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Geomorphic and fossil coral evidence bearing on the origin of coastal mushroom rocks at Bathsheba, Barbados

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ABSTRACT

Large fossiliferous limestone boulders exhibiting distinctive cap-and-pedestal morphologies occur along the Bathsheba coastline of Barbados, within the predominantly siliciclastic Scotland District. Traditionally attributed to mass wasting from Upper Coral Rock (UCR) exposures at Hackleton's Cliff, approximately 1.5 km inland and 300 m above the shoreline, these mushroom rocks may instead originate from nearby Middle Coral Rock (MCR) exposures. We investigated the origins of three representative mushroom rocks through qualitative fossil coral comparisons, examination of limestone exposures and their geomorphic setting, and observations of intertidal bioerosion. Fossil coral taxa identified in the mushroom rocks correspond more closely with those observed in nearby MCR exposures than at Hackleton's Cliff. Although non-standardized sampling prevents definitive provenance determination, fossil correspondence and outcrop distribution support a proximal MCR source as a plausible alternative. Localized rockfall or slope failure may explain emplacement, although transport from Hackleton's Cliff cannot be excluded. Contemporary chiton activity indicates ongoing biological modification of basal pedestals but cannot establish the timing of emplacement or morphological development. These initial findings suggest that the mushroom rocks may reflect formerly more extensive coastal limestone exposures and demonstrate the value of integrating paleontological observations with geomorphic evidence when investigating coastal boulder origins.

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Barbados; coral limestone; mushroom rock; paleoenvironment; West Indian chiton

Introduction

Barbados' coastline, particularly around the Bathsheba area (Scotland District and northeast coastal region), hosts scattered fossiliferous coral limestone and mixed lithology sedimentary boulders of all sizes (Figure 1). While some smaller rocks are undoubtedly the product of headland erosional forces (e.g. sea stacks/stumps, cliff collapse), the majority of larger boulders, often referred to as "mushroom rocks" locally due to their distinctive base-pedestal shape, diverge from the Scotland District's typical geology characterized by sandstones, marls, clay/silt/mudstones, and older oceanic basement sediments. Because of this difference in rock type, the

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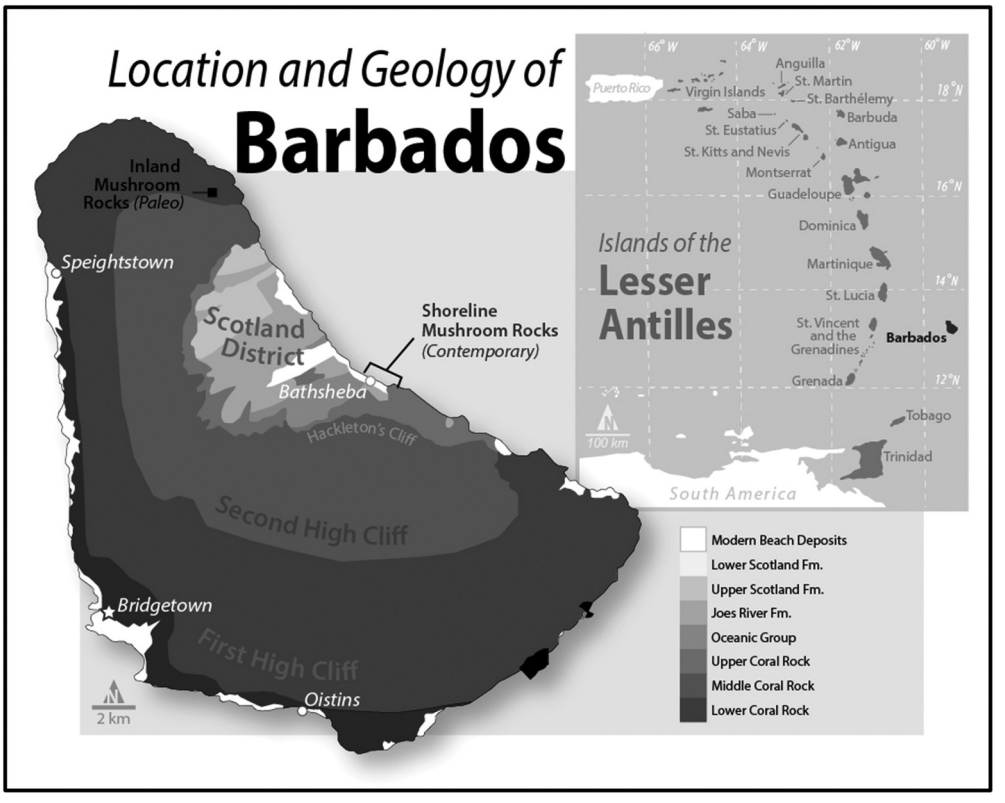

Figure 1. Map of Barbados showing location and basic, generalized geologic divisions of Barbados. Notice specifically the location of Bathsheba on the central-east coast and "shoreline mushroom rocks" area where many (contemporary) mushroom rocks are found. Also note the "inland mushroom rocks (paleo)" in the far north, approximately one kilometer from the current shoreline, illustrating a relict coastal landform found on an ancient marine terrace, showing prior sea level (see Allen & Paradise, 2022).

prevailing supposition suggests that these large limestone boulders likely originated from mass wasting processes along the ridge of Hackleton's Cliff (UCR, Upper Coral Rock terrace, usually dated ~600kya to 484kya), situated ~1.5 km away and nearly 300 meters above the current coastal location of the mushroom rocks (with ~20% slope beginning from the Cliff's base). Yet, younger limestone exposures (MCR, Middle Coral Rock terrace, often dated 484kya to 127kya) closer to the shoreline exhibit more similarities in fossiliferous coral species with the larger mushroom rocks than those at Hackleton's Cliff. This implies a potentially nearer source for the mushroom rocks rather than the traditionally cited Hackleton's Cliff UCR.

While no literature states exactly *where* along Hackleton's Cliff the boulders that became Barbados' mushroom rocks originate, literature does highlight the cliff as a likely source (cf., Donovan & Harper, 2005; Poole & Barker, 1983; Speed, 1981; Speed & Cheng, 2021; Taylor & Mann, 1991), which suggests that large boulders fell to the northeast coast via mass wasting events, perhaps brought on by differing strata, e.g. the geologic contact between the underlying, locally unstable sedimentary strata and

loosely consolidated sandstones. The (scant) literature, however, pays no attention to the smaller-extent, interdigitated Middle Coral Rock terrace outcrops scattered along the current coast.

