UNUSUAL HOLOCENE SERPULID-TUFA BIOHERMS, ENRIQUILLO VALLEY, DOMINICAN REPUBLIC: MORPHOLOGIES AND PALEOENVIRONMENTAL IMPLICATIONS

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ABSTRACT

**During the early Holocene, rising waters of the Caribbean Sea flooded the
Enriquillo Valley of southwestern Dominican Republic. A fringing coral
reef developed and flourished along the margins of the Enriquillo Seaway
for several millennia, until the seaway became restricted due to a
combination of slowed sea-level rise, tectonic uplift, and increased
sedimentation. Following changes in salinity and death of the coral reef
by about 5 ka, meter-scale bioherms composed of the tubes of
opportunistic, aggregating serpulid worms and associated with carbonate
tufa that precipitated from the ancient lake or declining seaway waters
formed along the steep walls of the valley over a period of 1,000 years or
more. Paleoenvironmental conditions likely conducive to formation of
these unusual bioherms include: non-normal marine salinity, warm and
restricted waters, periods of stable water level, high Ca^{2+} and CO_3^{2-}
influx, and moderate wave action. Although apparently rare elsewhere in
the rock record, occurrences of serpulid-tufa bioherms provide useful
constraints on paleoenvironmental settings. In previous literature,
variations in terminology used to describe both tufa and serpulid-tufa
bioherms have hindered intersite comparisons. Herein, serpulid-tufa
bioherm structures are described at macro-, meso-, and microscales, and
the varied bioherm macromorphologies are classified as individual,
clustered, terraced, and patch types. These form descriptions are
compared with previously published classifications of similar structures;
the goal is to facilitate development of a comprehensive and universal
classification of serpulid-tufa bioherms to further understand their
formation and paleoenvironmental significance.**

INTRODUCTION

Large and distinctive meter-scale carbonate bioherms and biohermal
ridges lie above Miocene bedrock and, in some cases, directly on
Holocene fringing coral reef deposits that occur around the periphery
of hypersaline Lago (Lake) Enriquillo in the southwestern Dominican
Republic (Fig 1). These bioherms are composed primarily of serpulid
tubes and tufa, a rare combination described previously from only a few
other sites (e.g., Cirilli et al., 1999; Jasionowski, 2006). The purpose of
this paper is to characterize in detail the morphologies of these unusual
bioherms, and to identify the paleoenvironmental and climatic
conditions contributing to their formation.

Previous studies of Holocene deposits of the Enriquillo Valley
investigated the characteristics and paleoenvironmental history of the
fringing coral reef found directly below the serpulid-tufa bioherms
(Mann et al., 1984; Taylor et al., 1985; Stemann and Johnson, 1992;
Guerard et al., 2004; Greer et al., 2009). Greer and Swart (2006) and
Greer et al. (2009) specifically emphasized the role of mid-Holocene
climate and climate change on the paleoenvironments of the Valley.
Serpulid-tufa bioherms of this study were previously described as
calcareous tufa of probably algal origin or algal stromatolites (Mann

et al., 1984) or spheroid thrombolitic algal stromatolites (Taylor et al.,
1985). Tourist guidebooks for the area described the mounds in general
terms as coral structures. Curran and Greer (1998) first recognized the
significant role of serpulids in the formation of these bioherms, and
Glumac et al. (2004) and Guerard et al. (2004) emphasized the
importance of both serpulids and tufa in mound development. Herein,
we refer to the various mound forms as serpulid-tufa bioherms.

Serpulids are calcareous tube-forming polychaete worms with near-
ubiquitous global occurrence in marine waters, which thrive in a wide range
of temperatures, salinities, and water depths. While over 300 modern species
of serpulids are known, only about 10 percent are capable of forming
aggregates (ten Hove, 1979). Aggregations develop when mobile larvae
settle on adult tubes, leading to buildups that vary in shape from cylinders to
sheets. Judging from size differences and variable morphologies, several
serpulid species occur in the Lago Enriquillo bioherms, but tubes of only one
type—species unidentified because serpulid taxonomy is based primarily
upon soft body parts—form the framework of the bioherms.

Although serpulids typically occur as individual encrusters, the right
environmental conditions can lead to aggregation, which is commonly
an opportunistic response to environmental conditions unfavorable to
other faunal elements (ten Hove and van den Hurk, 1993). Serpulid
aggregates most commonly develop in restricted waters, particularly
sheltered bays, where salinities range outside of normal marine (ten
Hove and van den Hurk, 1993; Cirilli et al., 1999; Glumac et al., 2004)
and where dispersal of the free-swimming larvae is constrained (Moore
et al., 1998). Such conditions are unfavorable to most marine fauna,
thus reducing competition for food and space for the euryhaline
serpulids (e.g., ten Hove, 1979; Ferrero et al., 2005). Schlögl et al. (2008)
provided further review of serpulid paleoecology.

Serpulids reproduce sexually, and their larvae are mobile and
gregarious (Pernet, 2001). This leads to preferred settlement of larvae on
adult tubes of the same species, enhancing aggregation (ten Hove and van
den Hurk, 1993). In general, larvae settle on hard surfaces, where the
worms secrete calcareous tubes. Tube accretion rate is dependent upon
water temperature, salinity, food availability, and serpulid population
density, and can reach ~0.1 to 0.2 mm per day (Behrens, 1968). Although
tolerant of a wide range of environments, deep water with slow currents
appears unfavorable and may prohibit aggregation by the suspension
feeding serpulids (Moore et al., 1998). Furthermore, serpulids cannot
tolerate prolonged subaerial exposure (ten Hove and van den Hurk, 1993).

Like serpulids, tufa is found in a variety of environments, with large
deposits commonly present in alkaline lakes or calcium-rich fluvial settings.
We follow the definition of tufa as a cool-water (i.e., nonhydrothermal)
calcium carbonate precipitate (Glover and Robertson, 2003; as recom-
mended by Pedley, 1990). Tufa occurs globally in waters enriched in
dissolved calcium carbonate, and is generally microbially mediated (Pedley,
1990). In appearance, tufa is often rough and porous and, while it is
commonly associated with plant or animal remains, these organisms do not
directly precipitate tufa. Precipitation of tufa must occur on surfaces offering
sufficient physical support, frequently plant matter, lithic material, or
preexisting tufa. Increasing the temperature of a water body decreases
carbonate solubility, thereby facilitating tufa formation. Water turbulence,

FIGURE 1—Maps illustrating the location of study sites. A) The Dominican Republic within the Caribbean Sea. B) The Enriquillo Valley, located in the southwestern Dominican Republic. C) The five field sites of this study and the local topography.

as might occur with waves, streams, or waterfalls, increases CO_2 degassing and also encourages $CaCO_3$ precipitation (e.g., Nelson et al., 2005). In some alkaline lakes, CO_2 degassing due to seasonal mixing results in tufa precipitation (Arp et al., 2003). Tufa can develop in a wide variety of physical forms (e.g., Benson, 1994; Carthew et al., 2003; Glover and Robertson, 2003), which are detailed in our discussion.

The unusual combination of tufa and serpulid bioherms that postdate the Holocene coral reefs and are now exposed above present-day Lago Enriquillo indicates that substantial environmental change occurred in the Enriquillo Valley between the time of coral growth and construction of the bioherms (e.g., Taylor et al., 1985 and later references). Understanding these changes requires an accurate model of bioherm formation in this dynamic tropical environment. To accomplish this objective, we examined age, distribution, composition, and bioherm morphologies to interpret the unique paleoenvironmental conditions that contributed to formation and preservation of these unusual deposits. Better understanding of the Dominican serpulid-tufa bioherms likely will lead to recognition of similar features elsewhere and will enhance their usefulness as paleoenvironmental indicators.

GEOLOGIC SETTING

The northwest–southeast trending Enriquillo Valley is located on the island of Hispaniola in the southwestern Dominican Republic, near the Haitian border (Figs. 1A–B). This 95-km-long, fault-bounded valley is flanked by the Sierra de Neiba (north) and Sierra de Baoruco (south) mountain ranges. Steep valley walls lead to gentle lowland slopes, which continue into Lago Enriquillo. A low floodplain with maximum elevation of 4 m above sea level separates the eastern edge of Lago Enriquillo and Bahia de Neiba (Neiba Bay) of the Caribbean Sea. Bedrock of the valley is dominantly Miocene marine limestone with some Pleistocene shallow-marine limestone also present (Mann et al., 1984).

With its surface at about 40 m below sea level, present-day Lago Enriquillo occupies an area of about 200 km^2 in the western end of the Enriquillo Valley (Schubert, 2000). The lake is shallow (mean depth ~6 m; maximum depth ~40 m), and is fed by both rainwater and groundwater, with its level varying due to short-term climate changes and variations in storm activity patterns (Mann et al., 1984; Taylor et al., 1985; Schubert, 2000; Buck et al., 2005). Freshwater springs emerge from the surrounding bedrock and run into the lake at several points around its periphery. Lake salinity varies with seasonal and annual cycles in aridity and storm-driven precipitation. In recent years, salinities above 100‰ were recorded during periods of low surface-water level, with lowest recorded salinities of 35‰ following flooding events (Buck et al., 2005). Modern lake temperatures range from ~28 °C to 30 °C, although temperatures likely vary more widely during periods of enhanced precipitation. Modern mean annual

precipitation varies across the length of the lake, with values of 729 mm/yr on the northwest shore and 508 mm/yr on the southeast (Buck et al., 2005). Long-term data from a nearby weather station at Port-au-Prince, Haiti record mean annual temperature as 26.5 °C (Greer and Swart, 2006). Average monthly insolation values at the ground surface for 18°30′N and 71°30′W are, at present, 5.3 kW/m², with data provided by the NASA Atmospheric Science Data Center (available at http://eosweb. larc.nasa.gov/sse/).

Holocene marine history of the Enriquillo Valley began when rising sea level of the post-last glacial marine transgression led to flooding of the Enriquillo Valley at ~9.8 ka, forming the ancient Enriquillo Seaway (Mann et al., 1984; Taylor et al., 1985). With open contact to the Caribbean Sea, the seaway was of normal marine salinity and supported growth of a thriving and diverse fringing coral reef along its shores. Exposed fossil coral colonies of the fringing reef are found between 3 and 30 m below present sea level on the gentle slopes leading into modern-day Lago Enriquillo (Stemann and Johnson, 1992; Guerard et al., 2004; Greer and Swart, 2006; Greer et al., 2009).

