amounts of sediment at the mouth of the seaway by the Rio Yaque del Sur (Figure 1B) during the rise of base level in response to Holocene sea-level rise (Mann et al., 1984; Taylor et al., 1985). The Rio Yaque del Sur drains a large mountainous area to the north and northwest and is currently discharging into the Caribbean Sea (Figure 1B). Meander scars in the large alluvial plain between Lago Enriquillo and Bahia de Neiba (Figure 1B) indicate that the course of Rio Yaque del Sur has been variable in the past, and that the river was periodically discharging into the lake (Mann et al., 1984).

A fringing coral reef that had flourished along the margins of the seaway ceased to grow approximately 4,000 years before present when the cutoff from the sea occurred (Mann et al., 1984; Taylor et al., 1985; Greer and Swart, 1999; Greer, 2001; Guerard, 2001; Guerard et al., this volume). In the late mid-Holocene (4,500 to 2,500 years before present), following the cutoff of the seaway and the demise of the coral reef, calcareous serpulid worm-tube aggregates formed mounds atop the coral-reef sequence and on other substrates along the paleo-shoreline (Mann et al., 1984; Curran and Greer, 1998). These aggregates are now located from ~5 m below to ~3 m above present sea level and were examined at four sites around Lago Enriquillo (Figure 1B).

Serpulid mounds form a rim that marks the paleo-shoreline position along the steep, rocky northern slopes of the Enriquillo Valley composed of Miocene limestones (Figure 2A). Here the mounds commonly form impressive, two-tiered structures (Figure 2A). On flat terraces and

A)

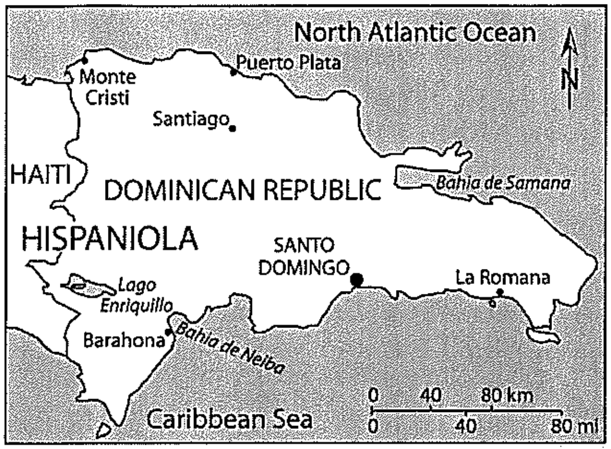
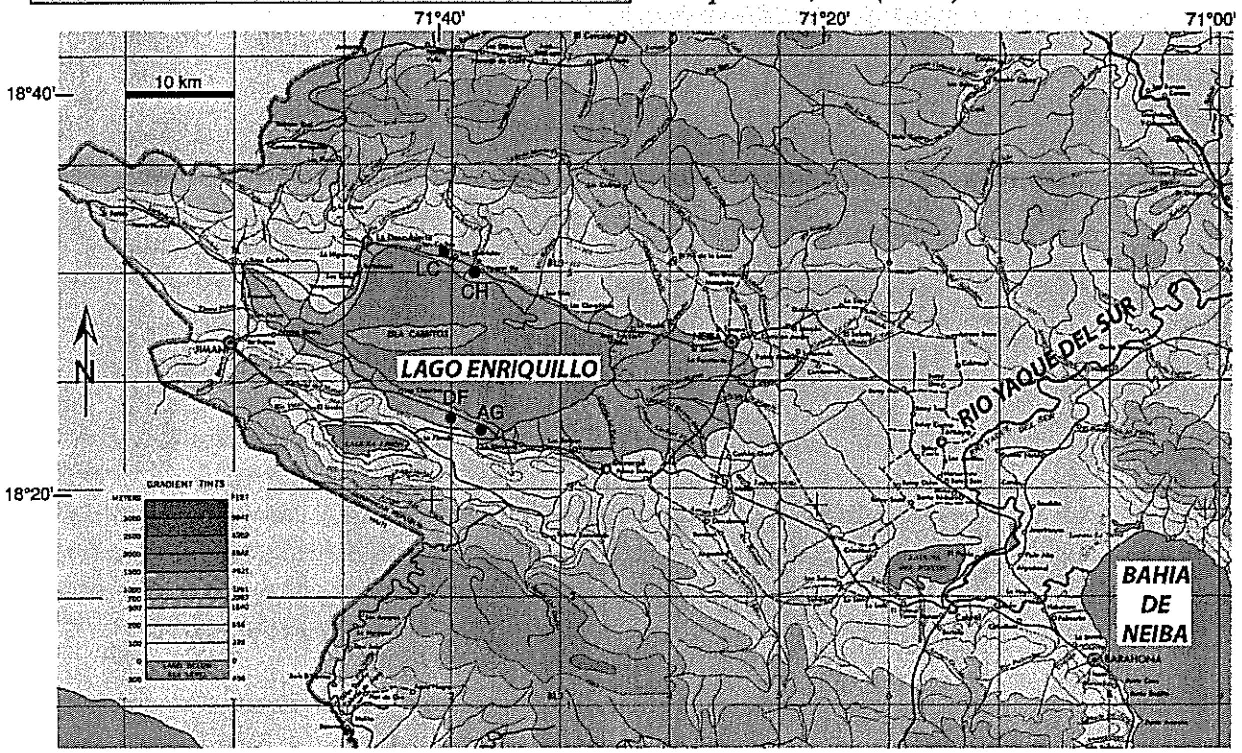


Figure 1. Maps of the study area in the Dominican Republic. A) Location of the Dominican Republic on the island of Hispaniola in the Caribbean Sea. The study sites are around Lago Enriquillo in the SW part of the country. B) Map of the Enriquillo Valley showing the locations of four study sites: LC-Las Caritas; CH-Cañada Honda; AG-Abuela Grande; DF-Devil's Furnace. Note the location of the Rio Yaque del Sur between Lago Enriquillo and Bahia de Neiba. Modified from the Dominican Republic Road Map 1:250,000 (1961).

B)



slightly more gentle northern slopes, the serpulid aggregates form large isolated hemispherical mounds and smaller more irregular mounds with knobby exteriors and some with a characteristic organ-pipe structure (Figures 2B,C; see also Figure 7 in Guerard et al., this volume). These mounds are coated with porous calcareous tufa.

Similar irregular mounds also formed on top of the coral reef and other beach and nearshore carbonate substrates along the gentle southern slopes of the valley (Figure 3). Upslope from such mounds, on very gently sloping surfaces, serpulid aggregates form laterally extensive fields of up to 10 cm tall, low-relief mounds (Figure 3). These mounds have weathered outer surfaces and no macroscopic evidence for tufa coatings.

Fresh mound surfaces reveal serpulid aggregates composed of intertwined, curved, randomly oriented tubes (Figure 4A). These tubes consist of low-Mg calcite, range from ~0.5 to 1.5 mm in diameter, and reach up to 2 cm in length (Figure 4B). The tubes have a variety of shapes, some with thick ridges that may represent periods of stunted growth (Figure 4B). In thin section, serpulids are recognized by their characteristic circular to elliptical cross sections surrounded by porous micritic, microsparitic and peloidal carbonate sediment (Figure 4C).