To address this gap in research and better understand the potential provenance of the Bathsheba mushroom rocks, we conducted qualitative comparisons of fossil coral taxa identified in three representative mushroom rocks, nearby Middle Coral Rock (MCR) exposures, and the Upper Coral Rock (UCR) at Hackleton's Cliff. We also examined the spatial distribution and geomorphic setting of existing MCR outcrops to assess the plausibility of localized mass wasting as an alternative to long-distance transport from Hackleton's Cliff. Additionally, observations of West Indian chiton activity and the characteristic cap-and-pedestal morphology were considered in relation to post-emplacement bioerosional modification. Together, these observations provide a basis for reassessing the traditionally proposed provenance of the mushroom rocks and suggest that nearby MCR exposures represent plausible alternative source locations, although the precise origins and timing of emplacement remain unresolved.

Distinguishing between these potential source locations is important not only for establishing the provenance of the mushroom rocks but also for understanding the geomorphic processes responsible for the evolution of the Bathsheba coastal landscape. Derivation from Hackleton's Cliff would require the movement of large limestone blocks across much of the intervening Scotland District terrain, whereas a proximal MCR source would suggest localized slope failure associated with the progressive modification of formerly more extensive coastal limestone exposures. The latter interpretation would place greater emphasis on the combined influence of differential erosion, outcrop retreat, and subsequent intertidal bioerosion in shaping the present coastline. Accordingly, reassessing the provenance of these boulders provides an opportunity to examine how inherited geological structures, mass movement, and contemporary coastal processes may interact in the evolution of mixed carbonate–siliciclastic landscapes.

Given Barbados' distinctive geological and geomorphic setting within the Lesser Antilles, we first provide an overview of the island's geological development and the characteristics of the Bathsheba study area, with particular attention to the distribution of coastal mushroom rocks, nearby limestone exposures, and potential mass movement processes. We then describe the qualitative field investigations and fossil coral comparisons used to assess alternative provenance interpretations, together with observations of contemporary coastal bioerosion. The resulting evidence is subsequently presented and discussed in relation to the potential origins, emplacement mechanisms, and post-emplacement morphological development of the mushroom rocks.

Site setting

Overview of geologic and tectonic background of Barbados

The island of Barbados originated from accretion of trough sediments during subduction of the Atlantic Oceanic lithosphere beneath the Caribbean magmatic arc and the Tobago forearc basin, creating Barbados' accretionary prism during the late Early Pleistocene (Allen, 2017; Day & Day, 2017; Garmon et al., 2017; Schellmann & Radtke, 2004; Speed, 1981). The island, with no volcanic basis, represents the structural high of the overall prism above sea level making it unique in the Lesser Antilles (Day & Day, 2017; Garmon

et al., 2017). As noted in Figure 1, the Scotland District – located in the east-northeast of the island – is geologically distinct from the rest of coral limestone-based Barbados, hosting mainly non-coral-based Tertiary sedimentary rocks such as sandstones, shales, silt/mud/claystone, and marls, likely stemming from South America's deep ocean sediments which settled on uplifted and uplifting limestone during the Eocene (Allen & Paradise, 2022; Cruden et al., 2014; Donovan & Harper, 2005; Patel, 1995).

Contemporary Barbados began uplifting around 700,000 years ago at an average rate of 300 mm per 1000 years (Day & Day, 2017; Speed, 1981; Speed & Cheng, 2021). Uplift occurred in stages, marking-out separate terraces, with a morphology change occurring sometime after the last interglacial period around 127,000 and 112,000 years ago (Muhs & Simmons, 2017), where each terrace representing a (paleo) fringing reef hosting various coral species fossils such as *Acropora spp, Diploria spp, Montastraea spp*, and *Porites spp* (Mesolella, 1967), and each uplifting reef system comprising zone successions: a fore-reef, reef-crest, and back-reef of individual reef units overlying each other (Radtke & Schellmann, 2005). These terraces developed through successive episodes of reef growth associated with glacio-eustatic sea-level fluctuations and the continuing tectonic uplift of Barbados, as carbonate-producing environments were established at suitable water depths during successive interglacial highstands (Mesolella et al., 1970; Schellmann & Radtke, 2004). The mushroom rocks along Bathsheba's shoreline occur adjacent to a shallow limestone pavement (visible from shore) that extends seaward for approximately 100 m or more in some locations. In the Scotland District, the diapir sediment is exposed, and both tectonic processes and past (large) mass wasting events remain apparent in the landscape (Patel, 1995).

Taylor and Mann (1991) suggest that a coral cap once covered the tertiary sediment rocks on Hackleton's Cliff (Upper Coral Rock terrace, UCR), but due to mass wasting, the resistant Quaternary coral cap was separated from less resistant tertiary sedimentary rock, exposing the high slopes and soft friable rocks, making them more susceptible to deep decay and subsequent erosion. Alongside this process, extreme rainfall further weakened the structure, and erosion likely occurred more readily in the Scotland District (Barker & McGregor, 1995). In terms of sediment transport, Acker and Stearn (1989) state that clastic rocks from the Scotland District traveled (presumably downslope) to the east-northeast coast of Barbados during periods of heavy rainfall via river discharge – though they give no indication of the rocks' sizes – while Poole and Barker (1983) suggest large boulders (including the mushroom rocks currently on Bathsheba's shores) could have "easily" slid down the hillside due to the Scotland District's " … greasy oceanic clays", even though they give no specific evidence for *where* they may have originated.

The Scotland district

Located on the north-east of Barbados, the Scotland District is found mainly in the parishes of St. Andrew and St. Joseph with an area over 40 km^2 that takes the shape of a semi-circle, being bordered by a steep cliff face inland. This study centers specifically on the areas in the Scotland District: Bathsheba Park's beach, located on Barbados' northeast coast, and Hackleton's cliff (a "coralstone" high cliff), located approximately 1.5 km southwest from said beach (Figure 1).