By about 5 ka, all corals of the fringing reef had died owing to restricted water flow from the Caribbean Sea. At that time, runoff may have increased as a function of enhanced precipitation during the Holocene Thermal Maximum (Haug et al., 2001; Greer et al., 2009), leading to erosion and deposition of large volumes of fluvial sediment into the mouth of the bay (Mann et al., 1984, Taylor et al., 1985). Slowed sea-level rise following Holocene global maximum temperatures (Hodell et al., 1991; Haug et al., 2001) in conjunction with increased precipitation-driven erosion may have enabled sediment to accumulate above the mid-Holocene sea level, restricting connection with the sea and creating an ancient Lago Enriquillo (Mann et al., 1984; Greer and Swart, 2006).

Subsequently, in many areas around the periphery of the valley, meter-scale serpulid-tufa bioherms formed directly on the surfaces of fossil corals, seaway beachrock, and Miocene bedrock of the valley walls. Occurring on both steep valley walls and gentle slopes, these bioherms were formed underwater at times when lake levels were higher than at present. Due to low modern lake levels, both the corals of the Holocene fringing reef and the bioherms are spectacularly exposed in numerous localities around the Enriquillo Valley.

METHODS

Field Methods and Classification Scaling Scheme

Field investigations focused on five study areas with excellent fossil bioherm exposures: Cañada Honda, Cañada Honda West, Las Caritas, Devil's Furnace, and Abuela Grande (Fig. 1C). Particular emphasis was placed on the Cañada Honda site owing to spectacular exposures at
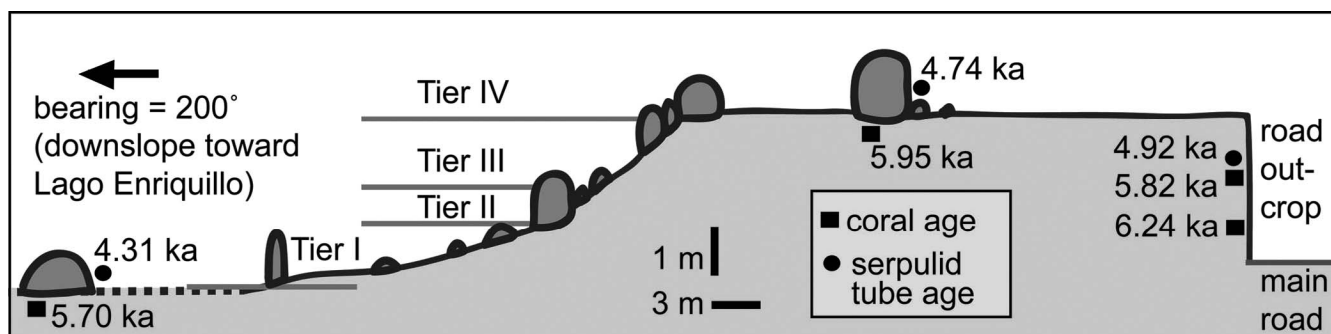
FIGURE 2—Linear profile of bioherm Tiers I–IV at the Cañada Honda field location. Radiocarbon ages are calibrated to calendar years before present.

that locality that permit reconstruction of tiered bioherm relationships (Fig. 2). Access to all sites is from the main road that circumnavigates the lake. Samples for subsequent petrographic analyses (scanning electron microscope [SEM] and thin sections) were collected from the fossil bioherms and, where available, from corals at each study site. Samples of both *Montastraea annularis* and *Acropora cervicornis* corals for ^{14}C dating were collected as close to the bioherm-coral contact as possible. Bioherm material from directly above the contact, as well as from the very tops of several bioherms, was also collected. Selected larger bioherm samples were collected to examine the relationship between various bioherm components and for making petrographic thin sections. All samples are maintained in the Smith College Department of Geosciences repository.

We classified the Lago Enriquillo serpulid-tufa bioherms using the scaling scheme for thrombolite bioherms recommended by Shapiro (2000). In this classification, megastructure refers to overall form of a given deposit, macrostructure refers to decimeter- or meter-scale deposit components, mesostructure to macrostructure textures that are visible to the naked eye, and microstructure to microscopic configurations. Similarities exist between the Shapiro (2000) and Carthew et al. (2006) schemes, but because we did not observe any actively forming tufa sites in the Lago Enriquillo area, we did not classify based on depositional environment (e.g., Carthew et al., 2006). Our classification is focused on bioherm and tufa descriptions, and their relationship to serpulids and mollusks within the bioherms. Throughout the Enriquillo Valley, megastructure of the bioherms can be described as biohermal buildup.

Geochronology

Six coral and four serpulid samples from coral-bioherm contact zones were selected for radiocarbon dating at Lawrence Livermore National Laboratory. Due to the uncertainty of initial radiocarbon activity during tufa sedimentation (Pazdur et al., 2002), Enriquillo tufa samples were not processed for radiocarbon dating. Close to 100% aragonite composition of the visibly unaltered coral samples was confirmed by XRD (X-ray diffraction) analysis. Serpulid tubes, here composed of low-Mg calcite, were cleaned, and those with unaltered appearance were selected. Several serpulid tubes from the same location were combined to reach a minimum mass of 0.01 g.

Radiocarbon ages were calculated using a Libby half-life of 5,568 years, and converted to calendar years using the online CALIB 6.0 calculator (Stuiver et al., 2005, updated to CALIB 6.0, see CALIB at http://calib.qub.ac.uk/). For the coral ages, a marine reservoir correction of 400 years was made, with a ΔR of 50 years. No correction was made for marine reservoir age for serpulid tube dates because the relative influence of marine and continental waters is unknown and temporally variable for this restricted basin.

Serpulid tubes also were selected from the bioherm-coral contact for stable isotope analyses. Data from these analyses will be combined with similar data from serpulid tube samples taken around Lago Enriquillo and elsewhere by others and us, and interpretation of these data will be

the subject of a later paper. Initial reports are available in Glumac et al. (2004), Guerard et al. (2004), Doss (2006), and Winsor (2006).

RESULTS

This section describes the types of mollusks and microfossils found within the bioherms, and presents results of our geochronologic analyses of serpulid tube and coral samples. The serpulid-tufa bioherms are systematically described in terms of their macro-, meso-, and microstructures. Our findings are summarized in the overview of the characteristics of bioherms from each study site that integrates information from all aspects and scales of this study.

Mollusks and Microfossils

Mollusk shells compose varying proportions of the Enriquillo bioherms. Within the bioherm framework, whole bivalve and gastropod shells commonly occur in clusters and are associated with both serpulid aggregations and tufa (Fig. 3). Mollusk shell clusters are also often concentrated at the boundary between corals and overlying bioherms (Fig. 3A). Fragmented bivalve and gastropod shells occur in loose sediment pockets of calcareous mud to coarse sand-sized grains composed mainly of skeletal fragments, peloids, and tufa fragments (Figs. 3B–C). Also present within this sediment are specimens of ostracode species that represent a range of salinity tolerances (Medley et al., 2007). The most common mollusk and ostracode species identified from the Lago Enriquillo bioherms are listed in Table 1, along with species-specific salinity tolerances.

Radiocarbon Dating

The 10 coral and serpulid tube dates of this study range in age from 6.24 to 4.04 ka, with the Cañada Honda samples matching very well with relative-age predictions based on stratigraphy and elevations of the samples (Table 2, Fig. 2). An *Acropora cervicornis* coral from about 0.5 m below the contact with serpulid aggregations yielded the oldest date (6.24 ka) of this data set. The remaining five coral samples were in contact with serpulid aggregations and range in age from 5.95 to 5.70 ka. Two *Montastraea annularis* corals from similar elevations at Cañada Honda and Cañada Honda West yielded ages just twenty years apart, well within the error range of these measurements. The ages of an additional pair of *M. annularis* samples, one from Cañada Honda and another from Abuela Grande on the opposite side of Lago Enriquillo, are also indistinguishable within analytical error range, indicating good correlation of events of bioherm development around the lake.

