Island slopes and jumbled shell beds

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Abstract: Shell beds pose questions of provenance, but determining the degree of pre-depositional transport of bioclasts can be speculative. Bioclastic beds deposited on a broad, shallow continental shelf may consist of a minimally transported accumulation. In contrast, islands may have steep shelves and accumulate disharmonious bioclastic assemblages in deeper water. The latter are a signature of the stratigraphic record on many islands. Herein, we contrast differing examples of jumbled shell beds preserved around islands. The Lower Permian Mengkara Formation of Sumatra preserves deep-water facies at the base of a volcanic section. Nektonic cephalopods overlie a fine-grained ash containing a diverse association of terrestrial pollen. The Lower Miocene Montpelier Formation of Jamaica yields allochthonous packstones and slide blocks of reef limestone embedded in chalk; the ichthyofauna indicates deposition in ≥200 m water depth. Abundant evidence that deposition occurred in a deep-water turbidite basin flanking a volcanic island is found in the Middle Miocene Grand Bay Formation of Carriacou, the Grenadines. Diverse, deeper water taxa are preserved in association with land snails, hermatypic scleractinians, algal balls and planktic pteropods. The famous Upper Pliocene Bowden shell beds, Jamaica, preserve terrestrial, shallow-water, deep-water and planktic taxa.

‘Based on live/dead comparisons, exotic bioclasts are typically minor components of most assemblages and are often derived from nearby habitats’ (Anderson 2001, p. 291).

The origins, geometry and interpretation of shell beds are of perennial interest to palaeontologists, stratigraphers and sedimentologists (Kidwell 1991; Kidwell & Brenchley 1994). Shell beds pose questions of provenance: determining degree of transport of bioclasts before deposition may be speculative, although it can often be broadly determined. Fifty years ago, palaeontological assemblages were commonly considered to be allochthonous and transported shells needed to be teased apart from in situ components (such as examples given by Ager 1963, p. 183 et seq.), but other ideas (Dodd & Stanton 1981, p. 21) perhaps lean more towards considering many accumulations as autochthonous or paraautochthonous. Thus, Meldahl (2001, p. 263) thought that ‘dead shells of transported species are generally rare, and when present in a shell assemblage are typically derived from immediately adjacent habitats. Long-distance transport is rare.’ In the same volume, Anderson (quotation above) and Allmon (2001, p. 305) essentially echoed these sentiments: ‘most postmortem movement of organic remains is within the geographical range of the original life habitat, or at least within the time-averaged range of the species’.

We do not dispute these conclusions of Allmon, Anderson and Meldahl per se; bioclastic beds deposited in a shallow-water environment on a substrate of low topography or slope may be preserved as minimally transported shelly accumulations. However, we consider such deposits to be largely limited to continental shelves. In extreme contrast to such autochthonous occurrences, the stratigraphic successions of islands in oceanic and tectonically active environments in SE Asia, the Antilles and presumably elsewhere suggest that shell beds in these settings may have a very different history. Typically, oceanic islands have narrow shelves and steep slopes, which favour downslope transport of shells and the accumulation of disharmonious bioclastic assemblages in deeper water. These are derived from a range of water depths, the bioclasts being ‘swept up’ and mixed together during downslope transport of sediment. We suggest herein that disharmonious bioclastic assemblages are a signature of the stratigraphic record on oceanic islands. Although the identification of such shell beds is easier in Neogene successions (Donovan 2002), they can be recognized in the Palaeozoic (such as in the studies by Whittington 1958; Clarkson et al. 1992; Harper & Stewart 2008; Candela & Harper 2010; Harper et al. 2011). Herein, we contrast differing examples of such jumbled shell beds sensu lato preserved around islands. Such deposits may be produced by transport of, say, only a few kilometres or less laterally, but through hundreds of metres water depth (in contrast to the more extreme examples considered by Anderson (2001, p. 291): ‘However, long-distance bulk-sediment transport (500 km), which displaces death assemblages en masse, can take place if a significant depositional gradient exists’).

