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Geomorphology of the uplifted Pleistocene atoll at Henderson Island, Pitcairn Group

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Henderson Island, in the Pitcairn Group, preserves a Pleistocene atoll physiography with the rim of the raised reef structure, supporting spur and groove topography, enclosing a central lagoon. Excellent preservation of coral reef communities occurs along the ancient atoll rim and within the central lagoon. The previously interpreted depositional nature of the fossil atoll structure is herein corroborated with geomorphologic and stratigraphic evidence from previously un-visited portions of the island. Stratigraphic and lateral facies relationships indicate a physiographic zonation which includes spur and grooves, outer reef flat, lagoon margin, and an interior lagoon with patch reefs. The *in situ* occurrence and zonation of reef coral communities around the periphery and within the interior of the island appear to reflect the original physiography of the atoll lagoon, with the most pronounced reef development on the SE side of the original atoll. Stratigraphic units which comprise the raised atoll lagoon structure represent different time intervals, so the atoll lagoon structure formed during various sea level fluctuations. The modern atolls of the Pitcairn Group, Oeno and Ducie, provide some comparisons (similarities and differences) with the fossil lagoon on top of Henderson Island.

ADDITIONAL KEY WORDS:—carbonate – reef zonation – palaeogeography – Quaternary – coral reef – Pitcairn Islands – spur and groove – atoll – lagoon.

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INTRODUCTION

Henderson Island in the Pitcairn Group is one of the few remaining uninhabited raised atolls (Fosberg, Sachet, & Stoddart, 1983). The initial observations on the central depression of Henderson Island made during the

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1934 Mangareva Expedition (St. John & Philipson, 1962; Fosberg *et al.*, 1983) led to the speculation that Henderson Island preserved an elevated atoll with a central fossil lagoon. These speculations were confirmed in the 1987 Smithsonian Expedition to the Pitcairn Islands by Paulay & Spencer (1988) and Spencer & Paulay (1989). The purpose of this paper is to provide some further details on the fossil atoll structure, using additional data from some previously unknown parts of the island. The goals of this paper are to: (1) detail what is presently known of the raised reef structure at the top of Henderson Island, (2) present additional observations made during the 1991 Sir Peter Scott Commemorative Expedition to the Pitcairn Islands, and (3) compare the raised fossil atoll of Henderson Island with the modern atolls at nearby Ducie and Oeno in the Pitcairn Group.

OVERVIEW OF THE UPLIFTED ATOLL AT HENDERSON ISLAND

Paulay & Spencer (1988) and Spencer & Paulay (1989) provided the first detailed descriptions of the raised atoll based on observations from the northern and northwestern portions of Henderson Island. They recorded the depositional nature of the raised atoll with an outer rim composed of an outer reef flat and a lagoon margin, and a fossil lagoon with patch reefs.

In the northwest, the outer rim is composed of two zones. (Paulay & Spencer, 1988; Spencer & Paulay, 1989). The first zone occupies a band extending from just adjacent to 250 m SE of the cliff top margin. It is composed of joint-bounded limestone blocks or *lineations* 0.2–0.5 m high and pinnacles greater than 1 m in height, alternating with gravel patches composed of unconsolidated branching coral rubble (Fig. 1). The lineations may exhibit such features as straight-sided basins 0.5 m deep, 2.0 m in diameter and solution holes with vertical walls up to 2.5 m high and flat floors 3 m in width. The well-indurated lineations and low pinnacles are dominated by branching coral rubble composed of *Acropora* spp., *Pavona* sp(p)., *Pocillopora* sp(p)., and *Porites* sp(p). Due to the reef physiography, the abundance of unconsolidated branching coral rubble, and the presence of frequent *Turbo argyrostomus* and *Tridacna maxima* shells, Spencer & Paulay (1989) interpreted this zone as the outer reef flat of the original atoll.

The second zone begins around 250 m from the seacliff margin where a pinnacle karrenfeld is the contact between the island rim limestones and the central lagoonal depression (Spencer & Paulay, 1989). Here, a landscape of sharp recrystallized limestone pinnacles and solution pits has a vertical relief of up to 2 m. The karrenfeld extends for about 100 m. Inland from the karrenfeld is a vertical drop of about 3 m over a horizontal distance of 15–20 m to the interior lagoonal depression.