Overall, our data indicate about a 250-year range in ages of corals found along the major disconformity at the contact with bioherm material at all sites (Fig. 2, Table 2). These ages are consistent with those presented by Greer et al. (2009), who reported an age of 5.38 ka for their youngest coral sample from the valley. Serpulid tubes from the coral-
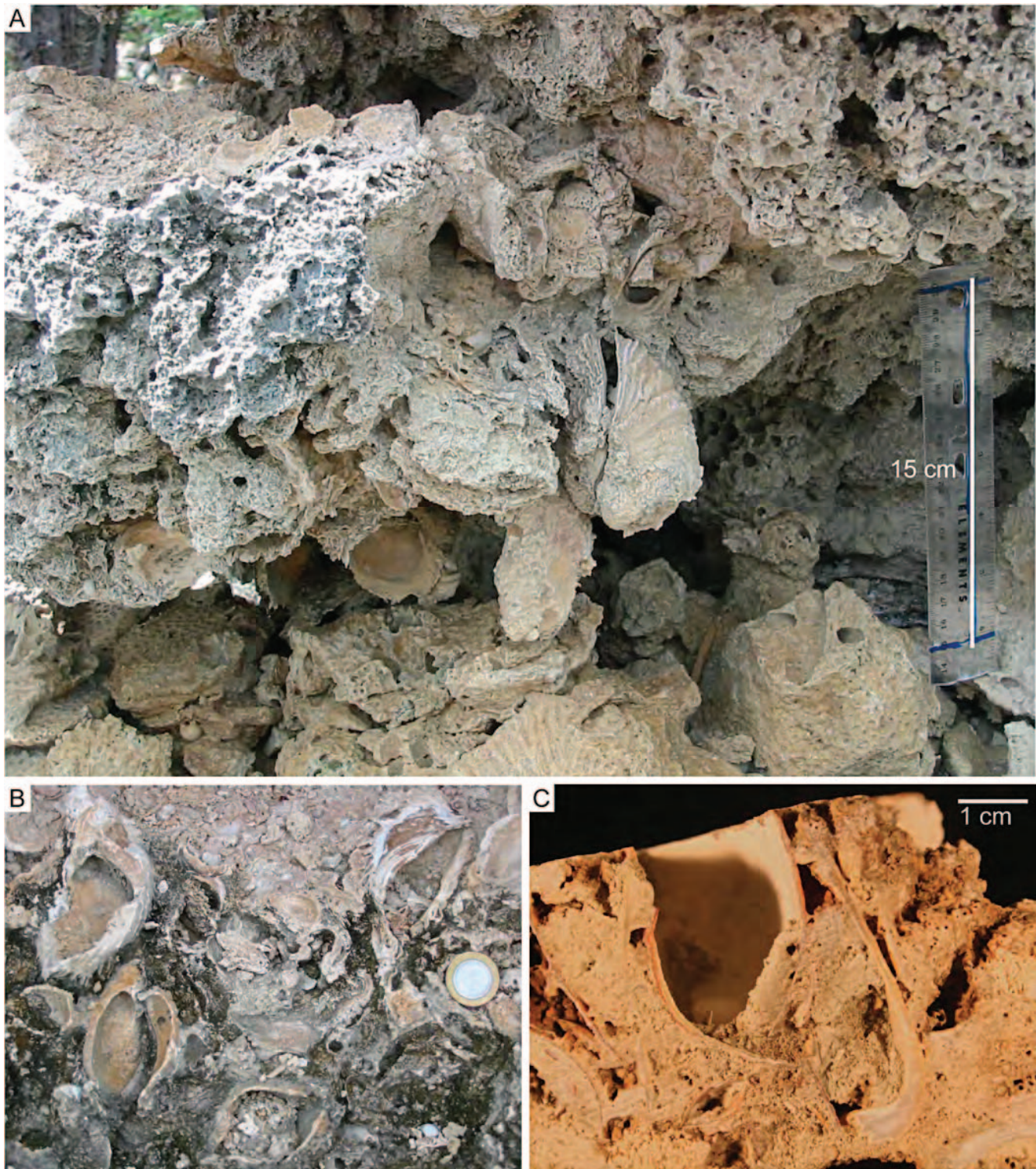
FIGURE 3—Bivalve shells within or near Lago Enriquillo bioherms. A) Bivalves encrusting *Montastraea annularis* colony, with patch bioherm material overgrowth. B) A typical bivalve layer dominated by *Chama* sp. within clustered bioherms. Coin for scale = 2 cm diameter. C) Bivalve shells exposed in cut slab from a patch bioherm.

bioherm contact range in age from 4.92–4.04 ka (uncorrected calendar ages), with serpulids of youngest age being present at the lower elevation sites.

Macroscale Structures

Bioherms of four different morphologies—individual, clustered, patch, and terrace—as illustrated in Figure 4, are present within the five study areas of the Enriquillo Valley (Fig. 1C). Each bioherm type is associated with different elevations, underlying-surface media, and slopes, and contains different proportions of serpulid tubes, tufa, mollusk shells, and interstitial sediment (Table 3).

Individual bioherms predominate at Cañada Honda, Cañada Honda West, and Devil's Furnace. Their distinguishing features include physical separation from adjacent, similar bioherms and domal shape (Fig. 4A). The larger of these mounds are approximately 3–5 m in diameter, and 2–3 m tall. Exteriors of individual bioherms are

TABLE 1—Taxonomy, general environmental preferences, and occurrence in the Enriquillo Valley of common mollusks and ostracodes associated with serpulid-tufa bioherms (environmental preferences for mollusks from Warmke and Abbott, 1961; Abbott, 1974; for ostracodes from Purper, 1974; Teeter, 1975; Stout, 1981; Maddocks and Iliffe, 1986; Mourguiart and Carbonel, 1994; Wang, 2010). Salinity definitions are from Neale (1988): oligohaline = 0.5‰–5‰, mesohaline = 5‰–18‰, polyhaline = 18‰–30‰. Microfossils are from loose sediment processed from a Cañada Honda West patch bioherm; * = most common ostracode species within serpulid-tufa sediment pockets; ‡ indicates ostracode species previously recorded in the Enriquillo Valley by Guerard et al. (2004) and Medley et al. (2007).

Mollusk-ostracode taxonomy	Preferred salinity	Occurrence in Enriquillo Valley
Hydrobiid snails, including *Littoridinops monroensis*	Oligohaline to mesohaline, often around springs (Buck et al., 2005)	Very common, both within bioherms and on bioherm exteriors
Brachidontes modiolus	Can occur in a range of salinities	Common in serpulid aggregation layers from serpulid colonization pulses
Neritina piratica	Oligohaline, swampy areas	Common in patch bioherms
Pinctada imbricata	Polyhaline to full marine, shallow water, hard substrate	Common in patch bioherms
Chama cf. *C. sinuosa*	Associated with reefs	Most prominent bivalve at coral-bioherm contacts
Candonopsis sp.*	Freshwater to slightly oligohaline	Ostracode within sediment
Eucypris cf. *E. elliptica*	Freshwater to oligohaline	Ostracode within sediment
Cytheridella boldii‡	Oligohaline	Ostracode within sediment
Cyprideis salebrosa‡	Euryhaline; presence of nodes on valves indicates oligohaline conditions	Ostracode within sediment
Loxoconcha fischeri‡	Meso- to polyhaline	Ostracode within sediment
Propontocypris sp.‡	Shallow marine; may tolerate salinity fluctuations	Ostracode within sediment

uniformly composed of a weathered, porous mixture of serpulid tubes and tufa. Individual bioherms were observed only at midlevel elevations in the valley, perhaps owing to the essentially flat surfaces present at those elevations. These bioherms are composed of a high percentage of serpulid tubes (≤ 80%, e.g., Fig. 5), but also include a mixture of tufa varieties, mollusk shells, and interstitial sediment (Table 3).

Clustered bioherms were observed only at Cañada Honda (Fig. 4B), although the distinction between clustered and other bioherm types is not strong in some cases, and this morphology may exist, undocumented, elsewhere. Composed of relatively small mounds (≤0.5 m tall) coalescing in both vertical and horizontal directions, clustered bioherms can extend vertically over several meters of elevation change. Horizontally, clustered bioherms extend on the decimeter scale, and were observed to extend ~30 m by Mann et al. (1984). The medium for this morphology is typically other clustered bioherms and coral rubble; these bioherms have similar composition to that of individual ones.

The third macroscale category is that of patch bioherms (Fig. 4C). Found at Cañada Honda, Cañada Honda West, and Abuela Grande, the most distinctive characteristic of this morphology is that coral colonies of *Montastraea annularis* are the exclusive medium for bioherm development. Additional distinguishing features include that patch bioherms are composed of numerous small, closely spaced bioherms, and that the overall bioherm shape is asymmetric, often enlarged on the windward side. Because these bioherms are limited to the top surfaces of domal *M. annularis*, their areal extent is limited to the exposures of these surfaces. Large patch bioherms were observed to be 4–5 m in diameter and 1–2 m tall. Patch bioherms were observed only on gentle slopes at relatively low elevations around the modern lake. This morphology incorporates a greater proportion of sediment,

mollusk shells, and friable tufa than any of the other three bioherm types.

Terraced bioherms constitute the final macroscale category (Fig. 4D). This morphology developed only on steep slopes of the Enriquillo Valley walls, including the Las Caritas site, and is the most visually distinctive of the four types. Other than being constrained to steep slopes at relatively high elevation, distinguishing bioherm characteristics include broad lateral extent (5–10 km on the north side of the lake, with small intermittent gaps), two-tiered structure, relatively high proportion of densely lithified tufa, occasional occurrence of caves (Glumac et al., 2004), and a total height ≥3.5 m.

Mesoscale Structures

Mesoscale features of Enriquillo Valley tufa fall into three categories: densely lithified tufa, smooth knobby tufa, and friable tufa (Fig. 6). Densely lithified tufa is creamy to pinkish tan in color. In some samples, it is present in thin (<1 cm wide) meandering bands, both within and along the exterior rim of bioherms (Figs. 6A–B). Toward the exterior of some bioherms, this material forms the base for a rough, porous coating consisting of small columns (<2 cm high) of interconnected or networked material. This tufa type is also common as thicker, cavity-riddled material. In some samples, tightly packed serpulid tubes, indicating a preference for aggregation on this medium, surround densely lithified tufa. In general, densely lithified tufa gives way to other materials toward the exterior of a given bioherm.

Smooth knobby tufa is porous and more fragile than the densely lithified form and is commonly located as a rind on bioherm exterior surfaces (Fig. 6C). Well-preserved, easily observed examples of this tufa type also coat large cavities within bioherms. This tufa has a smooth

TABLE 2—Radiocarbon dates calibrated to calendar years (in ka = thousands of years before present; Stuiver et al., 2005) of coral and serpulid tube samples from paired coral-mound contact levels (exception is CH-1-5, located 0.5 m below contact). See Figure 2 profile for precise locations of the Cañada Honda samples.

