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A RAPID RECONNAISSANCE OF A QUATERNARY EOLIANITE ISLAND OF AUSTRALIA: ROTTNEST ISLAND, WITH COMPARISONS TO THE BAHAMAS

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ABSTRACT

Rottnest Island, 19 km^2 in area and 18 km off the coast of Western Australia, is an approximation of a Bahamian island. The island is primarily covered by Pleistocene and Holocene eolian calcarenite suites, with scattered reef and lagoonal facies at low elevations. Pleistocene eolianites dominate the island, and appear to contain a collection of units that would be independent formations if described from The Bahamas. Trace fossils are abundant, including vegemorphs and the first reported cluster burrows in Pleistocene eolianites. Unequivocal examples of flank margin caves were located in Salmon Bay, while at Thompson Bay possible flank margin caves are overprinted by coastal erosion. Fish Hook Bay and Wilson Bay have excellent examples of sea caves and arches. Banana holes and pit caves were not observed, but tafoni are common. Based on abundant vegemorphs and occasional calcarenite protosols, regressive-phase Pleistocene eolianite facies from the last interglacial (MIS 5e) are common. As a fresh-water lens above modern sea level never existed in these dunes, flank margin cave development was limited to older, less prominent facies.

INTRODUCTION

The purpose of this paper is to describe aspects of the Quaternary eolian calcarenite geology of Rottnest Island (Figure 1) as determined by a rapid reconnaissance and compare those aspects to the Bahamian stratigraphic model, and to the flank margin cave model. The paper contains no specific measurements or sample analyses; the purpose of the rapid reconnaissance was to determine if field observations could establish the utility of the Bahamian models in this Australian island setting. The oral presentation given at the 14th Symposium on the Geology of the Bahamas and Other Carbonate Regions, and the abstract for that presentation, dealt with Kangaroo Island, Australia in addition to Rottnest Island. The Kangaroo Island information has been submitted to a journal for publication, so only the Rottnest Island observations are presented in this abstract and paper.

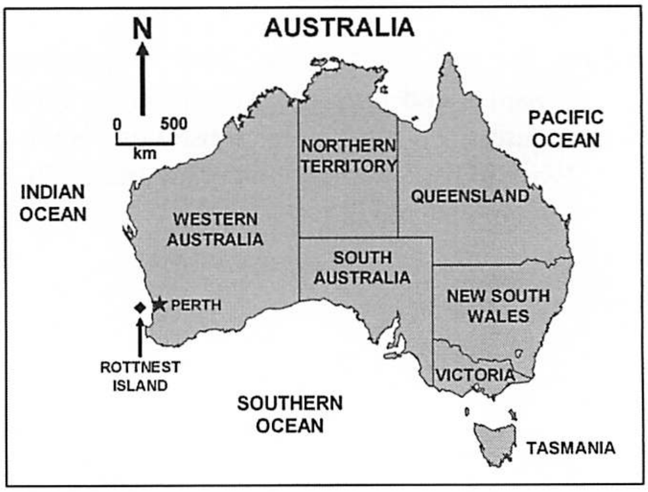

Figure 1. Map of Australia showing the location of Rottnest Island.

Bahamian Stratigraphy

The islands of the Bahamian Archipelaconsist solely of Quaternary carbonates (Figure 2).

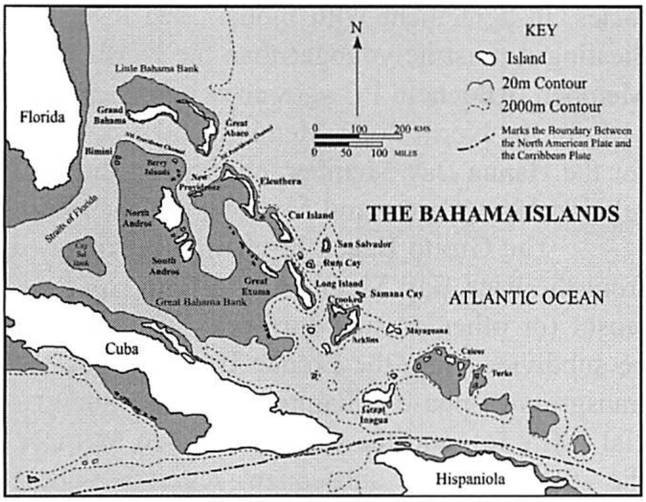

Figure 2. Map of the Bahamian Archipelago.

These carbonate rocks are primarily eolian calcarenites (or eolianites), with beach, reef and lagoonal facies of Late Pleistocene age found at elevations below 8 m. A stratigraphy that is applicable to all Bahamian Islands was developed on San Salvador Island (Carew and Mylroie, 1985; 1995a; 1997) and is based on carbonate units that were deposited during glacioeustatic sea-level highstands, separated by erosion surfaces (unconformities) created during glacioeustatic sea-level lowstands (Figure 3). The stratigraphy is based on field relationships, which have subsequently been confirmed by geochronologic methods (Carew and Mylroie, 1995a; 1997). This stratigraphy has been refined by others, notably Hearty and Kindler (1993) who used amino acid racemization techniques to make subdivisions and additions to the basic stratigraphic model. Such refinements, being laboratory based, cannot be reliably assessed in the field. As a result, the general model of Carew and Mylroie (1995a; 1997) continues to be the standard tool for initial reconnaissance fieldwork in the Bahamas and elsewhere. The San Salvador model has been successfully exported to New Providence Island (Carew et al., 1992, 1996), South Andros Island (Carew et al., 1998), Eleuthera Island (Panuska et al., 2002), Long Island (Curran et al., 2004), Cat Island (Mylroie, et al., 2006), and Rum Cay (Mylroie et al., 2008a) as a series of field guides produced by the Gerace Research Centre (GRC) on San Salvador Island. The stratigraphic model has also been successfully utilized to update the coastal Quaternary carbonates of the eastern Yucatan Peninsula (Kelley et al., 2006).

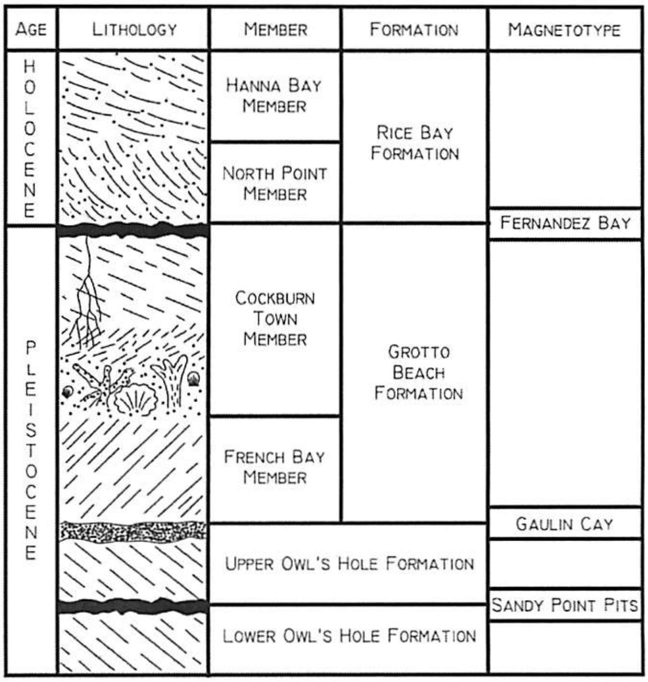

Figure 3. The stratigraphic column for the Bahamas, based on observable field relationships supplemented by paleomagnetic analysis (Carew and Mylroie, 1997).

The geologic model can be summarized as follows. The Bahamas represent carbonate banks that have been in existence since Mesozoic time as tectonically stable and isostatically subsiding platforms. Today, the surficial geology is entirely Quaternary limestone, modified by karst processes. The major control of Quaternary Bahamian geology has been glacioeustasy. The steep-sided platform nature of the Bahama Banks means that for about 85% of the Quaternary, the banks have stood above sea level as subaerial platforms. During glacioeustatic highstands, however, the platform tops were partially inundated by marine water and the carbonate factory initiated. During the initial transgression of the sea across the platform, eolianites were produced as wave action and rising sea level constantly kept lagoon and beach sediments mobilized to produce *transgressive-phase* eolianites. During the sea-level highstand, reefs grew up to wave base, lagoons became quiescent, eolianite production declined and strand plains prograded into the lagoons. When sea level began to fall, the declining wave base mobilized lagoonal sediments, and *regressive-phase* eolianites developed, commonly over-stepping reefs and subtidal deposits. When the platform was again emergent due to glacioeustatic sea-level fall, epikarst development and pedogenic processes influenced by African dust-fall dominated the landscape. Hard, red terra rossa paleosols were produced. The Quaternary geologic record of the Bahamas consists of carbonate depositional packages formed during sea-level highstands, separated by terra rossa paleosols formed during the ten-times longer sea-level lowstands.

The stratigraphy of the Bahamas (Figure 3) consists of the Holocene *Rice Bay Formation*; a terra rossa paleosol; the trangressive-phase eolianite/subtidal/regressive-phase eolianite carbonate package of the *Grotto Beach Formation* from the last interglacial (MIS 5e, ~125,000 years BP); a terra rossa paleosol; and eolianites and terra rossa paleosols from several earlier sea-level fluctuations designated as the *Owl's Hole Formation*. The Holocene Rice Bay Formation can be further subdivided into the North Point Member and the Hanna Bay Member. The North Point Member lacks an overlying terra rossa paleosol, indicating a Holocene age, and has foreset beds dipping below modern sea level. Sea level had to be on the platform to create carbonate allochems, but below modern levels, to deposit this eolian calcarenite unit. The North Point Member must have been deposited during the Holocene transgression, hence its designation as a transgressive-phase eolianite. The Hanna Bay Member, as with the North Point Member, lacks a terra rossa paleosol and so is Holocene in age. Its foreset beds grade into back beach and beach facies, in agreement with modern sea level, indicating it must be younger than the North Point Member. Allochem ^{14}C ages center around 5,000 yBP for the North Point Member, and 3,000 yBP for the Hanna Bay Member, confirming the field relationships (Carew and Mylroie, 1995a; 1997).

The Grotto Beach Formation is separated from the Rice Bay Member by a terra rossa paleosol (or other erosion surface). The unit can be subdivided into the French Bay Member, the transgressive-phase eolianite of the last interglacial (MIS 5e), and the Cockburn Town Member, the still stand and subsequent regressive-phase deposits. As the last interglacial (MIS 5e) glacioeustatic highstand was about 6 m higher than at present, subtidal facies from that stillstand are preserved in the rock record above modern sea level. Previous glacioeustatic highstands were either not high enough, or were too long ago for subtidal deposits to still be above modern sea level given isostatic subsidence rates in the tectonically stable Bahamas of 1-2 m per 100 ka (Carew and Mylroie, 1995b). Fossil coral reefs, subtidal indicators such as herringbone cross bedding, and beach facies are common in the Cockburn Town Member below 8 m elevation. Fossil coral reefs from the entire Bahamas, dated by U/Th methods (Carew and Mylroie, 1995b), fall into the time range of ~131 to 119 ka, confirming the interpretation that subtidal units above modern sea level are from the last interglacial (MIS 5e). Because subtle and extensive fieldwork is necessary to differentiate progradational carbonates deposited during a stillstand from the regressive-phase deposits of the subsequent regression, the eolianites for both the stillstand and the regression of the last interglacial (MIS 5e) are lumped, with the subtidal facies, into the Cockburn Town Member.