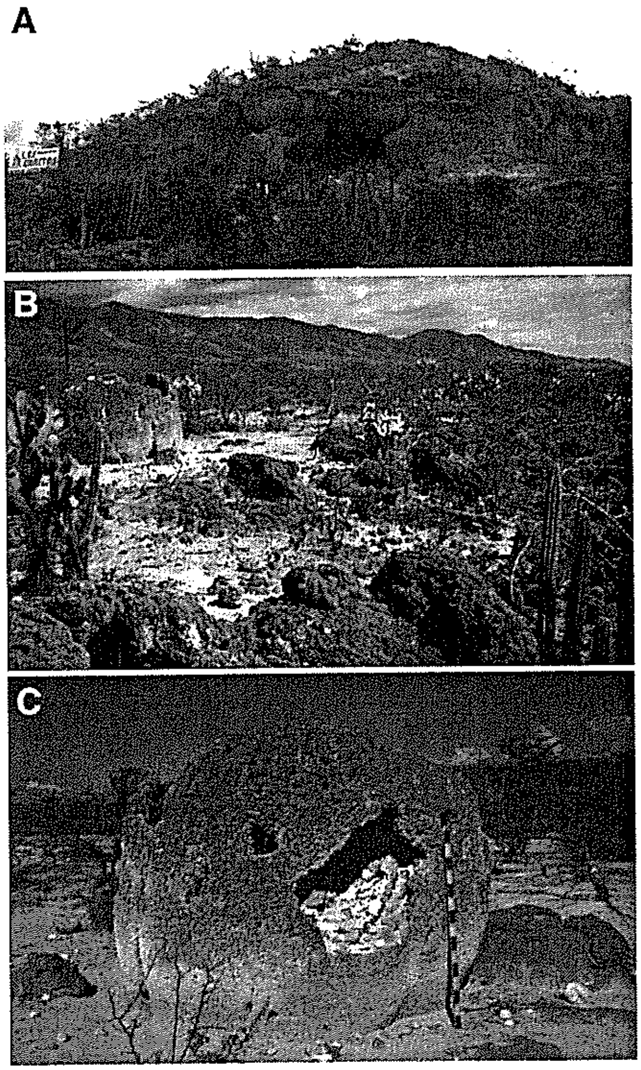
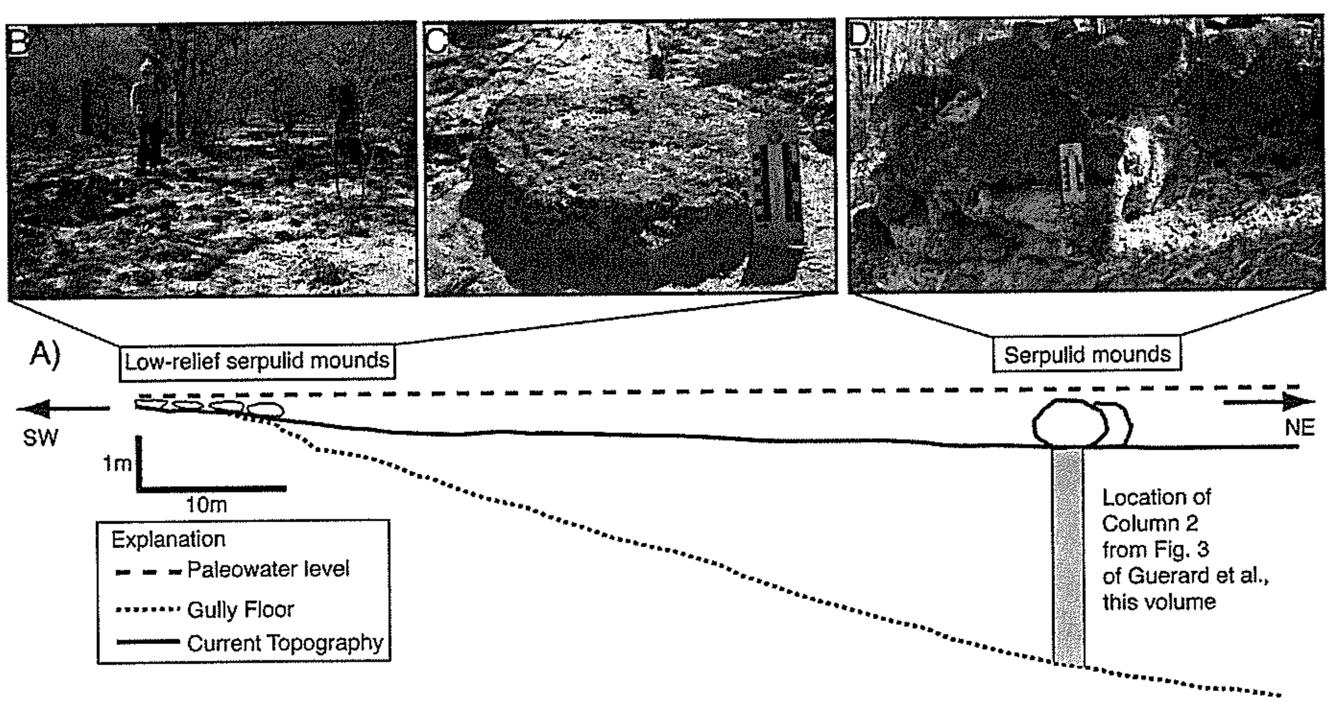


Figure 2 (left). Examples of serpulid mounds along the northern slopes of Enriquillo Valley. A) Two-tiered structures at the Las Caritas locality. Individual mounds are up to 2 m tall. B) A 2 m tall, hemispherical mound on a flat terrace (left) and many smaller irregular mounds on a gentle slope (center front and to the right) at the Cañada Honda locality. C) Close-up of the hemispherical mound shown in 3B. Jacob's staff = 1.5 m.

Figure 3 (below). Examples of serpulid mounds along the gentle southern slopes of Enriquillo Valley. A) Schematic sketch of the gully at the Abuela Grande locality that exposes the coral reef succession topped by serpulid mounds (see Guerard et al., this volume). B and C) Fields of low-relief serpulid mounds upslope from poorly developed irregular mounds on the coral rubble substrate (D). Photoscale = 16.5 cm.



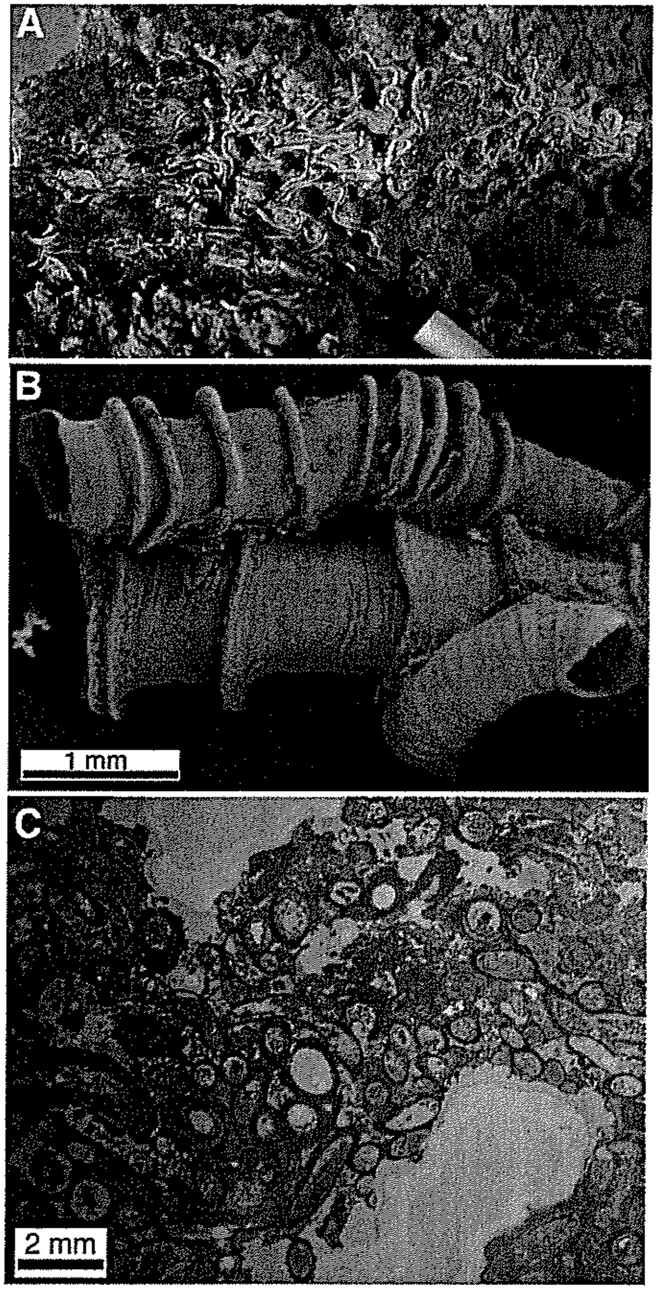


Figure 4. Photographs of serpulid tubes from the Dominican Republic. A) Aggregate of curved, intertwined serpulid tubes. B) SEM photograph showing a variety of serpulid tube shapes. C) Photomicrograph of serpulid aggregate showing circular to elliptical serpulid tubes surrounded by porous micritic, microsparitic and peloidal carbonate sediment.