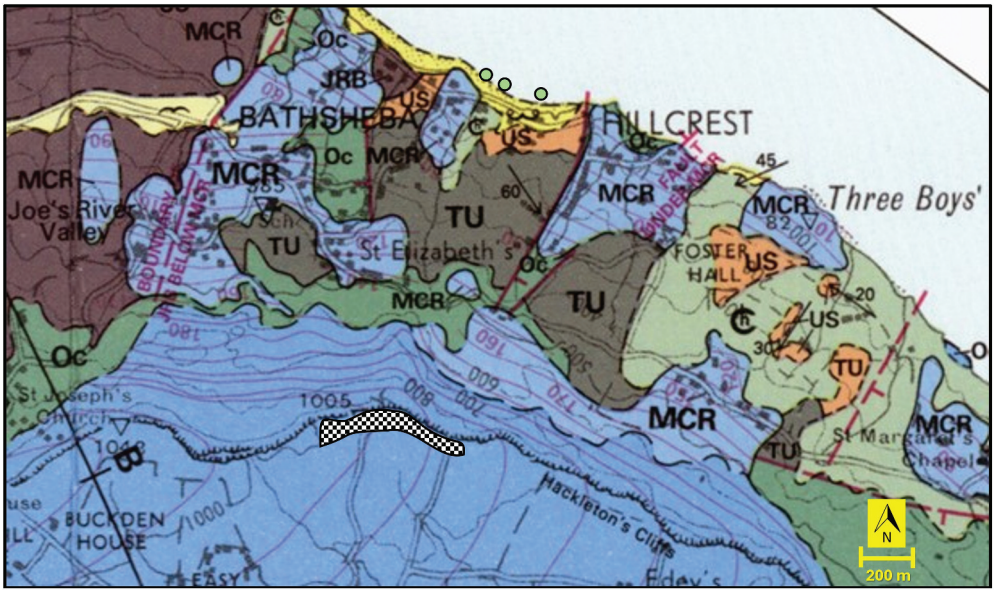

Figure 2. Geologic map of Hackleton's Cliff and Bathsheba by Poole and Barker (1983). MCR: middle coral Rock; oc: oceanics group Undivided; TU: T unit (Upper Scotland formation); US: Upper Scotland formation Undivided; JRB: Joe's river Beds; C (light green): head and Scree; dark blue surrounding "Hackleton's cliffs": Upper coral Rock; bright yellow along the coast: modern beach deposits; black and white checkered area: previous always-presumed source location of mushroom rocks at Bathsheba beach Park. Bright green dots represent approximate locations of rocks 1, 2, and 3 (from left to right).

The Scotland District's geology differs from the coral cap found throughout the rest of Barbados. Structural units include the Oceanic nappes/formation, Bissex Hill nappe, Pelagic and Hemi-pelagic suites, Terrigenous suite and Morgan Lewis member (Scotland formation), and Debris flow suite (Joe's River Formation) (Figure 2; cf., Speed, 1981). The rock types in these units include marl, mudstone, siltstone, quarts-sandstone, and conglomerate alongside anomalous fossilized coral outcrops (parts of the MCR; Speed, 1981), indicating that much of the rock material in this area has an overall softer composition than that of the coral stone, and is therefore more susceptible to (faster) deterioration and subsequent erosion. Due to the unstable folded and faulted strata within the area, the Scotland District remains prone to landslips and uneven topography, making it historically sparsely populated. Today, however, the geological suites are juxtaposed with populated communities and (continually repaired) roads within the Bathsheba area. While there are numerous mushroom rocks of all sizes along Barbados' east and northeast coasts, at Bathsheba Park beach three random mushroom rocks were selected for this study as representative samples (Figure 3; see also Figure 1 for general location).

Mushroom rocks, local geology, and geomorphic features

Barbados' Scotland District coastline hosts multiple mushroom rocks, also referred to as rock pedestals. These large boulders are geomorphic landforms of varying sizes, some of which can be formed via wind erosion (e.g. yardangs) and commonly found



Figure 3. Mushroom rocks along the coast of Bathsheba Beach Park beach surveyed for this study, labeled from west to east: rock 1, Rock 2, and Rock 3.

in desert areas (Mashaal et al., 2020). Regardless of this basic definition, most mushroom rocks are *not* formed by wind. More commonly, differential decay processes (e.g. salt decay, chemical decay, rainsplash/water, bioerosion) that exploit fractures/weak joint spacing, perhaps aided by saltation/deflation of fines constantly targeting a low-to-ground section of a large stone or outcrop can cause the sides to erode, giving the rock base a slender appearance whilst the top is overarching like that of a mushroom cap (Figure 4; Mabbutt, 1977 Twidale & Campbell, 1992; Grab et al., 2011).

Literature on Bathsheba's mushroom rocks specifically is limited, although Donovan and Harper (2005, p. 29) expressly note the mushroom rocks were " ... presumably derived from the face of the Hackleton's Cliffs to the south west", with a popular publication (Cook & Abbott, 2011) forwarding that assumption. However, multiple authors also refer to limestone blocks or slabs which detached from the east-facing escarpment/cliff face and may have found their way to the coastline sometime in the past (i.e. Hackleton's Cliff; see Day & Day, 2017; Hearn et al., 2001; Hodgson et al., 2002; Patel, 1995; Poole & Barker, 1983). Such assumptions are based on the Scotland's District's geology which – because it hosts natural oil seeps and sometimes-oily strata (see Speed & Cheng, 2021) – can lead to soil creep and landslides (though the last recorded major mass wasting event in the area occurred in 1908). These presumptions could also stem from side-of-the-road observations of potentially recent mass wasting events found along the interdigitated MCR outcrops in the Bathsheba area (Figure 5). Because of this geology then, it has been presumed that a mass wasting event separated part of the cliff and a series of large boulders tumbled (and presumably slid at least part of the way) down a ~ 20% slope to present-day Bathsheba Park beach from approximately 1.5 km above the present shoreline.

