CORAL REEF STRUCTURE AND ZONATION OF THE PHOENIX ISLANDS

BY

DAVID OBURA

ABSTRACT

The eight islands of the Phoenix Group in the Republic of Kiribati vary in size from 17.5 to 1.03 km across. Three major reef types are present in the islands: outer reef slopes, lagoon reefs and channel patch reefs. Channel reefs are negligible and limited to small patches. Lagoon reefs are well developed in Kanton and Orona, growing on relict reef structures and controlled by circulation of water in the lagoons. Outer reefs have the most vibrant growth of corals, with four depth zones clearly shown by reef geomorphology and coral communities: a) deep slopes below 20-25 m varying from 45-85^{o} slope, of rocky substrate and extensive rubble and sand chutes transporting material down the island slopes; b) reef edge varying between 15-20 m where the deep steep slope transitions into the flatter reef platform above. The reef edge tends to be the most vibrant area of coral growth with highest cover and diversity of corals; c) reef platform, from about 15 m to 5 m deep, comprising the broadest zonation band on the reefs and showing clear differentiation with exposure of the reef slope to wind and waves; and d) surge zone, generally from 5 m to the surface, dominated by surge channels and with coral growth limited by wave energy. On average almost 3/4 of the island perimeters show evidence of high exposure to waves and wind, generally comprising the northeast to southern-facing flanks of the islands. The remaining 1/4 were classified as leeward or sheltered shorelines, generally on west and northwest-facing flanks. The total reef area was calculated as 33.9 km^2, of which 24.0 km^2 is windward reef, 7.3 km^2 is leeward reef and 2.6 km^2 is lagoon reef (71, 22 and 8 %, respectively). Overall, the proportion of outer reefs in surge, platform, edge and deep slope zones was 15, 60, 10 and 15 % respectively. Kanton dominates the island group with 35% of all reef area and 55 % of lagoon coral reefs. The islands group roughly into 3 clusters: Kanton and Orona with the largest area of reefs and lagoons with healthy coral communities (55 % of reefs), Nikumaroro, Enderbury and Manra have intermediate outer reef areas (31 % of reefs) and Birnie, McKean and Rawaki have the smallest island size but proportionately larger reef platforms (14 % of reefs).

P.O.BOX 10135, Mombasa, Kenya. Tel/fax: +254-41-548 6473. dobura@cordioea.org

INTRODUCTION

The Phoenix Islands are the central island group of the Republic of Kiribati, with the Gilbert Islands to the west, the Line Islands to the east, and in a line between Fiji and Hawaii (Fig. 1). The Kiribati Phoenix Group (174.8° W to 170.1° E Longitude and 2.5° to 5°S Latitude) comprises eight islands with two submerged reef systems spread over some 100,000 km^2 of ocean. Two outlying islands north of the equator, Baker and Howland, are United States dependencies and lie 300 km from the Phoenix Islands. The island group is among the remotest islands in the central Pacific, lying over 1,000 km from the Gilbert group to the west, 1,500 from the Line islands to the east and 500 km from the Tokelaus, the closest islands to the south.

Reflecting their isolation, the Phoenix Islands have received only scanty marine scientific attention, and much of it related to activities on the islands by British and United States companies and government agencies from the Second World War until the late 1970s. A research expedition in 1939 resulted in a taxonomic fish collection (Shultz 1943), which was followed by studies on seabird populations in the 1960s (Clapp, 1964), and a focused collection of corals from McKean island in the early 1970s (Dana, 1975). It was not until 1972-73 that detailed marine surveys were conducted, comprising a comprehensive study of Kanton Atoll (Smith and Henderson, 1978), including work on lagoon circulation and biogeochemistry (Smith and Jokiel, 1978), coral taxonomy and biogeography (Maragos and Jokiel, 1978) and lagoon and leeward reef coral distributions and assemblages (Jokiel and Maragos, 1978). These studies established a basic zonation for the lagoon environments of Kanton atoll.

In addition, apart from basic estimates from aerial photographs of reef area coverage on Kanton by Jokiel and Maragos (1978) there is no available information on the spatial dimensions of the islands and reef habitats. The purpose of this chapter is to present basic statistics and dimensions on the coral reefs of the Phoenix Islands, to support further work on the islands.

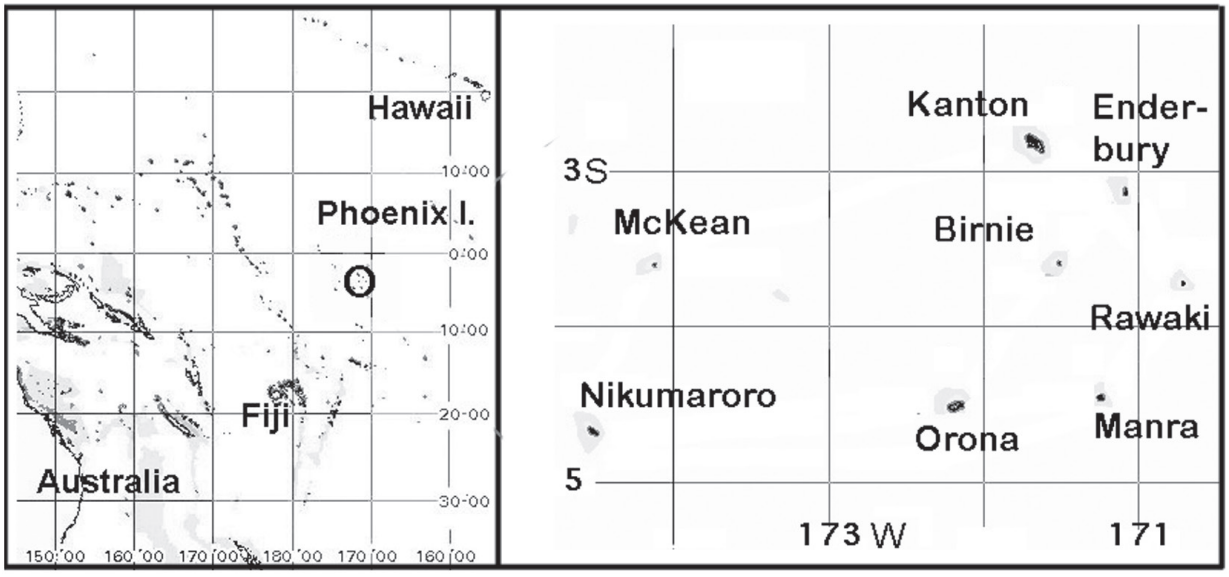

Figure 1. Location of the Phoenix Islands in the central Pacific (left), and map of the island group (right).