Baffin Bay, Texas

Baffin Bay is the southernmost bay along the Texas Gulf coast (Figure 5A). The bay is connected to a backbarrier lagoon—Laguna Madre—and is separated from the Gulf of Mexico by a large barrier island—Padre Island (Figure 5B). The Baffin Bay/Laguna Madre system is the only major hypersaline lagoon in the semi-arid regions of the United States (Zheng, 1963). The bay has a small tidal range (approximately 15 cm), average water depth of about 1.5 m, and water temperatures that range from 10° to 30°C (Behrens, 1973). The restricted water circulation, combined with high evaporation and warm air temperatures, results in average salinities of 40-60 ‰ although a salinity range of 0-100 ‰ has been recorded (Breuer, 1957).

Serpulid aggregates occur in waters about 0.5 to 2.5 m deep and are rarely exposed at low tide (Andrews, 1964). Previous radiocarbon dating suggests that serpulid reef growth occurred at approximately 3,000 years before present and again within the past 300 years (Behrens, 1973). The aggregates form patch reefs at the mouth of the bay and larger reef fields within the bay (Andrews, 1964). This study examined three reef-field sites with completely submerged serpulid aggregates and one partially exposed patch reef (Figure 4B).

The examined serpulid patch reef is semi-elliptical in shape, covers an area of about 5 x 10 m, and is elongated approximately north to south (Figure 6A). This patch reef consists of numerous irregularly shaped serpulid aggregates surrounded by water 1-1.5 m deep and is similar to examples described in detail by Andrews (1964). He measured water depths of 0.5-1 m around patch reefs and noted that these reefs were commonly exposed 30-40 cm above the water surface in neap tides and 10-15 cm at normal water levels. Andrews (1964) described these patch reefs as small isolated masses that vary in outline from simple circular forms 7.5 m in diameter to ellipsoidal forms reaching 40 m in length.

The examined reef-field sites (Figure 5B) are also similar to those of Andrews (1964), who waded in the bay to describe the characteristic size and shape of these completely submerged serpulid aggreggates. According to his descriptions, reef fields are composed of small areas of reef rock up to 4.5 m in diameter separated by areas of sandy

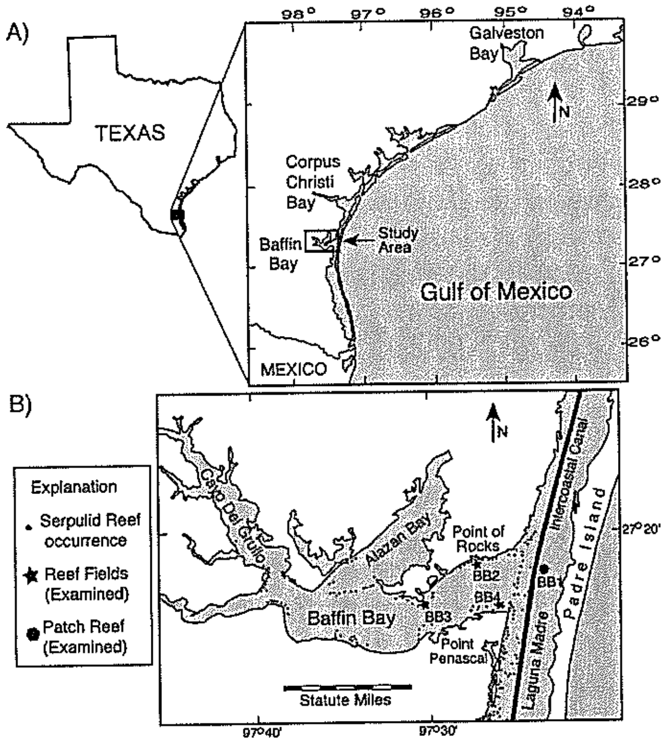


Figure 5. Maps of the study area in south Texas. A) Location of Baffin Bay along the Gulf coast. B) Map of the Baffin Bay area showing the distribution of serpulid aggregates or reefs documented by Andrews (1964), and the location of the three reef-field sites and one patch-reef site examined in this study (modified after Andrews, 1964).

bottom. Reef fields occur as large expanses of scattered reef rock up to 45 x 90 m in size and projecting 30-45 cm above the substrate in water depths averaging 1 m (Andrews, 1964).

Our field observations focused on the largest and best exposed portion of the serpulid patch reef, which reaches about 40 cm above water level and is about 1 m long and 0.7 m wide (Figure 6A). The serpulid patch reefs at Baffin Bay are unique in that they have an alternating stratification of random and oriented tube growth patterns (Figure 6B; Andrews, 1964). In contrast, serpulid aggregates forming reef fields exhibit only random growth patterns. Oriented aggregates are made up of nearly straight, vertical serpulid tubes that range from 0.7 to 3 cm in length and have an average diameter of 1-2 mm (Figure 6C). These tubes are made of aragonite. The serpulid tubes have concentric ridges of low relief on the outer surfaces and have a tube-wall thickness of approx-

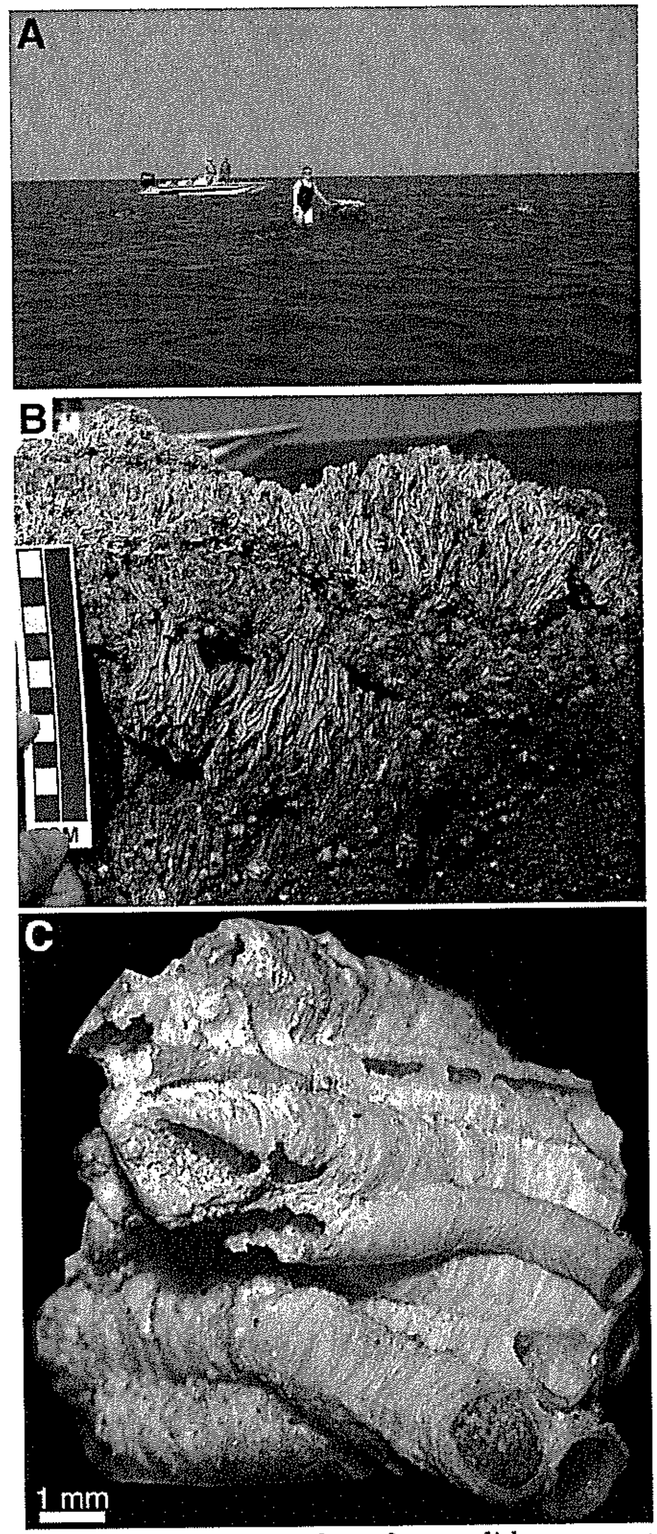


Figure 6. Photographs of serpulid aggregates from Baffin Bay, Texas. A) Partially exposed patch reef, reaching up to 40 cm above the water level. B) Close-up of the exposed patch reef showing stratification pattern of alternating vertically oriented and random serpulid tubes. C) Aragonitic serpulid tubes from Baffin Bay.

imately 0.2-0.3 mm (Figure 6C). Randomly oriented aggregates consist of sinuous, curved, and tightly intertwined serpulid tubes. Like oriented tubes, they are aragonitic in composition and commonly have low relief outer rings. Generally, these serpulid tubes are smaller than those forming oriented aggregates.