Typically, oceanic islands have steep submarine slopes. As an illustration, a cross-section through a typical island arc such as the Lesser Antilles (see, for example, diagrammatic representations by Perfit & Williams (1989, fig. 3) and Donnelly (1994, fig. 3.1b)) emphasizes the steep slopes of not just islands in the active arc, but of all Antillean islands. That is, it is true not just for active volcanic islands, but also for volcanically extinct parts of arcs (such as Carriacou and Jamaica, discussed below) and for subaerially exposed parts of the accretionary prism such as Barbados. (See Trechmann (1937, pp. 347–348) for a relevant discussion of ‘exotic blocks’ in Barbados.) Such steep island slopes naturally favour sediment transport into deep water.

Such deep-water deposits show a distinctive set of sedimentological, ichnological and palaeontological features. Sedimentology typically shows evidence of submarine mass flow, the beds commonly having erosive bases and turbiditic signatures. The ichnological and palaeontological features provide the starkest evidence of downslope transport in that they typically incorporate disharmonious (‘jumbled’) assemblages in which taxa from demonstrably different environments are preserved in close association. Trace fossil associations may include both deep-water burrows (Zoophycos) and borings more typical of the photic zone (Entobia, Gastrochaenolites) as in the Middle Miocene Grand Bay Formation.
of Carriacou (see below). Body fossils show a mixing of biotas that demonstrate the misleading notion of Meldahl’s and Allmon’s assertions in such settings. A typical example is the Upper Pliocene Bowden shell beds of SE Jamaica (see below), where land snails are found in the same beds as planktonic gastropods typical of an open ocean environment.

What causes the accumulation of such deposits? The downslope movement of soft-sediment or lithified masses under the influence of gravity would obviously transport biota from shallow into deeper water, sweeping up and engulfing bioclasts, both dead and alive, from intermediate, progressively deeper water depths. Such a sediment body close to the edge of the island slope could be set in motion downslope by a number of features, from which we regard catastrophic sector collapse, earthquakes and tropical storms as the most probable. The first two may be associated with volcanism that, in turn, provides volcaniclastic sediments for the basin (Jackson et al. 2008). All may be a common influence in tropical islands, particularly those that form part of an island arc.

Early Permian Mengkarang Formation, Jambi Province, Sumatra

The first illustration is from the Lower Permian succession of Sumatra (Fig. 1; Van Waveren et al. 2007). Trace element analysis indicates that the Mengkarang Formation was deposited as part of a volcanic arc (Booi et al. 2009). Petrology of the samples indicates that the deposits are for the major part volcaniclastic rocks with very few epiclastic deposits. Deep-water facies occur at the base of the section. An association including nektic cephalopods overlies a fine-grained ash containing a diverse association of terrestrial pollen representing phytohydrophytic, hygrophytic and mesic to xeric plants (Van Waveren et al. 2005, 2010; Booi et al. 2008, 2009).

This section is 500 m long and is exposed in the Merangin River, where rapids cut into the strongly silicified pyroclastic deposits (Fig. 2). Bed thickness decreases up-section. At the base of the section are very thick beds of pebbly tuffs grading into thinner beds interlayered with shales and typified by a marine signature. On top of the first tuffaceous interval, the petrography of the rocks shows tuffaceous rock fragments and broken shells (most probably brachiopod fragments) in the same bed. The fossiliferous deposits include a thin, parallel-bedded ash, which displays a full pollen spectrum and is sandwiched between brachiopod- and nautiloid-bearing beds in what, sedimentologically, appears to be turbiditic.

Part of the difficulty of examining Palaeozoic successions may be in determining what was shallow water and what was deep water (but see Fortey 1975). In this instance, the pollen represents a diverse terrestrial biota of wetter and drier palaeofloral elements that are also observed, albeit as macroscopic remains, higher in the section. Such a pollen spectrum with bisaccate pollen is known to represent the most distal facies of an alluvial input system, as opposed to more proximal facies represented by coarse-grained, opaque equidimensional material (Whitaker 1984; Van Waveren 1989), also observed higher in the section. The pollen is preserved by what appear to be distal marine beds on the basis of the palynofacies and the palaeontology (nautiloids, reworked shells). This basal interval from the Mengkarang Formation is characterized by (1) thick pebbly tuffs interlayered with limestone (in one case with broken shells, probably brachiopods) grading into shaly intervals, overlain by (2) parallel-bedded, fine-grained ash holding a rich pollen assemblage (Fig. 3a) directly overlain by a similar fine lithology holding a nautiloid shell (Fig. 3b), and overlain, in turn, by (3) marine shales containing brachiopods (Stereochia semireticulata). All brachiopods have the same orientation, where the sulcus is directed to the base of the section and, as such, are interpreted as in situ (Fig. 3c).