In contrast to the northwest side of Henderson Island, pinnacled outcrops occur up to 1 km from the northern island margin. Spencer & Paulay (1989) estimated the maximum height of the island rim in this zone to be 33.6 m above present sea level 250 m in from the cliff edge. The wide expanse of pinnacled outcrops seaward of the highest point is attributed to a paleo reef flat similar to that occurring on the northwestern margin of the island. The paleo reef flat probably also extends landward of the maximum height of

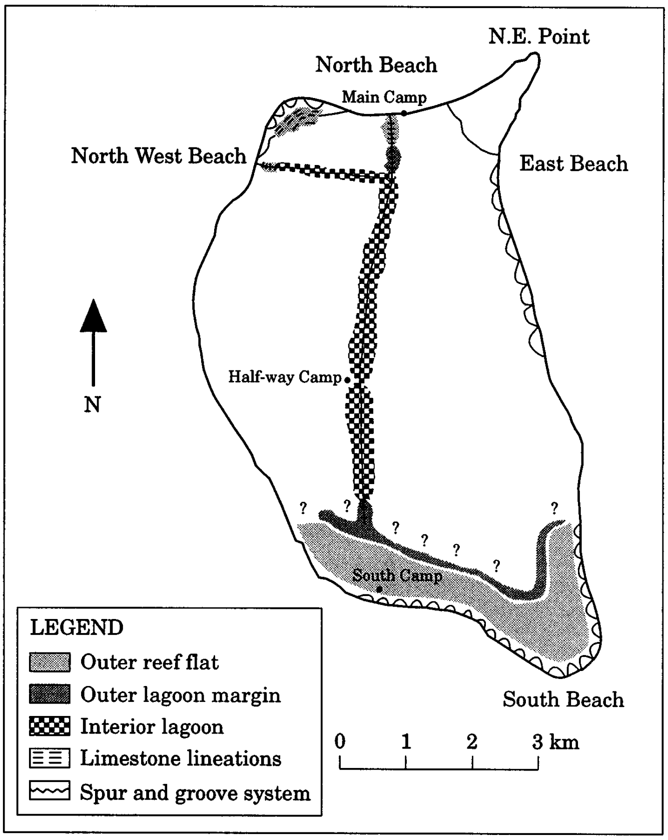

Figure 1. Plan view of geomorphologic structures of the top of Henderson Island. Northwest Point and the southern and eastern sides of the island have abundant spur and groove features comprising the seaward margin of their outer rim. The outer rim of the northern and northwestern sides is characterized by a series of pinnacled limestones and lineations which represent the outer reef flat and the outer shallow margin of the atoll lagoon. Both the southern side and the northwestern side have a broad field of pinnacle topography (karrenfeld) between the seaward margin of the outer rim and the outer margin of the lagoon. At the southern end of the island, there is a clear zonation pattern in the composition of the coral assemblages and increasing development of spur and groove structures to the southeast.

the island rim, and grades into a lagoon margin, which itself grades into the interior lagoon (Spencer & Paulay, 1989).

The interior depression of Henderson Island has been interpreted as a fossil lagoon (Fosberg *et al.*, 1983; Paulay & Spencer, 1988; Spencer & Paulay, 1989). Spencer & Paulay (1989) noted local topographic highs, up to 15 m across, within the interior depression. These areas are dominated by rubble of >2 cm thick *Acropora* spp. branches with lesser abundance of *Montastrea* sp. 1, *Favia stelligera*, branching *Porites* sp(p)., stoutly branching *Acropora* spp. (5 cm branch diameter), *Pocillopora* sp(p). and *Pavona* sp(p). Paulay & Spencer (1988) and Spencer & Paulay (1989) interpreted these areas as large lagoonal patch reefs. Other reef complexes discovered by these authors on the northern and northwestern interior are composed of massively branching and tabloid *Acropora* spp.

METHODS

During the Sir Peter Scott Commemorative Expedition to the Pitcairn Islands in 1991, I was able to spend several weeks at the raised atoll of Henderson Island, and several days each at Ducie and Oeno atolls. The variable geomorphology of both the outer rim and the interior depression of Henderson Island was investigated at four major locations on top of the island (Fig. 1): (1) along the N-S trail leading from Main Camp in the North to South Camp in the southern portion of the island; (2) between North Beach and North West Beach along an unvegetated band ranging from 100–200 m wide along the northwest trail; (3) between North Beach and East Beach along the East Beach trail and about a 100 m band inland from the cliffs at East Beach; and (4) along an unvegetated coastal band ranging from 500–1000 m wide extending for approximately 3 km between South Camp and South Point and a further 2 km northeast of South Point and approximately 2 km west/northwest of South Camp again along the southern coast. Because the northern and central portion of Henderson Island are heavily vegetated, the majority of geological investigations were made in the southern portion of the island.

In order to understand the variability in the reef coral taxonomic composition throughout the raised atoll, sets of transects were laid on the spurs of the spur and groove systems, and throughout the outer reef flat in the southern and northwestern portions of the island. Taxonomic investigations will be reported elsewhere, but here I report coral abundance results from three spurs from the southern end of Henderson Island, where line transects were laid perpendicular to the long axis of the spur. Three transects were laid on each spur and recordings of transect intercepts were taken every 30 cm. Lengths of transects ranged from 20.7 to 29.7 m with a mean of 24.9 m ($n = 9$; Table 1).