METHODS

Descriptions of the islands and reefs of the Phoenix Islands were derived from underwater observations and analysis of charts and maps of the islands.

Coral Reef Structure and Zonation

In situ observations of the coral reefs of the Phoenix Islands, including quantitative analysis of benthic community structure were used to characterize the principal habitats of the island reefs, and major zonation patterns with depth (Stone et al., 2001; Obura and Stone, 2003; Obura et al., this volume). These descriptions were also informed by the literature on coral reef structure and zonation, particularly of oceanic Pacific reefs and past work on Kanton atoll (Maragos and Jokiel, 1978; Jokiel and Maragos, 1978) and more broadly in the Line islands and remote central Pacific islands (Brainard et al., 2004).

Geographic coordinates of all sample sites were recorded using handheld GPS, along with observations on wave exposure, visibility, and weather conditions. Survey site locations are detailed in Appendix 1.

Coral Reef and Island Dimensions and Statistics

Statistics on island, lagoon and reef dimensions were derived from two primary sources used in conjunction with each other and geo-referenced on the GIS system at the Environment and Conservation Division (ECD) of the Ministry of Environment Lands and Agricultural Development in Tarawa, Kiribati. GIS shapefiles from the ECD were combined in Adobe Photoshop with images of charts of the Phoenix Islands (showing depth soundings and some contours) and satellite photographs (showing various coastline features and structures within Kanton lagoon). The composite island and reef images are shown here with study sites located using GPS coordinates. The following measures were estimated from the images:

- Maximum Length (km) – measured; longest axis of island.
- Lagoon Area (km^2) – measured; area of lagoon, excluding channels.
- Reef Perimeter (km) – measured; perimeter length of approximated 20 m depth contour, i.e. the reef edge (see section below). Windward and leeward reef perimeters were calculated based on observations on each island.
- Reef Width (m) – measured; shortest distance between the outer intertidal/wave zone indicated on charts and the approximate 20 m depth contour. Average of 10-13 samples around perimeter of each island. Since most reefs drop off steeply below 15-20 m (see results), the area of reef beyond 20 m is assumed to be negligible compared to that < 20 m.
- Reef Area (km^2) – calculated; reef perimeter multiplied by reef width.

CORAL REEF STRUCTURE AND ZONATION

To date 67 separate sites have been surveyed quantitatively or qualitatively in the Phoenix Islands, during the expeditions in 2000, 2002 and 2005 (Table 1). Due to accessibility restrictions, surveys have concentrated on leeward as compared to windward outer reefs, and a large concentration of survey sites in the large lagoon at Kanton (Table 2). Channel sites were only surveyed quantitatively on Kanton and Orona.

Table 1. Overall sampling of the Phoenix Islands by the New England Aquarium Phoenix Islands Expeditions in 2000, 2002 and 2005. Numbers shown are the total days and research dives in each year, and the number of survey sites by island in each year.

	Year			
	2000	**2002**	**2005**	**Combined**
Total sampling, each year				
# days	13	26	12	
# research dives (approx.)	376	736	117	
Number of sites, by island				
Birnie		3		3
Enderbury	4	5	4	5
Kanton	8	25	11	25
Manra	3	4	2	4
McKean	2			2
Nikumaroro	6	10	6	12
Orona	3	9	8	12
Rawaki	3	3	4	4
TOTAL	29	59	35	67

Table 2. Number of sites sampled in each major reef habitat.

	Outer reefs		Lagoon	Channel	
Island	Leeward	Windward			Total
Kanton	6	3	15	1	25
Orona	3	6	3		12
Nikumaroro	5	5	1	1	12
Enderbury	3	2			5
Manra	2	2			4
Rawaki	3	1			4
Birnie	1	2			3
McKean	2				2
Total	25	21	19	2	67

Outer Reefs

The outer reefs of the Phoenix Islands have a highly consistent topography, characteristic of oceanic atolls. A rocky consolidated bottom extends from the wave zone down to between 15-20 m depth. Below this the bottom slopes steeply, usually made of up compacted rubble and boulders, though in the steepest places being a solid wall, to depths of over 1000 m within several hundred meters horizontal distance. In some locations steep sand and rubble slopes predominate, the latter made up of loose broken coral (from both live and fossil reefs). The outer reefs are easily distinguished into 4 zones, present at most sites (Fig. 2):

Reef slope – deep slopes below 20-25 m and extending beyond visible depths, between 45-85^{o} slope. This zone was surveyed quantitatively from 20 to 50m deep. Upper slopes tended to have high cover of rubble and *Halimeda*, and in some locations up to 60-70% coral cover. Soft corals were common, dominated by leathery forms. Rubble and sediment transport down the slopes was present in all locations.

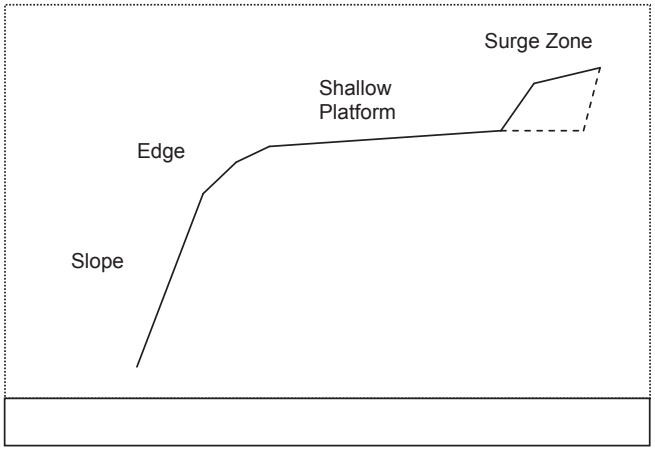

Figure 2. Profile typical of Phoenix Islands reefs

Reef edge – transition zone between the steep slope and the near-horizontal shallow platform above, the reef edge tended to occur between about 12-20m depth, variable by exposure level and island. In some locations the reef edge was a sharp transition, barely 10-15 m wide, in others there was no clear difference in slope between about 15-30 m on the slope and about 10 m in the shallows. In general, the edge had the highest cover and diversity of hard corals.

Platform – from the top of the reef edge at 12-20 m to the shallow zone dominated by wave surge at 5-6 m. This zone comprised the largest area coverage of coral reef, extending out 1 km at its widest (on Birnie) and averaging 200 m wide on most islands. In areas of low wave exposure, this zone is covered with hard and soft coral growth with close to 70-100% cover in patches; at highly exposed sites, this zone is dominated by rubble from continually breaking hard coral patches and coralline algae. In some locations the 'platform' is broken into a series of spur and groove formations, or with large bowl 'cut-outs' on highly exposed shores, or short cliffs of 5-10 m height.