The first documentation of living serpulids in the area was by Cole (1981) who reported that *Hydroides dianthus* was well established in the reef structure. Local fishermen, aware of reef distribution for navigational reasons, believe that the reefs are currently growing (pers. comm., 2001). Our field observations in October 2001 revealed several polychaete worms within the serpulid aggregates, but the species was not identified. Serpulid tubes examined were largely empty (or filled with sediment), and the submerged portions of the reefs were heavily encrusted by barnacles and algae. Thus, the examined serpulid reefs did not appear to be actively growing.

STABLE ISOTOPE ANALYSIS OF SERPULID AGGREGATES

Methods

Samples for stable isotope analysis were collected by breaking individual tubes from the serpulid-aggregate samples. The tubes were cleaned by ultrasound to remove any loose sediment. Tube material was picked under a binocular microscope, crushed with an agate mortar and pestle, and selected for XRD analysis prior to roasting. Powdered, roasted samples were dissolved in 100% H_3PO_4 at 70°C for 5 minutes using an on-line automated carbonate preparation system (Kiell III) linked to a Finnigan-MAT DeltaXL+ ratio mass spectrometer. Standard isobaric and phosphoric acid fractionation corrections were applied and precision was monitored through daily analysis of a variety of carbonate standards. Internal analytical precision was maintained at 0.10‰ for $\delta^{18}O$ and 0.06‰ for $\delta^{13}C$. All results are reported in permil (‰) relative to the Vienna Peedee belemnite standard (VPDB).

Results

Samples of individual aragonitic serpulid tubes were collected from (1) aggregates of oriented and random tubes from the patch reef; and (2) random serpulid aggregates from two reef field sites (Figure 7). Isotopic compositions of oriented tubes from the patch reef vary substantially: the $\delta^{18}O$ values range from about –5.0 to +0.6 ‰, and their $\delta^{13}C$ values are between –4.1 and –0.3 ‰ (Figure 7). The most negative $\delta^{18}O$ values (about –5 to –3 ‰) correspond with serpulid tubes from the base of layers with oriented tube patterns, whereas many of the data points with the most positive $\delta^{18}O$ and $\delta^{13}C$ values (>–1 ‰) represent oriented tubes from the uppermost parts of these layers. There is also significant variation between segments of individual tubes analyzed, and their values do not seem to define any obvious trends (Figure 7). Samples of random tubes from the patch reef and the reef fields show a substantial overlap and have a narrower range of $\delta^{18}O$ values (about –2 to +0.5 ‰) than oriented serpulid tubes, while their $\delta^{13}C$ values show a similar scatter (ranging from –4.7 to –0.8 ‰; Figure 7).

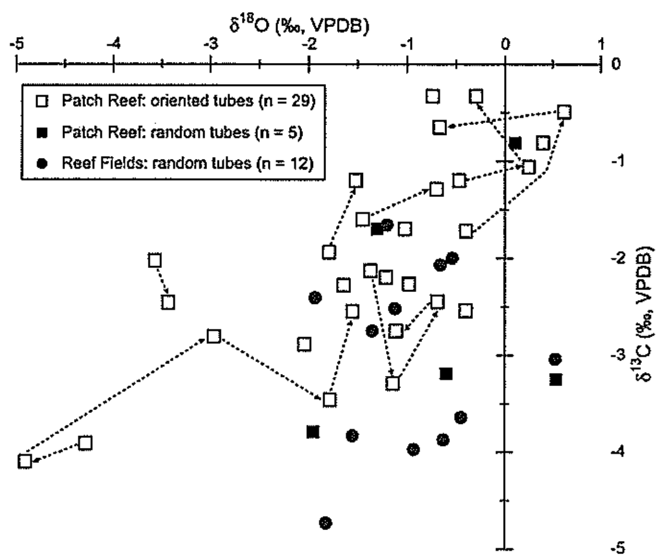


Figure 7. Stable isotope compositions of serpulid tubes from Baffin Bay. Data points representing segments of individual tubes analyzed are connected with dashed arrows in the direction of tube growth.

Interpretations and Implications

Previous stable isotope studies suggest that serpulids secrete tubes with $\delta^{18}O$ values in equilibrium with the surrounding seawater, but their $\delta^{13}C$ values may deviate by about –7 to –4 ‰ from equilibrium due to vital effects (Veizer, 1983; Videtich, 1986; Wefer and Berger, 1991). The large range of isotopic compositions of oriented serpulid aggregates in patch reefs of Baffin Bay suggests that growth of oriented tubes occurs under a variety of environmental conditions (Figure 7). The most negative stable isotope values likely reflect decreased salinity and possibly also an increased input of terrestrially derived organic carbon during episodes of increased freshwater discharge into the bay. The fact that the most negative $\delta^{18}O$ values in the suite of samples analyzed represent serpulid tubes from the lower part of oriented layers suggests that initiation of oriented growth may be promoted by episodes of decreased water salinity in this otherwise hypersaline lagoonal area.

There is a general trend of increasing $\delta^{18}O$ and $\delta^{13}C$ values upward within the oriented layers. This may reflect the increased residence time of bay waters during which they become enriched in ^{18}O by evaporation and enriched in ^{13}C by progressive removal of ^{12}C by organisms. Variable isotopic compositions of individual tube segments (Figure 7) also indicate varying environmental conditions during tube secretion. A maximum measured length of an individual tube of ~30 mm may represent between 150 and 300 days of growth, assuming growth rates of 0.1 and 0.2 mm/day (Behrens, 1968). Thus, the differences in isotope composition of individual serpulid tube segments likely reflect annual seasonal variations in water temperature, salinity, and organic productivity within the bay.

The overlapping isotopic compositions of random tubes from the patch reef and the reef fields suggest very similar conditions during serpulid growth, which is also suggested by the similar appearance of these aggregates. In comparison with serpulid tubes from oriented aggregates, the relatively narrow range of $\delta^{18}O$ values of randomly oriented tubes indicates lower variability of water composition or temperature during their formation (Figure 7). The rather large scatter in $\delta^{13}C$, on the other hand, may indicate variable terrestrial carbon input, organic productivity rates, and/or vital effect. It has been proposed that random tubes form by the rapid (1.5 to 2.5 mm/day) growth of serpulids early in their life cycle (Behrens, 1968). Thus, individual tubes from these aggregates may have been secreted during rather short time periods (less than 2 or 3 weeks) during which environmental conditions did not vary as significantly as during the growth of longer oriented tubes. Additionally, the relatively narrow range of $\delta^{18}O$ values may indicate that initiation of rapid growth of randomly oriented tubes may occur during specific times of the year (on an annual or seasonal cycle) during optimal water salinity and temperature conditions.

The Dominican Republic

Results

All serpulid tubes from aggregates in the Dominican Republic are randomly oriented. The stable isotope study focused on the comparison between serpulid tubes encrusted on corals from the underlying coral reef succession at the Abuela Grande locality (units 1-2 and 4-5 from column 2 on Figure 3 in Guerard et al., this volume) and tubes from a serpulid layer interbedded within the coral reef at Abuela Grande (unit 3, column 2, Figure 3 in Guerard et al., this volume), with those from the overlying serpulid mounds (unit 6, column 2, Figure 3 in Guerard et al., this volume) from this and other localities (Figure 8). Serpulid tubes encrusted on corals have some of the most positive $\delta^{18}O$ and $\delta^{13}C$ values in the suite of samples analyzed. All other samples are substantially depleted in ^{13}C (~ –5.5 to –2.0 ‰), and are also depleted in ^{18}O (~ –10.5 to 0 ‰; Figure 8).