| Sample	Location	Type	Age (ka) +/− 0.04 kyrs	Notes
CH-1-7-10a	Cañada Honda	Serpulid tube	4.92	At road cut; attached to coral of CH-1-7-10b
CH-1-7-10b	Cañada Honda	*A. cervicornis*	5.82	Encrusted by serpulid tubes
CH-1-5	Cañada Honda	*A. cervicornis*	6.24	0.5 m below CH-1-7-10
CH-3-4	Cañada Honda	Serpulid tube	4.74	Attached to CH-3-2 coral
CH-3-2	Cañada Honda	*M. annularis*	5.95	Tier IV; encrusted by serpulid tubes
CH-6-1	Cañada Honda	Serpulid tube	4.31	Attached to CH-6-3 coral
CH-6-3	Cañada Honda	*M. annularis*	5.70	Base of patch bioherm; in contact with bioherm material
CHW-1-2	Cañada Honda West	*M. annularis*	5.93	Tier IV
AG-1-1	Abuela Grande	Serpulid tube	4.04	Attached to AG-1-6 coral
AG-1-6	Abuela Grande	*M. annularis*	5.70	Encrusted by serpulid tubes
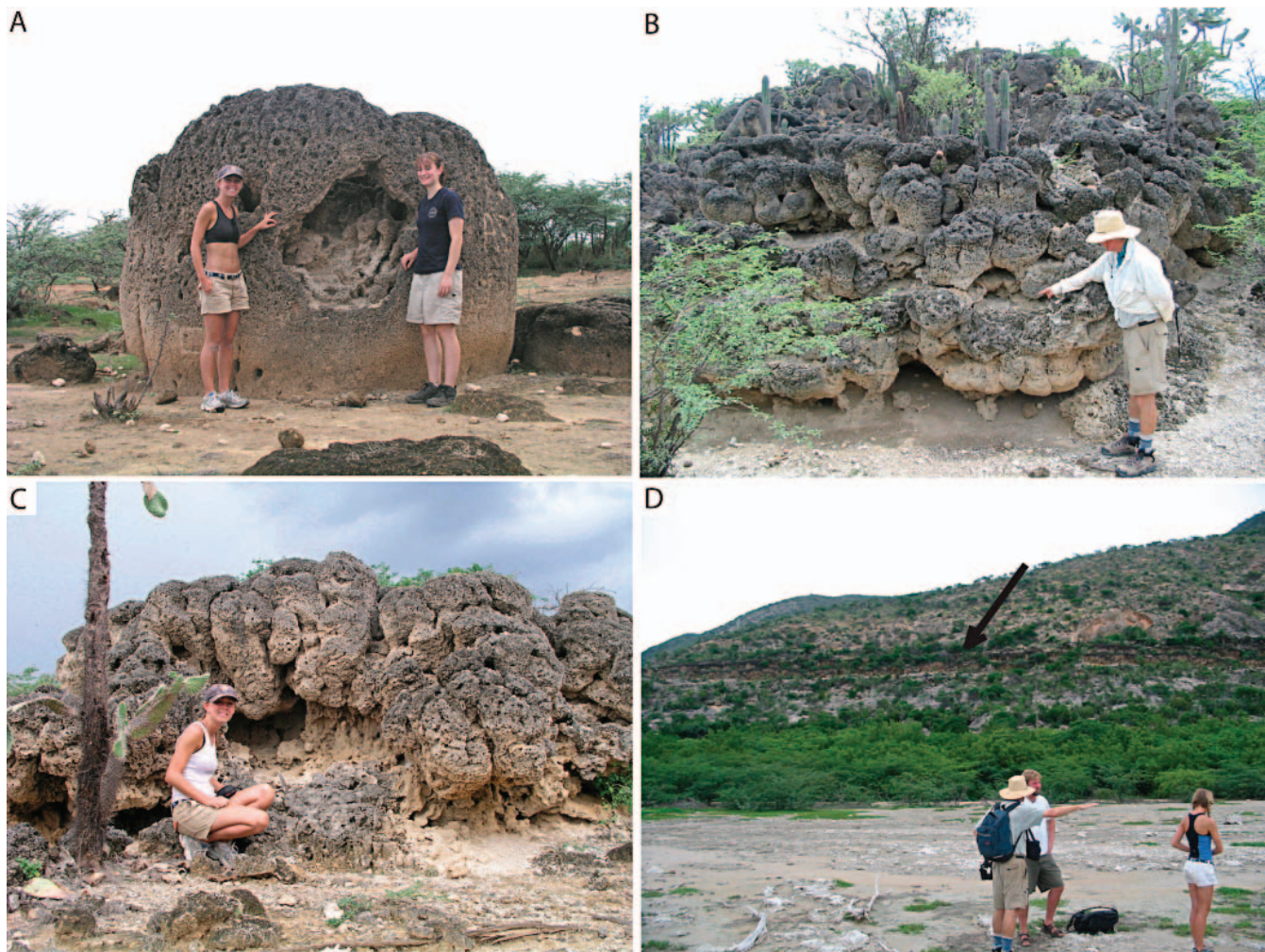
FIGURE 4—Macroscale classification of Enriquillo Valley bioherms. A) Individual bioherm, Cañada Honda site. B) Clustered bioherms at Cañada Honda. C) Patch bioherm at Cañada Honda. D) Laterally extensive terraced bioherms along the steep northern slopes of the valley.

TABLE 3—Summary of serpulid tube and tufa mesoscale components, bioherm descriptions, and relationships of these materials to other components and bioherm types.

| Component	Description	Relation to other components	Type of bioherm
Densely lithified tufa (Fig. 6A, B)	Creamy to pinkish tan, translucent, hard, dense; occurs in thin meandering bands, thicker porous masses, and small columns	Found adjacent to all listed components; encrusted by serpulid tubes and smooth knobby tufa; forms other than the columnar structures are rarely found on bioherm exteriors	Individual, possibly clustered, patch, terraced
Smooth knobby tufa (Fig. 6C)	Tan, opaque; smooth knobby surface with friable porous interior; can be bush shaped	Encrusts serpulid tubes, densely lithified tufa, and mollusk shells; often toward the exterior of bioherms	Individual, clustered, patch, terraced
Friable tufa (Fig. 6B)	Grayish white, crumbly; often porous; no internal structure	Within cavities surrounded by densely lithified tufa, serpulid aggregations, and/or mollusk shells	Individual, possibly clustered, patch, terraced
Laminated tufa (thin section only; Fig. 7E, 8A)	Thin, nonporous; laminations 10–200 μm thick	Found only on surfaces exposed to open air; adjacent to both serpulid tubes and mollusk shells	Patch, possibly others
Serpulid aggregations (Fig. 5)	Clusters of tubes 1–3 cm in length, 0.5–1.5 mm in diameter	Encrust densely lithified tufa, mollusk shells, and coral fragments; absent from unconsolidated or friable material	Individual, clustered, patch, terraced
Mollusk shells (Fig. 3)	Whole and fragmented bivalve and gastropod shells of various sizes	Often within loose sediment or friable tufa; interiors of whole bivalves contain loose sediment; serpulids and tufa encrust	Individual, clustered, patch, terraced (upper tiers)
Interstitial sediment (Fig. 6B)	Mud-sized to coarse carbonate sediment; includes shell and tufa fragments, and microfossils	Within cavities in bioherms, and as shell fillings	Individual, clustered, patch, terraced
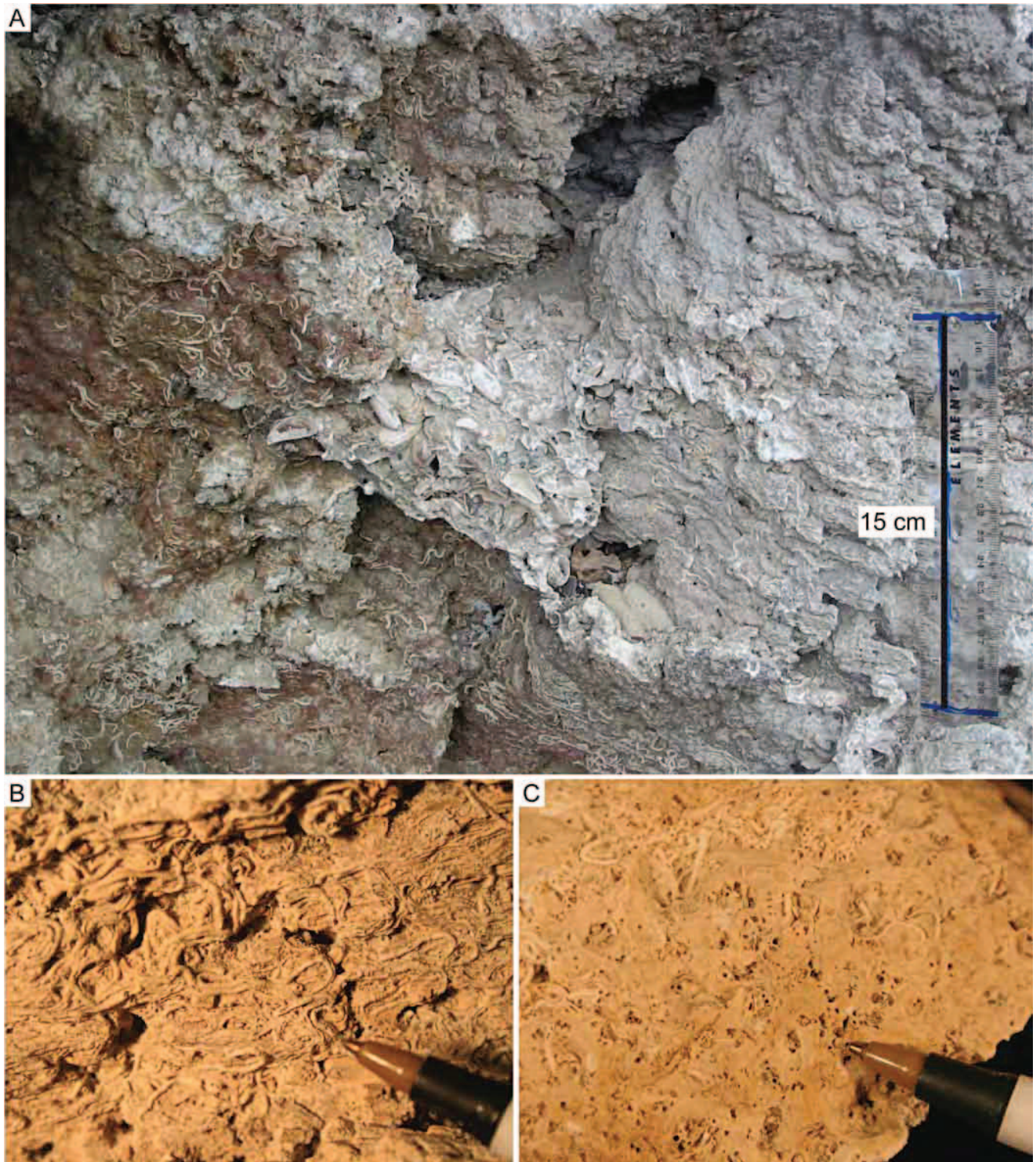
FIGURE 5—Serpulid aggregations within bioherms. A) and B) Well-preserved serpulid tubes from individual bioherms with decimeter-scale regions dominated by serpulid tubes; pen tip for scale. C) Weathered serpulid tubes from Las Caritas terraced bioherms that are similar in appearance to some Enriquillo Valley tufa rinds; pen tip for scale.

and knobby surface (Fig. 6C) and ranges in thickness from ≤1 mm to ~1 cm. Below the surface of the thicker layers, 0.5 to 3 mm diameter clumps of this material are networked and include many cavities (Fig. 6B). Serpulid aggregates, mollusk shells, and densely lithified tufa are all found coated by smooth knobby tufa. On the exterior, smooth knobby tufa material weathers to form a rough, more porous surface.