Surge zone – from 5-6 m to the surface, this zone is typically cut into buttresses and surge channels with up to 3 m vertical relief, with low-relief coral and algae growth, and high cover of coralline algae. On sheltered slopes branching corals grow abundantly

on buttresses and encrusting corals in the grooves where sand-movement allows. On windward slopes growth forms are restricted to encrusting/submassive forms, and very robust, low-relief branching colonies.

There were clear differences in the habitat, general topography and benthic cover of leeward and windward reefs, typically with higher coral cover on leeward slopes. Windward reefs tend to have large areas with low coral cover and high rubble cover, and on the reef slopes *Halimeda*.

Channels

Channels were only present on the three islands with lagoons – Nikumaroro, Orona and Kanton. They were shallow for Orona and Nikumaroro (< 1 m), and only navigable by small boat at high tide. The Kanton channel is 10 m deep through its center, due to blasting during the Second World War. In all cases the high current flow in the channels prevents the development of extensive coral reefs, with minor development of small patch reefs where substrate within the channels allows. The Kanton channel was dominated by a rubble bottom.

Lagoons

True lagoons are present at three islands – Nikumaroro, Orona and Kanton. They vary strongly from each other, and the individual characteristics are highlighted in the island descriptions below. In common, however, they are all highly restricted lagoons compared to most other atoll environments, having only 1 permanent outlet in the case of Nikumaroro and Kanton, and restricted shallow inlets on Orona. Maximum depths recorded during dives were 4 m (Nikumaroro), 16 m (Orona) and 26 m (Kanton). All three of the lagoons are characterized by soft silty bottoms of very fine carbonate material, with raised rocky features of varying heights, apparently remnants of reef growth and geological processes in the past. In Nikumaroro these were low-relief patches. In Kanton and Orona these could rise from the deepest bottoms to the surface, and were of varying pillar and patch-reef shapes. In Kanton they also come in the form of linear reef structures (see details below, and Jokiel and Maragos 1978, Maragos and Jokiel 1978). Any growth of corals, invertebrates and algae occurs on these hard substrate patches, or on rubble pieces on the sandy floors. Lagoon communities were highly differentiated between the islands. Kanton had the most highly developed lagoon, with four zones, one of which harboured profuse growth of *Acropora* tables at over 80% cover (though see Alling et al. this volume, Obura and Mangubhai, in review).

ISLAND DESCRIPTIONS AND DIMENSIONS

The Phoenix Islands are small compared to many of the islands and groups in the central and south Pacific, and only three of them have lagoon environments. The following island descriptions are listed in order of island area, with statistics being reported from Table 3.

Table 3. Island and reef dimensions for islands in the Phoenix group. See methods for details of each measure. Islands ordered by decreasing outer reef perimeter.

Island	Windward slopes (km^2)					Leeward slopes (km^2)					Total
	Total	surge	platform	edge	slope	Total	surge	platform	edge	slope	
Kanton	8.45	1.30	5.18	0.79	1.18	1.93	0.27	1.08	0.23	0.35	10.38
Orona	4.29	0.66	2.63	0.40	0.60	1.62	0.22	0.87	0.21	0.32	5.91
Enderbury	2.59	0.42	1.66	0.20	0.31	1.19	0.18	0.71	0.12	0.18	3.78
Nikumaroro	2.59	0.35	1.40	0.34	0.51	1.04	0.16	0.65	0.09	0.14	3.64
Manra	2.16	0.32	1.30	0.21	0.32	0.81	0.12	0.47	0.09	0.14	2.97
Birnie	2.49	0.43	1.74	0.13	0.19	0.16	0.01	0.05	0.04	0.05	2.64
McKean	0.84	0.12	0.50	0.09	0.13	0.43	0.07	0.27	0.04	0.06	1.27
Rawaki	0.58	0.09	0.36	0.05	0.07	0.17	0.03	0.11	0.01	0.02	0.74
Total	23.98	3.69	14.77	2.21	3.31	7.35	1.05	4.20	0.84	1.26	31.33
%		15.4	61.6	9.2	13.8		14.3	57.1	11.4	17.1	

Kanton Atoll (Aba-Riringa)

Kanton is the largest atoll in the Phoenix group (Fig. 3), with a maximum length of 17.5 km oriented on a northwest-southeast axis. The atoll reef perimeter of 51.0 km encloses a lagoon of approximately 56 km^2. The atoll has only one channel on the western side, a secondary channel further north on the western side having been blocked in the 1950s by construction. The channel was blasted and dredged to a depth of 10 m during the Second World War and drains a lagoon volume of approximately 186 x 10^6 m^3 (Smith and Henderson 1978). With an average depth calculated at 6.2 m (and maxima of > 26 m) and a tidal exchange of 0.7 m, approximately 11% of the lagoon volume changes on each tide, twice a day. Kanton's lagoon is highly complex, with 4 zones being identified by past workers (Jokiel and Maragos 1978) and confirmed during these surveys:

a) A Pass zone approximately 2 km radius from the channel, in which water exchange is high and extensive staghorn and tabular *Acropora* colonies predominated. The primary reef structures in this zone are relict pillars, bommies and patch reefs on which the current coral community grows in profusion, with sand channels in between becoming increasingly fine and silty with distance from the channel (sites K8-10, K15-16);
b) A Line Reef zone extending eastwards and taking up most of the central lagoon area. This zone is dominated by ancient reef structures that form a reticulate but predominantly north-south pattern in the lagoon and visible in remote sensing images. The reef tops reach up to just below low tide level making navigation in the lagoon hazardous. In between, depths have been recorded at > 26 m, with very fine silty muds on the bottom and murky water, apparently completely still and with minimal circulation. Coral growth is minimal, apparently limited by poor water chemistry (Jokiel and Maragos 1978; sites K5-7).
c) A Back Lagoon zone with small patch reefs on a sandy/silty bottom and coral communities characteristic of inner reef/high sediment areas, similarly limited as in the Line Reef zone. (sites 2-4).
d) An Altered zone, to the north of the Pass zone. This area was apparently affected by closure of the secondary channel and contains dead coral colonies and fine tables

still in growth position, covered by very fine silt and algal turf (sites K12-14). It is not clear though if dead tables still in growth position at the time of these surveys (2000-2005) were killed from pass closure in the 1950s, or by some other more recent impact.