Comparison with Baffin Bay

The demise of the fringing coral reef and initiation of serpulid aggregate formation in the Dominican Republic occurred during the restriction of marine influence in the area (Mann et al., 1984; Taylor et al., 1985; Greer and Swart, 1999; Greer, 2001; Guerard, 2001; Guerard et al., this

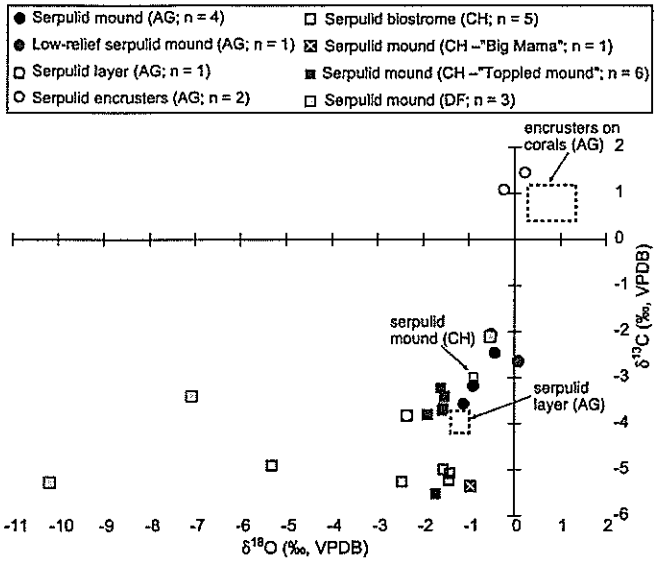


Figure 8. Stable isotope compositions of serpulid tubes from the Dominican Republic. A comparison with data reported on Figure 9 in Guerard et al. (this volume) is shown with dashed fields. See Figure 1B for the location of study sites (CH-Cañada Honda; AG-Abuela Grande; DF-Devil's Furnace) and Figure 3 for details on serpulid mound distribution at Abuela Grande.

volume). The resulting variable water salinity conditions may have been similar to those within Baffin Bay today. Despite this, differences in isotopic compositions of serpulid tubes from the Dominican Republic and Baffin Bay were expected because these tubes are composed of different carbonate mineralogies (low-Mg calcite and aragonite, respectively), occur in different geological and geographical settings, are of different age, and were likely formed by different serpulid species. The isotope values of the serpulid aggregates from these two localities, however, show a significant overlap (Figure 9). The majority of serpulid tubes have their $\delta^{18}O$ values between about –2 and 0 ‰, which likely reflect optimal salinity and temperature conditions for serpulid growth and aggregate formation. The $\delta^{18}O$ values above 0 ‰ may reflect serpulid tube secretion from waters that experienced more evaporation, whereas more negative values (about –10 to –3 ‰) indicate increased freshwater influence, potentially coupled with temperature increase. The wide range of $\delta^{18}O$ values supports the euryhaline nature of serpulids, but the clustering of data suggests that there may be an optimum range of conditions for serpulid growth (Figure 9).

Other Interpretations and Implications

Isotopic compositions of serpulid tubes encrusted on corals from the Dominican Republic are interpreted to represent normal marine conditions (Figure 8; see also Guerard et al., this volume). The pronounced difference of about 3‰ between the $\delta^{13}C$ values of tubes encrusting on corals and those from the serpulid layer within the coral reef succession at Abuela Grande as well as tubes from mound-building aggregates is significant, as it likely reflects increased input of terrestrially derived carbon depleted in ^{13}C to the waters in which serpulid aggregates were forming. The associated decrease in the $\delta^{18}O$ values (<–0.5‰) supports the increased input of terrestrial carbon, which may be related to the increased influx of freshwater. This is in agreement with interpretations by Guerard et al. (this volume) that the serpulid layer in the coral reef sequence at Abuela Grande and all of the serpulid aggregates from the Enriquillo Valley formed in waters of lower salinity than normal marine water. This conclusion is supported by the association of serpulids with other euryhaline microfossils (Guerard, 2001; Guerard et al., this volume).

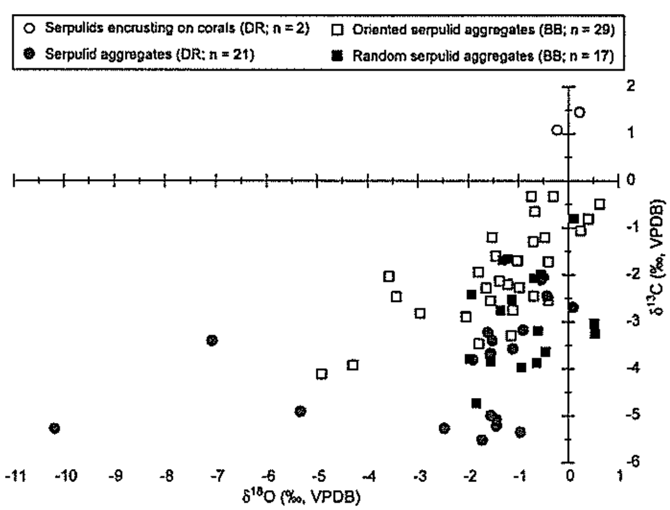


Figure 9. Comparison of stable isotope compositions of serpulid tubes from Baffin Bay (BB) and the Dominican Republic (DR).

The most negative $\delta^{18}O$ values measured in the two serpulid aggregate samples from the Devil's Furnace locality (–10.2 and –7.1 ‰) and from one sample at the Cañada Honda locality (–5.3 ‰), likely reflect serpulid growth from freshwater that had experienced very little or no evaporation or mixing with marine or lake water. The ^{18}O depletion may have been augmented by elevated temperatures during tube secretion. Temperature increase alone cannot account for these highly negative $\delta^{18}O$ values, and direct rainfall into the water could not have produced such a great shift because $\delta^{18}O$ values of meteoric waters in coastal areas at such low latitudes (18°) are only slightly lower (-3 to -2 ‰ SMOW) than those of seawater (0 ‰ SMOW; Bowen and Wilkinson, 2002). It is possible that heavy rainfall in the mountains further inland may have caused large amounts of isotopically depleted waters to be periodically discharged by rivers and streams into the Enriquillo Valley. The largest river in the area, the Rio Yaque del Sur, was most likely the greatest contributor of both ^{18}O and ^{13}C-depleted water during time periods when it was discharging into the Enriquillo Valley (Figure 1B). This discharge was most likely crucial for maintaining hyposaline conditions and high nutrient levels for serpulid growth during the closure of the Enriquillo seaway and in raising the Lago Enriquillo level above present day sea level upon the complete cutoff of the seaway as suggested by the elevation of the serpulid mounds.

A sample from the low relief mound at the Abuela Grande locality (Figure 3) is an exception to the general ^{18}O depletion in tubes from serpulid aggregates. The $\delta^{18}O$ value of this sample is similar to that of the coral-encrusting serpulid tubes (Figure 8). This sample came from the gentle slope to the south of the lake where serpulid aggregates formed small, poorly developed mounds downslope and expansive low relief mats upslope (Figure 3). The gentle topography at this locality resulted in laterally extensive and restricted shallow water areas that were subjected to increased evaporation. This is substantiated by the $\delta^{18}O$ value of serpulid tubes from the low-relief mound upslope at the Abuela Grande locality, which is slightly more positive than serpulids from the larger mound downslope, and in fact represents the most positive $\delta^{18}O$ value of all serpulid aggregates examined (Figure 8).

TUFA COATING ON SERPULID MOUNDS IN THE DOMINICAN REPUBLIC

Description

Most of the serpulid mounds from the Dominican Republic (except those from the Abuela Grande locality; Figure 3) are coated by porous tufa precipitate (Figure 10). The most extensive (up to 20 cm thick) tufa coatings are found on the tall mounds that formed along the steep northern slopes of the valley. Weathering produces a very brittle texture and grayish appearance of the tufa (Figure 10A). Fresh tufa is light brown in color, and it commonly has a sharp contact with the serpulid mound interior (Figure 10B). Up to 5 cm thick tufa also coats the steep northern rocky slopes to about 3 meters above the serpulid mounds (Figure 11).