As such, the proposed derivation from Hackleton's Cliff has not been independently demonstrated. What is known, however, is rock pedestals such as Barbados' coastal mushroom rocks often represent notched rocks formed by a combination of wave-action and herbivorous invertebrates (i.e. chitons, echinoids, and/or



Figure 4. Representative examples of different mushroom rock types. A. Sandstone yardang in Paracas National reserve, Peru, created mainly by aeolian processes (though in this location along the Pacific Ocean coast, salt decay also contributed). B. Limestone coastal mushroom rock along the coast of Aoshima island (part of the "Ogre's Washboard"), Kyushu, Japan, created through wave and tidal action (no biological organisms). C. Limestone ("coralstone") mushroom rock, Bathsheba, Barbados, exhibiting a cap-and-pedestal morphology potentially modified by intertidal bioerosion, wave action, and other coastal weathering processes (specifically, Rock 3 used in this study; see Figure 6). D. Sandstone yardang-esque pedestal rock in Wadi Rum, Jordan (locally known as "chicken rock"), created mainly via salt decay, with perhaps very small, low-to-ground aeolian processes. for size comparison, a is approximately two-meters across at its base, B is one-meter tall, C is ~11 × 9 meters, and D is just under four-meters tall. All photos by author.

gastropods) feeding on the algae via scraping, breaking down the weaker limestone rocks during that action (Allen & Paradise, 2022; Donovan & Harper, 2005; Glynn & Manzello, 2015; Rasmussen & Frankenberg, 1990; Santini et al., 1991). The tidal range in the Caribbean is approximately one-meter, which is close to *all* of the Barbados mushroom rock's stalk lengths (Figure 6; Allen & Paradise, 2022) and, further, this tidal range provides warm and moist environmental conditions for algae to develop, attracting the bio-eroding organisms (i.e. the West Indian chiton, cf., Donovan & Harper, 2005).

Mass wasting has played an important role in the geomorphic development of the Scotland District, where steep slopes, structurally disturbed sedimentary strata, and periods of intense rainfall contribute to slope instability (Ally, 1996; Day & Day, 2017; Patel, 1995). Indeed, historical and contemporary landsliding is documented within the Scotland District (cf., Cruden et al., 2014). Within the Bathsheba area, discontinuous Middle Coral Rock (MCR) exposures occur among the predominantly siliciclastic formations, including locations near the present shoreline where large limestone boulders are also found (Figures 2 and 5). These geological and geomorphic relationships provide the local context for



Figure 5. Coastal limestone boulders adjacent to an MCR headland east of Bathsheba Beach Park (a slightly embayed beach). The MCR exposure occurs among the mixed sedimentary lithologies of the Scotland District. Photographs were taken from approximately the same location, looking east (A) and west (B), near the Hillcrest area identified in Figure 2. The positions of the three representative mushroom rocks examined in this study are indicated in B. The juxtaposition of large coastal boulders and nearby limestone exposures illustrates the potential for localized rockfall or mass wasting although the precise source locations, transport mechanisms, and timing of emplacement have not been established.

examining the provenance of the coastal mushroom rocks and the potential processes associated with their emplacement.

Methods

This study focuses on the vicinity of Bathsheba Park and Hackleton's Cliff, St. Andrew, Barbados (Figures 1 and 3), and examines the potential provenance and subsequent morphological development of three large coastal mushroom rocks within the Scotland District. To evaluate whether these rocks originated from the traditionally proposed Upper Coral Rock (UCR) exposures at Hackleton's Cliff or from nearby Middle Coral Rock (MCR) outcrops, the investigation employed three complementary approaches:

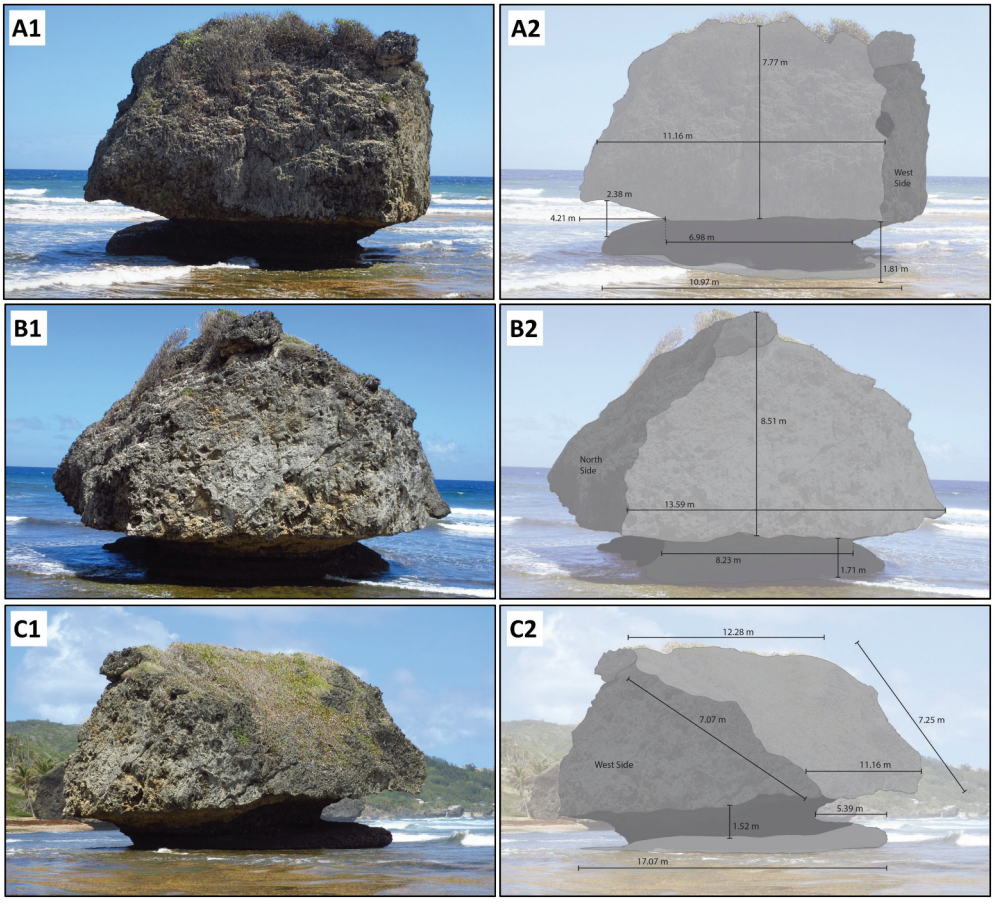

Figure 6. Rock 3 measurements (from Allen & Paradise, 2022, used with permission of authors). A1 & A2: north aspect and measurements, respectively; B1 & B2: west aspect and measurements, respectively; C1 & C2: southwest aspect and measurements, respectively. The measurements document the present narrowing of the basal stalk relative to the broader upper portion of Rock 3 (and other Barbados mushroom rocks).