A terra rossa paleosol (or other erosion surface) separates the Grotto Beach Formation from the underlying Owl's Hole Formation. In the field, eolianites are extremely difficult to differentiate. Hand specimen analysis in the field, and even later petrographic examination in the laboratory, cannot reliably tell Pleistocene eolianites apart; morphostratigraphy is also unreliable (Carew and Mylroie, 1995a; 1997). However, because eolianites are constructional deposits that can reach 60 m above sea level in the Bahamas, such deposits from numerous glacioeustatic sea-level highstands in the Bahamas prior to the last interglacial (MIS 5e) can be expected to exist, despite isostatic subsidence. Because of the patchy nature of eolianite deposition, it is extremely rare to be able to observe these eolianites stacked one atop the other, to provide an obvious stratigraphic relationship. The eolianites from northern Eleuthera, described by Kindler and Hearty (1995), are a classic exception. As a result of this uncertainty, the Owl's Hole Formation was created by Carew and Mylroie (1985) to include all eolianites deposited before the last interglacial (MIS 5e). Extensive paleomagnetic analysis of terra rossa paleosols has allowed Owl's Hole Formation eolianites to be differentiated by secular variation (right-hand column of Figure 3). No magnetic reversals were found, so the eolianites are less than 780 ka old (Panuska et al., 1999). As with AAR dates, such differentiation is only available later in the laboratory, not in the field. Calcarenite protosols, white, immature fossil soils, occur within and on eolianites and represent a pause in deposition within a glacioeustatic sea-level highstand, as opposed to the mature terra rossa paleosols that form during an extended period of time associated with a glacioeustatic lowstand (Carew and Mylroie, 1991).

Figure 4 demonstrates how the stratigraphy of Quaternary carbonate units can be determined from field relationships in the Bahamas and elsewhere. Full treatments of Bahamian geology and hydrology can be found in *Geological Special Publication 300* (Curran and White, 1995), and in chapters 3 and 4 of *Geology and Hydrogeology of Carbonate Islands* (Vacher and Quinn, 1997). The book *Bahamian Landscapes* (Sealey, 2006) offers a broad overview of Bahamian geology targeted to the lay reader. A field guide to San Salvador (Mylroie and Carew, 2008) provides abundant, specific information about the geology and karst of San Salvador Island, the starting point for modern stratigraphic studies in the Bahamas.

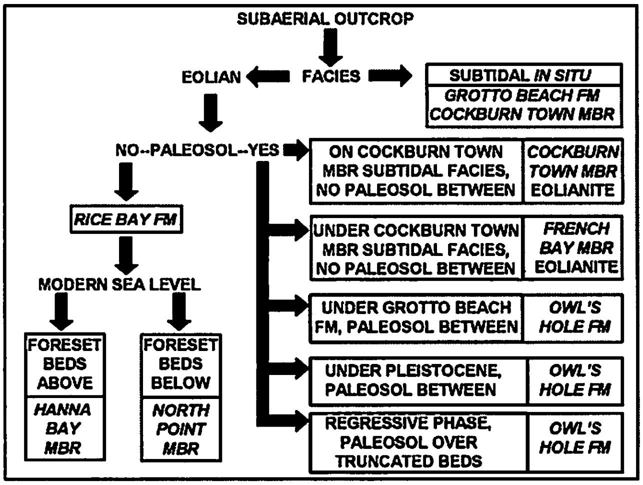

Figure 4. Flow diagram using field relationships to identify carbonate rocks in the Bahamas Mylroie and Mylroie, 2009b).

Bahamian Karst

San Salvador Island occupies a small isolated bank within the Bahamian archipelago. All stratigraphic and karst features present must be explicable in terms of the island's small size and the young age of the limestones (<800,000 years). Karst features on other Bahamian islands, including large islands on large banks, are identical to those on San Salvador, and the ideas of karst development established on San Salvador have, like the stratigraphy, been successfully exported across the archipelago (Mylroie and Mylroie, 2007; 2009a; 2009b). The karst features present are quite different from those found in older, diagenetically-mature limestones of continental interiors. The carbonate rocks of the Bahamas are considered *eogenetic*; they have never been buried or undergone significant diagenesis (Choquette and Pray, 1970). Subaerial caves fall into three main categories (Figure 5):

Pit caves are vadose shafts that collect water from the epikarst and conduct it toward the water table. *Banana holes* form from dissolution caused by vadose-phreatic mixing of water at the top of the fresh-water lens, supported in part by organic accumulation and decay. Most of these cavity entrances are collapse dolines and have a diameter/depth ratio >1. They are named for one of the specialty crops (bananas) grown within them, where the soil is richer and wetter than on the dryer land above.

The largest voids are *flank margin caves*, which develop in the distal margin of the fresh-water lens, under the flank of the enclosing landmass. In this environment, vadose-phreatic mixing at the top of the lens is superimposed on the marine - fresh water mixing zone at the base of the lens. Organic materials collect at both the top and bottom of the lens where decay produces CO$_2$ and potentially anoxic H$_2$S-derived acidity; the lens margin also superimposes these environments. Finally, as the lens cross section decreases at the lens margin, flow velocities increase, bringing reactants in, and taking products out, rapidly. These factors create an exceptional dissolutional setting. Smaller flank margin caves show single or ramiform passages, others are larger and far more complex and complicated with typical spongework or branchwork patterns (Palmer, 2007). Complete reviews of the model can be found in Mylroie and Carew, 1995, and in Mylroie and Mylroie, 2007.

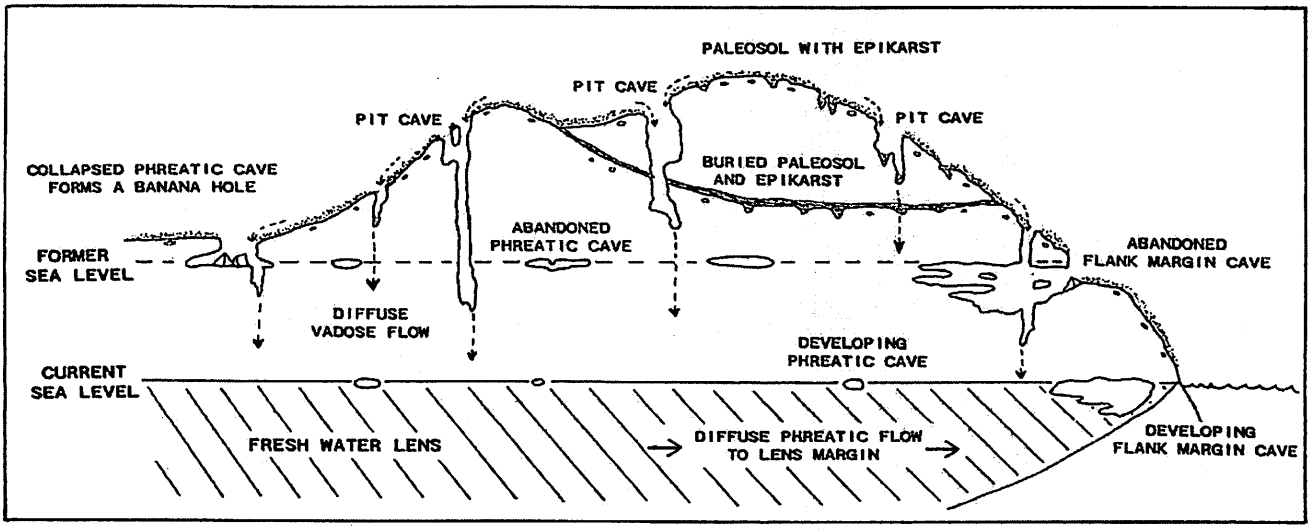

Figure 5. Common cave and karst features of the Bahamas visible in the current subaerial environment. Blue holes are not shown (Mylroie and Carew, 1995).

The flank margin cave model has been successfully exported throughout the Bahamas (Mylroie and Mylroie, 2009a; 2009b), and around the world, to Puerto Rico (Lace, 2008) and Isla de Mona (Frank et al., 1998), eastern Yucatan Peninsula (Kelley et al., 2006), the Mariana Islands (Jenson et al., 2006), Fais Island (Mylroie et al., 2008b), and New Zealand (Mylroie et al., 2008c). The flank margin cave model is a subset of the Carbonate Island Karst Model, or CIKM, used to unify the various types of caves and karst found on carbonate islands, and islands with carbonates, around the world (Jenson et al., 2006; Mylroie and Mylroie, 2007).

A complication involving flank margin caves is their similarity to sea caves, and to tafoni (singular, tafone), which are both found in coastal and inland cliffs cut into eolian calcarenites. Sea caves are produced by wave action on coastal eolianite outcrops (Waterstrat, 2007; Waterstrat et al., in press); tafoni by wind action and wetting and drying along cliffed eolianites (Owen, 2007). Both sea caves and tafoni form by weathering and erosion working from the outside inward. Flank margin caves form by dissolution working inside the eolianite. Flank margin caves, which form without entrances, only develop entrances after surface processes have breached into them. So a large opening on a sea cliff could have three modes of formation. The different mechanisms of formation allow these three cave types to be quantitatively differentiated from map surveys (Owen, 2007; Lace, 2008). In the field, any large cave with a restricted entrance(s) is most likely a flank margin cave. If the void has calcite precipitates such as stalactites and stalagmites, it is most likely a flank margin cave; but the absence of such deposits does not mean the void is not a flank margin cave. Phreatic dissolution to make a flank margin cave also forms unique smooth and curvilinear wall surfaces that are readily identifiable in the field (Mylroie and Mylroie, 2007). A key point to emphasize is that if a flank margin cave can be conclusively identified in a host rock, then it represents a past fresh-water lens, and hence sea level, position. The rock unit hosting the cave therefore must be at least as old as the initiation of that sea-level highstand.

ROTTNEST ISLAND

Geology

Rottnest Island is located in the Indian Ocean 18 km west of the coastal city of Perth in Western Australia (Figure 1). The island is approximately 11 km long, east to west, and 4.5 km wide, with 19 km^2 of area (Figure 6). As with many Bahamian islands, Rottnest is entirely Quaternary carbonate rock and sediments. The standard reference is the review paper by Playford (1997), who explains the island as a three-fold rock stratigraphy, with one Holocene subtidal unit (Herschel Limestone), one Pleistocene subtidal unit (Rottnest Limestone), and an eolian unit that spans the Pleistocene to early Holocene (Tamala Limestone). The Rottnest Limestone, which contains a fossil reef facies U/Th dated to MIS 5e (Playford, 1997), is limited to a single outcrop at Fairbridge Bluff (Figure 6). The Tamala Limestone is entirely eolianite, and is named for, and correlated with, eolianites on the Western Australia mainland. Playford (1997) believed eolianite deposition was tied to sea-level lowstands, not highstands as is now understood to be the case (Carew and Mylroie, 1995a, 1997), which explains his ending of Tamala eolian deposition in the early Holocene, prior to the Holocene transgression (Figure 6). Murray-Wallace et al. (1989, in Hearty 2003), made modifications to an early version of Playford's stratigraphy as part of a view of the Perth area, but generally kept the three-fold stratigraphy. Hearty (2003) recognized that the Rottnest eolianites are tied to highstands. Hearty (2003), using amino acid racemization (AAR), also noted the basic three-fold stratigraphy, but used AAR to subdivide the Tamala's Pleistocene units, adding a MIS 5a-c eolian unit to the Rottnest Limestone in addition to the standard MIS 5e eolian units. Hearty (2003) was able to differentiate older Pleistocene units on the Australian mainland, but not on Rottnest, into MIS 7-9, 9-11, and >11 age units. His results, in contrast to Playford (1997), indicate that the majority of Rottnest Island is MIS 5 in age, and older Tamala units are not common. These results also demonstrate the imprecision of AAR dating; however there are few alternative options for dating these rocks.