The modern atolls of Oeno and Ducie were also visited. Observations of

TABLE 1. Transect lengths and % coral abundance from 9 linear point transects laid on three fossil spur and groove structures at the southern end of Henderson Island

Transect		Length (m)	% coral abundance
S/G 1	Tr 1	32.4	32
S/G 1	Tr 2	30.6	41
S/G 1	Tr 3	28.2	37
	mean	30.4	37
S/G 2	Tr 1	21.9	42
S/G 2	Tr 2	25.5	30
S/G 2	Tr 3	28.1	32
	mean	25.2	35
S/G 3	Tr 1	21.6	33
S/G 3	Tr 2	25.5	32
S/G 3	Tr 3	23.1	37
	mean	23.4	34
Grand mean		26.3	35

the reef geomorphology on these islands were made using SCUBA and snorkelling.

SOME NEW OBSERVATIONS ON THE GEOMORPHOLOGY AND STRATIGRAPHY OF THE FOSSIL LAGOON

Several new observations made during the 1991 Expedition to Henderson Island corroborate the depositional nature of the fossil atoll structure. This additional evidence comes from analysis of the geomorphology of the top of Henderson Island, including outer rim and spur and groove structures; stratigraphic and lateral facies relationships, and the spatial variability of reef corals around the periphery and within the interior of the island.

Geomorphologic structures

The original geomorphology of the fossil atoll at the top of Henderson island appears to be preserved intact and includes an outer rim with spur and groove structures and an outer reef flat, a lagoon margin and an interior lagoon. The outer rim of the raised atoll is characterized by pinnacled limestone outcrops and is best preserved on the southern side of the island. At North West Point and on the southern and eastern sides of Henderson Island the seaward margin of the outer rim preserves an extensive spur and groove system, which on the southern side may give rise seaward to another series of valleys and ridges. Such submarine topography is evident today on the eastern side of Henderson Island. On the north and northwestern sides of the island, excluding North West Point, a series of limestone buttresses (Spencer & Paulay, 1989) may also be the erosional remnants of a previous spur and groove system. A central lagoonal depression is characterized by abundant corals and coral rubble in a gravel facies and local topographic highs with abundant reef coral assemblages that probably represented patch reefs in the ancient lagoon. The transition between the outer atoll rim and the lagoon is an inner margin composed of pinnacled outcrops and lineations separated by shallow basins.

Spur and groove system

The seaward margin of the outer rim on the southern and eastern sides of Henderson Island is expressed as abundant spur and groove structures (Fig. 2). Spur and groove structures were mapped on the southern side of the island as here low vegetation provides conditions for sampling and observation. The structures were oriented perpendicular to the present coastline. An extremely fossiliferous reef assemblage drapes the spurs. Both massive and branching corals are preserved upright, whole and in place, and are up to 2 m in their largest dimension. Large massive *Porites* sp(p). and branching *Acropora* spp. are common.

The grooves are filled with mainly branching coral rubble, presumably derived from the coral colonies living on the spurs. The composition of the grooves continues underneath the adjacent spurs (see below). An idealized spur and groove with stratigraphic units is given in Figure 3. The spurs range from 2–6 m above the floor of the grooves and are typically higher

Figure 2. Oblique aerial photograph of the paleo spur and groove topography preserved at the southern end of Henderson Island. The spur and groove topography is preserved best here, at North West Point, and in some of the cliff sections at East Beach. The spurs and grooves at the southern end are perpendicular to the modern cliff line. Severe erosion along the whole southern and eastern sides of the island is the result of the prevailing weather direction from the SE. North is toward the right in the photograph.

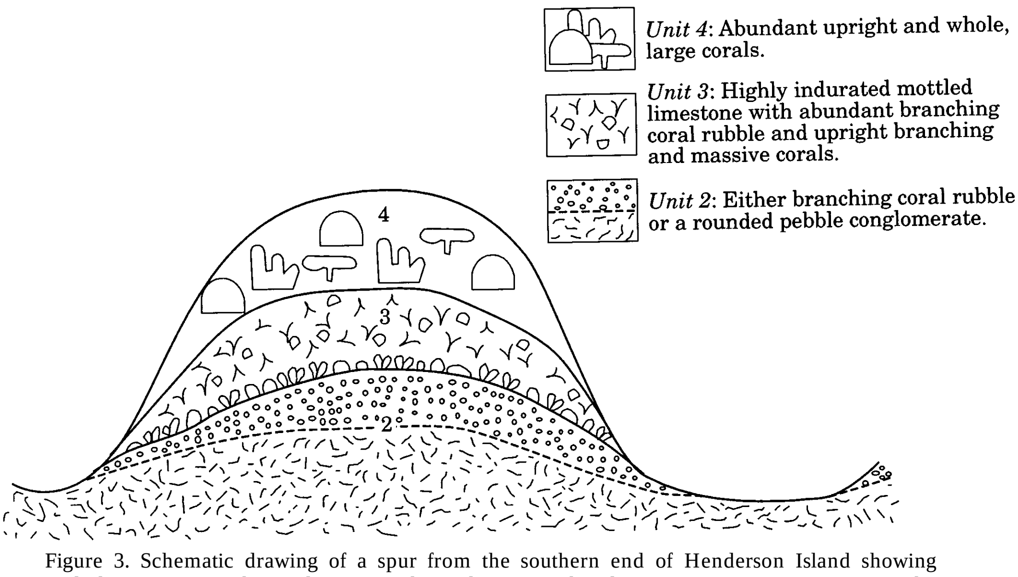

Figure 3. Schematic drawing of a spur from the southern end of Henderson Island showing underlying stratigraphy and stratigraphic relations with adjacent groove. *Units 2–4* can be correlated with the type section at East Beach and represent different episodes of reef development. *Unit 2* is composed of a rounded pebble conglomerate underlain by a branching coral rubble lithology which continues underneath the groove floor. A clear coral colonization event is evident at the base of *Unit 3*. *Unit 4* contains a prolific fauna of large whole upright massive, and stout branching acroporid corals.