- Qualitative comparisons of fossil coral assemblages among the mushroom rocks and potential source exposures,
- Assessment of intertidal bioerosion as a mechanism contributing to the development of the characteristic cap-and-pedestal morphology following emplacement,
- Examination of the spatial distribution and geomorphic setting of nearby MCR exposures to evaluate the plausibility of localized mass wasting and short-distance emplacement.

Together, these approaches provide a basis for assessing alternative provenance interpretations while distinguishing potential source locations and emplacement processes from subsequent coastal modification.

To assess potential similarities in fossil composition among the proposed source locations, we conducted qualitative field examinations of three

representative mushroom rocks, two nearby Middle Coral Rock (MCR) outcrops, and the portion of Hackleton's Cliff corresponding to the Bathsheba coastal area (Upper Coral Rock, UCR). All accessible sides of the three mushroom rocks were examined, although their upper (top) surfaces could not be inspected owing to access limitations. At each location, observations focused on identifying the predominant fossil coral taxa visible on accessible rock surfaces, rather than systematically counting individual colonies or surveying standardized exposure areas. As such, the resulting comparisons represent the principal taxa identified during field examination rather than exhaustive inventories of the fossil assemblages at each location. Because neither the number of specimens examined nor the area surveyed was standardized among exposures, the presence of particular taxa was considered more informative than their apparent absence. Accordingly, fossil similarities and differences were evaluated qualitatively and used as one line of evidence, alongside the locations of existing limestone outcrops, the spatial distribution and geomorphic setting of nearby limestone exposures, and boulder morphology, to assess the relative plausibility of the proposed provenance interpretations.

The second component examined the potential contribution of intertidal bioerosion to the development of the mushroom rocks' characteristic pedestal morphology following emplacement. To examine this potential, we considered published carbonate removal rates associated with the grazing activity of West Indian Chiton (*Chiton tuberculatus* and *Acanthopleura granulata*). Glynn and Manzello (2015, Table 4–2) report an erosion rate of 394 g CaCO3 m−2 yr−1 for this species, associated with a grazer abundance of 22 individuals m−2 at La Parguera, Puerto Rico. This value represents carbonate removal per unit substrate area under particular ecological conditions rather than an erosion rate attributable to an individual chiton, meaning the published rate cannot be multiplied directly by the number of chitons observed on a boulder face. Although contemporary chiton abundance was recorded around the basal perimeter of Rock 3, the corresponding density over the actively grazed surface, together with its historical variability, could not be established. The published erosion rate was therefore considered only as ecological context for interpreting the potential contribution of chiton grazing to post-emplacement modification, without calculating rock-specific carbonate removal or the duration of pedestal development.

The third component of the investigation examined whether the distribution and geomorphic setting of existing Middle Coral Rock (MCR) exposures could support a proximal source for the Bathsheba mushroom rocks. This assessment considered the present location and approximate elevation of nearshore limestone outcrops, their relationship to the surrounding Scotland District lithologies, and published estimates of uplift and tropical limestone weathering rates (Donovan & Harper, 2005; Lace & Mylroie, 2016). Although these rates provide a general context for the long-term modification of Barbados' limestone terraces, they do not independently establish the former height or geometry of individual outcrops. In this light, the paleo-source assessment was undertaken as a qualitative assessment of potential source locations and their geomorphic relationships rather than a precise reconstruction of former topographic elevations.

Results

Fossil coral distribution

Fossil coral taxa were identified through qualitative field examinations of three representative mushroom rocks along the Bathsheba coastline (Figure 3), two nearby Middle Coral Rock (MCR) outcrops, and the portion of Hackleton's Cliff corresponding to the study area (Upper Coral Rock, UCR). The MCR exposures occur within the coastal zone where limestone outcrops are interdigitated with the predominantly siliciclastic formations of the Scotland District (Figure 2). The observations documented both similarities and differences in the predominant coral taxa identified among the mushroom rocks and potential source exposures.

Rock 1, situated along the Bathsheba shoreline, contained four principal fossil coral identifications: *Montastraea annularis*, *Montastraea-I trinitatis*, and two *Diploria* species (Neogene Marine Biota of Tropical America [NMITA], 2004a). The same two *Diploria* species were observed in Rock 2, indicating correspondence in the fossil taxa identified in these two boulders. Rock 3 contained three principal coral identifications: *Montastraea-I trinitatis*, *M. annularis*, and *Diploria* spp. The two nearby MCR outcrops, situated in the vicinity of Rocks 1 and 3, contained three principal coral identifications: *M. annularis*, *M. trinitatis*, and *Diploria* spp. (Figures 7 and 8), corresponding with those observed in the representative mushroom rocks. A small number of fossil West Indian top shells (*Cittarium pica*) were also observed within one of the MCR exposures (Figure 8). The coral identifications are broadly consistent with previously reported fossil assemblages