One of the debates regarding Bahamian stratigraphy is the existence of MIS 5a units. Carew and Mylroie (1995a; 1997) maintain that there is no conclusive field evidence for a MIS 5a unit in the Bahamas. Evidence from Bermuda, based on AAR analyses, suggests MIS 5a eolianites exist there (Vacher and Hearty, 1989). Hearty and Kindler (1993) presented AAR data to suggest that units mapped on San Salvador by Carew and Mylroie as regressive-phase MIS 5e eolianites were actually MIS 5a eolianites. One purported

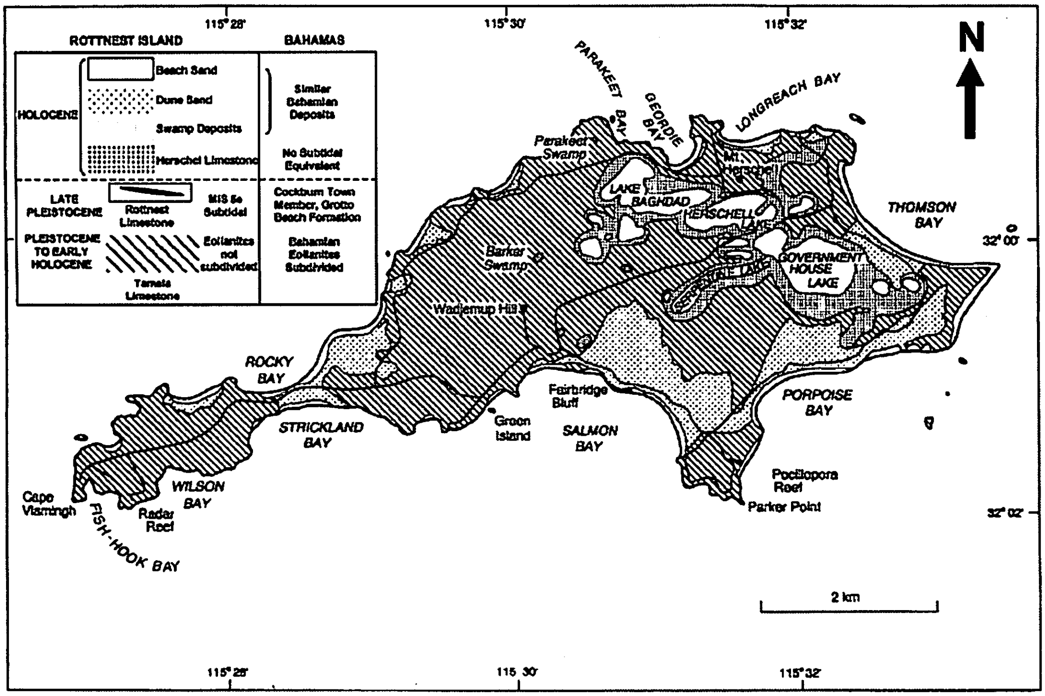

Figure 6. Geologic map of Rottnest Island, showing comparison to Bahamian Stratigraphy. The Rottnest Limestone outcrop is at Fairbridge Bluff. The Herschel Limestone surrounds the lakes. Modified from Playford, 1997.

piece of field evidence reported by Hearty (1998) from Eleuthera to support a MIS 5a eolianite was questioned by Panuska et al. (2002). Another outcrop on San Salvador Island interpreted by AAR to be a MIS 5a outcrop (Hearty and Kindler, 1992; 1993) later showed Holocene ^{14}C ages from the allochems. While a terra rossa paleosol is expected between MIS 5a and 5e outcrops (Hearty, 1998; 2003), at the Gulf on San Salvador, purported MIS 5a rocks overstep a MIS 5e fossil reef with only a calcarenite protosol in between, consistent with a MIS 5e regressive-phase field interpretation. MIS 5a deposits may well exist in the Bahamas, but no determinative field relationships have been demonstrated. As will be noted later, the units designated MIS 5a-c on Rottnest Island fit the criteria used in the Bahamas to identify MIS 5e regressive-phase eolianites (Carew and Mylroie 1995a, 1997; Mylroie and Carew, 2008).The main focus of the rapid reconnaissance of Rottnest Island was to determine if flank margin caves had developed in the eolianites of the island, as none had been reported in the literature. The search for such karst features resulted in an examination of many eolianite outcrops, primarily those in coastal locations. From those field studies, a few interesting observations can be made. These observations are presented in the chronological order in which they were made, August 21-23, 2006, going clockwise around Rottnest Island from the Bathhurst Lighthouse at the northern end of Thompson Bay (Figure 6) at the northeast tip of the island.

Stratigraphy and Karst Relationships

Bathurst Lighthouse

The Holocene/Pleistocene boundary was obvious at Bathurst Lighthouse on the eastern end of Rottnest Island. As seen in Figure 7, the upper unit would be the Holocene Herschel Limestone, as it lacks a terra rossa paleosol. Playford

(1997) defined the Herschel Limestone as the Holocene lagoonal facies surrounding the interior water bodies in the eastern interior of Rottnest Island. That name is expanded to label the Holocene eolianites reported here. Playford (1997) apparently did not recognize any lithified Holocene eolianites; Hearty (2003) found evidence of some Holocene eolianite production. The observations reported here indicate that Holocene eolianite production, as was the case in the Bahamas, is more voluminous than earlier workers believed. As the relationship of sea level to this Holocene eolianite was not apparent, it can only be considered equivalent to the Rice Bay Formation of the Bahamas; a member status cannot be indicated. The lower eolian unit in the outcrop is under a terra rossa paleosol (Figure 7) so it is Pleistocene.

Figure 7A also shows a small cave in the Herschel Limestone. This void is not a flank margin cave, which would be impossible at that elevation in a Holocene eolianite, but a tafone (plural, tafoni), a weathering pocket formed by wind action and wetting and drying (Owen, 2007). The void is a small, simple chamber without any secondary calcite deposits.

South from the Bathurst Lighthouse, a series of cave openings are found along the coastal cliffs (Figure 8). These caves appear to be flank margin caves, but are currently being subjected to wave attack with consequent cliff retreat, so they are quite open to the elements in places. The host eolianite has a rich collection of plant trace fossils, or vegemorphs, which have been used in the Bahamas to identify regressive-phase eolianites (Carew and Mylroie, 1995a, 1997; Birmingham et al., 2008). These rocks appear to contain flank margin caves, but because MIS 5e regressive-phase eolianites could not host a fresh water lens above modern sea level, these eolianites are most likely from the older, pre-MIS 5e

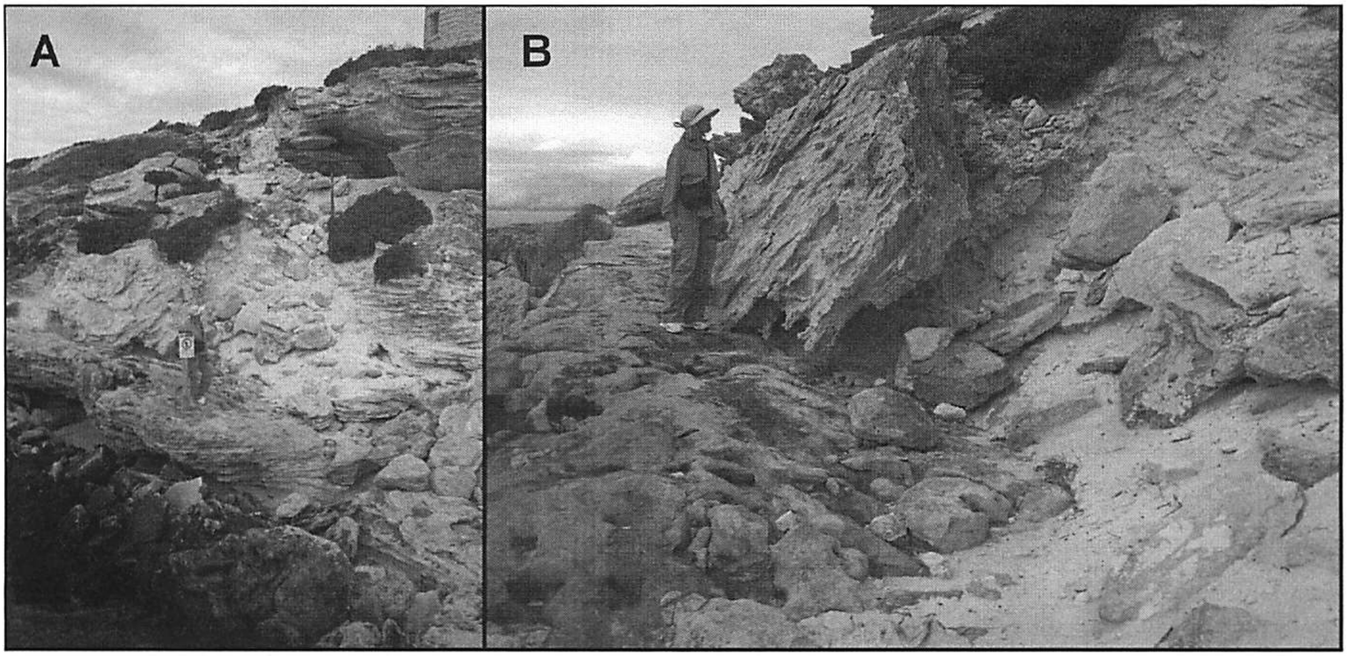

Figure 7. A) Outcrop of Herschel Limestone below Bathurst Lighthouse north of Thompson Bay. The upper eolianite lacks a terra rossa paleosol, indicating that it is Holocene in age. The person is standing on a terra rossa paleosol, indicating the lower unit is Pleistocene. The base of the Bathurst lighthouse is visible in the upper right; below the lighthouse, the apparent cave opening is a tafone (wind erosion pocket), not a flank margin cave. B) Close up of the terra rossa paleosol seen in A.