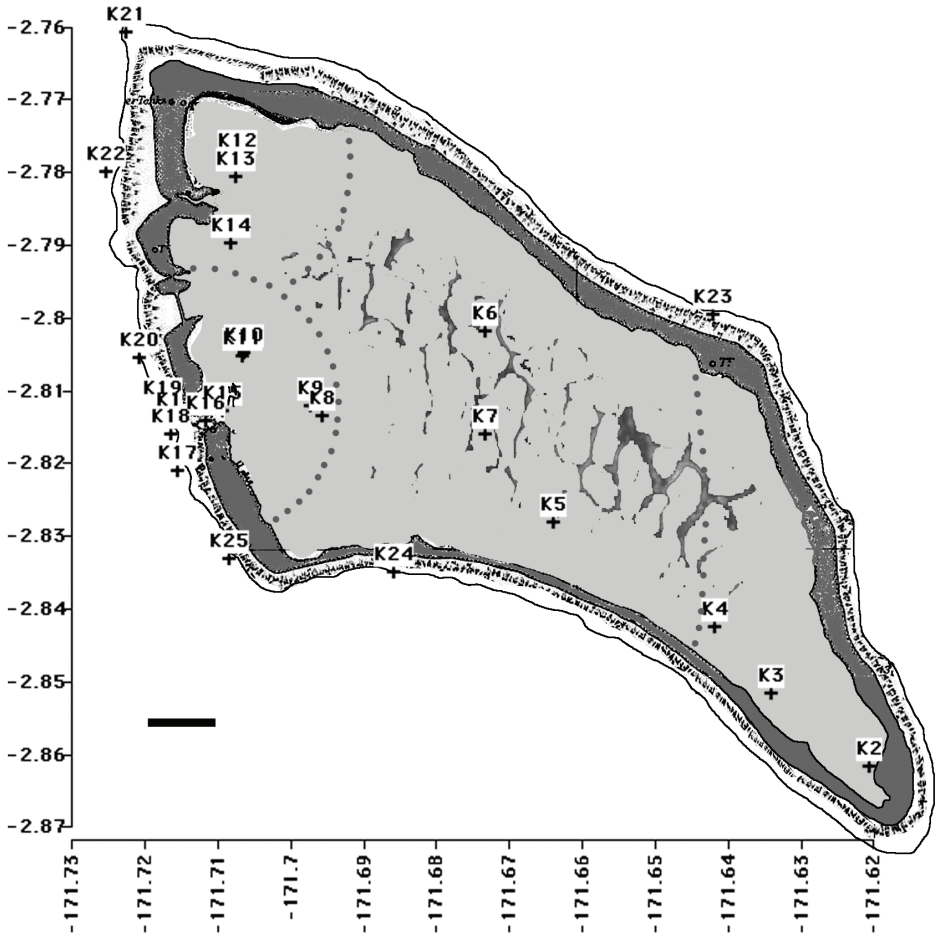

Figure 3. Kanton atoll. The map shows land features of the atoll (dark grey), the lagoon (light grey), intertidal reef (stippled area) and approximate location of the 15-20 m reef edge (continuous line). Survey sites are coded by numbers and marked by the crosses (Appendix I). The axes show degrees south and west in decimal format and the scale bar in all figures represents 1 km. In the Kanton map additional detail is shown of the line reef structures within the lagoon (adapted from satellite photographs) and the dotted circles within the lagoon show zones corresponding to Jokiel and Maragos 1978 (see text).

The outer reef area of Kanton is estimated at 10.38 km^2. The entire northeastern, eastern and southern flanks of the island (from sites K21 to K25) show windward exposed characteristics, slightly less than 4/5 of the island rim. The western flank is the only sheltered leeward face, over 1/5 of the island rim and the largest leeward shore of the island group. The subtidal reef width calculated for Kanton is typical for the island group, at 166 m. All shores have a steep drop-off starting uniformly at 15-20 m, broken only by the deep entrance to the channel.

Orona Atoll (Hull)

Orona is the second largest atoll (Fig. 4), with a maximum length of 9.9 km oriented on a northeast-southwest axis. The atoll reef perimeter of 30.8 km encloses a lagoon of approximately 22 km^2, with numerous inlets on the northern and southern side and is thus the leakiest of the atolls in the Phoenix Islands. Like Kanton, Orona's lagoon contains a variety of remnant knolls and pinnacles, though no line reef structures. Lagoon survey sites O2 and O3 were located on these structures, with maximum depths of 12-15 m being recorded with rubbly corals on broken up substrate at the base of the knolls, and soft sand substrates continuing down to deeper depths. The far east of the lagoon is very shallow and sheltered from the predominantly easterly winds and weather, and is dominated by fine sand. The west of the lagoon is deeper and rougher due to the fetch of the lagoon with patch reef structures. On both sandy and rocky substrates, dense patches of *Tridacna* (dominated by *T. squamosa*) clams littered the lagoon of Orona, with densities in patches at over 50 m^{-2}. These were generally of small to medium size, and were not seen in such aggregations in other islands of the group.

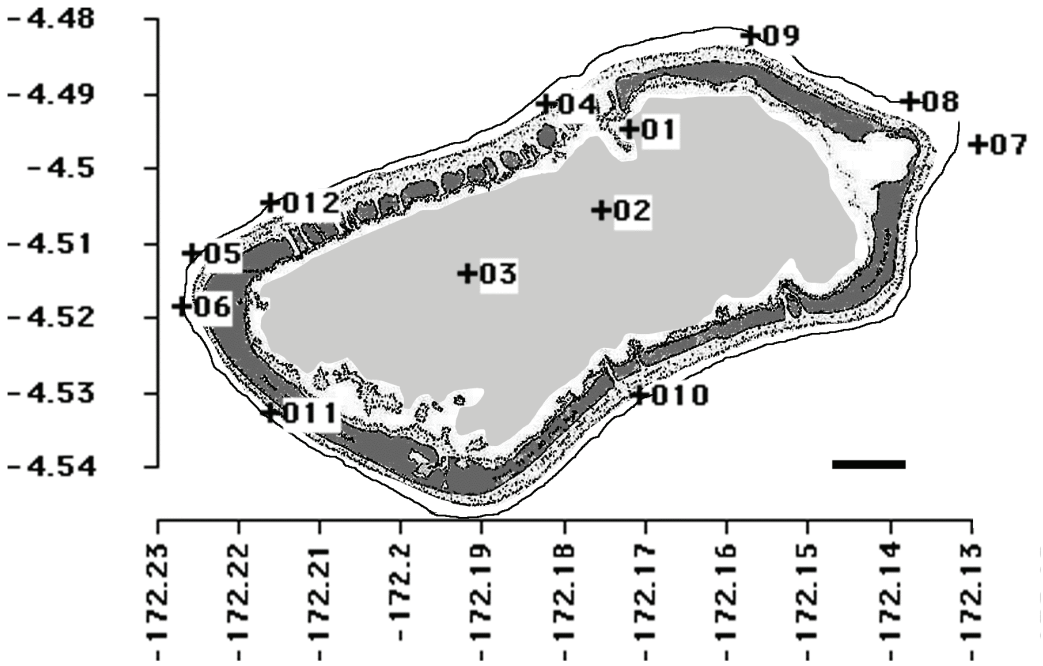

Figure 4. Orona atoll (Hull) in the Phoenix Islands. The map shows land features of the atoll (dark grey), the lagoon (light grey), intertidal reef (stippled area) and approximate location of the 15-20 m reef edge (continuous line). Survey sites are coded by numbers and marked by the crosses (Appendix I). The axes show degrees south and west in decimal format and the scale bar in all figures represents 1 km.