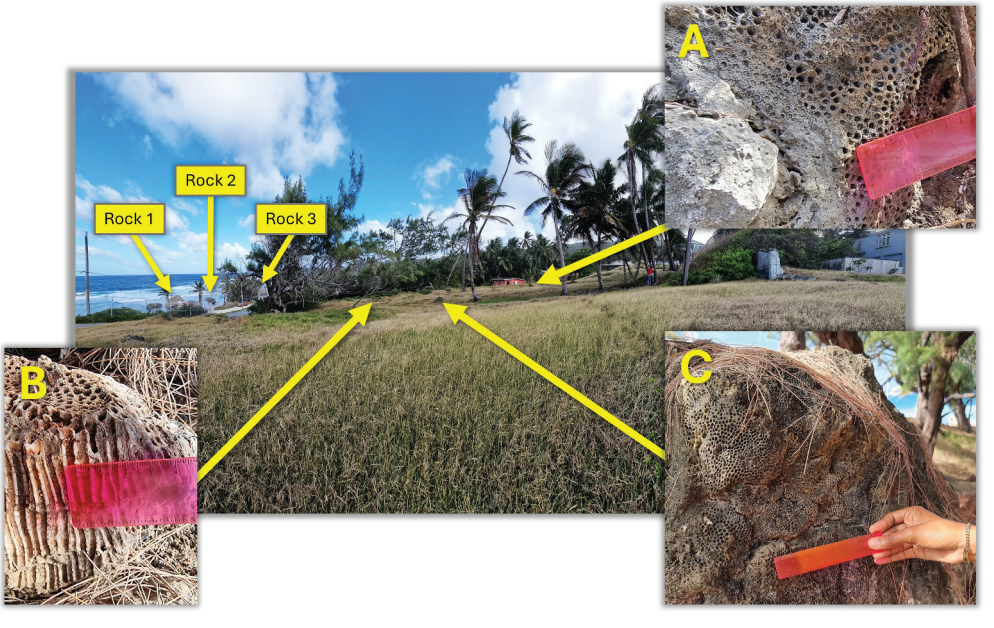

Figure 7. Looking east over MCR outcrop area west of mushroom rocks used in this study. A: *Montastraea-I trinitatis*; B & C: *Montastraea annularis*. Entire grass-covered area is the interdigitated MCR. Line of trees directly behind orange/pink-colored house represents top of small river edge (and the side of the MCR). Note person in red shirt under inset C for overall scale.



Figure 8. Looking east at MCR outcrop southeast of Rock 3. A & B: *Diploria spp.;* C: west Indian top shell (*Cittarium pica*) fossil layer, suggesting a previous colony. Note that the two outcrops represented in a & B were once a single outcrop which was split to create the road (originally a railway line).

from the coral limestone terraces of Barbados (Mesolella, 1967; Muhs & Simmons, 2017; Schellmann & Radtke, 2004) and, overall, the three examined mushroom rocks exhibited recurrences of *Montastraea* and *Diploria*, although the particular combinations of identified taxa varied among individual boulders.

Examination of the portion of Hackleton's Cliff corresponding to the Bathsheba coastal area identified four principal coral taxa: *Diploria* spp., *Diploria sarasotana*, *M. cavernosa-1*, and *M. annularis* (NMITA, 2004a, 2004b). The occurrence of *Diploria* spp. and *M. annularis* indicates some correspondence between the UCR exposure, the examined mushroom rocks, and the nearby MCR outcrops. However, *D. sarasotana* and *M. cavernosa-1*, both observed at Hackleton's Cliff, were not identified during examination of the three mushroom rocks or the two MCR exposures. Conversely, *M. trinitatis*, observed in the mushroom rocks and nearby MCR exposures, was not recorded during examination of the selected UCR exposure. These differences describe the taxa identified during field examination rather than their demonstrated absence from the respective limestone formations, as the observations were not based on standardized sampling areas or exhaustive fossil inventories.

Potential source exposures and bioerosional modification

The nearby MCR exposures occur within a coastal landscape characterized by marked lithological contrasts and substantial modification of original/parent limestone terraces. The investigated southwestern MCR exposure presently reaches approximately 20 m above sea level. Although published geological interpretations assign a broad range of Pleistocene ages to limestone exposures mapped as MCR (Day & Day, 2017; Muhs & Simmons, 2017; Schellmann & Radtke, 2004), the

geological age of the specific Bathsheba exposure examined in this study has not been independently established. Consequently, the mapped MCR designation does not necessarily indicate that all exposures assigned to this unit represent a single episode of reef formation or emergence. In terms of our findings, what this means is the present distribution of limestone exposures identifies potential source locations considerably closer to the mushroom rocks than the traditionally proposed UCR exposures at Hackleton's Cliff (Figure 2). The present distribution of MCR exposures identifies potential source locations substantially closer to the mushroom rocks than Hackleton's Cliff, although their former dimensions and configurations remain uncertain.

The mushroom rocks exhibit pronounced cap-and-pedestal morphologies, characterized by relatively broad upper portions supported by narrower basal stalks. To document the geometry of this form, measurements of Rock 3 reported by Allen and Paradise (2022; Figure 6) were considered alongside observations of contemporary intertidal biological activity. The measurements indicate substantial narrowing of the basal stalk relative to the broader upper portion of the boulder, producing a recessed surface within the intertidal zone. In this study, a total of 73 chitons was observed around the basal perimeter of Rock 3, with similar activity noted on Rocks 1 and 2, although precise counts were not obtained at those locations owing to wave conditions. These observations document contemporary grazing activity along the recessed basal surfaces, but neither cumulative carbonate removal nor the duration of pedestal development could be determined. Still, such observations could provide a basis for considering the role of bioerosion in the subsequent modification of the mushroom rocks.

Discussion

The combined fossil coral and geomorphic evidence provides a basis for reconsidering the provenance and subsequent morphological development of the Bathsheba mushroom rocks. The following discussion evaluates competing source and emplacement interpretations, considers the role of post-emplacement bioerosion, and examines the broader implications for coastal landscape evolution.

Fossil correspondence and its limitations

The fossil coral comparisons provide an initial basis for reconsidering the traditionally proposed provenance of the Bathsheba mushroom rocks. Across the three representative boulders, the predominant taxa identified during field examination included *Montastraea annularis*, forms identified as *M. trinitatis*, and *Diploria spp*. These also occurred in the two nearby Middle Coral Rock (MCR) exposures examined within the Bathsheba area (Figures 7–11). Along the trail beneath Hackleton's Cliff in the Upper Coral Rock (UCR), *Diploria spp*. and *M. annularis* were likewise observed, together with forms identified as *Diploria sarasotana* and *M. cavernosa* (Figure 12). The observed correspondence is therefore closer between the mushroom rocks and the nearby MCR exposures, although the shared taxa indicate that the fossil evidence does not uniquely distinguish the proposed source formations.



Figure 9. Coral fossil species in Rock 1. A: *Montastraea annularis*; B: *Diploria spp.*; C: *Montastraea-I trinitatis*.