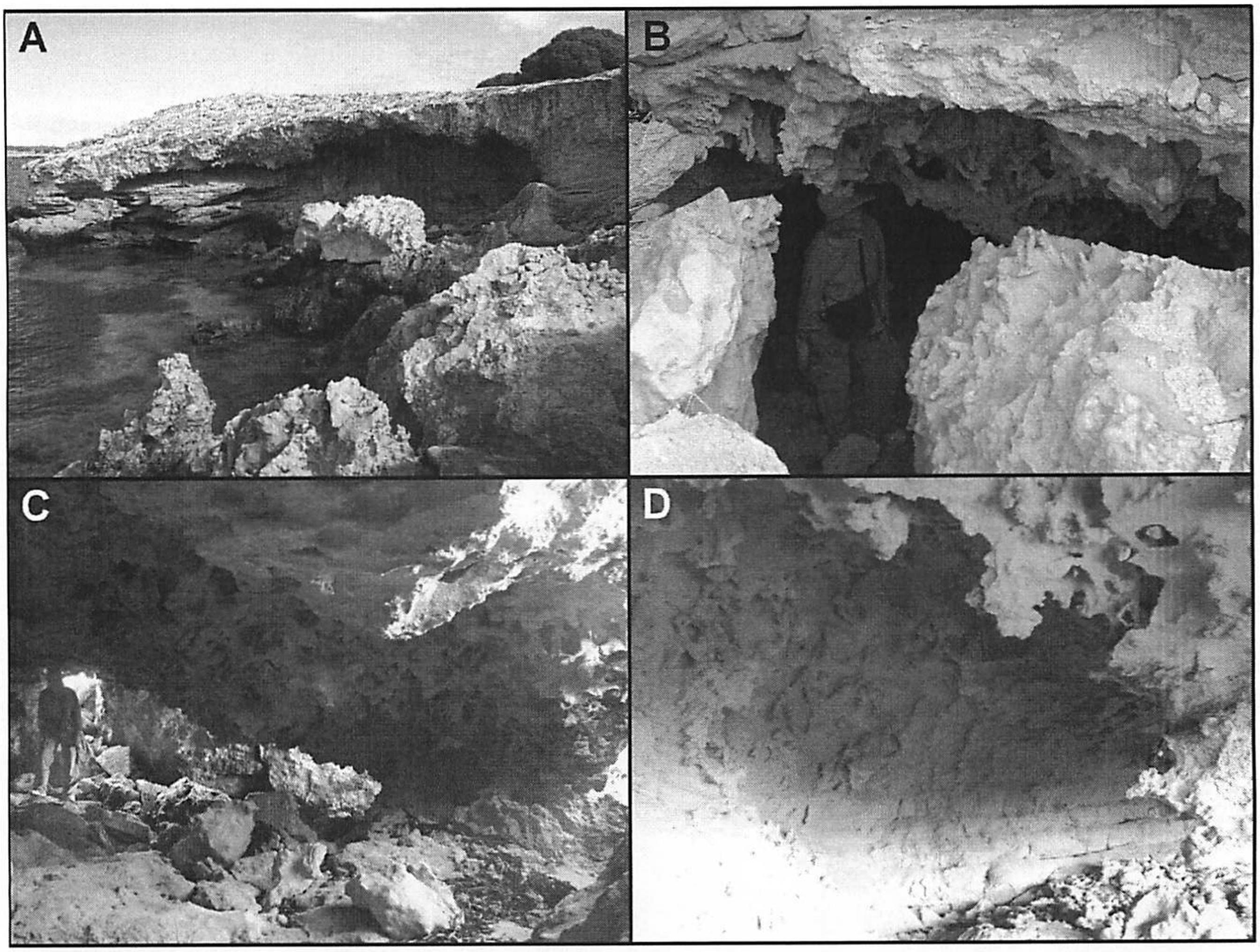

Figure 8. A) Cave opening in the sea cliffs south of Bathurst Lighthouse. The cave is being attacked by modern wave action. B) Entrance into a flank margin cave adjacent to the cave pictured in A. Note the vegemorphs hanging from the cave roof. C) Inside the cave shown in B. Note the complex vegemorphs forming the cave roof and part of the pillar on the right side. D) Back wall of a breached flank margin cave adjacent to the cave in B. Note that the vegemorphs have significant penetration into the dune mass, a good indication of regressive-phase eolianite origin; black flashlight on far right is 15 cm long for scale.

Pleistocene units on Rottnest Island (Owl's Hole Formation equivalent). The rock cannot be MIS 5e transgressive-phase eolianites (French Bay Member equivalent of the Bahamas) as the abundant vegemorphs preclude a trangressive depositional environment (Birmingham et al., 2008). If these eolianites truly contain flank margin caves, they cannot be MIS 5a or MIS 5c in age.

Vegemorphs are not the only trace fossils found along this section of coast. Within the tafoni developed in the Holocene Herschel Limestone at Bathurst Lighthouse (Figure 7) is a cluster burrow (Figure 9A). Cluster burrows are trace fossils believed to be produced in eolianites by sphecid wasps (Curran and White, 1999). While these features are common on San Salvador and other Bahamian islands (e.g. Martin, 2006), this is their first reported observation from Austra-

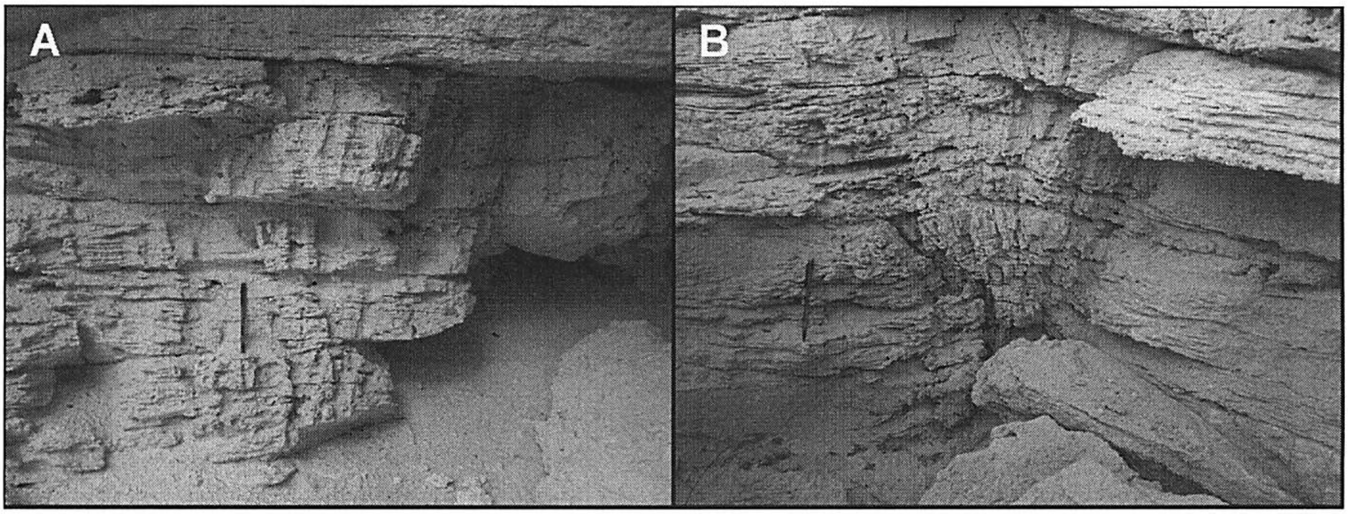

Figure 9. A) Cluster burrow believed formed by a sphecid wasp, in the Holocene Herschel Limestone, within the tafone shown in Figure 7A. B) A second cluster burrow, but this time in the Pleistocene eolianite near the location of the caves in Figure 8, south of Bathurst Lighthouse. Pencil 15 cm long for scale.

lia. Significantly, within the Pleistocene section just south of the Bathurst Lighthouse, is another cluster burrow (Figure 9B). Cluster burrows in Pleistocene eolianites have not been previously reported in any location. To find both Holocene and Pleistocene cluster burrows in such close proximity is therefore highly unusual.

Salmon Point

The sea cliffs developed in eolianites at Salmon Point have a well-developed terra rossa paleosol with abundant vegemorphs (Figure 10). The terra rossa paleosol indicates a Pleistocene age for the unit. They also contain numerous infilled dissolution pits, which being more lithified than the surrounding eolianite, have weathered out in positive relief in this coastal setting. The pits, when forming, conducted water from the epikarst into the eolianite. That fluid transfer, and subsequent infill, resulted in micritization of the pit walls and the infilling material, most likely at the time when the terra rossa paleosol covering the outcrop became micritized. As a result the pit and its infill are very resistant to erosion. Open pit caves were not observed during the reconnaissance, and infilled pits were rarely more than a few meters in depth. The rock here fits the criteria for a regressive-phase eolianite. Its appearance is remarkably similar to units mapped on San Salvador as Cockburn Town Member (MIS 5e), but that is purely an anecdotal comment. The unit could as easily be a regressive-phase unit of pre-MIS 5e eolianites, or MIS 5a-c if AAR interpretations are correct.

Fairbridge Bluff

West of Salmon Point, at the midpoint of Salmon Bay, is Fairbridge Bluff with a classic MIS 5e fossil reef (Playford, 1997). The reef outcrops from sea level to a little over 3 m elevation (Figure 11). The corals are predominantly various *Acropora* sp and *Goniastrea* sp (Playford, 1997), with molluscan-rich debris and coral fragments filling in the space between coral heads (Figure 11D). Szabo (1979) dated the fossil reef to 132 +/- 5 ka, indicating a MIS 5e age, which places it in the Rottnest Limestone. A terra rossa paleosol caps the fossil reef (Figure 12), further proof of its Pleistocene age, and indicating that the reef was exposed

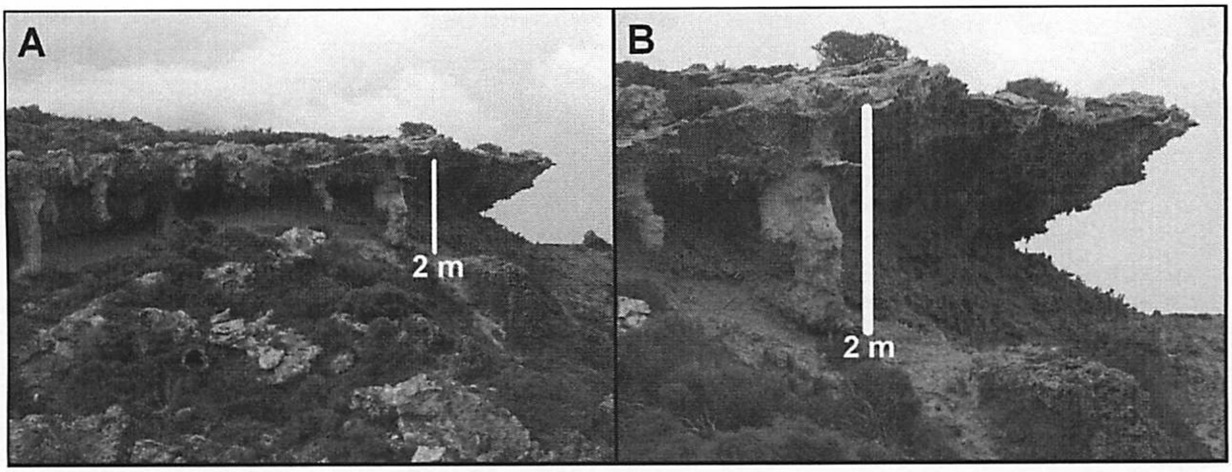

Figure 10. Infilled dissolution pits at Salmon Point (next point west of Parker Point on the east side of Salmon Bay in Figure 6). A) series of pits descending from a terra rossa paleosol surface. The pit infills are lithified to a greater extent than the surrounding eolianite, and weather out in positive relief in this coastal setting. B) Close up of the largest infilled pit in A. Note the numerous vegemorphs in this locality.