The outer reef area of Orona is estimated at 5.91 km^2. The entire northeastern, eastern, southern and southwestern flanks of the island (from sites O9 to O11) show windward exposed characteristics, approximately 2/3 of the island rim. The northwestern flank and western point (sites O4 to O6) are sheltered leeward locations, approximately

1/3 of the island rim. The subtidal reef width of Orona is 159 m, with steep drop-offs starting uniformly at 15-20 m. Orona is the only island to have an extensive shallow bank on its most windward point (survey sites O7 and O8), extending out about 500 m.

The western point (O6) is a unique site in the Phoenix Islands. It is strongly dominated by turf and fleshy algae (both brown algae and *Halimeda*) with < 5% coral cover even before recent human settlement in 2001, giving it the appropriate name 'Algae Corner'. A large ship's chain was located at the southern end of the study site potentially causing iron enrichment and suppression of coral and invertebrate growth, and the site appears subject to natural eutrophication from nutrient accumulation based on lagoon production, terrestrial vegetation and groundwater seepage (see Obura et al. this volume).

Nikumaroro Atoll (Gardner)

Nikumaroro is the smallest of the three atolls (Fig. 5) with a maximum length of 7.0 km and a similar shape and orientation to Kanton. The atoll rim perimeter of 21.6 km encloses a lagoon of approximately 6 km^2, with one inlet on the western side, and one on the southern side that is periodically open depending on weather and sedimentation conditions. It thus has the most restricted circulation of the lagoons in the Phoenix Islands, and the water within the lagoon is a milky colour with visibility less than 1 m.

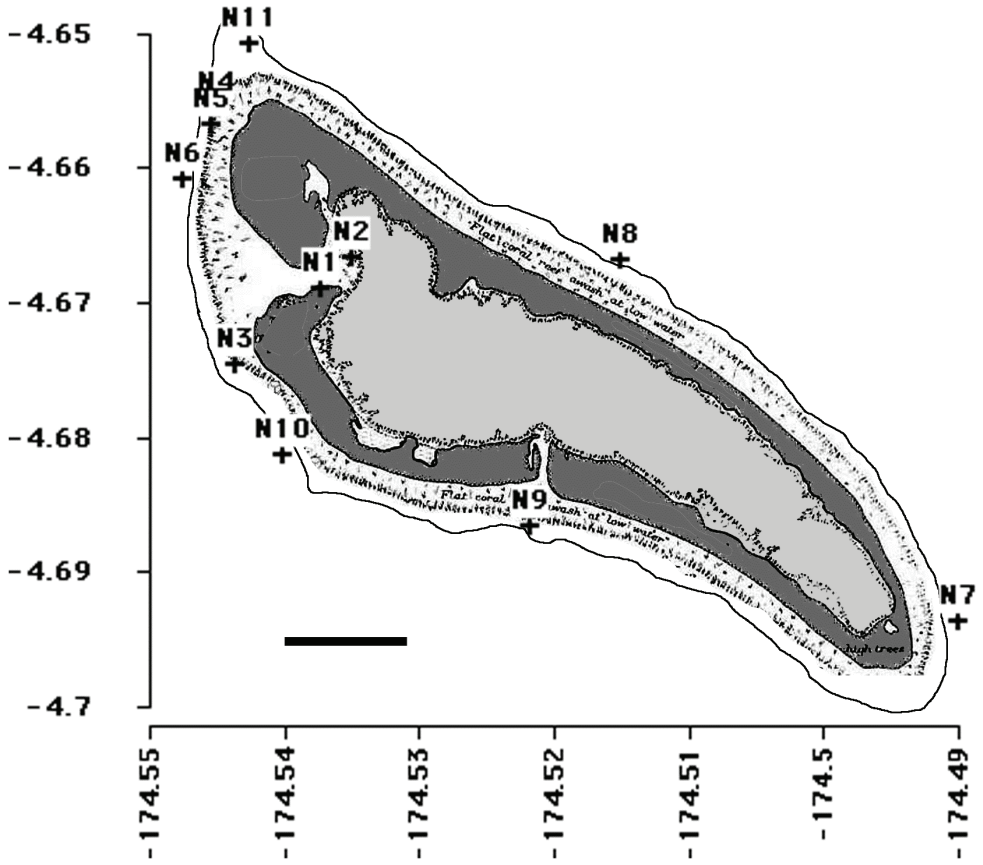

Figure 5. Nikumaroro atoll.

Lagoon survey sites N1 and N2 were located just inside the channel on the rubble bottom and an adjacent patch reef, and maximum depths in the lagoon are estimated at 3-4 m.

The outer reef area of Nikumaroro is estimated at 3.64 km^2, about the same size as Enderbury and only slightly larger than Manra. The entire northern to southwestern flanks of the island (from sites N11 to N10) show windward exposed characteristics, approximately 4/5 of the island rim. The western flank (north of site N10 to N4) is well sheltered. The intertidal reefs of Nikumaroro are relatively broad due to the wide intertidal reef shelf at the lagoon channel. The subtidal reef platform averages 151 m wide and is particularly narrow on the western shore where the reef drops from the intertidal rim to > 40 m within 50 m in some locations. The north/northwestern point is a typical feature of some of the islands (including Kanton, Phoenix, Birnie), where the platform extends out several 100s of meters from the reef crest and is swept by strong westerly currents and waves from the northeast shoreline, and sometimes strong southerly currents flowing up the leeward reef. These meet over the northern platform at the point creating swirling currents and a rip-current off the island, attracting large aggregations of barracuda, jacks and other schooling and pelagic predators.