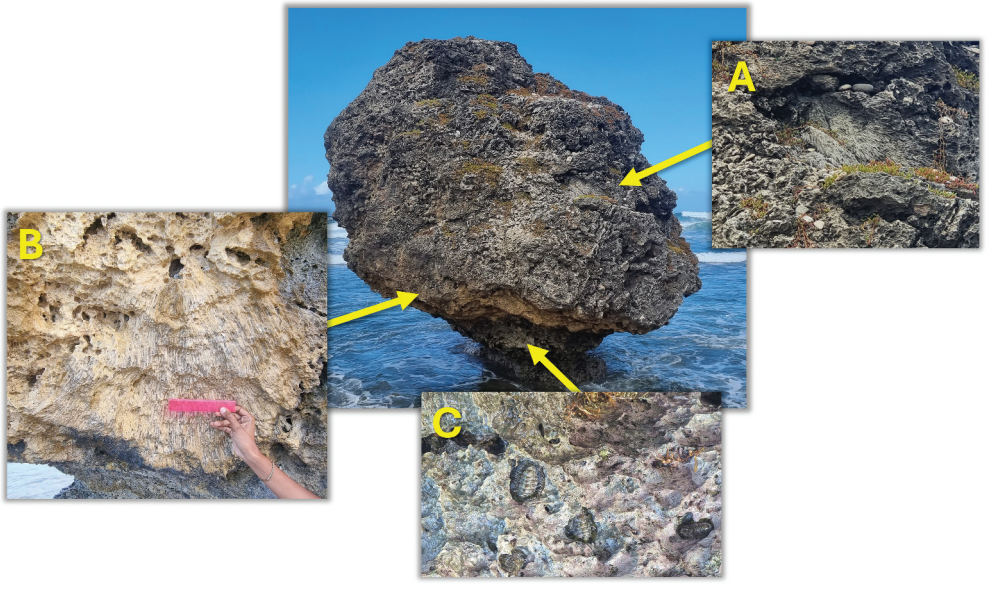

Figure 10. Coral fossil species in Rock 2. A & B: *Diploria spp.*; C: West Indian chiton (*Acanthopleura granulata*).

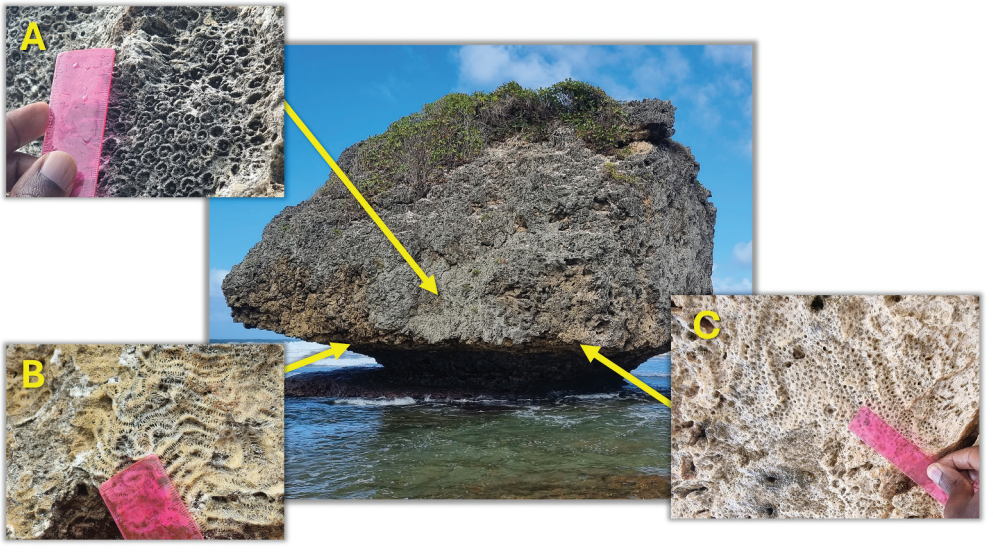

Figure 11. Coral fossil species in Rock 3. A: *Montastraea-l trinitatis*; B: *Diploria spp*.; C: *Montastraea annularis*.

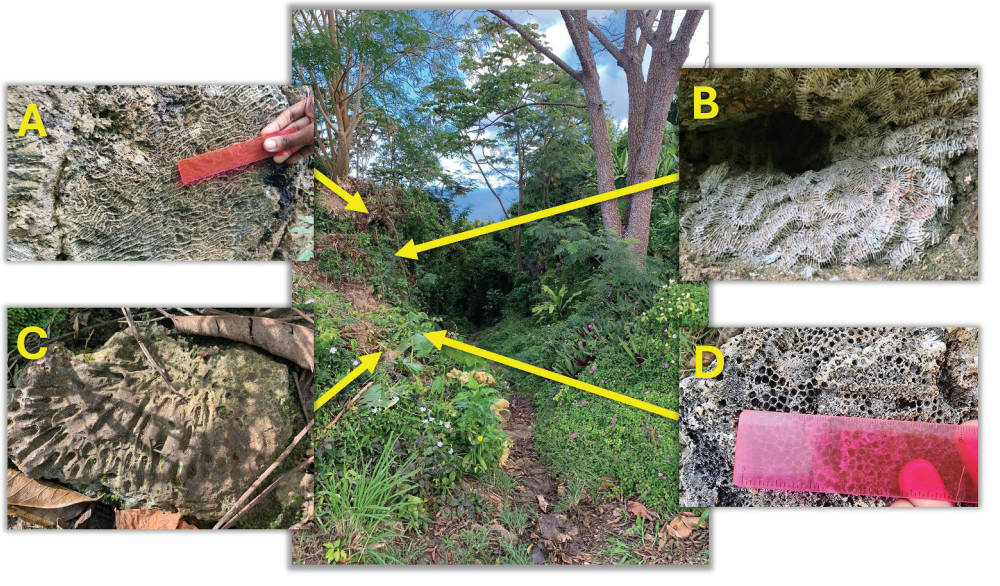

Figure 12. Coral fossil species along the path beneath Hackleton's Cliff Park. A: *Diploria spp*.; B: *Montastraea annularis*; C: *Montastraea cavernosa-1*; D: *Diploria sarasotana*. The forms illustrated in C and D were observed at the examined UCR exposure sites but were not identified during the qualitative examinations of the three mushroom rocks or two nearby MCR exposures.

These comparisons require qualification. Although the observed fossil correspondence is consistent with a proximal MCR source, the qualitative nature of the observations and incomplete exposure of the examined surfaces prevent definitive provenance determination or exclusion of Hackleton's Cliff. The fossil evidence is therefore most informative when considered alongside the spatial distribution and geomorphic setting of the potential source exposures.