Thin sections of tufa precipitated on serpulid mounds reveal circular outlines of serpulid tubes (commonly truncated), gastropods, and the characteristic porous, patchy texture of micritic to microsparitic tufa carbonate (Figure 12A). A common component of tufa is elongated, radial, microsparitic aggregates with well preserved, cyanobacterial filaments (Figure 12B). Associated with these aggregates are gastropods, many of which are hydrobiids (Curran and Greer, 1998; Guerard, 2001; Guerard et al., this volume). Cyanobacterial aggregates are commonly truncated and coated with thin iron-oxide crusts (Figure 12B). Iron-oxide-rich micrite is found in many of the dissolution-enlarged voids and is characterized by the presence of irregular microfractures and rare *Microcodium*. Poorly lithified peloidal and skeletal sediment infills the pores in the tufa precipitate and the underlying serpulid aggregates (Figure 12B).

Stable Isotope Analysis

Stable isotope values of tufa are expected to reflect the composition of the ambient waters from which the tufa precipitated (Das and Moanti,

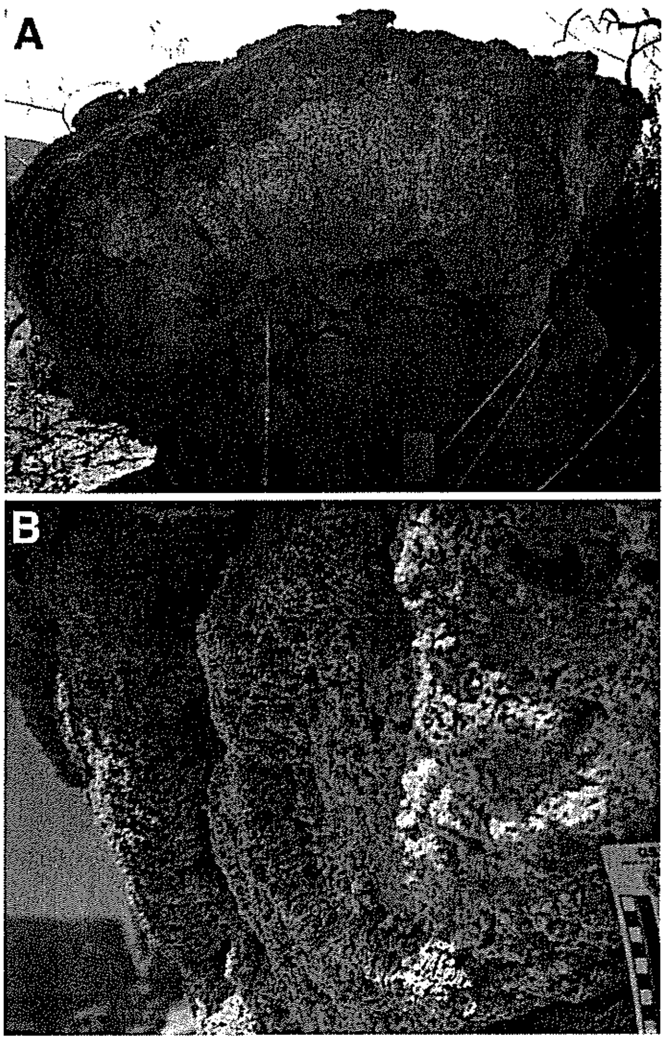


Figure 10. Tufa coatings on serpulid mound exteriors. A) Dark exterior coating of weathered tufa on a serpulid mound from the Devil's Furnace locality. Notebook for scale is 19 cm tall. B) Fresh tufa coatings on serpulid mounds at the Las Caritas locality. Note sharp contact with the mound interior. Scale is in cms.

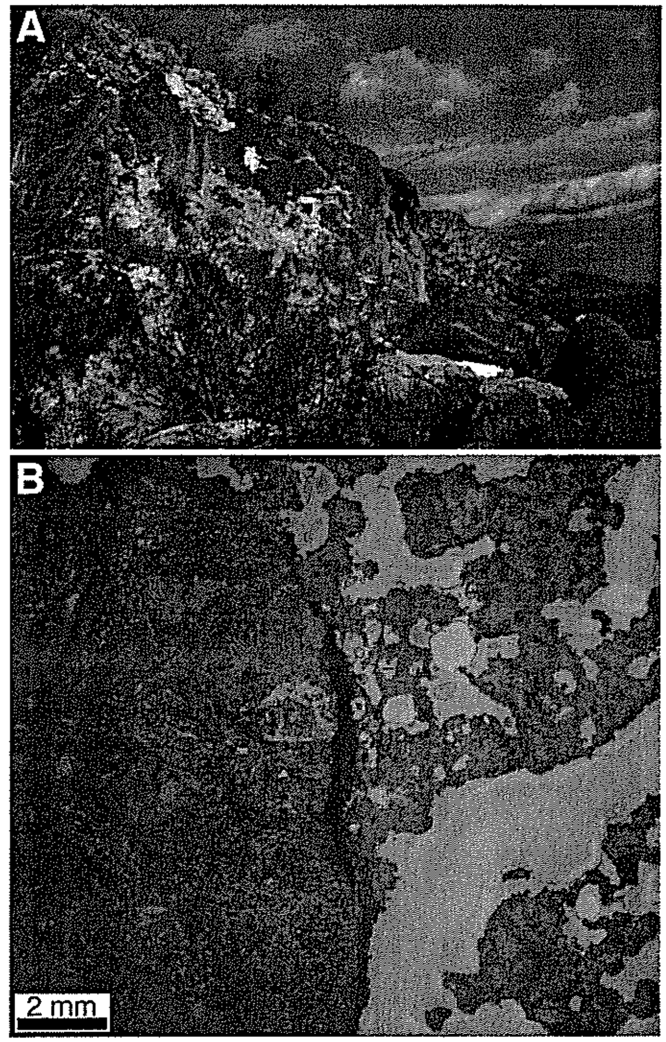


Figure 11. Photographs of tufa coatings on Miocene bedrock on the steep northern slopes. A) At the Las Caritas locality tufa coating is present about 3 m above the top of the highest serpulid mound (pinnacle in the lower right corner). B) Photomicrograph of porous tufa (on the right) coating the bedrock (on the left; foraminiferal-algal wackestone-packstone). The contact between tufa and bedrock is marked by a thin coating of iron oxide. Tufa precipitate has a very porous, patchy texture composed of micritic to microsparitic carbonate.

1997). The processes that promote tufa precipitation, including cyanobacterial calcification (Riding, 2000), although organically influenced, conform to the rules of inorganic carbonate equilibrium chemistry (Andrews et al., 1993).

Stable isotope compositions of low-Mg calcite from the tufa precipitate were analyzed and compared to those of serpulid tubes and other associated carbonate components (Figure 13). These include laminated travertine precipitate at the contact between the bedrock and the serpulid mounds at the Las Caritas locality, micritic and microsparitic matrix between serpulid tubes, rare thin calcareous (caliche) crusts within the serpulid mounds, and hematitic micrite associated with tufa (Figure 13). The $\delta^{18}O$ values of these components are similar to or are slightly more positive than those of the serpulid tubes, with most of the values clustering between about –2 and 0 ‰ (Figure 13). Exceptions are the two tufa samples from the Devil's Furnace locality, which have substan