The pollen spectrum, the fine parallel bedding, and the marine brachiopod and nautiloid assemblage indicate that we have a distal and relatively deep facies from the volcanic slope.

Lower Miocene Montpelier Formation, Jamaica

Three examples are presented from the Neogene of the Antilles. Neogene deposits are simpler to analyse than those of the Palaeozoic because preservation is generally good and the included taxa commonly have living relations that help delineate environmental parameters; indeed, some species may still be extant and many ichnospecies will have modern representation. It is also easier to identify terrestrial, shallow- and deep-water components in these geologically younger rocks. The Antilles remain tectonically active (Case et al. 1984; Jackson 2011) and island slopes are typically steep. Neogene deep-water deposits have been uplifted and permit examination of palaeoenvironments whose modern analogues may be under many hundreds of metres of water. The three Antillean deposits have been chosen for their contrasting settings, to demonstrate something of the variety of island slope bed deposits in this region.

Duncans Quarry in north central Jamaica exposes a Lower Miocene chalk sequence (Figs 4 and 5), part of the Montpelier Formation of the White Limestone Group (Mitchell 2004, fig. 8), deposited away from the active arc during a period of tectonic quiescence and submergence in the island, but uplifted over the past 10 Ma (Robinson 1994, p. 122). This includes slide blocks of hermatypic scleractinian reef limestones derived from shallow water, commonly with a maximum dimension of 2–3 m. Slide blocks are a not uncommon component of the Jamaican Cenozoic succession.
However, the unusual feature of the slide blocks at Duncans Quarry is that they preserve a reef fauna, trapped within the coral blocks. There are thus two faunas that, in this example, are not mixed intimately per se, but in the chalk (deep water) and in the reefal slide blocks (shallower water), which occur in discrete areas of the quarry. Furthermore, there are no known Lower Miocene reefs in Jamaica, so the allochthonous clasts provide a sample of an otherwise unknown palaeoenvironment. Indeed, this is a feature of all three Antillean Neogene examples; each preserves evidence of shallow-water and/or terrestrial palaeoenvironments that are otherwise unknown.

The shallow-water biota of the slide blocks is dominated by scleractinian corals (15 species, mainly massive Montastraea spp.), identified by Stemmann (2004, p. 101) and interpreted to be derived from an original forereef environment. Within the interstices of these corals is a vagile benthic biota that would not be unexpected in shallower water at the present day. For example, the fossil decapod crustaceans (crabs) include members of genera that are obligate associates with corals (Portell & Collins 2004) and the echinoid Echinometra cf. lucunter is similar to modern shallow-water rock ‘borers’ that break down reef rock (Donovan et al. 2005). Perhaps the most notable ‘victim’ of the slide blocks is Aturia sp. B of Portell et al. (2004), one of the last nautiloids of the Antillean region.

The fauna of the Miocene chalk is very different. The most distinctive echinoderm elements are rare columnals and other ossicles of isocrinid crinoids, indicating a water depth of ≥150 m by comparison with modern environments (Meyer et al. 1978; Donovan et al. 2005). These are associated with a small fauna of terebratulid brachiopods (Harper & Portell 2004). Stalked crinoids (mainly isocrinids) and terebratulid brachiopods are a common association in deeper water settings in the Neogene of the region (Donovan & Harper 2001).
This determination of the deep-water deposition of the Miocene chalk is supported by the sedimentology (Mitchell 2004, pp. 13–14) and a diverse fauna of fish teeth. Indeed, these indicate yet deeper water: ‘Extant species of both Deania and Scymnodon are essentially bentho-pelagic inhabitants of continental slopes, being rarely found in less than 200 m of water’ (Underwood & Mitchell 2004, p. 164).