on their western sides than on their eastern sides. They are 30–50 m in length and 10–15 m in width. Eastward of South Point the spur and groove structures give rise seaward to another set of valley and ridge structures similar to those which now occur at a depth of 20–30 m on the eastern side of Henderson Island (Blake, 1995; Blake & Pandolfi, in press). The eastern side of the island including the cliff sections contains spur and groove structures similar to, but smaller in scale than, those from the southern side of the island. At North West Point, between North Beach and North West Beach, spur and groove structures are found immediately adjacent to the seacliffs and at North and North West Beaches the buttress limestone of Spencer & Paulay (1989) may also be erosional remnants of a previous spur and groove system.

The fact that most coral colonies on the spurs appear to be *in situ*, and thus that the geomorphology of the spurs appears to be well preserved, invites comparison of the living coral cover with the fossil coral abundances. Fossil coral abundances along 3 southern spurs ranged from 30% to 42% with a mean of 35% ($n = 9$) (Table 1). Paulay & Spencer (1988) reported living coral cover, measured by random counts, of only 6% at 11 m depth on the northern reef slope of Henderson Island. Estimates of living coral cover in both Irving (1995), and Blake & Pandolfi (in press) were greater. Estimates of living coral cover ranged from 5–25% along North Beach, 10–40% at North West Point, 20–30% at North East Point, 10–40% along the west coast, 10–80% along the east coast, and 5–60% at South Point (Irving, 1995; Blake & Pandolfi, in press). Thus coral abundance on top of the fossil spurs falls within the range of coral cover presently observed at Henderson Island (Table 2). In making this comparison, a direct relationship between fossil coral abundance and living coral cover is not implied; only that the *estimates* made on the living coral cover and the *measured* fossil coral abundance on the spurs appear to be concordant. Such comparisons should be interpreted with extreme caution, however, because time averaging of

TABLE 2. Comparison between estimated living coral cover around Henderson Island, and measured coral abundance found on the fossil spur and grooves

Locality	Living coral cover[a]
Living	
North Beach	5–25%
Northwest Point	20–30%
Northeast Point	10–40%
East Beach	10–80%
South Point	5–60%
	Fossil coral abundance[b]
Fossil	
South Point	35%

[a] Estimates from Irving & Jamieson 1995, and Blake (personal communication).

[b] Measured from transects taken on fossil spurs—see Table 1.

many temporally distinct coral assemblages might give the appearance of greater abundances than what actually occurred during any single time interval.

Outer reef flat

The spur and groove structures on the southern end of the island give way to a pinnacled karrenfeld that extends over 300 m inland. The pinnacled karrenfeld between the spur and groove structures and the outer lagoon margin likely represents an outer reef flat system equivalent to that in the northern part of the island found by Spencer & Paulay (1989).

The pinnacled karrenfelds on Henderson Island preserve some or all of the three depositional units described below. In the northwest, the pinnacles have abundant branching coral rubble with branching *Acropora* spp., echinoderm debris (pencil urchin spines), and *T. argyrostomus* preserved throughout the lithology. These pinnacles can be stratigraphically divided into a lower branching coral rubble *Unit 2* and an upper *Unit 3* characterized by the colonization of massive corals. These units correspond to *Units 2* and *3* from the southern and eastern sides of the island (see below). Toward the tops of the pinnacles, massive coral colonies increase in abundance and *T. maxima* occurs. To either side of the pinnacle karenfeld is expressed mainly the lower *Unit 2*. In the southern portion of Henderson Island the same stratigraphy is preserved in the pinnacled karrenfeld of the outer reef flat and lineations of the lagoon margin, but here *Unit 4* may also be present, occurring as a sugary, perhaps dolomitic, limestone (Fig. 4).