Friable tufa composes the third mesoscale category (Fig. 6A). This material constitutes a large proportion of some bioherms. Grayish white in color, friable tufa ranges from easily powdered with one's fingers to a hardness level nearly comparable with densely lithified tufa. Friable tufa is also observed within interiors of large bivalve shells. Whole and fragmented mollusk shells are commonly found scattered within this tufa, and friable tufa also surrounds networks of densely
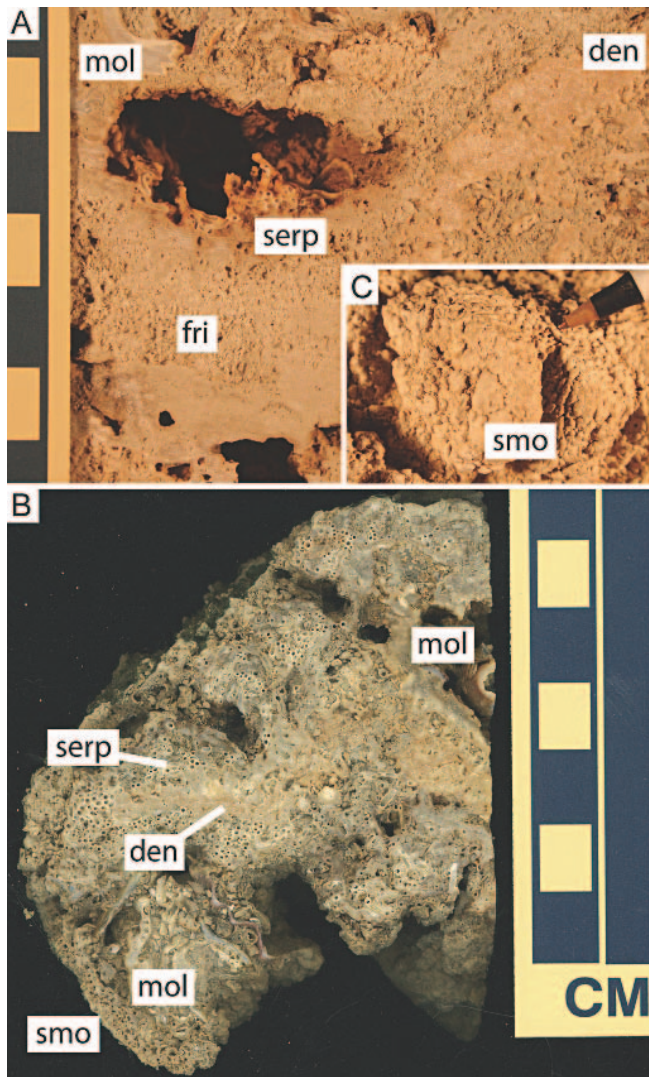
FIGURE 6—Mesoscale classification of Enriquillo Valley tufas. A) Patch bioherm slab from Cañada Honda West. B) Patch bioherm slab from Cañada Honda. C) Smooth, knobby tufa from the exterior of A). Pen tip for scale. Bioherm components include serpulid aggregations (serp), mollusk shells (mol), and the mesoscale structures: densely lithified tufa (den), friable tufa (fri), and smooth knobby tufa (smo).

SEM imaging of smooth knobby tufa (Fig. 7F) revealed two distinct fabrics. The exterior material is smooth and nonporous, even at high resolution. This fabric quickly grades into relatively rough, porous material within 0.1 mm of the surface, formed by interconnecting cavities and nodules at a 10 µm scale (Fig. 7F). A sample of smooth knobby tufa from several millimeters into the interior of a bioherm displayed the same cavity-nodule structure.

While apparently rare, laminated tufa was identified in samples from Abuela Grande (Fig. 7E) and Cañada Honda (Fig. 8A). This tufa type also may occur at other localities, but was not observed elsewhere in the field. The examined laminated tufa is thin, with layers ≤0.8 mm thick, and present only on exposed surfaces adjacent to areas that appear to have been truncated by weathering and erosion. Coloration and density of material distinguishes individual laminations, which are only about 10–200 µm thick and can include micropeloids (Fig. 7E). Laminated tufa is found adjacent to serpulid tubes, gastropods, and micropeloidal, densely laminated tufa (Fig. 8A).

Tufa composition at the microscale is evident in thin-section photomicrographs, with composition varying between localities but generally consisting of a combination of micrite, microsparite, and in some places hematitic micrite (Berrios, 2002; Fig. 8B). Staining of petrographic thin sections (using Alizarine Red S and Feigl's solutions) indicated that in the Enriquillo Valley, tufa consisting of micrite and microsparite is nearly uniformly calcite, with the exception of rare patches of aragonite (Berrios, 2002). XRD analyses on Enriquillo Valley tufas and serpulid tubes demonstrated their low-Mg calcite composition (Glumac et al., 2004).

Integrative Descriptions of the Study Sites: Cañada Honda

This site extends along flat to gently sloping terrain on the north side of Lago Enriquillo (Fig. 1C). The high density of bioherms and variation in slope and bioherm shapes make this an excellent study area, with four tiers (Tiers I–IV) of bioherm development bounded and defined by extensive layers of *Acropora cervicornis* coral rubble. The main road forms the northern border of the site, and here a road cut reveals a thick layer of *A. cervicornis* rubble below a poorly defined layer of bioherm material (Fig. 9A), composing Tier III (Fig. 2). At the contact between *A. cervicornis* and bioherm material, serpulid tubes encrust the upper surfaces of many individual coral fragments (Fig. 9B). Directly above the contact, serpulid tubes and tufa form small, somewhat indistinct organ-pipe forms surrounded by poorly sorted carbonate sediment (Fig. 9A).

Continuing south from the road cut to the Tier IV area (Fig. 2), the slope of Cañada Honda bears numerous large individual bioherms. Here, bioherms rest on *Montastraea annularis* coral colonies, *A. cervicornis* rubble, or a thin layer of sediment. Individual bioherms of Tier IV range in height from 0.1 m—these smaller bioherms may, in some cases, be rubble fallen from larger bioherms—to 2.9 m. Covered with a rough, porous exterior that often forms a continuous dome, the interiors of bioherms at this location commonly have an organ-pipe structure (Glumac et al., 2004) with an intricate arrangement of columns of serpulid tubes, tufa bioherm material, and voids.

A steeper slope, comprising Tiers II and III, marks a transition in bioherm morphology to clustered bioherms (Fig. 2). In the area of densest growth of clustered bioherms (Tiers II and III), relatively small bioherms are joined together, forming a stair-step mass of bioherm material (Fig. 4B). Commonly, laterally constrained beds of bivalve encrusters, dominated by *Chama* sp., are present within the bioherms or mark their vertical boundaries (Figs. 3B, 4B).

Southward into Tiers I and II, the slope decreases and individual bioherms dominate (Fig. 2). These bioherms are smaller and of a more irregular domal shape than those of Tier IV. South of Tier I, a gentle slope littered with fossil bivalves, gastropods, and coral rubble extends toward Lago Enriquillo. Several large (over 1 m in height and 2.5 m in width) dome-coral colonies of *M. annularis* protrude from the surface.
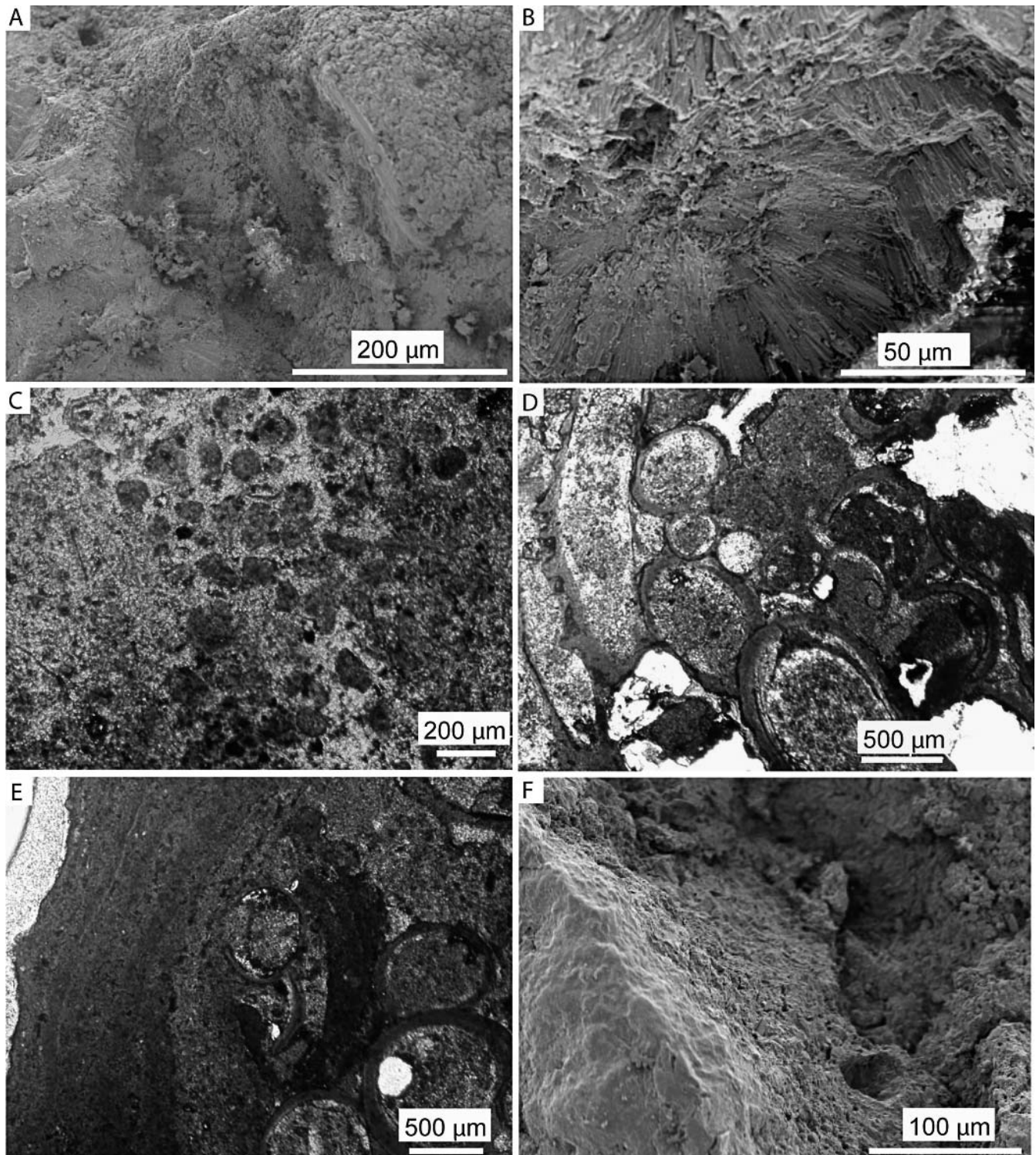
lithified tufa (Fig. 6A). Serpulid aggregations are generally not found on or within this material.