Middle Miocene Grand Bay Formation, Carriacou, the Grenadines

The Middle Miocene Grand Bay Formation of Carriacou in the Grenadines, southern Lesser Antilles are (Fig. 6), represents a very different depositional setting. The Miocene sedimentary succession of Carriacou is composed of four formations. The Belmont, Kendeace and Carriacou formations (Early–Middle Miocene) represent a shallowing-up sequence (turbidites to shallow-water limestones); they are exposed on the south coast and dip to the east. The Grand Bay Formation (Middle Miocene) is exposed on the east coast and dips to the south; it was laid down in a different basin. The Grand Bay Formation is a turbidite sequence preserving autochthonous deep-water burrows (Fig. 7), and shelly fossils (some bored) from a variety of terrestrial and marine palaeoenvironments.

This succession has caused some confusion in its environmental interpretation in the past. Speed et al. (1993) recognized the four Miocene formations as a shallow-upwards succession throughout (that is, deposited in a single basin) and thought that the Grand Bay Formation supported this: ‘At least the bulk of the formation is marine, but indicators of its bathymetry are lacking. The prevalence of sandstone with steep dunelike cross-laminations of high amplitude suggests it partly originated as beach deposits’ (Speed et al. 1993, p. 55). Speed et al. did not recognize the numerous sedimentary features related to turbiditic deposition in the Grand Bay Formation (Donovan et al. 2003), similar to
components. Shallow-water and terrestrial components include hermatypic scleractinian corals, algal balls, shallow-water molluscs (Donovan et al. 2003, pp. 269–271, table 3). The last provides a (small) insight into the Miocene terrestrial biota of the Grenadines, which is otherwise unknown. Only shallow-water bioclasts (marine molluscs and scleractinian corals) preserve evidence of borings (Pickerill et al. 2002), all for dromes; none are known from land snails, suggesting only a brief residence time in shallow water.

Other molluscs are deep-water taxa, such as Perotrochus, Echinophoria and Onastus (Donovan et al. 2003, fig. 4), and planktonic pteropods. Fragile hermatypic scleractinian corals, typical of deeper water, are more abundant than the fragmentary remains of shallow-water, hermatypic corals. Like the Montpelier Formation of Jamaica, and despite the differences in sedimentary setting, the fauna is unusually rich, in numbers if not diversity, of two groups typically associated together in deeper water palaeoenvironments in the Antillean Neogene (Donovan & Harper 2001), the terebratulid brachiopods (Donovan et al. 2003, pp. 263–264; Harper & Pickerill 2008) and crinoids (Donovan & Veltkamp 2001). The latter include three species of stalked crinoid and many hundreds of specimens, an exceptional occurrence for the region. The Grand Bay Formation is the only crinoid-rich deposit in the Antilles and the only association of crinoids with land snails of which we are aware, a uniquely disharmonious occurrence. Burrows are uncommon, but moderately diverse, including Chondrites, Planolites, Skolithos, Thalassinoides and Zoophycos (Donovan & Harper 1999; fig. 7), amongst others (Donovan et al. 2003, p. 269). Again, depth of deposition was in over 150 m of water, based on multiple lines of evidence (Donovan et al. 2003, pp. 269–271, table 3).

**Late Pliocene Bowden shell beds, Jamaica**

Some parallels, but also some differences (Table 2), are afforded by the Late Pliocene Bowden shell beds of the Bowden Formation, SE Jamaica (fig. 4). This is probably the most widely known deposit in the Antilles, owing mainly to the superb monograph of the benthic molluscs by Woodring (1925, 1928). Although poorly exposed, the four shell beds have produced over 600 species of fossil molluscs (Donovan et al. 1998) and several hundreds of other taxa (Rácz 1971; Donovan 1998). The type section is typically poorly exposed and overgrown, but loose blocks are rich in fossils. The Bowden Formation is a siliciclastic sequence deposited since the uplift of Jamaica about 10 Ma ago, but later than the last active volcanism on the island.

The four shell beds (fig. 8) have a total thickness of about 5 m and were deposited as sediment gravity flow deposits in a turbiditic environment, below storm wave base (Pickerill et al. 1998). Beds are coarse-grained sandstones or conglomerates with amalgamated beds and erosive bases, containing many thousands of clasts, particularly bioclasts.