On the southern end of the island a gradient in both the extent and coral community composition of the broad outer reef flat is apparent. Near South Point, between the spur and groove structures to seaward and the outer margin of the lagoon, the coral fauna is dominated by large low domes and stout branching growth forms of *Acropora* cf. *palifera* and *A.* cf. *gemmifera* (Fig. 4). The '*A.* cf. *palifera*/*A.* cf. *gemmifera* zone' is gradually compressed from South Point westward. At South Point it is greater than 200 m wide, 300 m west of South Camp it is up to 100 m wide, and westward of South Camp

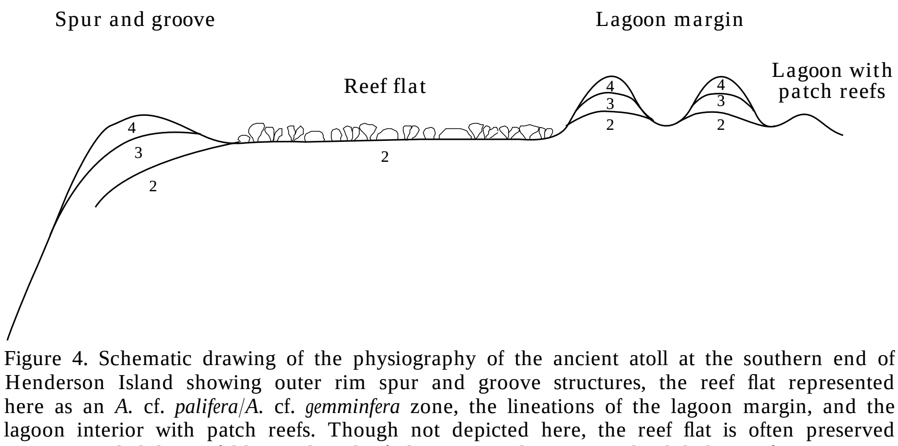

Figure 4. Schematic drawing of the physiography of the ancient atoll at the southern end of Henderson Island showing outer rim spur and groove structures, the reef flat represented here as an *A.* cf. *palifera*/*A.* cf. *gemminfera* zone, the lineations of the lagoon margin, and the lagoon interior with patch reefs. Though not depicted here, the reef flat is often preserved as a pinnacled karrenfeld. Landward of the spur and grooves, the lithology of *Unit 4* is a grey sugary, possibly dolomitized limestone. Units are the same as depicted in Fig. 3. (Not to scale).

it is only 50 m wide. It is replaced westward of South Camp by a mixed assemblage of branching and massive corals. On the northwestern part of the island the gravel patches between the lineations, found between 0 and 250 m inland, are also dominated by branching *Acropora* spp. colonies, both stout branched and slender branched forms, including in place, whole and upright colonies of stoutly branching *Pocillopora eydouxi*, *A.* cf. *palifera*, and *A.* cf. *gemmifera*. Some monospecific stands of *A.* cf. *palifera* are up to 3 m diameter and plates of *A.* cf. *hyacinthus* are up to 2 m diameter. Gravel patches also contain *Pavona* sp(p)., branching and massive *Porites* sp(p). and *Montastrea* sp(p). The robust acroporid zone appears to be more patchy and compressed, however, on the northern portion of the island than on the southern. The expansive zones of *Acropora* cf. *palifera* and *A.* cf. *gemmifera* of the southern part of the island are not apparent on any other side of the island.

The spatial variability in both spur and groove development and the reef coral communities is inferred to reflect the original physiography of the atoll as controlled by the prevailing wind, wave, and storm regimes. The southern side of Henderson Island is represented by the most complete development of paleo spur and groove topography and an extensive zone of wave-resistant corals, the *Acropora* cf. *palifera*/*A.* cf. *gemmifera* outer reef flat zone (Fig. 4). This, coupled with the extensive zone of alternating lineations and shallow basins (see below), lying between the *Acropora* cf. *palifera*/*A.* cf. *gemmifera* outer reef flat zone and the deeper interior lagoon, indicates that the windward side of the atoll faced SE (as it does today). This apparent difference in zonation pattern, and the magnitude and frequency of the spur and groove system is consistent with the most pronounced reefal development having taken place on the SE side of the original atoll.

Lagoon margin

As with the northern and northwestern sides of Henderson Island, the outer margin of the lagoon on the southern side of the island is marked by a series of limestone lineations with intervening shallow basins that occur between the pinnacle karrenfeld of the outer reef flat and the deeper lagoonal basin represented in the central depression. Whereas the lineations occur inland up to 1 km from the northern and northwestern coastlines, in the south they extend to about 1.5 km. The orientation of seven lineations occurring between 750 and 1050 m inland from North Beach is remarkably consistent, ranging from N37°E to N58°E, and thus subparallel to the northwestern coastline. In contrast, the orientation of the southern lineations is highly variable, ranging between 315° and 56°N. This zone of lineations probably coincides with the shallow outer margin of the atoll lagoon. Landward of this zone starts the interior depression of the central lagoon with a much more diverse faunal assemblage.

Lagoon and patch reefs

A heavily vegetated central depression characterizes the interior of Henderson Island. The well preserved coral fauna here is dominated by branching *Acropora* spp. rubble, though branching *Pavona* sp(p). and *Porites* sp(p). also occur. Massive corals are less abundant in the interior of the island, but may be locally dominant. In many places the massive and branching coral fauna is represented by corals in growth position. Branching *Acropora* spp. may form large monospecific stands up to 3 m in their largest dimension. *Tridacna*, *Turbo* and other clams are locally abundant.