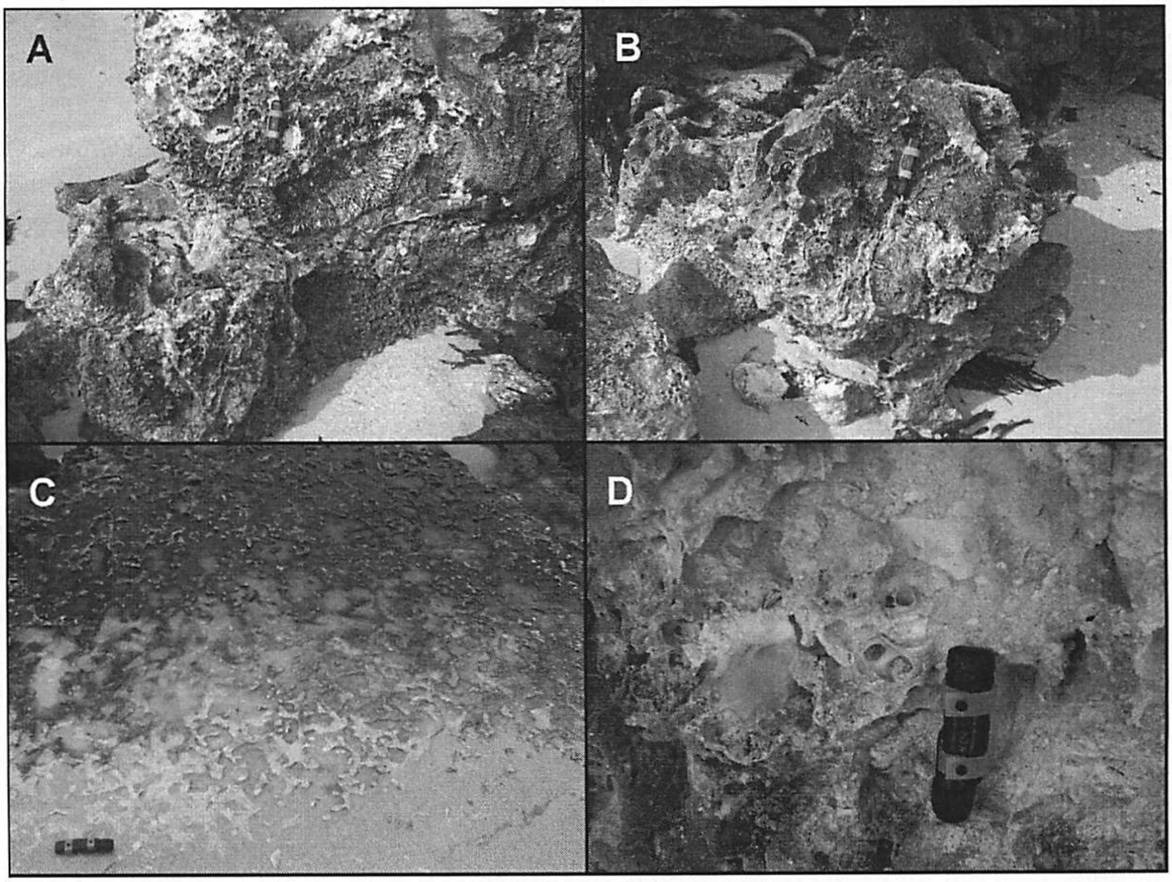

Figure 11. Fossil MIS 5e reef at Fairbridge Bluff (flashlight in all cases 15 cm for scale). A and B) Coral heads, Goniastrea sp (?) in coastal outcrop. C) Wave-planed section of Acropora sp; note casual similarity to vegemorphs. D) Fossil molluscan and coral fragments between coral heads.

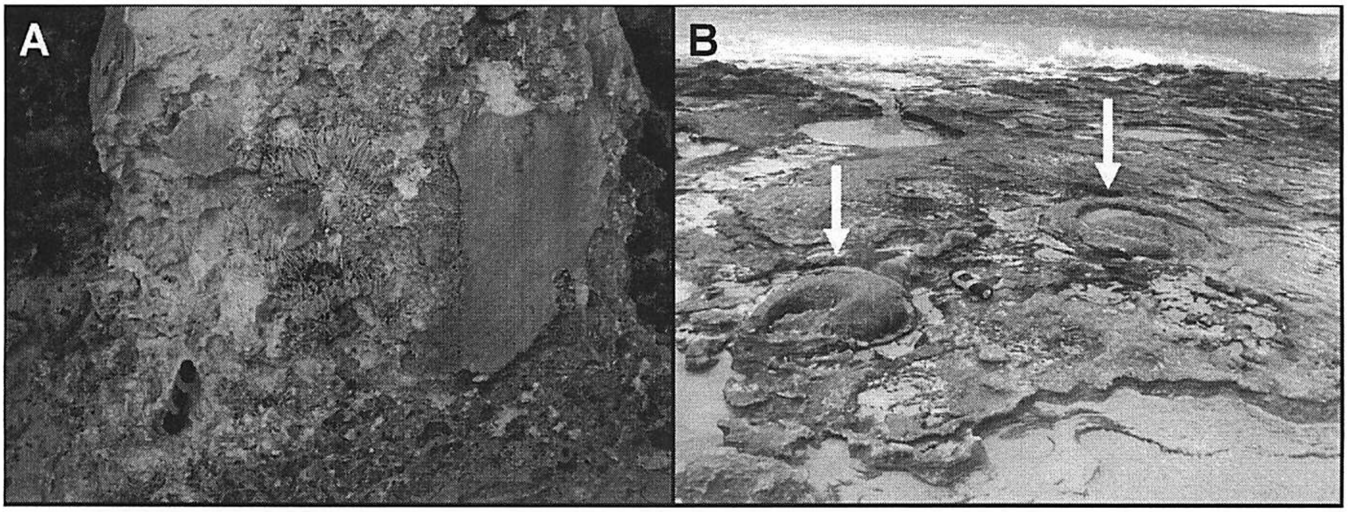

Figure 12. Fairbridge Bluff (flashlight 15 cm for scale in both cases). A) Coral head with patches of a red micritc crust from a terra rossa paleosol overlaying it. B) Dissolution pits (arrows), infilled with resistant terra rossa material, partially planed off by wave erosion. In color, these two mounds are bright red.

to subareal weathering processes at the end of MIS 5e without any intervening eolian deposition.

Western Salmon Bay

The western side of Salmon Bay is mapped by Playford (1997) as Tamala Limestone. The cliffs are eolianites (Figure 13) that have a terra rossa paleosol, but lack significant vegemorph development, and so are interpreted to be Pleistocene transgressive-phase deposits. These cliffs host a series of small to medium-sized voids that are unequivocally flank margin caves (Figures 14 and 15). The voids are chambers entered by openings formed by slope retreat of the enclosing eolianite. The caves are made of globular chambers (Figure 14 C & D), and have entrances smaller than the chambers inside. The walls and ceiling show classic phreatic dissolutional morphology of cupolas and dissolution tubes (Figure 16). Secondary calcite formations, such as flowstone (Figure 17) are found. This evidence indicates a flank margin cave origin for these voids. Figure 17 is instructive, for flowstone found inside notches on cliffs in the Bahamas have been interpreted to be terra rossa paleosols *within* the rock, as opposed to flowstone *on* the rock, with misidentification of the stratigraphy a result. Such notches have also been misidentified as fossil bioerosion notches instead of breached flank

Figure 13. Eolianite outcrop on the west end of Salmon Bay, east of Green Island (Figure 6). The outcrop is capped by a terra rossa paleosol, but lacks vegemorph development, indicating it is a transgressive-phase eolianite. Vertical height of the outcrop is 6 m.

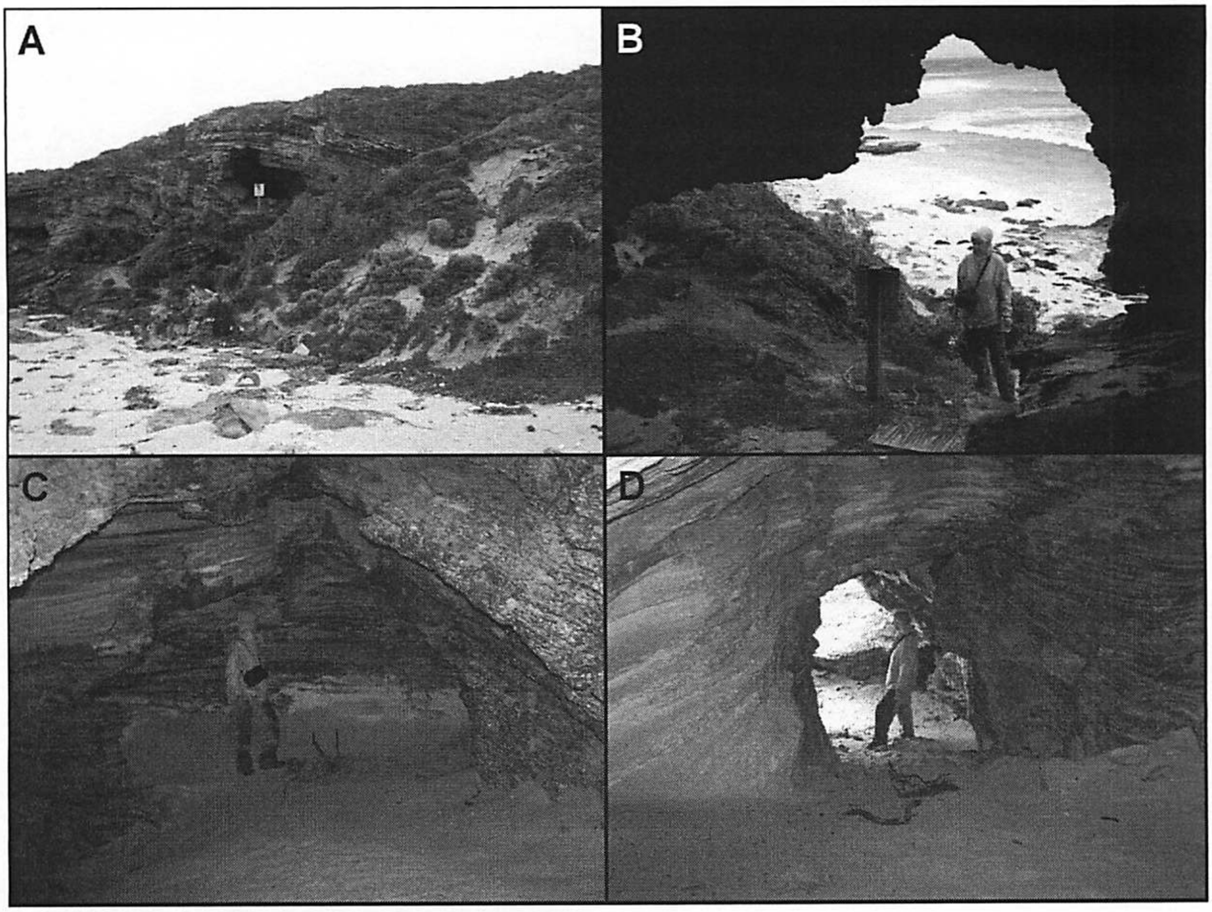

Figure 14. Flank margin cave at the eastern end of the Tamala Limestone outcrop at the west side of Salmon Bay. A) Eastern entrance to the cave. B) Looking out the entrance shown in A. C) Main chamber of the cave. D) West entrance of the cave, at a lower elevation than the eastern entrance.