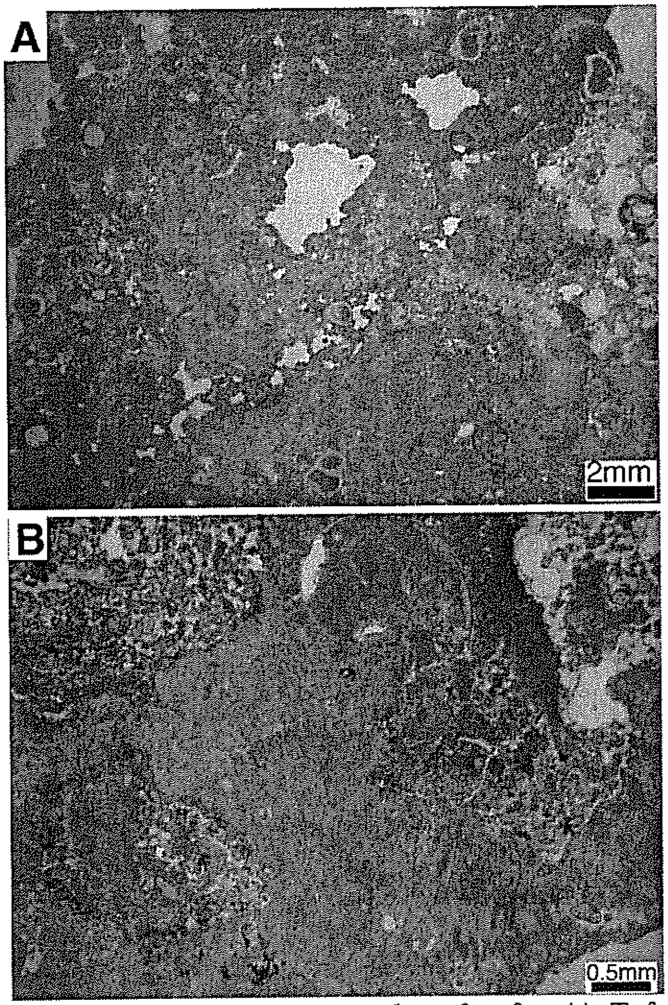


Figure 12. Photomicrographs of tufa. A) Tufa precipitated on serpulids showing truncated, circular outlines of serpulids, gastropods, and the characteristic porous patchy tufa texture. B) Radial aggregates of cyanobacterial filaments with one large gastropod (upper center). Thin iron-oxide rim coats truncated cyanobacterial aggregates. The space between aggregates is filled with fractured hematitic micrite and poorly lithified peloidal and skeletal sediment.

tially more negative $\delta^{18}O$ values (Figure 13). The $\delta^{13}C$ values of these various carbonate components, on the other hand, are significantly more positive than those of serpulid aggregate tubes, ranging from about –1.5 to +4 ‰ (Figure 13). Detailed discussion of all these components and the significance of their isotopic compositions, however, is beyond the scope of this paper.

Tufa as a Substrate for Taino Petroglyphs

The porous tufa coatings on the serpulid mounds served as a very unusual, but highly suitable substrate for the carving of Taino Indian petroglyphs (Berrios, 2002; Berrios et al., 2002). The petroglyphs are representations of Taino deities and human faces, some with artistic characteristics and elaborate facial expression (Figure 14). Depth of petroglyph carvings is proportional to the thickness of the porous tufa substrate and reaches up to 10-11 cm. The largest petroglyphs are up to 50 cm in diameter. Carved surfaces are reddish brown in color, similar to the surrounding tufa substrate. Modern graffiti made in this substrate reveal the light gray to brown color of freshly exposed tufa, permitting a distinction between authentic Taino carvings and contemporary imitations (Berrios et al., 2002)

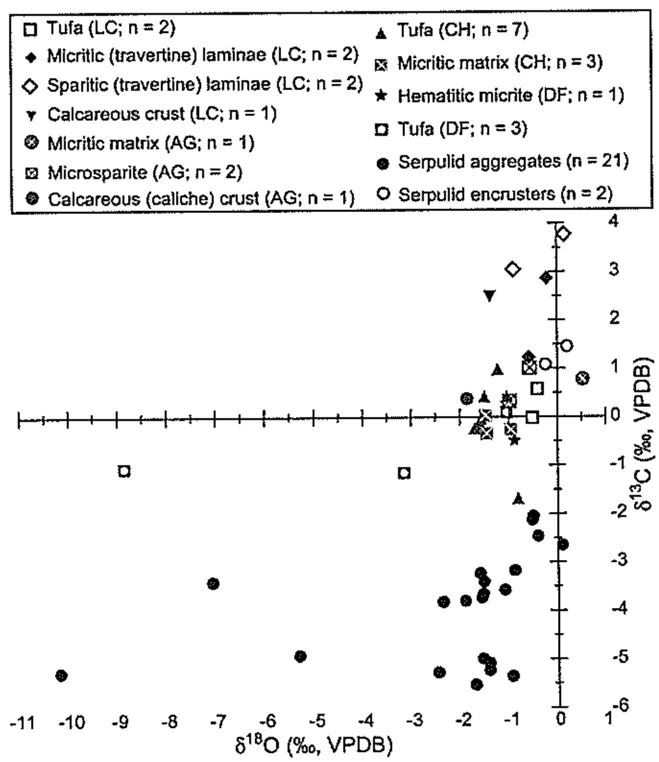


Figure 13. Stable isotope composition of tufa and various associated carbonate components from the Dominican Republic. Study sites: LC-Las Caritas; CH-Cañada Honda; AG-Abuela Grande; DF-Devil's Furnace (see Figure 1B).

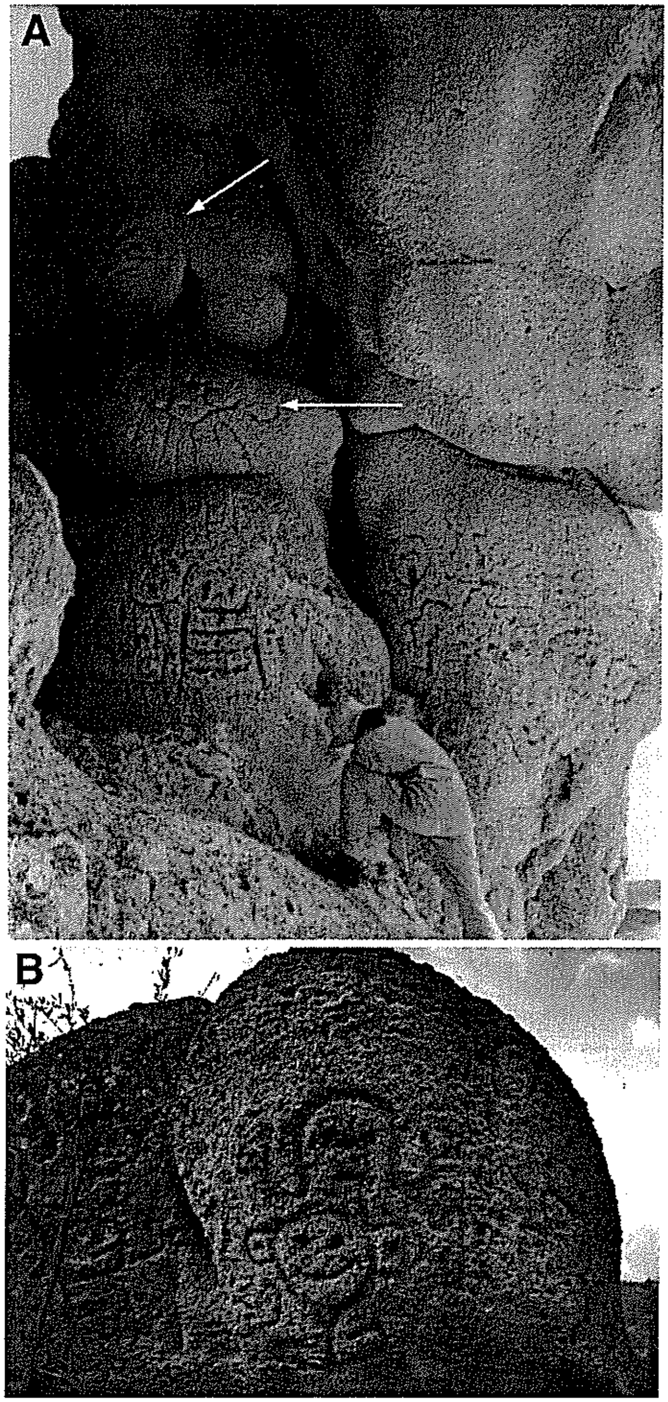


Figure 14. Taino Indian petroglyphs. A) Large concentration of carvings in the thick tufa precipitate on spectacular serpulid mounds at the Las Caritas locality. Even though most carvings represent faces (B) some resemble objects such as a sun and heart (arrows). The diameter of the carved face in B is 50 cm.