### Table 1. Comparison of palaeobathymetric determinations of the Miocene of Carriacou (modified after Donovan et al. 2003, tables 1 and 2)

| Formation          | Jung (1971)                      | Speed et al. (1993)                      |
|--------------------|---------------------------------|------------------------------------------|
| Grand Bay Fm.      | ‘mixture of shallow-water and some deeper water forms … deposited at … possibly 150 to 200 meters’ (p. 157) | ‘indicators of bathymetry are lacking … partly originated as beach deposits’ (p. 55) |
| Carriacou Fm.      | ‘mollusks … clearly point to a tropical shallow-water environment’ (p. 156) | ‘probably a complex of platformal and periplatformal deposits’ (p. 54) |
| Kendeace Fm.       | Molluscs, including pteropods, were ‘deposited at a depth greater than 200 meters’ (p. 156) | ‘A shallowing of the Kendeace site relative to that of the Belmont is suggested’ by various lithological and palaeontological features (p. 54) |
| Belmont Fm.        | An included suite of benthic molluscs are ‘indicative of a shallow-water environment’ (p. 154) | ‘subwavebase, probably deepwater deposits [with turbiditic features] … sediment-gravity flow deposits’ (pp. 52, 53) |

Jung (1971) is considered correct apart from the Belmont Formation; Speed et al. (1993) are incorrect regarding the Grand Bay Formation.

### Table 2. Presence/absence chart of some key sedimentological, palaeontological and ichnological features of the Middle Miocene Grand Bay Formation of Carriacou and the Upper Pliocene Bowden shell bed of Jamaica, separated into deeper water and shallow-water–terrestrial origins

|                       | Grand Bay Fm. | Bowden shell bed |
|-----------------------|---------------|------------------|
| **Deeper water features** |               |                  |
| Turbidites or mass flows | +             | +                |
| Zoophycos             | +             | −                |
| Azooxanthellate corals | +             | ?                |
| Stalked crinoids       | +             | −                |
| Terebratulids          | +             | +*               |
| Holoplanktonic gastropods | +         | +                |
| Deep-water teleosts    | −             | +                |
| **Shallow-water–terrestrial features** |               |                  |
| Land snails            | +             | +                |
| Zooxanthellate corals  | +             | +                |
| Shallow-water benthic molluscs | +   | +               |
| Aturia†                | −             | +                |
| Bored clasts           | +             | +                |
| Algal balls            | +             | −                |

*present; −, absent; ?, the most recent review of the corals of the Bowden shell bed listed only zooxanthellate corals (Budd & McNeill 1998).

†These are amongst the youngest nautiloids known in the Caribbean region.

those that they had correctly noted in the Belmont Formation, or the abundant evidence provided by palaeontology and ichnology. Jung (1971) correctly identified the deep-water mollusc fauna of the Grand Bay Formation associated with elements washed in from shallow water and land (Table 1). Jung also noted the occurrence of shallow-water molluscs in the turbiditic Belmont Formation, making it a second disharmonious fossil assemblage on the island.

The Grand Bay Formation is composed essentially of a sequence of bioclastic and volcanogenic turbidites, dominantly fine- to coarse-grained sandstones. The volcanoclastic turbidites in the Grand Bay Formation probably formed as a consequence of volcanic eruptions along the southern Lesser Antilles are during the Early to Middle Miocene. A single andesitic system appears to be responsible for the volcanoclastic turbidites of the Grand Bay Formation; reworked pyroclastic deposits were temporarily stored on a shallow shelf prior to deposition in a deep-water basin (Donovan et al. 2003; Jackson et al. 2008).

The biota of the Grand Bay Formation (Table 2) shows a notable contrast between diverse terrestrial, shallow-water and deep-water components. Shallow-water and terrestrial components include hermatypic scleractinian corals, algal balls, shallow-water molluscs and the land snail Pleurodonte lehneri (Trechmann) (see Jung 1971, plate 18, figs 3–15). The last provides a (small) insight into the Miocene terrestrial biota of the Grenadines, which is otherwise unknown. Only shallow-water bioclasts (marine molluscs and scleractinian corals) preserve evidence of borings (Pickerill et al. 2002), all for dromes; none are known from land snails, suggesting only a brief residence time in shallow water.

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and terebratulid brachiopods are rare, being known from a single (Janssen 1998). Unlike the other deposits, crinoids are unknown reviewed by Donovan et al. (1998, p. 43) of a palaeowater depth for the Bowden Formation at Bowden of 100–250 m. Stringer’s data suggest a depth of deposition in agreement with the estimate of Kohl & Robinson (1998). The moderately diverse burrows of the Bowden Formation (Pickerill et al. 1996) support a conclusion that deposition was in deeper water, whereas borerings in shelly and lithic substrates in the Bowden shell bed show a close ichnological similarity to those of the shallow marine, Late Pleistocene Port Morant Formation (Pickerill & Donovan 1999).