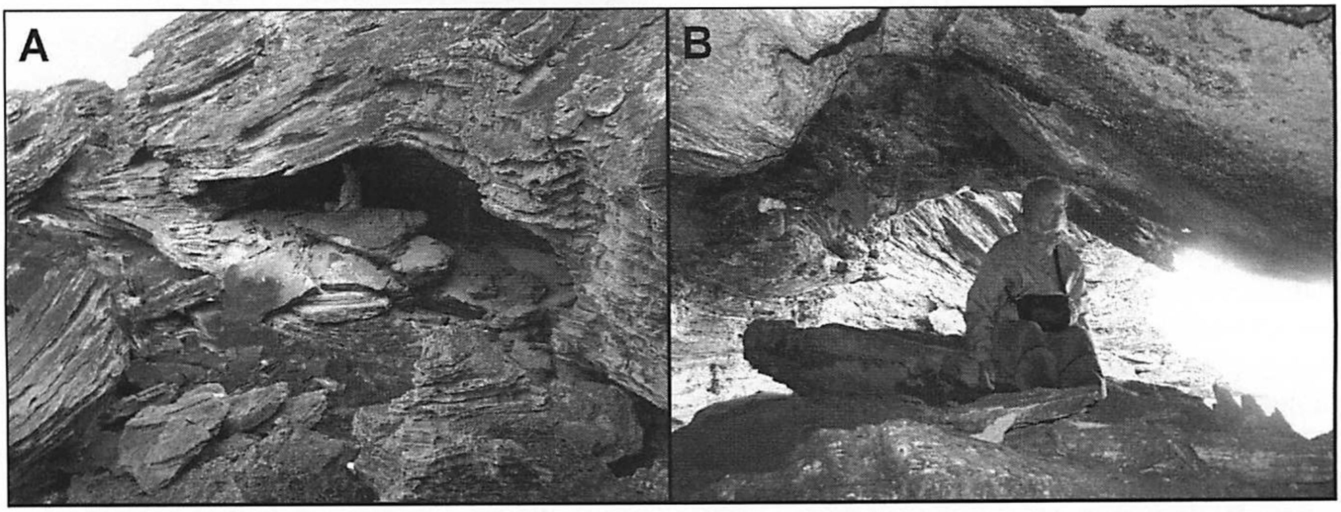

Figure 15. Flank margin cave at the western end of the Tamala Limestone outcrop at the west side of Salmon Bay. A) Main entrance to the cave. B) Inside the cave looking out the main entrance.

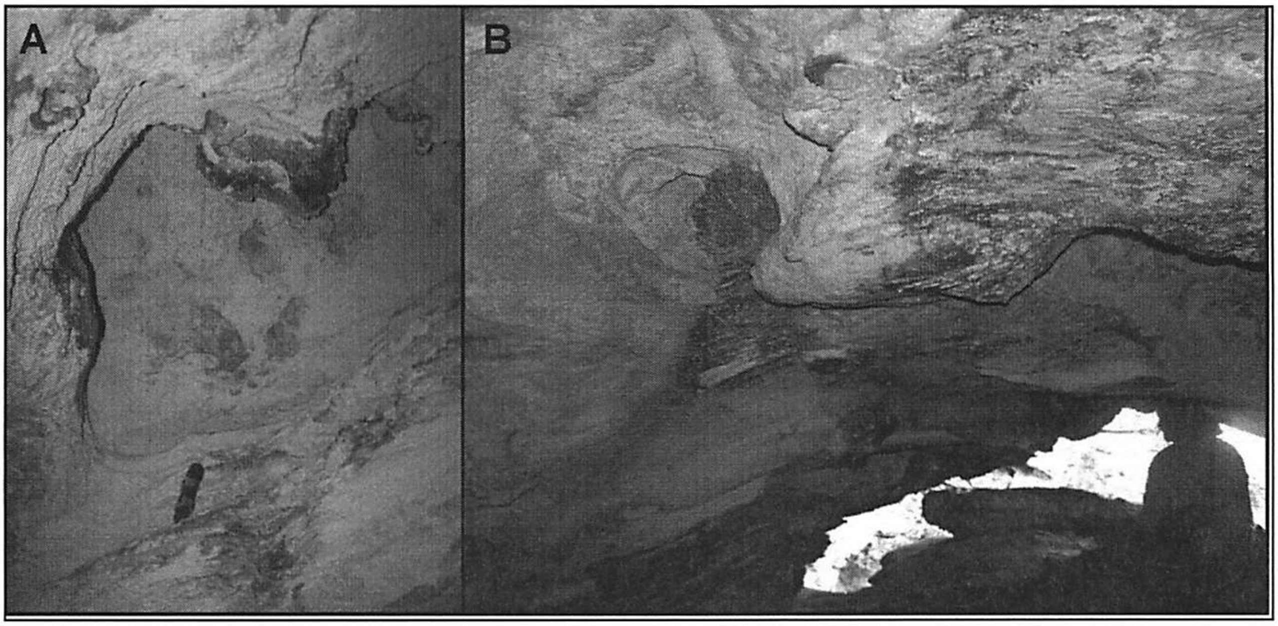

Figure 16. Ceiling morphologies in the flank margin cave shown in Figure 14. A) dissolution cupola in the cave ceiling (flashlight is 15 cm long for scale). B) Dissolution tube encrusted in flowstone. Person seated in the lower right for scale.

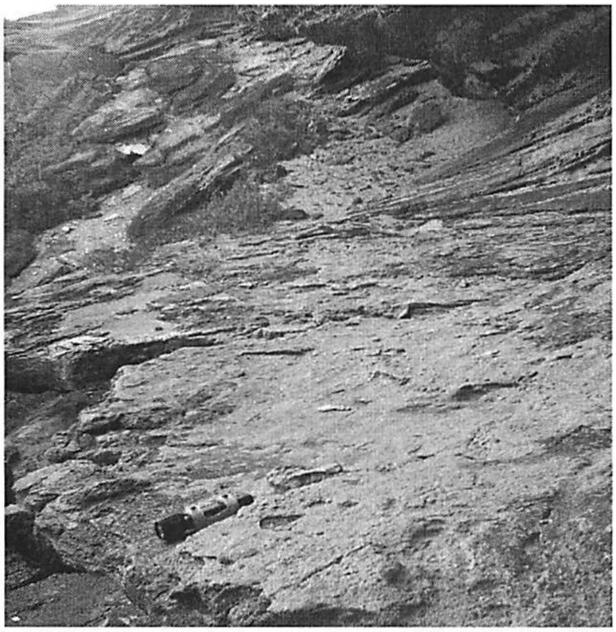

Figure 17. Breached western extension of the cave shown in Figure 14. Flashlight is 15 cm long for scale. The pale coating in this image is pink to red in color, and is a flowstone that developed on the cave floor before the cave was breached by surface erosion.

margin caves (Carew and Mylroie, 1991). The rock here is either a transgressive-phase eolianite from MIS 5e (and hence equivalent to the French Bay Member of the Bahamas), or a transgressive–phase eolianite from an earlier highstand event (Owl's Hole Formation equivalent).

Wilson Bay and Fish Hook Bay

Wilson Bay and Fish Hook Bay, at the extreme southwest end of Rottnest Island, display outcrops that appear to be exact analogues for outcrops observed in the Bahamas. Sea arches are common along this coast (Figure 18), a predictable outcome given the high eolianite cliffs and strong wave action. The eolianites here show well-developed calcarenite protosols within the body of the outcrop (Figure 19), with terra rossa paleosols capping the outcrop. As with the outcrop at Salmon Point (Figure 10), this configuration is common in the Bahamas, and there it is diagnostic of MIS 5e (Carew and Mylroie,1995a, 1997) or MIS 5a (Hearty and Kindler, 1993).

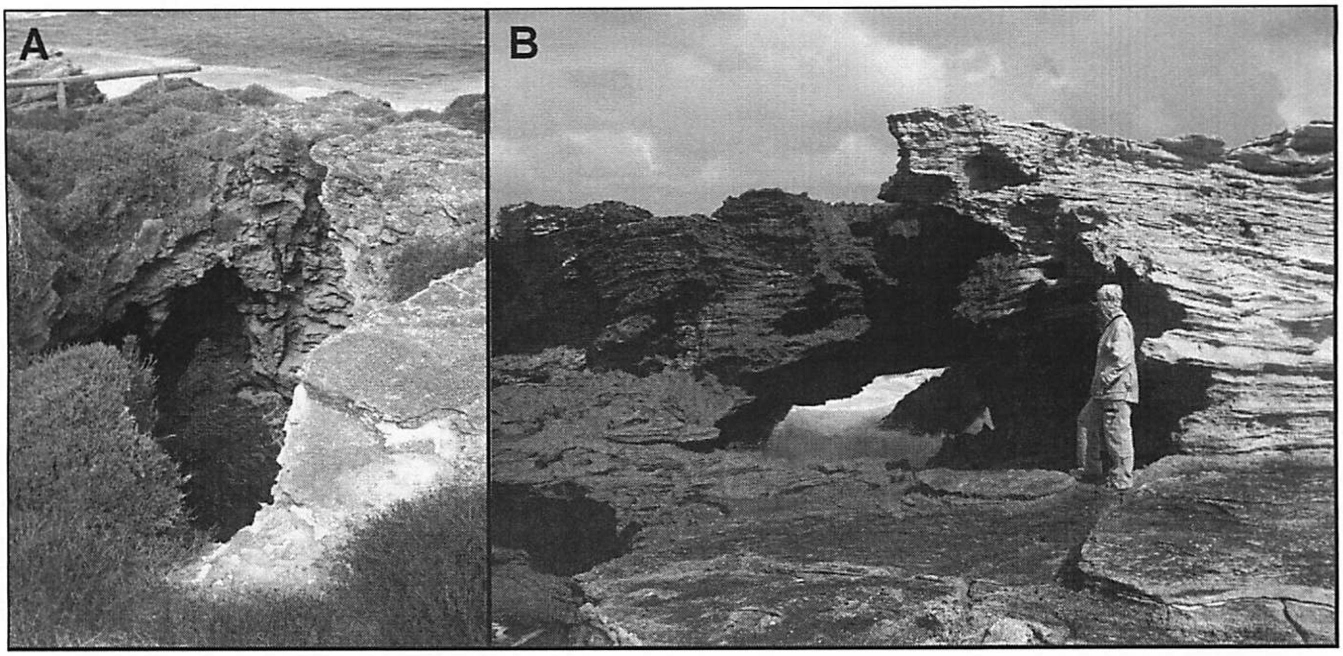

Figure 18. Sea Arches along the coast at Fish Hook Bay. A) Large arch, guardrail in upper left for scale. B) Small arch in the active surf zone.

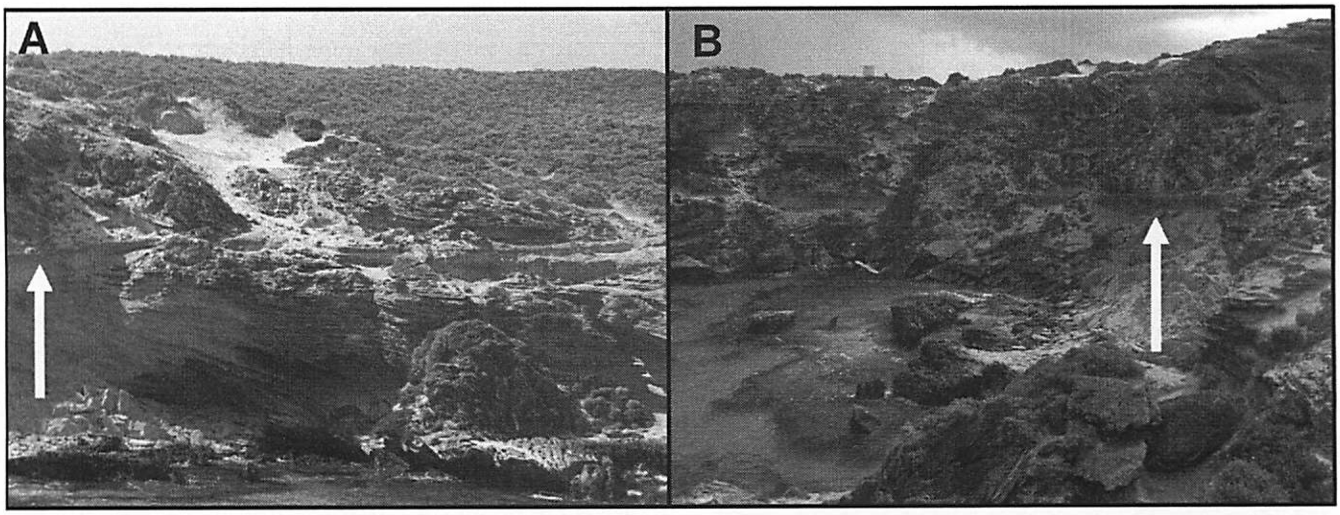

Figure 19. Calcarenite protosols (vertical arrows) within eolianites, with terra rossa paleosols capping the outcrops. A) Wilson Bay. B) Fish Hook Bay.