Interpretations

Aggregates of filaments indicate that tufa precipitation was induced or mediated by photosynthetic cyanobacteria in very shallow waters (Figure 12B). It is possible that patchy, peloidal micrite surrounding these cyanobacterial aggregates is a product of carbonate precipitation by heterotrophic bacteria commonly associated with cyanobacteria (Chafetz, 1986; Riding, 2000; 2002). Thus, precipitation of tufa at an elevation about 3 meters above the tallest serpulid mounds (or about 5 meters above present sea level) indicates the paleowater level at or just below the highest tufa occurrence, with precipitation in the most shallow water and in the splash zone (Figure 11A). The increased Lago Enriquillo level likely reflects the input of freshwater during discharge of the Rio Yaque del Sur into the newly formed lake (Figure 1B). Precipitation of tufa under hyposaline conditions is supported by the association with the gastropods *Littoridinops monroensis*, which have been identified as a brackish/ freshwater hydrobiid species (Curran and Greer, 1998; Guerard, 2001; Guerard et al., this volume).

When possible vital effects on $\delta^{13}C$ values of calcareous serpulid tube secretion are removed (by adding 4 to 7 ‰ to the measured values; Veizer, 1983; Videtich, 1986; Wefer and Berger, 1991), it becomes apparent that isotopic compositions of the tufa carbonates and serpulid tubes from the aggregates that served as the substrate for tufa precipitation do not differ substantially from each other (Figure 13). This suggests that tufa precipitation and serpulid mound formation in the Dominican Republic occurred under similar conditions from waters of similar composition. A slight ^{18}O enrichment of individual tufa carbonate components relative to some of the serpulid tubes from the underlying aggregates (Figure 13) may reflect tufa precipitation from waters that have experienced a slightly greater amount of evaporation. This is consistent with tufa precipitation near the water surface and during progressive lake evaporation. As the lake was evaporating and the lake level was decreasing, microbes progressively coated elevated substrates of tufa mounds as they became available in shallow water. At the same time, serpulids, as non-photosynthetic organisms, continued to exit and form aggregates in deeper, more turbid waters.

Evaporation of Lago Enriquillo ended tufa precipitation and exposed the tufa-coated serpulid mounds to weathering and erosion. This is evidenced by the truncation of cyanobacterial aggregates, their coating with iron oxides, and the presence of fractured hematitic micrite with *Microcodium* in the pore space between aggregates (Figure 12). All of these are characteristics of carbonates modified and/or formed during subaerial exposure (Klappa, 1978; Wright and Tucker, 1991). Physical breakdown of delicate tufa and associated gastropods under subaerial conditions produced peloidal and skeletal sediment, which infiltrated into the pore spaces of the underlying tufa and serpulid aggregates (Figure 12B).

The carvings in the tufa-coated serpulid aggregates provide unique insights into the most recent history of the area and its inhabitation by Taino Indians. Sites with the greatest concentration of petroglyphs may indicate the location of villages between 1510 and 1533, when Tainos, under the leadership of Chief Enriquillo, fled to the Enriquillo Valley during a revolt against Spanish rule (Rouse, 1992; Berrios et al., 2002). Despite some recent desecration by graffiti, preservation of the tufa substrates and these unique petroglyphs is enhanced by the semi-arid climate in the area today.

DISCUSSION

Aggregation behavior of serpulids seems to be environmentally controlled and is enhanced by lack of predation and/or competition for food, which may be facilitated by the lack of water circulation and departures from normal salinity and temperature ranges (Ten Hove, 1979; Ten Hove and Van den Hurk, 1993). Such conditions provide unfavorable environments for stenotopic organisms and allow eurytopic organisms such as serpulids to flourish. Restricted environments with such conditions exist behind a large barrier island in the Baffin Bay area (Figure 5) and were established in the Dominican Republic by the cutoff of a Caribbean seaway (Figure 1).

Serpulid patch reefs at the mouth of Baffin Bay form mainly by vertical growth in comparison to the horizontally expansive reef fields found within the bay. This morphological difference may be a direct result of reef location within the bay complex. Shallow water depths within the bay prohibit serpulid reef fields from vertical growth. Although the entire bay is protected from direct marine influence and has a small tidal range, the mouth of the bay is likely a slightly less restricted setting with somewhat deeper water in places and with more current activity. This may prevent larvae from settling over large areas. A combination of these processes results in the formation of slightly taller patch reefs that cover much smaller areas.

Examples of similar relationships between water depth and serpulid-mound distribution and morphology were observed in the Dominican Republic. At the Abuela Grande locality, for example, serpulid aggregates formed on a gently sloping substrate where the water depth may have been too shallow for the development of tall serpulid mounds (Figure 3). In this nearshore environment, small serpulid mounds formed in slightly deeper water (~1 m deep) and the low relief mounds formed in more shallow water (<0.5 m) upslope (Figure 3). In these shallow waters, serpulid aggregates were unable to grow to the impressive heights found in the deeper waters that existed along the steep northern shores (Figure 2A).

Water depth also played a significant role in the formation of calcareous tufa coatings on the serpulid mounds from the Dominican Republic. Tufa is thickest and best developed on large mounds that formed in deeper water (Figure 10), and Abuela Grande is the only locality where tufa was not observed in the field. This supports the interpretation that water at this site was very shallow and suggests that with lake evaporation there may have not been enough time for tufa to precipitate (Figure 3).

Throughout the history of Lago Enriquillo, its water level fluctuated due to the interplay between evaporation rates and freshwater influx. Early in the history of the lake, the water level may have also been affected by periodic coastal flooding during major hurricanes. The formation of the impressive two-tiered serpulid mound structures along the steep northern slopes of the Enriquillo Valley attests to the fluctuating lake levels (Figure 2A). Variable water levels resulted in fluctuating salinity and in the generally highly variable environmental conditions throughout the area. Stable isotope compositions of serpulid tubes and tufa precipitates from various sites and stratigraphic levels likely reflect unique details about these conditions and warrant further examination (Figures 8 and 13).

Variations in environmental conditions are also suggested by petrographic observations and stable isotope compositions of serpulid tubes from Baffin Bay (Figures 6 and 7), and more work is needed to fully understand these conditions and their control on serpulid growth. A unique variation in conditions at the mouth of Baffin Bay resulted in the characteristic stratification patterns observed in the serpulid patch reefs: alterntating layers of vertical and randomly oriented tubes (Figure 6). This stratification was originally described by Andrews (1964) who theorized that episodes of random growth may reflect adverse ecological conditions, whereas periods of oriented growth may reflect optimal conditions. Furthermore, Andrews (1964) suggested that ecological change and the resulting growth patterns may be directly related to variable water salinity.

These hypotheses were not directly confirmed by the results of stable isotope analysis (Figure 7). Instead, the results suggest that initiation of oriented serpulid growth in Baffin Bay occurred in waters of lowered salinity, and that during the formation of oriented aggregates, the water salinity fluctuated greatly, but the water became, in general, more saline. The overall scatter of isotope data supports the concept of serpulids as euryhaline organisms that secrete tubes under a variety of conditions, but the clustering of the majority of data points also suggests that most serpulid tubes may have been secreted during short periods of optimal growth conditions. This also suggests that aggregates of randomly oriented tubes likely formed by rapid growth and the accumulation of a large number of individuals during these optimal time periods. The remarkable and somewhat surprising similarity in stable isotope compositions of serpulid tubes from Baffin Bay and the Enriquillo Valley (Figure 9), suggests that the conclusions drawn for Baffin Bay could be applied to the Dominican examples.

CONCLUSIONS

(1) Serpulid aggregates form under highly variable environmental conditions (particularly with respect to salinity), which eliminate competing species and allow the euryhaline serpulids to flourish.

(2) Serpulids live in fresh to hypersaline water, but most aggregates form under more narrowly defined, optimal (hyposaline?) conditions.

(3) In the Dominican Republic, such conditions were established by the creation of Lago Enriquillo through restriction and cutoff of a mid-Holocene reentrant from the Caribbean Sea and by the freshwater input into the lake.

(4) The distribution and morphology of serpulid mounds were controlled by the bathymetry and water depth of Lago Enriquillo.

(5) With decreasing lake levels, serpulid mounds provided suitable substrates for microbially induced precipitation of tufa near the water surface.

(6) Evaporation of Lago Enriquillo ended tufa precipitation and exposed the tufa-coated serpulid mounds to weathering and erosion.

(7) Preservation of the tufa substrate and the Taino Indian petroglyphs carved in the 16th century is enhanced by the semi-arid climate in the area today.

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