Microscale Structures

In the Lago Enriquillo bioherms, smooth knobby tufa and densely lithified tufa (mesoscale classification categories) also were observed as distinctive in the size range that Shapiro (2000) reserved for microscale tufa forms. Those two categories, as well as a third category, laminated tufa, are recognized.

SEM imaging of densely lithified tufa demonstrated that while containing rougher areas, this tufa is primarily smooth and nonporous (Fig. 7A) and in some areas exhibits a radial crystalline structure (Fig. 7B). These calcitic structures differ from the radial structures formed by cyanobacterial filaments and observed in thin section (Berrios, 2002). Densely lithified tufa has a micritic and often micropeloidal structure in thin section (Figs. 7C–E; Dupraz et al., 2004). Micropeloids give tufa a patchy appearance, are typically between 20 and 200 µm in diameter, and are found in close association with serpulid tubes, being present even inside the tubes (Figs. 7D–E).

FIGURE 7—Microscale classification of Enriquillo Valley tufas. A) SEM image of densely lithified tufa. B) SEM image of densely lithified tufa with radiating crystalline structure. C) Photomicrograph of densely lithified tufa with micropeloidal texture. D) Photomicrograph of densely lithified tufa with micropeloidal texture inside serpulid tubes. E) Photomicrograph of laminated tufa near serpulid tubes, and densely lithified tufa with micropeloidal texture within tubes. F) SEM image of smooth knobby tufa with nonporous, exterior material (to the left) and porous interior material (right side of the photograph).

These corals have a columnar to platy structure and host numerous encrusters, including barnacles and mussels. *Chama sp.* bivalves are especially abundant in some areas, forming large clusters near the contact between *M. annularis* and bioherm material (Fig. 3A). The tops of these coral colonies are relatively smooth and are heavily bored by lithophagid bivalves, resulting in well-defined examples of the trace fossil *Gastrochaenolites torpedo*, with shells of the lithophagid trace-makers commonly preserved. In addition, each observed coral colony is topped by a very large and squat (over 3 m wide, ~1.5 m tall), patch bioherm. These patch bioherms have mushroomlike forms that incorporate columns (Figs. 4C, 10A), with uneven and often heavily weathered upper surfaces.
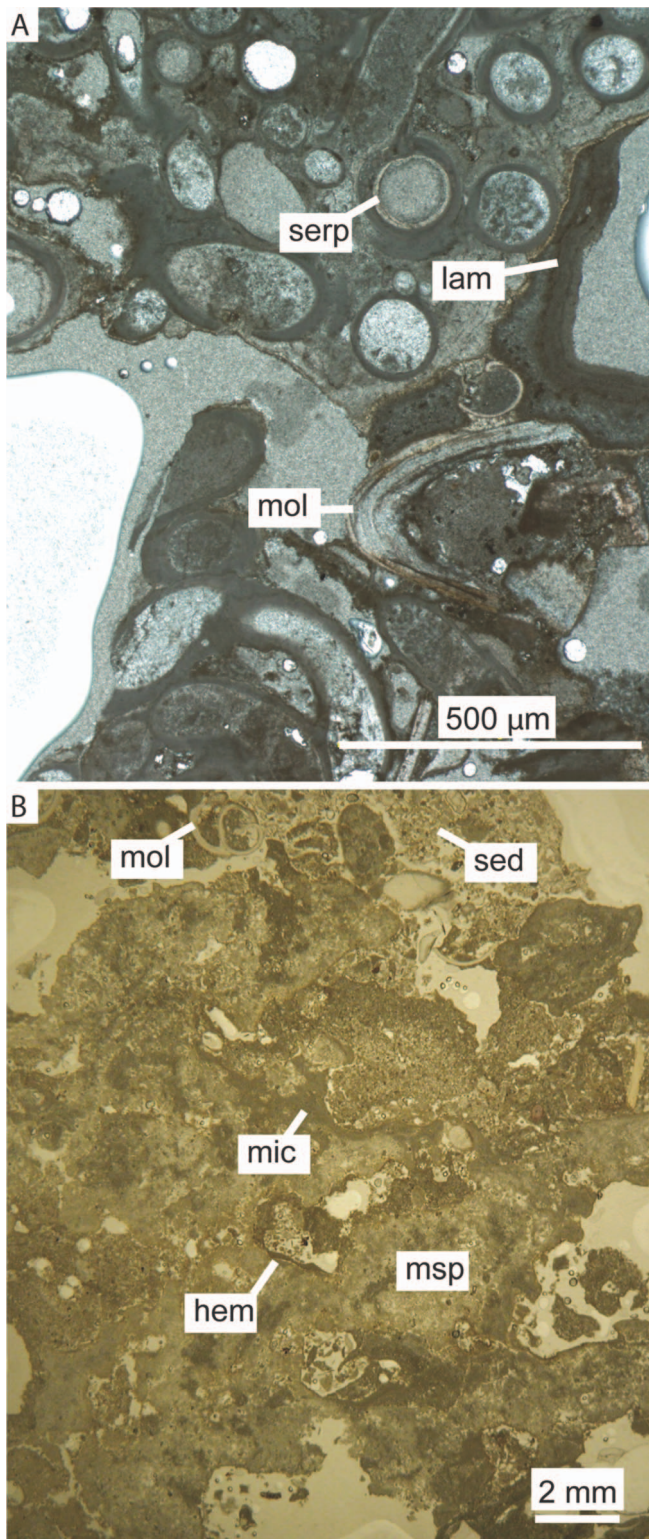
FIGURE 8—Photomicrographs of bioherm material. A) Cañada Honda individual bioherm material displaying serpulid aggregation (serp), laminated tufa (lam), and mollusks (mol). B) Sample from the exterior of an Abuela Grande bioherm, illustrating micrite (mic), patchy micrite to microsparite (msp), and hematitic micrite (hem), as well as mollusks (mol) and poorly lithified sediment (sed). Photo courtesy of Lisa Berrios.
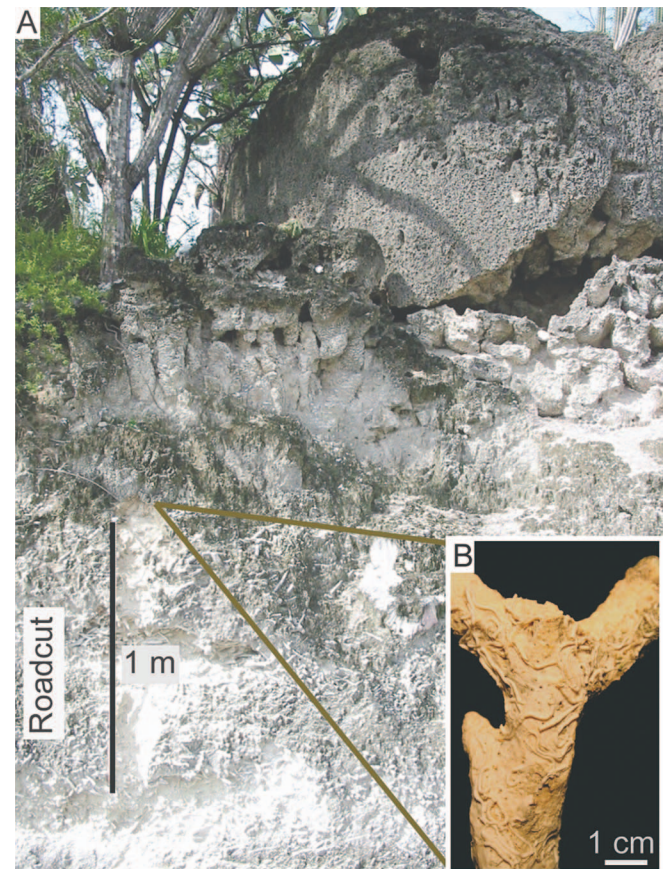

FIGURE 9—Road cut exposure at Cañada Honda (origin point for the profile of Fig. 2). A) Succession showing an *Acropora cervicornis* layer transitioning upward into organ-pipe serpulid-tufa bioherm material, with individual bioherms on top. B) *A. cervicornis* fragment encrusted with serpulid tubes.

Cañada Honda West

This site is situated ~1 km west of Cañada Honda along the main road (Fig. 1C). Cañada Honda West comprises a generally flat field with numerous small, individual bioherms that are less well defined than the individual bioherms of Tier IV at Cañada Honda. A short distance toward the lake, patch bioherms atop *Montastraea annularis* coral colonies dominate. Patch bioherms here are large, with uneven surfaces (Fig. 10B), and are similar to those present at Cañada Honda. Here, *M. annularis* colonies observed below the patch bioherms have unusually tall and well-formed columns (Fig. 10B). Bioherm material rests directly above these columns, with a thin outer coating of rough porous material draping downward over the sides of many columns. Some large encrusting bivalves are present between the *M. annularis* columns, and the bioherm material itself contains many bivalve shells.