Hearty (2003) reports AAR data from these outcrops consistent with a MIS 5 interpretation.

The landforms here are distinctive. The terra rossa material has infilled dissolution pits, as at Salmon Point (Figure 10), creating resistant features that weather out in positive relief, inverting the topography. Initially, the resistant infilled dissolution pits act as pillars supporting the terra rossa paleosol material as wind energy excavates the poorly-cemented sands beneath (Figure 20A). Vegemorphs are common (Figure 20B). Continued weathering and erosion eventually strips the terra rossa paleosol and the underlying hillside landward, leaving the infilled dissolution pits as isolated pillars (Figure 20 C&D). The end result is a classic inversion of topography.

The eolian surface above Wilson Bay has weathered into a pattern of polygons (Figure 21 A&B). This phenomena has also been observed in the Bahamas on Eleuthera Island (Panuska et al., 2002) and Cat Island (Mylroie et al., 2006). Desiccation or salt wedging has been speculated as the cause (Panuska et al., 2002). Off shore, in the shallow lagoon, other polygonal features can be observed, at a larger scale (Figures 21 C&D). These are constructional features made by a kyphosid fish creating individual territories for algal "farming" (Playford, 1997).

Herschel Lake

Herschel Lake is one of a series of inland water bodies located in the northeastern portion of Rottnest Island (Figure 6). As noted earlier, this is

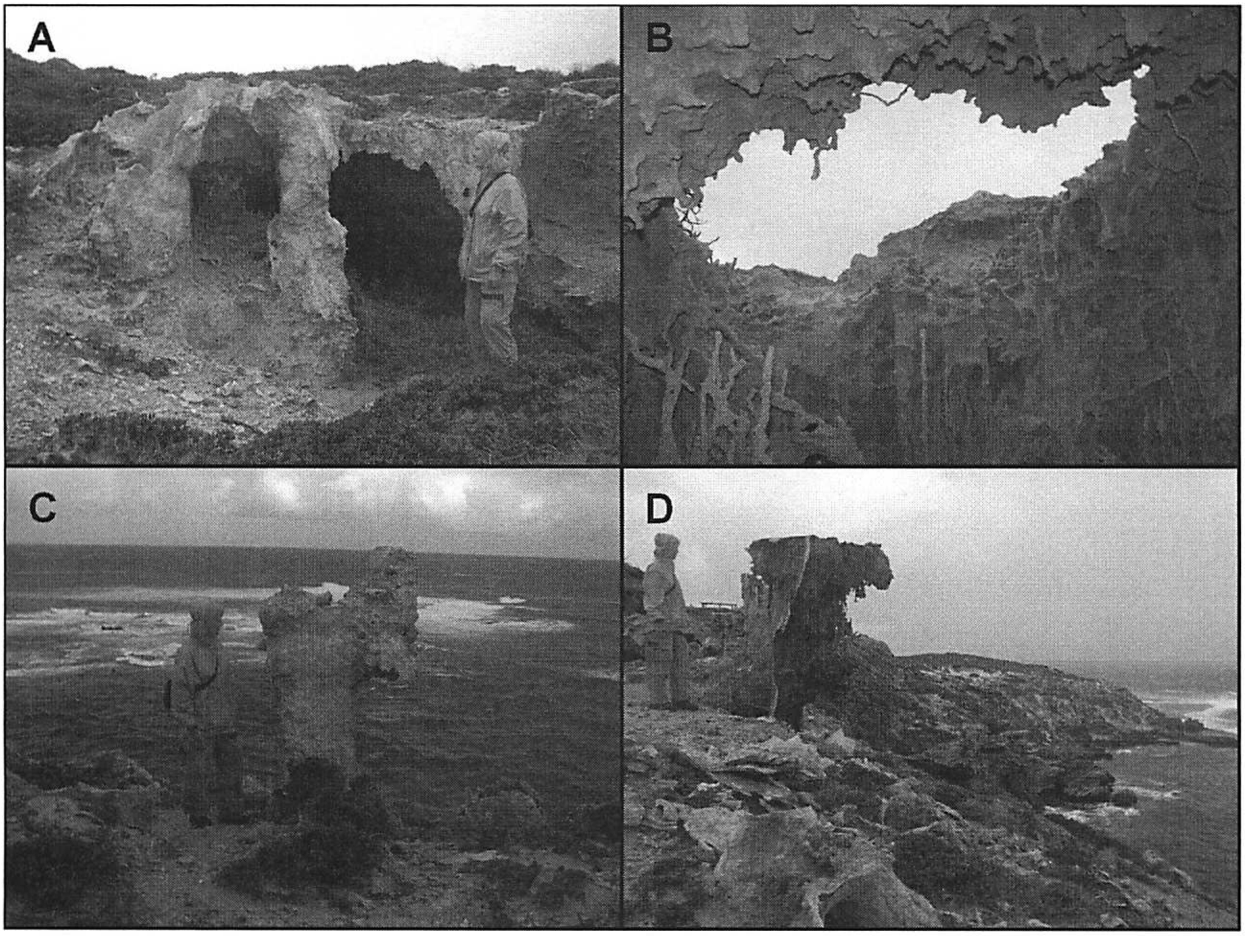

Figure 20. Infilled dissolution pits and vegemorphs, Wilson Bay. A) Outcrop forming a small cave by mechanical excavation of dune material from beneath a resistant terra rossa paleosol. Resistant infilled dissolution pits act as pillars to hold up the void roof. B) View inside the cave in A, looking out a hole in the roof, with abundant and varied vegemorphs. Hole is 60 cm across. C) Residual pillar formed from a resistant infilled dissolution pit. This situation represents a more advanced stage of A, where the terra rossa paleosol and hillside have been stripped back, leaving the dissolution pit as an example of inverted topography. D) Another example of the situation in C, about 25 m away to the east.

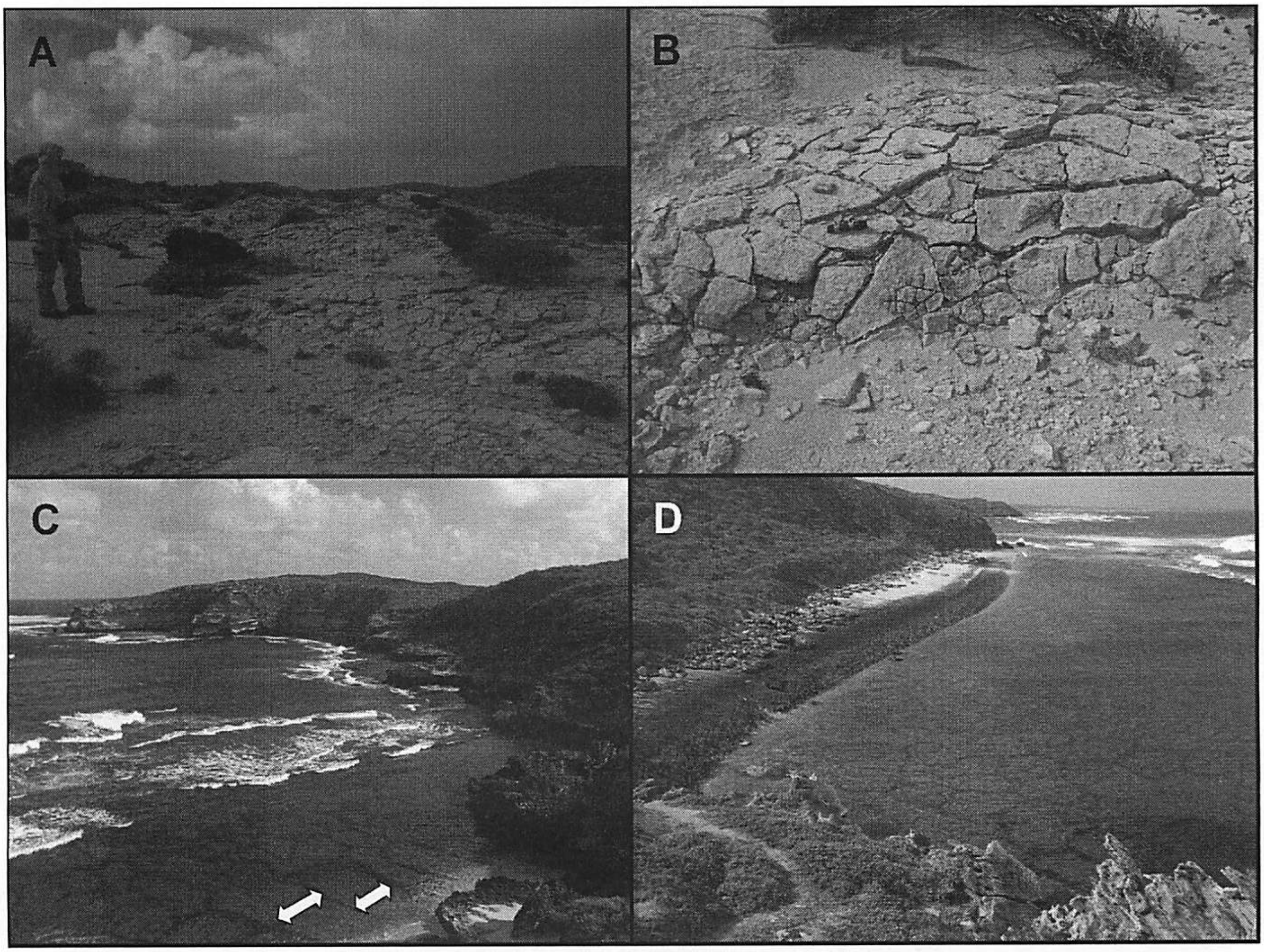

Figure 21. Polygonal forms, Wilson Bay. A) Polygonal cracking of an eolianite surface. B) Close up of A, flashlight 15 cm long for scale. C and D) Polygonal pattern expressed in the shallow off shore at Radar Reef, between Wilson Bay and Fish Hook Bay (doubled arrows mark polygon boundaries in C). This pattern is produced by territorial behavior and algal farming of a kyphosid fish (Playford, 1997).

the type locality for the Holocene Herschel Limestone and its lagoonal facies (Figure 22). The Indo-Pacific basin and Rottnest Island show evidence of a mid-Holocene sea-level highstand of a couple of meters (Playford, 1997), a feature that is not well documented in the Atlantic basin. The outcrops also show unusual features, such as seen in Figure 23, which may indicate the past presence of evaporites. The shoreline of Herschel Lake contains a number of eolianite outcrops with notches and voids in them. They were interpreted by Playford (1997) to be wave-cut or bioerosion notches, but in some cases they appear to be tafoni (Figure 24) and in other cases breached flank margin caves (Figure 25). If they are flank margin caves, they could be relict from the Pleistocene MIS 5e highstand, or they could be Holocene in age, relict from the mid-Holocene highstand. If Holocene in age, they would be one of the few flank margin caves known from the current sea-level highstand.