There is evidence for the patch reefs throughout the interior of the central depression. On the southern side they continue through to the outer shallow lagoon margin. Throughout the island interior a gently undulating surface periodically gives rise to hillocks of gravel patches which contain abundant fossil corals, mostly dominated by branching acroporid and, to a lesser extent, poritid and pocilloporid coral debris (patch reefs of Paulay & Spencer (1988) and Spencer & Paulay (1989)). These gravel patches are periodically interrupted by a more indurated lithology dominated by massive corals such as *Montastrea* sp(p).

Except for one small patch of shelly sand found 1.5 km south-east of North West Beach, no carbonate matrix finer than the pebble size fraction was observed on top of the central depression of the island (though some sands have been found in limestone solution pits, R. Preece, personal communication, 1994). Autochthonous biogenic sediment must have been continually transported outside of the lagoon. Indeed Paulay & Spencer (1988) and Spencer & Paulay (1989) suggested that the fossil lagoon had considerable interchange with the surrounding ocean because of the high diversity and prodigious growth of the reef corals, the presence of reef corals requiring oceanic water conditions, the rarity of species that are usually common under more stagnant conditions, and the lack of lagoonal sediments finer than coral rubble. Though not indicative of flushing (spur and groove systems occur in many places where lagoons do not), spur and groove structures could have provided adequate conduits for the removal of lagoon sediment.

Atoll stratigraphy

Stratigraphic and facies relationships on top of Henderson Island are preserved within the spur and groove structures, pinnacles and lineations found around the perimeter, and lineations and gravel patches found within the interior of the island. The southern side preserves the most complete stratigraphy and here three stratigraphic units were mapped: *2*, *3* and *4* (*Unit 1* representing the original atoll developed between 440–380 kyr; Blake & Pandolfi, *in press*; Blake, 1995). The 3 stratigraphic units present on the southern end of Henderson Island can be mapped for over 1 km on the southern portion of Henderson Island and *Units 2* and *3* also occur within the pinnacled karrenfeld of the northwestern part of the island.

Unit 2 is composed of either branching coral debris with lesser amounts of platy corals or a rounded pebble conglomerate in a coarse grained carbonate sand which may be loosely consolidated. The branching coral lithology usually comprises the floor of the grooves so the groove lithology is equivalent to *Unit*. Within *Unit 2* the pebble conglomerate may overly the branching coral rubble. The contact between the pebble conglomerate and branching coral rubble may include *Turbo argyrostomus*. The rounded pebble conglomerate contains clasts up to 30 cm in diameter, but mostly smaller rounded coral bioclasts 6–8 cm in diameter. The pebble conglomerate is extensive but not continuous. It occurs at topographic highs (the lower portion of exposed or recessed spurs) on the southwestern side of the island, and pinches out in the grooves where it gives rise to the underlying branching coral rubble facies. It is also present up to 500 m inland from the spur and groove structures where it underlies topographic highs adjacent to the outer margin of the fossil lagoon (Fig. 4). Here, the pebble conglomerate dips S.

Unit 3 is a light grey, well indurated, and mottled limestone with abundant branching coral rubble and branching and massive corals in place. The limestone is coarse grained and is composed mainly of bioclastic skeletal debris. *Unit 3* is the basal layer of the spurs where it is seen to drape over the underlying *Unit 2*. Beach sands also occur in the lower part of *Unit 3* at East Beach (Blake, 1995; Blake & Pandolfi, in press). The contact between the pebbly conglomerate of *Unit 2* and the mottled limestone of *Unit 3* is characterized by loosely consolidated carbonate sand, and/or colonization of abundant massive and stout branching corals. The latter can be seen both in the lateral transition from the spur and groove structures to the outer reef flat and vertically within the pinnacles landward of the spur and groove structures (Figs 3, 4). The zone of stoutly branched acroporids, the *A.* cf. *palifera*/*A.* cf. *gemmifera* zone, found on the southern end of the island, is stratigraphically equivalent to the base of *Unit 3*. It was found in sequence between the underlying *Unit 2* pebble conglomerate and overlying *Unit 3*. Where the *A.* cf. *palifera*/*A.* cf. *gemmifera* zone is laterally compressed, the contact between *Units 2* and *3* can be traced landward from the spur and groove structures where it grades laterally into a zone of massive corals colonizing the contact (again equivalent to the basal part of *Unit 3*).

Unit 4 is highly fossiliferous with abundant massive and branching corals, up to 2 m in height and width. The overwhelming abundance of upright coral colonies suggests that the corals found in *Unit 4* on top of the spurs were *in situ. Unit 4* forms a layer draping over *Unit 3* at all of the spur and groove formations. It disappears on top of the grooves and picks up again along the sides and tops of the spurs (Fig. 3). On top of the outer reef flat between the spur and groove structures and the outer lagoon margin, *Unit 4* grades laterally into a coarse grained sugary lithology, possibly dolomitized (Fig. 4).