Conclusions

‘The earthquake [of 1692] was generally destructive ... in Jamaica, and masses of rocks were detached from the heights’ (De la Beche 1833, p. 148).

De la Beche reminds us that earthquakes in Jamaica, which included two of the four examples of ‘jumbled shell beds’ herein, have long been a part of the environment of the island and were certainly strong enough to start a marine mass flow into deeper water. The other examples were both on volcanic islands, which were therefore also prone to earthquakes. Other triggers to movement include tropical storms.

Our survey of disharmonious fossiliferous associations in deep-water deposits around islands is very incomplete, but we have used a diversity of palaeoenvironmental examples to illustrate the features of ‘jumbled shell beds’. Oceanic islands with narrow shelves and steep slopes favour preservation of shelly, sedimentary accumulations of organisms derived from diverse environments in deep water. Or, to put it another way, diverse, disharmonious palaeontological assemblages are indicative of downslope transport in ancient island settings. Diverse environmental indicators (sedimentology, palaeontology and ichnology) may be used to determine the depth of deposition of such units.

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Fig. 8. Stratigraphic log of the Bowden shell beds (units 1–4 inclusive), Bowden Formation, parish of St. Thomas, SE Jamaica (after Pickerill et al. 1998, fig. 3 pars). M, ‘marlstone’; S, silstone; F, M, C, fine-, medium- and coarse-grained sandstone (sst.); Co, conglomerate.

Some previous ideas about depth of deposition have commonly been guided by the particular systematic interest of any given researcher, rather than integrating diverse lines of evidence. Pickerill et al. (1998, table 2) summarized the ideas on depth of deposition published in 10 papers between 1919 and 1994. Estimates varied from ‘<10 m’ (Vaughan 1919) and ‘shallow water’ (Goodfriend 1993) to ‘outer sublittoral (c. 100 m) or deeper’ (Robinson 1994) or ‘> 200 m’ (Woodring 1965; Katz & Miller 1993). Shallower estimates are probably due to the ‘pull’ of the groups being described, namely hermatypic corals (Vaughan) and land snails (Goodfriend). We agree with the estimate of Kohl & Robinson (1998, p. 43) of a palaeowater depth for the Bowden Formation at Bowden of 100–250 m. The narrow shelf of modern Jamaica favours development of large fan-delta and submarine fan systems. Pickerill et al. (1998, p. 19) suggested that the Yallahs Basin (Burke 1967; Etheridge & Wescott 1984), to the west of Bowden and attaining a depth of ±1200 m in less than 12 km from the shoreline, may be a model environment for the deposition of the Bowden Formation.

There are similarities to and differences from other Antillean deposits discussed herein (Table 2). Like the Grand Bay Formation, the molluscs are noticeably mixed, including the oldest land snails (Goodfriend 1993) from the island, shallow- and deep-water benthonic molluscs, including chitons, loliginid teuthoid statoliths (all reviewed by Donovan et al. 1998) and holoplanktonic gastropods (Janssen 1998). Unlike the other deposits, crinoids are unknown and terebratulid brachiopods are rare, being known from a single ventral valve of Argyrotheca (Harper & Portell 2003). Shallow shelf organisms are common, including calcareous algae (Rácó 1971), zooxanthellate scleractinian corals (Budd & McNeill 1998) and bryozoans (Taylor & Foster 1998). Perhaps the most impressive palaeontological evidence for deep-water deposition is provided by the diverse otoliths of teleostean fishes. Stringer (1998, table 2) summarized the known depth ranges of extant teleosts identified from the Bowden shell bed. These include many taxa that are known only from deeper water (≥200 m). Stringer’s data suggest a depth of deposition in agreement with the estimate of Kohl & Robinson (1998). The moderately diverse burrows of the Bowden Formation (Pickerill et al. 1996) support a conclusion that deposition was in deeper water, whereas borerings in shelly and lithic substrates in the Bowden shell bed show a close ichnological similarity to those of the shallow marine, Late Pleistocene Port Morant Formation (Pickerill & Donovan 1999).

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