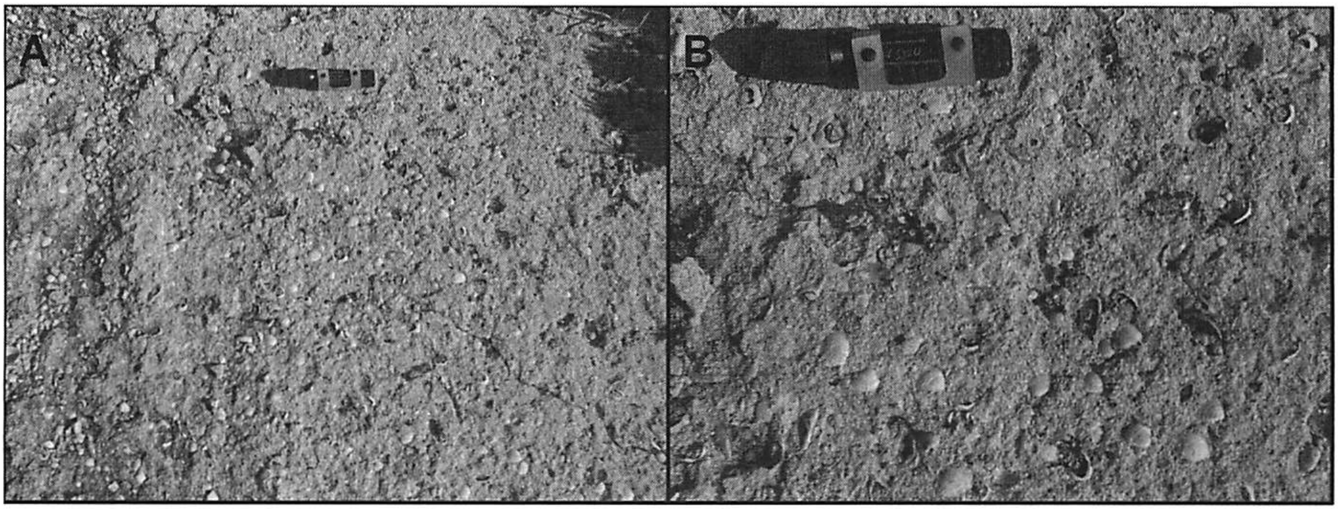

Figure 22. Lake Herschel area, flashlight is 15 cm long for scale (note that the flashlight shadow in low-angle morning sun extends the length beyond 15 cm). A) Lithified Herschel Limestone on the shore of Herschel Lake. This unit is a mollusc-rich lagoonal facies. B) Close up of the same outcrop.

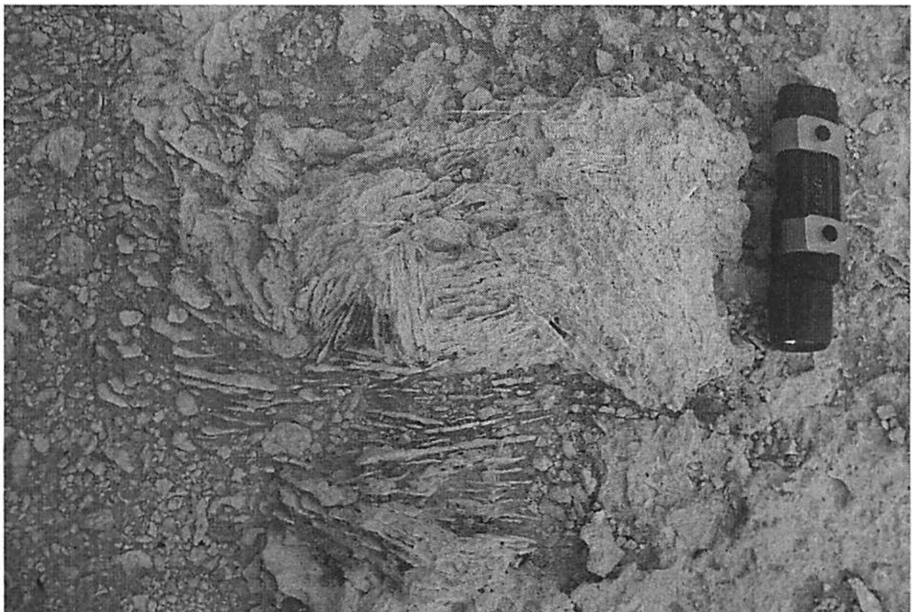

Figure 23. Flat lithified outcrop on the shoreline of Herschel Lake, showing a vertical bladed pattern that may relate to evaporite mineral activity. Flashlight 15 cm long for scale.

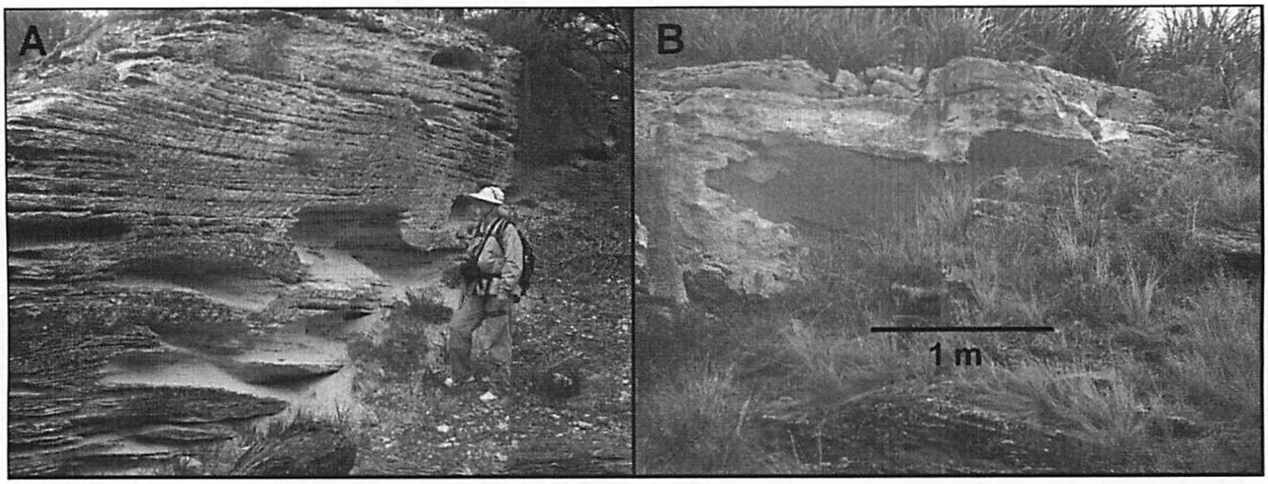

Figure 24. Eolianite ridge bordering Herschel Lake. A) Probable tafoni, recognizable by the white interior and the layer-parallel configuration. B) Another probable tafone.

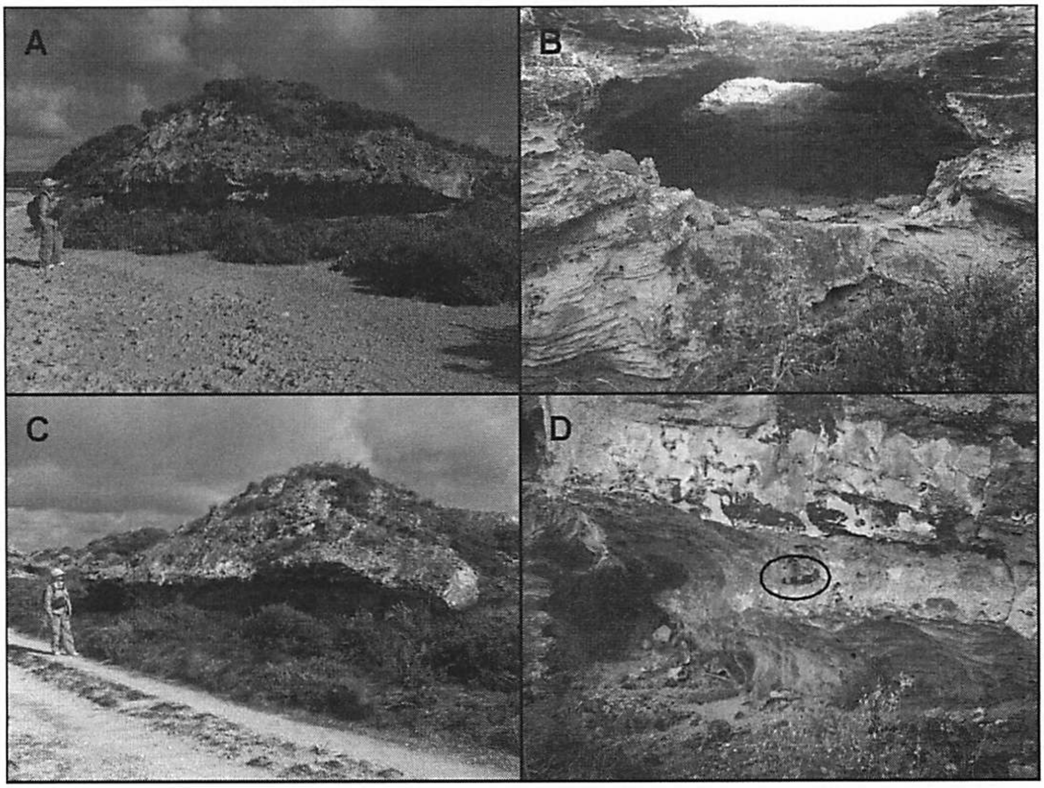

Figure 25. Voids in eolianites along the shore of Herschel Lake. Described by Playford (1997) as wave or bioerosion notches from the mid-Holocene sea-level highstand, they appear to be flank margin caves. A) Notch at the end of a dune; the notch does not have lateral continuity, but contains interior phreatic features. B) Short tunnel with phreatic wall sculpturing. C) Similar to A, a discontinuous notch with phretaic wall sculpturing. D) Close up of the back wall of one of the many notches along the shore of Herschel Lake. The notch contains curvi-linear phreatic sculpture and a thin layer of red flowstone. Flashlight 15 cm long for scale (in oval).

CONCLUSIONS

The reconnaissance of Rottnest Island was literally a whirl-wind tour. The goal to compare Rottnest Island to the Bahamian Islands by simple observation was accomplished. As expected with a stable tectonic setting, the geology of Rottnest Island fits well into the established model for Quaternary carbonate islands developed in the Bahamas. Eolian units associated with pre-MIS 5e, MIS 5e, and Holocene highstands were observed, as were MIS 5e subtidal facies, demonstrating the portability of the Bahamian model. Flank margin caves were identified, and their existence, as at Bathurst Lighthouse, helps constrain the available geologic interpretations. One major surprise was the discovery of cluster burrows in both Holocene and Pleistocene eolianites on Rottnest Island, their first reported observation from the southern hemisphere, and first reported observation in Pleistocene eolianites. The existence of potential flank margin caves on the shores of Herschel Lake open the possibility that the caves are Holocene in age, produced on the Indo-Pacific mid-Holocene sea-level highstand. If true, it would be an important documentation of the rapidity of the flank margin cave dissolution process, and emphasize the difference in Holocene sea-level history between the Indo-Pacific and the Atlantic basins. This paper was designed to report a rapid reconnaissance; hopefully, it will stimulate more in-depth work on this interesting Australian island with such strong similarities to Bahamian stratigraphy and karst landforms.

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