Competing source and transport mechanisms

The spatial relationships shown in Figure 2 present two contrasting, though not mutually exclusive, interpretations of boulder emplacement. Derivation from Hackleton's Cliff would require movement from the inland UCR escarpment across approximately 1.5 km of intervening terrain and an overall elevation difference of about 300 m. These values yield a simple average gradient of approximately 20%, but do not take into account the detailed, feral relief-like topography, or establish a transport route. The present landscape also cannot be assumed to reproduce conditions at the time of detachment. Episodic mass wasting from the more distant escarpment, potentially involving movement across heterogeneous and locally unstable Scotland District strata, therefore remains possible, even though a specific pathway and emplacement event have not been documented (Donovan & Harper, 2005; Poole & Barker, 1983; Taylor & Mann, 1991).

A compelling alternative is detachment from limestone exposures closer to the present shoreline. Discontinuous MCR outcrops occur within the mixed carbonate-siliciclastic terrain near Bathsheba, and large limestone blocks are present adjacent to more than a few of these exposures (Figures 2 and 5). Their juxtaposition provides a field-based reason to consider localized rockfall or slope failure followed by relatively short-distance displacement. Differential decay/weathering and erosion of the surrounding, less resistant sedimentary rocks, together with retreat or removal of portions of the limestone exposures, could have altered the former coastal configuration. Nevertheless, since neither the former height and geometry of these outcrops nor the precise timing of boulder emplacement can be reconstructed from regional uplift and surface-lowering rates alone, the proximal-source interpretation is better stated as geomorphically plausible, rather than demonstrated. Similarly, the angular forms of the larger boulders are compatible with limited modification during transport, but angularity cannot independently establish transport distance or mechanism, particularly where movement may have involved sliding or episodic slope failure rather than sustained rolling.

Post-emplacement bioerosion

The characteristic cap-and-pedestal morphology concerns a subsequent stage in the history of the mushroom rocks and should be distinguished from their geological provenance and emplacement. Measurements of Rock 3 reported by Allen and Paradise (2022; Figure 6) document pronounced narrowing of the basal stalk relative to the upper boulder. During our investigation, 73 West Indian chitons were observed around the basal perimeter of Rock 3, while chiton activity was also observed on Rocks 1 and 2 without corresponding counts. The

occurrence of grazing organisms along these recessed intertidal surfaces is consistent with a potential contribution from biological erosion to continued pedestal modification, alongside wave action and other coastal weathering processes (Allen & Paradise, 2022; Donovan & Harper, 2005; Glynn & Manzello, 2015; Rasmussen & Frankenberg, 1990; Santini et al., 1991).

These observations do not necessarily establish the rate or duration of pedestal development. The published carbonate-removal value discussed by Glynn and Manzello (2015) is expressed per unit area of substrate under particular ecological conditions, not per individual chiton, and therefore cannot be multiplied by the number of animals observed at Bathsheba to derive a rock-specific erosion rate. Nor is there evidence that contemporary chiton abundance represents the ecological conditions prevailing throughout the boulders' residence in the intertidal zone. In other word, while the geometry of the pedestal consequently provides evidence of modification after emplacement, no defensible numerical residence time or emplacement age can be inferred from the available observations.

Landscape evolution and future testing

The alternative provenance interpretations imply different histories of landscape development along the Bathsheba coast. If the boulders were derived from Hackleton's Cliff, their present positions would record substantial displacement from an inland escarpment. If they originated from nearby MCR exposures, they may instead preserve remnants of localized slope failures along a coastal margin where portions of the former limestone outcrops have subsequently been modified or removed. The fossil correspondence, proximity of surviving MCR exposures, and occurrence of large coastal limestone blocks collectively favor further consideration of the latter possibility. In either case, three stages must remain analytically distinct: formation of the parent reef limestone, detachment and emplacement of the boulders, and subsequent modification of their basal surfaces in the coastal environment.

Independent dating and more detailed stratigraphic comparisons of the mushroom rocks and candidate source exposures would provide a stronger test of the proposed provenance interpretations, especially where mapped limestone units may include deposits of different ages. Such dating would constrain the age of the parent limestone but would not necessarily establish when individual blocks detached or reached the shoreline, and evidence bearing directly on emplacement would still be needed. More systematic fossil surveys, detailed mapping of potential source exposures, and a topographic assessment of possible transport pathways would likewise help evaluate the alternatives. For the present investigation, the significance of the Bathsheba mushroom rocks lies in demonstrating how isolated coastal boulders can retain clues to source outcrops and geomorphic relationships no longer fully expressed in the contemporary landscape. While the Bathsheba findings are geographically specific, an interpretive approach as conducted for this study may be applicable to other uplifted carbonate coastlines and mixed-lithology environments where isolated boulders survive as relict indicators of former geomorphic conditions (cf., Allen & Paradise, 2022).

Conclusion

The fossil coral comparisons and geomorphic observations presented in this study provide a basis for reconsidering the traditionally proposed origin of the Bathsheba mushroom rocks at Hackleton's Cliff. The principal coral taxa identified in the three representative boulders correspond more closely with those observed in nearby Middle Coral Rock (MCR) exposures than with those recorded in the examined Upper Coral Rock (UCR) exposure. Together with the proximity and distribution of surviving coastal limestone outcrops, this correspondence supports localized rockfall or slope failure from MCR exposures as a plausible alternative to long-distance transport from Hackleton's Cliff, over 1.5 km away and more than 300 m upslope. However, the qualitative nature of the fossil observations, uncertainties surrounding former outcrop configurations, and the absence of an independently established transport pathway prevent definitive attribution to either source.

The present cap-and-pedestal morphologies and observed West Indian chiton activity provide evidence relevant to subsequent coastal modification but do not establish the timing of boulder emplacement or pedestal development. More broadly, the Bathsheba mushroom rocks illustrate how isolated coastal limestone boulders may preserve evidence of earlier geomorphic relationships within landscapes modified by differential erosion, slope processes, and changing coastal conditions. Further fossil comparisons, stratigraphic investigation, and detailed assessment of potential transport pathways are needed to test the alternative provenance interpretations.

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Author contributions

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Data availability statement

The data supporting this study consist of qualitative field observations, fossil coral identifications, photographic documentation, and published geological and geomorphological information described in the manuscript. No new geochronological or standardized quantitative fossil assemblage datasets were generated.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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