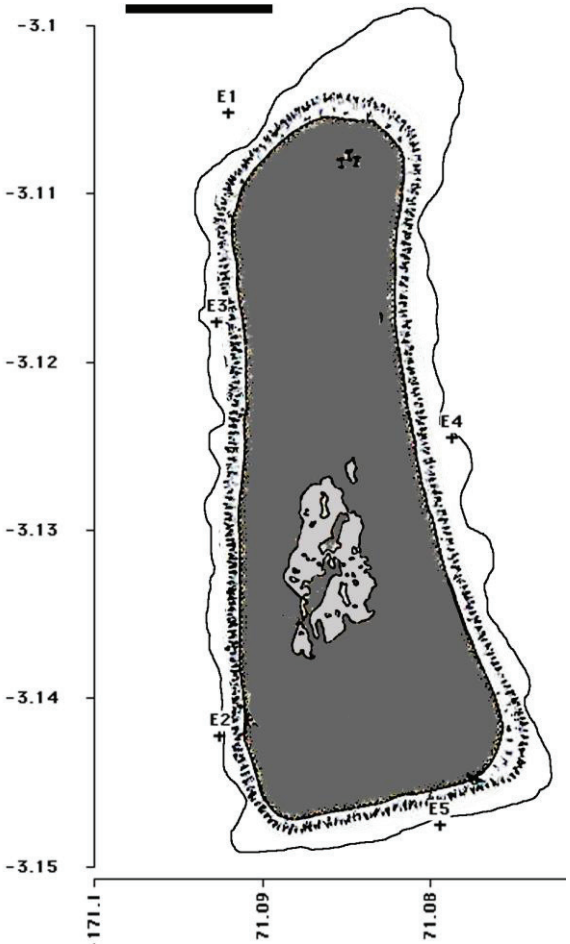

Figure 6. Enderbury Island.

Enderbury Island

Enderbury is the largest of the Phoenix Islands without a true lagoon, and is unique in being elongated north-south, measuring 4.6 km long (Fig. 6). As with the other small islands, it has a brackish pond in its center. The outer reef of Enderbury is estimated to have a perimeter of 16.3 km and area of 3.78 km^2, which is larger than the reef area of Nikumaroro. The northern to southwestern flanks of the island (incorporating sites E4 and E5) show windward exposed characteristics, just under 2/3 of the island rim. The western side is well sheltered by the long north-south axis of the island and makes up over 1/3 of the island rim, the longest leeward reef other than that of Kanton. The intertidal rim of Enderbury is narrow, while the subtidal reef width is 201 m with a platform sticking out to the northeast up to 700 m.

Manra Island (Hull)

Manra is the second largest of the Phoenix Islands (Fig. 7) without a marine lagoon, measuring 4.2 km across its widest axis (east-west), and like all islands smaller in size is nearly round in shape. The reef perimeter of 15.2 km is slightly shorter than Enderbury's. This island has the largest brackish lagoon, though the dense forest of trees and shrubs makes it difficult to access. The outer reef area of Manra is estimated at 2.97 km^2, slightly less than that of Enderbury due to the lack of an extended platform. The northeastern to southwestern flanks of the island (from site M3 almost to M2) show windward exposed characteristics, comprising 2/3 of the island rim. The northwestern

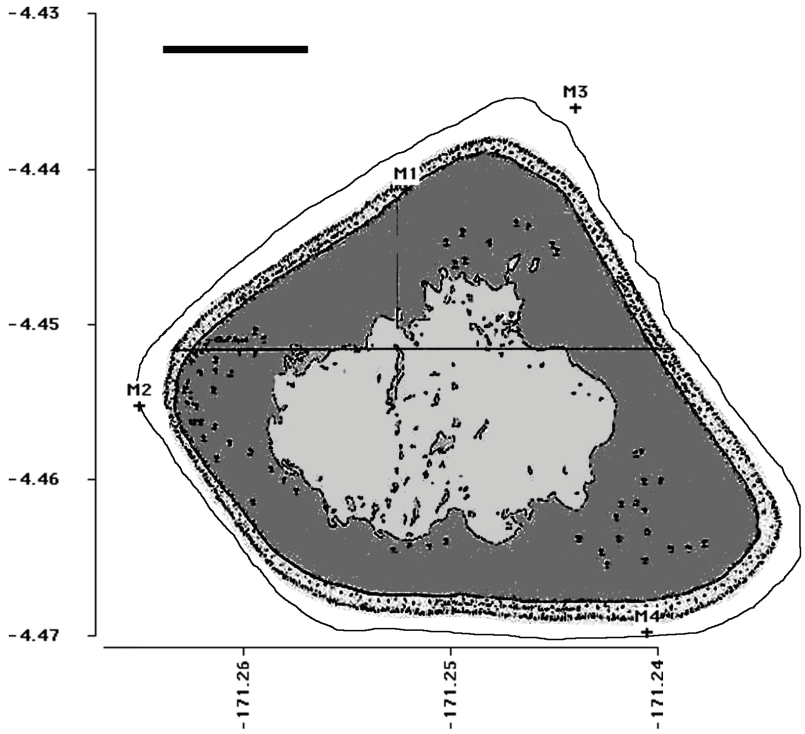

Figure 7. Manra Island.

side is the only sheltered flank of the island, about 1/3 of the island rim. The subtidal reef width is a relatively uniform 161 m wide. Manra is the smallest island with tree vegetation, including coconut trees and indigenous species.

Birnie Island

Birnie (Fig. 8) is the largest of the three smallest Phoenix Islands, in terms of reef area, though smallest in terms of island size. It is elongate, measuring 1.03 km along its longest axis. The reef perimeter of 8.12 km and area of 2.64 km^2 are high because of the long platform extending south (1.05 km, the longest in the island group) and north from the island. As with the other small islands, it has no lagoon, though the island does have a brackish pond in its center, and the entire northern to southern flanks of the island are exposed and windward. The western shore is more sheltered, though because of the island's small size there is no true leeward side. Because of the long subtidal reef extending south and exposed to wave energy, it is likely that > 4/5 of Birnie's reefs are 'windward' in nature, with only a small proportion to the west of the island being leeward. The subtidal reef averages 280 m wide, the widest among all the islands. This island was only visited once in 2002.