Las Caritas

Las Caritas (The Little Faces area of Taino Indian petroglyphs; Glumac et al., 2004) is located along the steep cliffs to the north of Lago Enriquillo, west of Cañada Honda (Fig. 1C). Here, two, or possibly three, tiers of terraced bioherms run laterally along the steep northern slopes of the Enriquillo Valley (Figs. 4D, 11). Unlike samples from other Enriquillo sites, these bioherms contain detrital sand and pebbles, likely derived from erosion of the higher valley walls. The terraces at Las Caritas are each over 1.5 m tall, with bioherm material forming an even, lobate exterior surface. In the lower part of the bottom tier, bioherm material appears to be composed almost exclusively of serpulid tubes. The rough, porous, weathered tufa surface layer seen at many
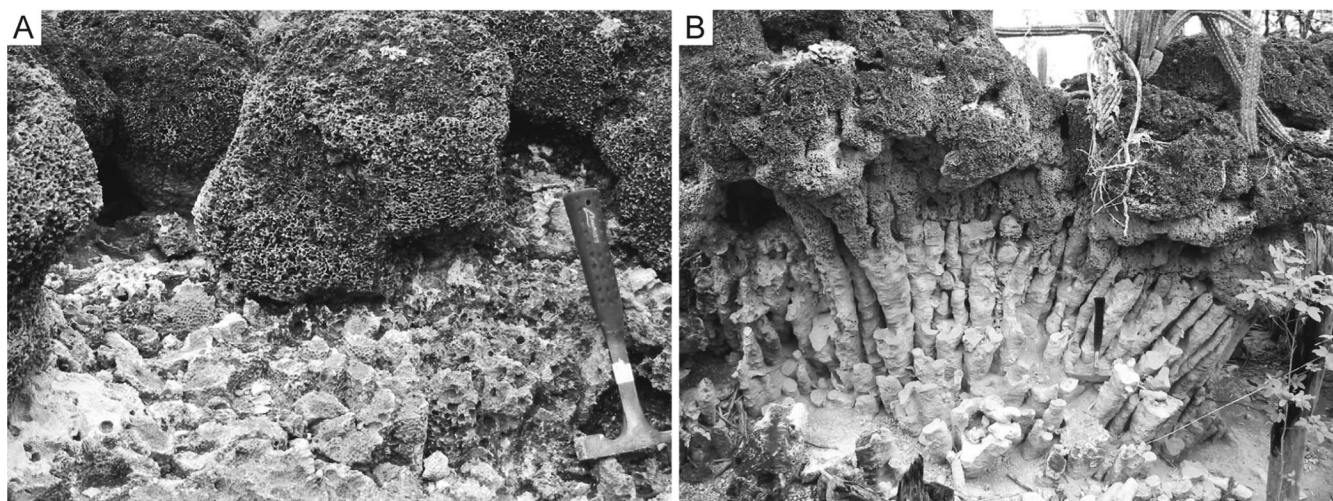
FIGURE 10—Patch bioherms developed directly upon *Montastraea annularis* colonies. A) Mushroom-shaped bioherms at Cañada Honda. B) Bioherm on columnar *M. annularis* at Cañada Honda West. Rock hammer = 28 cm.

other localities, including higher upslope on bioherms at Las Caritas, is absent here.

Above the lower portion of the bottom tier, a thin layer of porous bioherm material coats the less porous interior, composed primarily of serpulid-tube material. This porous layer thickens with increasing elevation toward the top of the terraces, and continues up the bedrock as a ~5 cm–thick sheet of tufa reaching up to 3 m above the uppermost bioherms (Glumac et al., 2004). This onlapping tufa material does not appear to include any serpulid tubes. Highly weathered, the surficial tufa is porous, reddish brown, and extremely friable. Onlapping tufa is not included in our bioherm classification scheme owing to the absence of associated serpulid tubes.

Abuela Grande

Abuela Grande is located on the southern side of Lago Enriquillo (Fig. 1C). A gully running towards the lake cuts through this gently sloping area and reveals excellent exposures of the underling reef sequence (Guerard et al., 2004). Bioherms in this area are generally less well developed than at the other Enriquillo Valley locations, and form both small, individual mounds and low relief, matlike structures

(Glumac et al., 2004; Guerard et al., 2004). Similar to Cañada Honda, the Abuela Grande study site contains bioherm material positioned directly above both coral rubble and *in situ* dome coral colonies (Guerard et al., 2004).

Devil's Furnace

Situated along the west side of the main road 3.2 km northwest of Abuela Grande (Fig. 1C), the Devil's Furnace site has a flat to gentle slope. Individual bioherms here are possibly two-tiered and generally linearly organized, with some scattering of individual bioherms upslope. These bioherms are well developed, but smaller than the individual bioherms of Tier IV at Cañada Honda, and in general appear to have a higher proportion of serpulid tubes than tufa. The rough, weathered exteriors of these bioherms are of variable composition, with some primarily composed of serpulid tubes and others with thick rinds (10 to 20 cm) of weathered dark gray to black tufa (Berrios, 2002).

DISCUSSION

Paleoenvironmental Interpretation of Bioherm Formation

Enriquillo Valley serpulid-tufa bioherms developed as a result of a confluence of several key environmental factors. Restriction of the Enriquillo Seaway around 5.5–5.3 ka (Greer et al., 2009) provided the foundation for conditions supportive of bioherm growth (Mann et al., 1984; Taylor et al., 1985). This would be consistent with variable or increased precipitation near the Holocene Thermal Maximum (Greer et al., 2009). Layers of concentrated mollusk shells within and between bioherms suggest repeated pulses of seawater circulation within the restricted waters of the seaway. Each pulse likely increased the salinity of ancient Lago Enriquillo waters and reintroduced mollusk larvae equipped to survive in near-normal marine salinities. The *Chama* sp. bivalve clusters between bioherm tiers (Fig. 3B) represent opportunistic proliferation of mollusks following enhanced seawater circulation before more restricted conditions were reestablished. During periods of bioherm formation, seaway restriction would have confined the mobile serpulid larvae, facilitating larval gregariousness and, thereby, accelerating aggregation (ten Hove and van den Hurk, 1993; Cirilli et al., 1999).

While the present restriction of Lago Enriquillo under a semiarid climate has produced hypersaline waters, mid-Holocene restriction near the Holocene Thermal Maximum likely resulted in a range of salinities, including hyposaline conditions. Given the tolerance of serpulids for
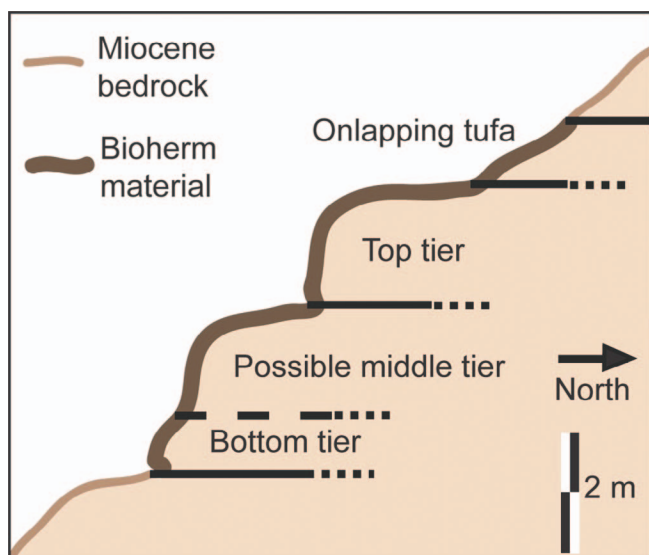

FIGURE 11—Schematic profile of tiered bioherms at Las Caritas.

highly variable salinity, a greater-than-modern range in salinities would be consistent with bioherm formation (ten Hove, 1979; ten Hove and van den Hurk, 1993; Glumac et al., 2004). Throughout bioherm development, hyposaline conditions would have reduced competition for nutrients and space, permitting euryhaline serpulids to aggregate. Such euryhaline mollusks as the bivalve *Brachidontes modiolus* and hydrobiid snails that preferred very low salinities (Abbott, 1974; Table 1), also likely benefitted from hyposaline conditions. In addition, a reconstruction of ancient Lago Enriquillo salinity history using ostracode pore morphologies (Medley et al., 2007) demonstrated that variable, low salinity conditions dominated between 4.7 and 2.9 ka. Serpulid tubes from coral-bioherm contacts were dated between 4.92 and 4.04 ka, suggesting that the conditions documented by Medley et al. (2007) likely characterize well the serpulid growth conditions.

A third obvious, though vital, environmental control on bioherm formation is that of Ca^{2+} and CO_3^{2-} availability (e.g., Benson, 1994; Glover and Robertson, 2003). In the Enriquillo Valley, groundwater springs originating in Miocene limestone bedrock provide continual resupply of $CaCO_3$ to Lago Enriquillo (Mann et al., 1984; Buck et al., 2005). The sustained flow of these springs, perhaps enhanced by increased rainfall in the region and seaway restriction, combined to create waters rich in Ca^{2+} and CO_3^{2-}. Buck et al. (2005) measured total ion concentrations in several springs and in lake water, and demonstrated that lake water Ca^{2+} concentrations are 130%–150% higher than that of the Caribbean Sea. Higher pH microenvironments produced by cyanobacteria may have enhanced tufa precipitation, which is supported by thin sections showing cyanobacterial filaments and by the absence of tufa under bioherm overhangs at Las Caritas, where cyanobacteria would have been relatively shielded from light. The microenvironments produced by cyanobacteria and their influence on tufa formation, however, are not well understood (Arp et al., 2001).

Four additional factors influenced the development of bioherms in the Enriquillo Valley: lake-level stability, warm waters, limited hard surface area, and wave action. Without periods of stable lake levels, the depth-sensitive bioherms could not have developed into meter-scale structures (e.g., Benson, 1994). The terraced bioherms of Las Caritas and the tiers at Cañada Honda and Cañada Honda West are evidence of such stability. Warm lake waters also contributed to bioherm development (e.g., Benson, 1994). In our scenario, when cool groundwater from springs laden with dissolved carbonate entered the warm lake, spring water CO_3^{2-} saturation state increased, leading to tufa precipitation (Benson, 1994; Nelson et al., 2005). Similarly, wave action against shorelines and preexisting bioherms enhanced tufa precipitation by increasing the CO_3^{2-} saturation state through CO_2 degassing (Nelson et al., 2005). This effect is most observable in the onlapping tufa present at Las Caritas, where a thin rind of tufa extends upslope from the terraced bioherms (Glumac et al., 2004, Fig. 11). Finally, the limited hard surface area on the lake bottom compelled serpulid larvae to settle in confined areas, leading to forced aggregation, as described by ten Hove (1979). When lake waters were near that of sea level, dead coral colonies, and later bioherm material and mollusks, provided needed hard surfaces. During periods of high lake levels, valley-wall bedrock also provided a suitable surface of colonization. Surface limitations partially explain the distribution of bioherm morphologies throughout the Enriquillo Valley.