Recent radiometric age dates from Henderson Island (Blake & Pandolfi, *in press*; Blake, 1995), revealed that the island is approximately 500 kyr and that the depositional units represent different transgressive phases of reef development. A detailed discussion of the radiometric age data and their relationship to the geological evolution of Henderson Island is found in Blake & Pandolfi (in press) and Blake (1995). Briefly, *Units 2* (340–320 kyr) and *3* (320–300 kyr) were formed during oxygen isotope stage 9, whereas *Unit 4* is believed to reflect prolific reef development between 285–275 kyr as part of oxygen isotope stage 8. *Units 2–4* can be correlated to the type section in East Beach (Blake & Pandolfi, in press; Blake, 1995). Dates from the buttress limestone at North Beach are similar to those obtained from spurs on the southern portion of the island, suggesting the coeval nature of the outer rim.

The stratigraphic and sea level history of Henderson Island may lend some insight into the mode of formation of the spur and groove system. Considerable attention has been given to the formation of spurs and whether spur and groove systems are the result of erosional or depositional processes or both. Roberts (1974) demonstrated the relationship of spur and groove formation to prevailing wind and wave directions, but many previous authors had suggested the same relationship (Stoddart, 1962; Shinn, 1963). Newell (1954) described algal spur and grooves which formed erosionally, but Shinn (1963) described spurs which formed as the result of active coral growth. Development of physiographic patterns in atolls are often controlled by antecedent topography and degree of water turbulence (Montaggioni *et al*., 1985). Construction of the Henderson Island spurs probably occurred on topographic highs related to reef growth during previous glacial stages. As each new period of reef growth ensued the spurs became more and more pronounced relative to the groove floors. As relative sea-level rose, spurs developed as corals stabilized the previous substrate and grew upward, enhancing the spur relative to the groove floor. The grooves then accumulated detritus from the spurs in the form of both fine bioclastic material (which may also have accumulated autochthonously) and branching coral rubble, which developed as talus from the spurs and possibly from *in situ* coral colonies (Fig. 3).

COMPARISON WITH OENO AND DUCIE: MODERN ATOLLS IN THE PITCAIRN GROUP

Comparison of the fossil Henderson Island lagoon with lagoons from Oeno and Ducie, the two other atolls in the Pitcairn Group, sheds some light on how the Henderson fossil lagoon must once have looked. Oeno Atoll has an island developed in the centre of the lagoon with an outer reef rim surrounding the island-lagoon complex. Devaney & Randall (1973) and Paulay (1989) gave brief descriptions of the lagoon and fore reef. The lagoon is uniformly shallow, less than 3 m deep, and has an undulating bottom of coral rubble and sand, with scattered reefs (Paulay, 1989). A sand spit extends from the eastern edge of the main island, and spur and groove structures occur without a reef crest on the southeast outer reef flat (Fig. 5). Within the lagoon the ‘patches of coral rock’ (Devaney & Randall, 1973) show previous extensive monospecific stands of branching corals (Fig. 6). Such monospecific coral stands do not presently occur within the lagoon.

By way of contrast, the lagoon at Ducie Atoll (Spencer, 1995; Fig. A4) is striking in its preservation of a formerly prolific coral fauna. Sparse live corals now encrust an *in situ* coral death assemblage which must represent a life assemblage of luxuriant coral growth. Rehder & Randall (1975) give estimates of water temperature and depth within the lagoon. They noted the paucity of life over 20 years earlier in Ducie lagoon, and both the 1987 visit of the RV Rambler (Paulay, 1989) and our visit in 1991 showed a similar pattern. Paulay (1989) noted a low cover of mostly *Montipora* spp. In addition, the large foraminifera, *Marginopora vertebralis* was abundant in the lagoon.

The present state of both of the other atolls of the Pitcairn Group are unsatisfactory as modern analogues for the fossil lagoon at Henderson Island. Though monospecific stands of corals characterize the lagoon at both Oeno

Figure 5. Aerial photograph of Oeno Atoll. A single island occurs in the centre of the lagoon and has a sand spit extending out from the eastern tip. The entire lagoon is less than 3 m deep. North is upward in the photograph. Photo courtesy of Olive Christian, Pitcairn Island.

and Henderson Island, the present lagoon at Oeno is probably shallower than the fossil lagoon at Henderson Island. In addition, there is no evidence of paleosols or any other terrestrial deposits which might signify former land masses (*motus*) within the fossil lagoon at Henderson Island, whereas *motu* presently occurs at both Oeno and Ducie atolls. At both Ducie and Oeno, sedimentation characterizes the lagoon whereas at Henderson Island little sand-sized sediment was found. The prolific stage of coral reef growth at Ducie Atoll, coupled with its surrounding spur and groove structures and deep lagoon were probably more similar than Oeno Atoll to the lagoonal development at Henderson Island.