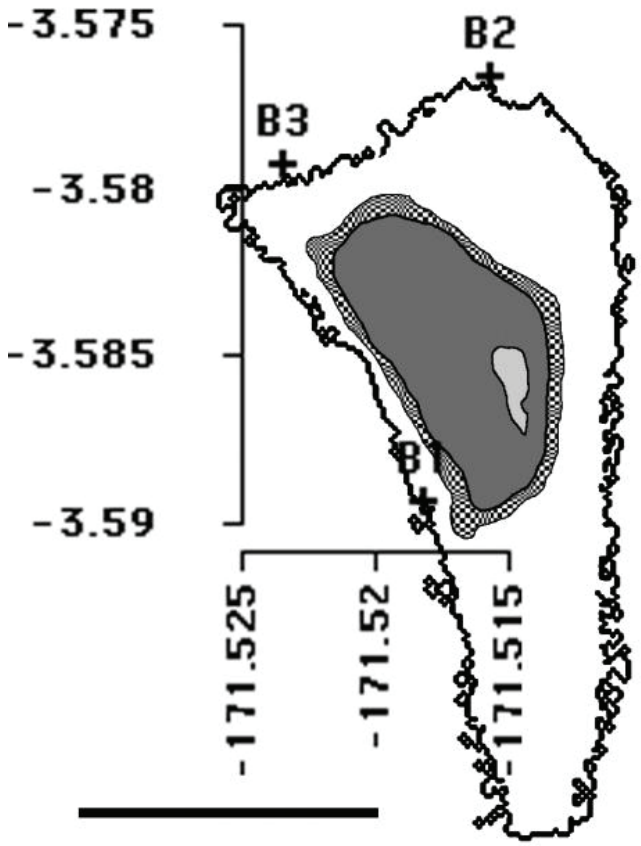

Figure 8. Birnie Island.

McKean Island

McKean (Fig. 9) is among the three smallest of the Phoenix Islands and is the most circular, measuring 1.07 km along its longest axis. The reef perimeter is 6.25 km and area is 1.27 km^2. As with the other small islands, it has no lagoon, though the island does have a brackish pond in its center. The entire northern to southwestern flanks of the island are expected to be windward in character (this zone has not been surveyed). The western side is more sheltered, though because of the island's small size there is likely to be no true leeward side. The subtidal reef width is 177 m. This is the least known island of the group, only being visited once in 2000.

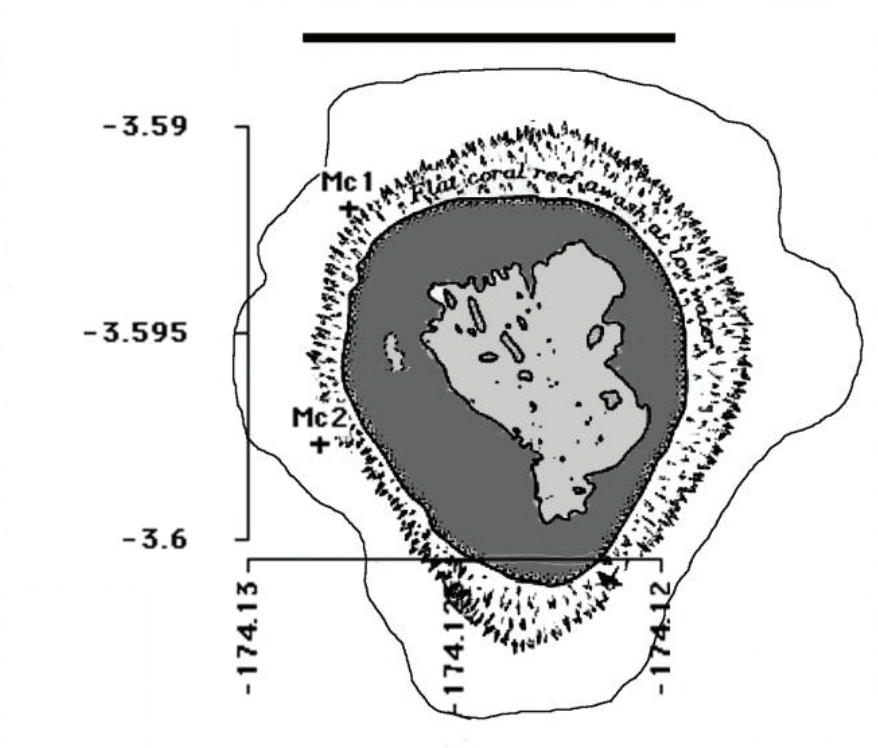

Figure 9. McKean Island.

Rawaki (Phoenix) island

Rawaki is among the three smallest of the Phoenix islands (Fig. 10), measuring 1.12 km along its longest axis. The atoll rim perimeter of 3.07 km, and area of 0.74 km^2 are the smallest of the entire group. As with the other small islands, it has no lagoon, though does have a brackish pond in its center. The entire northeastern to southeastern flanks of the island (incorporating site R4) show windward exposed characteristics, slightly more than 2/3 of the island rim. The western flank (sites R1 to R3) is sheltered, slightly less than 1/3 of the island rim. However because the subtidal reef width is relatively broad at 219 m due to an extension to the northeast and a broad eastern point, approximately 4/5 of Rawaki's reef area shows windward/exposed characteristics.

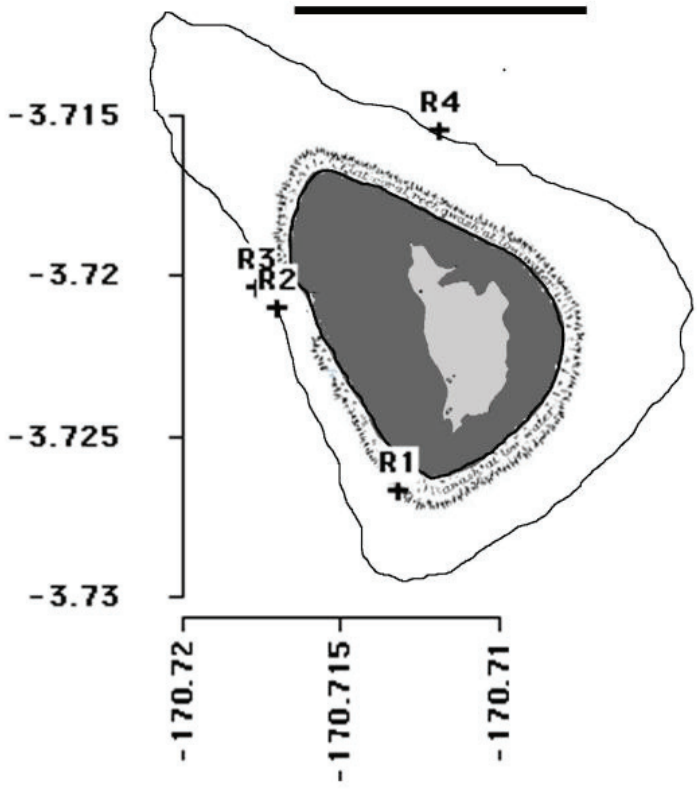

Figure 10. Rawaki Island.