Serpulids and tufa, though common entities, only rarely combine to construct meter-scale buildups. While it is possible that additional examples exist (particularly considering the varied terminology used to describe such formations and, therefore, the difficulty in performing intersite comparisons; see following section), two previously described sites are known to host serpulid-tufa bioherms. Late Triassic strata from Italy contain reefal buildups composed primarily of serpulid aggregations within a microbialite boundstone (Cirilli et al., 1999). These buildups are lenticular, approximately 10 m thick, and, as in the Enriquillo Valley, include serpulid aggregations encrusting mollusk

shells. In the Italian strata, however, buildups form large reef complexes up to several hundreds of meters thick, dwarfing the Holocene bioherm formations in the Enriquillo Valley. Interpreted to have formed in a mesosaline marine environment under eutrophic and low oxygen conditions and in an area with restricted circulation, these Triassic buildups likely developed under water conditions similar to those of the Enriquillo setting (Cirilli et al., 1999).

A second site is located in Ukraine and Poland, where Miocene microbialite reefs contain a small percentage of serpulid tubes (Jasionowski, 2006). Restricted, brackish conditions in this region concentrated dissolved Ca^{2+} and reduced taxonomic diversity, enabling serpulid-microbialite buildups to develop. Again, strong similarities exist between this site and that of Lago Enriquillo. This suggests that our description of paleoenvironmental conditions necessary for the formation of the Enriquillo serpulid-tufa bioherms may be applicable to other localities with a similar combination of unique environmental circumstances.

While serpulid-tufa bioherms are rare, decimeter to meter-scale caddisfly-tufa (or travertine) formations are well documented from numerous sites (e.g., Drysdale, 1999; Leggitt and Cushman, 2001; Carthew et al., 2003, 2006). Like serpulids, caddisfly larvae (order Trichoptera) are fully aquatic and build a hard protective casing that, in some cases, can attach to suitable media (e.g., Drysdale, 1999). In a tufa-depositing stream, tufa and caddisfly cases can intermingle, resulting in bioherm development. Nets woven by larvae for the purpose of straining food out of turbulent waters can also enhance tufa precipitation and bioherm growth (Drysdale, 1999). Caddisfly-tufa bioherms generally develop in freshwater, while serpulid-tufa bioherms are documented from brackish or even hypersaline conditions. Nevertheless, in many respects, the morphologies of caddisfly-tufa bioherms strongly resemble those of bioherms containing serpulids and suggest that serpulid and caddisfly larvae are capable of performing analogous ecological roles in their respective environments.

Bioherm Classification Schemes

Differences in bioherm-related terminology in the literature have led likely to assumptions about differences in bioherm form (Shapiro, 2000). Additional differences in terminology with regard to object descriptor (e.g., bioherm, stromatolite, microbialite, tufa, carbonate buildup, microbial buildup) further complicate intersite comparisons. Owing to wide variation in bioherm morphologies at every scale, no single published classification scheme corresponds exactly with ours for bioherms of the Enriquillo Valley. Nevertheless, numerous single categories in the literature correspond to our individual categories. In an effort to facilitate comparison between different study locations, classification categories from the literature that most closely resemble the Enriquillo Valley bioherm forms are identified. We restrict our discussion to works that explicitly attempt to develop classification schemes.

Our four bioherm macroscale categories, i.e., individual, clustered, patch, and terraced (Fig. 4), correspond to descriptions in Pedley (1990), Benson (1994), Shapiro (2000), Glover and Robertson (2003), and Carthew et al. (2003, 2006), as shown in Table 4. Although mound morphology is highly dependent on a specific combination of environmental conditions, certain mound categories described in the literature can be reasonably matched to the classification scheme developed for the Enriquillo Valley.

The classification scheme of Benson (1994) included bioherms found both along a lake shoreline and along fault lines of the warm, alkaline Pyramid Lake in California. Although the Benson (1994) classification categories are closest to Lago Enriquillo bioherm morphologies (Table 4), the Pedley (1990) and Glover and Robertson (2003) freshwater schemes also include categories comparable to the Enriquillo bioherms. The cascade model described by Pedley (1990) for cool freshwater tufas involves 1–2-m-tall, bulbous tufa mounds with shapes similar to the terraced bioherms at Las Caritas (Fig. 4D). In the Pedley

TABLE 4—Comparison of macroscale, mesoscale, and microscale classification terminology between Enriquillo Valley bioherms and other sites ([1]Pedley, 1990; [2]Benson, 1994; [3]Shapiro, 2000; [4]Glover and Robertson, 2003; [5]Carthew et al., 2003, 2006; [6]Dupraz et al., 2004.) *Onlapping tufa and tufa rinds were observed in the Enriquillo Valley, but are not included in our classification scheme, as explained in the text.

Macroscale classification: Enriquillo	Macroscale classification: other sites
Individual bioherm	[1]Algal bioherms, [2]barrel shaped, [3]domal hemisphericals, [4]domal mounds, [5]tufa stromatolites
Clustered bioherm	
Terraced bioherm	[1]Cascade tufa, [2]tufa girdles
Patch bioherm	[2]Mound shaped
Onlapping tufa*	[2]Sheet tufa

Meso- or microscale classification: Enriquillo	Meso- or microscale classification: other sites
Densely lithified tufa	[1]Peloidal tufa, [2]branching tufa (on weathered exterior of Enriquillo bioherms), [5]spongy tufa, [6]micropeloidal texture
Smooth knobby tufa	
Friable tufa	[3]Microdetrital tufa
Laminated tufa	[5]Densely laminated tufa
Tufa rinds*	[2]Nodular tufa, porous encrustations

model, mounds are formed in the splash zone below a waterfall and often incorporate large cavities or caves such as those seen at Las Caritas. A second model of cool-water tufa, shared by Glover and Robertson (2003) and Pedley (1990), is that of a lacustrine system. In this system, domal mounds (Fig. 4A), or as Pedley (1990) states, algal bioherms, form on hard media in lake waters with low wave energy.

Enriquillo Valley mesoscale and microscale forms also correspond to descriptions in the studies noted above, as well as in Dupraz et al. (2004; our Table 4). Alteration of certain forms (e.g., densely lithified tufa) due to weathering seems to result in some Enriquillo Valley classification categories being apparently incompatible with various descriptors in other classification schemes. Weathering alteration is therefore capable of causing considerable confusion when comparing tufa forms, particularly across wide time spans. Enriquillo Valley smooth, knobby tufa (Figs. 6C, 7F) does not appear to have an equivalent in any of the studies listed in Table 4. Both the weathered, hand-sample form and thin-section representations of smooth, knobby tufa are difficult to differentiate from other bioherm components. Other and specifically older tufas, therefore, may not host well-preserved examples of this form.

Although not strictly conforming to the Enriquillo classification scheme, Benson (1994) described decimeter-scale tufa characteristics similar to those seen in the Enriquillo Valley. The nodular tufa found at Pyramid Lake (Benson, 1994) is similar to the bulbous structures present on interior surfaces of bioherms at Cañada Honda (Fig. 6C). Furthermore, porous encrustations at Pyramid Lake appear similar to the tufa rinds observed by Glumac et al. (2004) at various sites near Lago Enriquillo. Interestingly, most of the tufa forms described by Benson (1994) that are applicable to Enriquillo samples were identified as forming in warm waters, including both ambient and hydrothermal. This suggests that cool- and warm-water tufas may form differently and therefore require independent classification schemes. Such differences are consistent with the observation by Carthew et al. (2003, 2006) that models describing temperate tufas are not always suitable for tropical tufa systems. The development of accurate models of tufa and bioherm formation would be facilitated through universal and consistent terminology, which could be used to enhance intersite comparisons and should be a future research goal.

CONCLUSIONS

The composition and morphologies of Holocene serpulid-tufa bioherms from the Enriquillo Valley, Dominican Republic, were

examined to characterize in detail these unusual structures and to determine a paleoenvironmental context for their development. Conclusions derived from this study are:

1. Macroscale classification of the Enriquillo bioherms yielded four categories: individual, clustered, patch, and terraced bioherms. Mesoscale categories of tufa include: densely lithified tufa, smooth knobby tufa, and friable tufa. Microscale classification also revealed densely lithified tufa and smooth knobby tufa, in addition to laminated tufa.

2. The unusual composition of Enriquillo Valley bioherms resulted from specific environmental conditions that developed after the mid-Holocene demise of the Enriquillo Seaway fringing coral reefs by about 5 ka (Greer et al., 2009). Restriction of the ancient Enriquillo Seaway from open circulation with waters from the Caribbean Sea close in time to the Holocene Thermal Maximum caused hyposaline conditions to develop, which permitted opportunistic serpulids to aggregate. Periods of stable lake levels and limited hard surface promoted development of bioherms to meter scale for a period of close to 1,000 years based on our serpulid radiocarbon dates. High Ca^{2+} and CO_3^{2-} concentrations in the seaway, owing to restriction and the inflow of spring waters originating from Miocene bedrock limestones, enabled tufa precipitation, which was further enhanced by year-round warm lake waters and wave action against the actively growing bioherms. Fluctuating salinity conditions persisted in the lake until at least about 2.8 ka based on radiocarbon dates from bivalves (Taylor et al., 1985; Medley et al., 2007) and analysis of ostracode pore morphometrics (Medley et al., 2007).

3. Although rare, serpulid-tufa bioherms have been documented from Upper Triassic strata in Italy and Miocene strata of Ukraine and Poland under environmental conditions similar to those described for the Enriquillo Valley. This suggests that bioherms of such unusual composition can be used to define a specific set of paleoenvironmental conditions.

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