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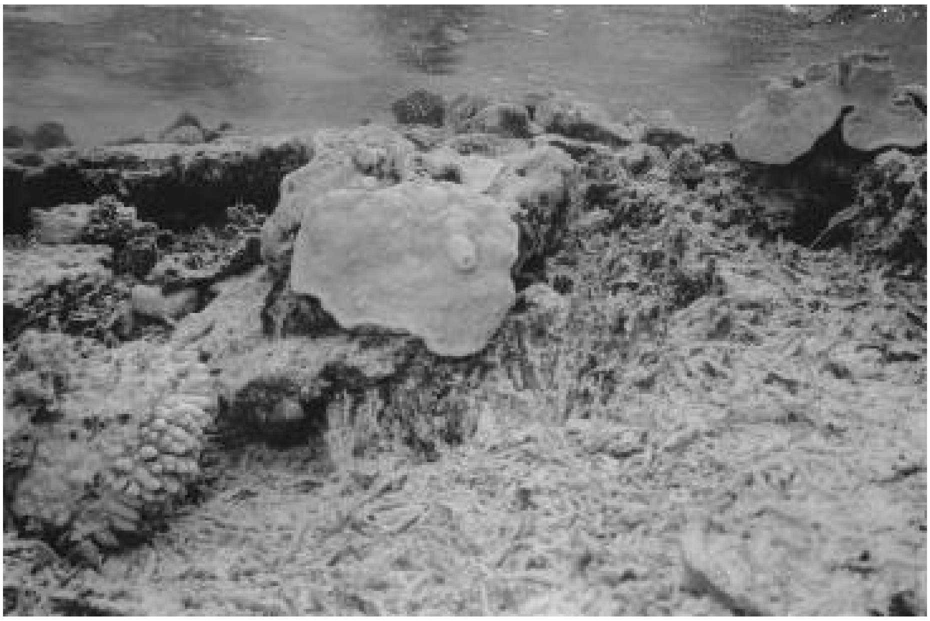

Figure 6. Large monospecific stand of dead branching coral comprising the reef structure within the lagoon in Oeno Atoll. Living corals have colonized these stands throughout the lagoon.

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REFERENCES

Blake SG. 1995. Late Quaternary history of Henderson Island, Pitcairn Group. *Biological Journal of the Linnean Society* **56:** 43–62.

Blake SG, Pandolfi JM. In press. Geology of the Carbonate Islands of the Pitcairn Group, Central South Pacific. In: Vacher L, Quinn T, eds. *Carbonate Islands of the World.* Amsterdam: Elsevier.

Devaney DM, Randall JE. 1973. Investigations of Acanthaster planci in Southeastern Polynesia during 1970–71. *Atoll Research Bulletin 169:* 1–35.

Fosberg FR, Sachet MH, Stoddart DR. 1983. Henderson Island (Southeastern Polynesia): Summary of current knowledge. *Atoll Research Bulletin 272:* 1–47.

Irving RA. 1995. Nearshore bathymetry and reef biotopes of Henderson Island, Pitcairn Group. *Biological Journal of the Linnean Society* **56:** 309–324.

Montaggioni LF, Richard G, Gabrie C, Monteforte M, Naim O, Payri C, Salvat B. 1985. Les récifs coralliens de l'île de Makatea, archipel des Tuamotus, Pacifique central: géomorphologie et répartition des peuplements. *Annales de l'Institut Oceanographique, Paris* **61(1):** 1–25.

Newell ND. 1954. Reefs and sedimentary processes of Raroia. *Atoll Research Bulletin 36:* 1–32.

Paulay G. 1989. Marine invertebrates of the Pitcairn Islands: Species composition and biogeography of corals, molluscs, and echinoderms. *Atoll Research Bulletin 326:* 1–28.

Paulay G, Spencer T. 1988. Geomorphology, palaeoenvironments and faunal turnover, Henderson Island, S.E. Polynesia. *Proceedings of the 6th International Coral Reef Symposium, Townsville, Australia* **3:** 461–466.

Rehder HA, Randall JE. 1975. Ducie Atoll: its history, physiography, and biota. *Atoll Research Bulletin 183:* 1–40.

Roberts HH. 1974. Variability of reefs with regard to changes in wave power around an island. *Proceedings of the Second International Symposium on Coral Reefs*, v. **2:** 497–512.

Shinn E. 1963. Spur and groove formation on the Florida reef tract. *Journal of Sedimentary Petrology* **33:** 291–303.

Spencer T. 1995. The Pitcairn Islands, South Pacific Ocean: plate tectonic and climatic contexts. *Biological Journal of the Linnean Society.* **56:** 13–42.

Spencer T, Paulay G. 1989. Geology and geomorphology of Henderson Island. *Atoll Research Bulletin 323:* 1–50.

St John H, Philipson WR. 1962. An account of the flora of Henderson Island, South Pacific Ocean. *Transactions of the Royal Society of New Zealand, Botany* **1:** 175–194.

Stoddart DR. 1962. Three Caribbean Atolls: Turneffe Islands, Lighthouse Reef, and Glover's Reef, British Honduras. *Atoll Research Bulletin 87:* 1–151.