DISCUSSION

Previous workers have noted the homogeneity of coral reefs of the Phoenix Islands, both zoogeographically (Maragos and Jokiel, 1978) and geo-morphologically (Jokiel and Maragos, 1978). These results are supported by observations reported here and in the accompanying chapters in this volume, with homogeneity within reef zones and of reef zones among islands. The methodology for obtaining area estimates here was based on overlaying data from charts, satellite images and existing GIS files. The values calculated vary to some degree from estimates for Kanton by Jokiel and Maragos (1978), who calculated a lagoon area of 49.6 km^2 and an atoll length of 17 km (compared to 56 km^2 and 17.5 km, respectively, measured here), but are close enough to be in agreement.

The islands in the Phoenix group vary incrementally in overall size, and thus in the dimensions and area of coral reefs (Table 3), with the exception of the lack of lagoon zones on all five of the smaller islands. A major goal of mapping was to specify the area of coral reef in each island/zone combination to facilitate study and management planning and zoning of the islands. The proportions of windward to leeward reefs (Table 3) enable a simple calculation of the area of windward and leeward reefs (Table 4). More problematic is estimation of coral reef habitats within the lagoons. Within the lagoons, coral growth was restricted to certain habitats, controlled by circulation (Jokiel and Maragos, 1978). Coral growth was abundant in the Pass Zone of Kanton lagoon,

Table 4. Reef area by major zone on each island (km2). Notes: a- reef area in Kanton lagoon Pass zone, calculated based on a half-circle of radius 2 km; b- reef area in remainder of Kan.

Island	Windward	Leeward	Lagoon	Total	%
Kanton	8.45	1.93	1.42(0.893[a], 0.53[b])	11.80	34.8
Orona	4.29	1.62	1.12	7.03	20.7
Enderbury	2.59	1.19		3.78	11.2
Nikumaroro	2.59	1.04	0.06	3.69	10.9
Manra	2.16	0.81		2.97	8.7
Birnie	2.49	0.16		2.64	7.8
McKean	0.84	0.43		1.27	3.7
Rawaki	0.58	0.17		0.74	2.2
Overall	23.98	7.35	2.60	33.93	

moderate on Orona and limited in all other lagoon zones on Kanton and in Nikumaroro. Jokiel and Maragos proposed an overall estimate of 5% of lagoon area to be suitable for coral growth. With improvements from the surveys conducted here, we postulate that coral reef may cover 25% of the Pass Zone on Kanton, 5 % of Orona's lagoon, and 1% of all other lagoon zones, giving first estimates for lagoon coral reef areas (Table 4).

Thus we estimate the Phoenix Islands have a combined coral reef area of 33.93 km^2 of which 23.98 km^2 is windward reef, 7.35 km^2 is leeward reef and 2.6 km^2 is lagoon reef (or 71, 22 and 8 %, respectively). Kanton dominates the island group with 35% of all reef area and 55 % of lagoon coral reefs, followed by Orona with 21 % of all reefs. Notably, the area of outer reef is higher on Enderbury than Nikumaroro. Interestingly, though Birnie is the smallest island in size, its reef area is only slightly less than Manra's due to the long shelf extending south. The wider and more extensive reef platforms on the smaller islands significantly increase their coral reef area. These broader reef platforms on the smaller islands are suggestive that they may have subsided further than the larger islands, with the islands representing a continuum of age and/or subsidence.

As a final calculation, the estimated reef area in each outer reef zone was calculated by island (Table 5). Thus the proportion of outer reefs in each of the reef zones is roughly similar between windward and leeward reefs, and in the percentages surge (15), platform (60), edge (10) and deep slope (15).

Overall, considering the various characteristics of island size and dimensions, orientation and reef area, the islands appear to cluster into three groups as follows:

1) the two largest islands with lagoons and extensive leeward reefs, Kanton and Orona (55% of all reefs);
2) three intermediate islands, Nikumaroro, Enderbury and Manra (31 % or reefs); and
3) the three smallest islands, Birnie, Rawaki and McKean (14 % of reefs).

Table 5. Area of outer reef slopes in the four main zones: surge zone, reef platform, reef edge and deep slope. The measured reef width to 20 m (Table 3) was assumed to include the reef edge (fixed at 20 m wide), the reef platform (80% of the remainder) and the surge zone (20% of the remainder), and the deep slope was fixed at 30 m wide.

Island	Windward slopes (km^2)					Leeward slopes (km^2)					Total
	Total	surge	platform	edge	slope	Total	surge	platform	edge	slope	
Kanton	8.45	1.30	5.18	0.79	1.18	1.93	0.27	1.08	0.23	0.35	10.38
Orona	4.29	0.66	2.63	0.40	0.60	1.62	0.22	0.87	0.21	0.32	5.91
Enderbury	2.59	0.42	1.66	0.20	0.31	1.19	0.18	0.71	0.12	0.18	3.78
Nikumaroro	2.59	0.35	1.40	0.34	0.51	1.04	0.16	0.65	0.09	0.14	3.64
Manra	2.16	0.32	1.30	0.21	0.32	0.81	0.12	0.47	0.09	0.14	2.97
Birnie	2.49	0.43	1.74	0.13	0.19	0.16	0.01	0.05	0.04	0.05	2.64
McKean	0.84	0.12	0.50	0.09	0.13	0.43	0.07	0.27	0.04	0.06	1.27
Rawaki	0.58	0.09	0.36	0.05	0.07	0.17	0.03	0.11	0.01	0.02	0.74
Total	23.98	3.69	14.77	2.21	3.31	7.35	1.05	4.20	0.84	1.26	31.33
%		15.4	61.6	9.2	13.8		14.3	57.1	11.4	17.1	

ACKNOWLEDGEMENTS

I would like to thank Mr. Kautoa Tonganibeia and Tererei Abete-Reema of the Environment and Conservation Division (ECD) of the Ministry of Environment Lands and Agricultural Development in Tarawa, for providing access to the GIS files used as a basis for this paper, and Conservation International for providing access to remote sensing imagery.

REFERENCES

Brainard, R, Maragos, J, Schroeder, R, Kenyon, J, Vroom, P, Godwin, S, Hoeke, R, Aeby, G, Moffitt, R, Lammers, M, Gove, J, Timmers, M, Holzwarth, S, Kolinski, S.
2004. The State of Coral Reef Ecosystems of the U.S. Pacific Remote Island Areas. USCR.

Clapp, R.
1964. Smithsonian Biological Survey. 01-18-14-90-81

Dana, T.F.
1975. Ecological aspects of hermatypic coral distributions in three different environments. Ph.D. Thesis, Univ. of California at San Diego.

Jokiel, P, Maragos, J.
1978. Reef corals of Canton atoll: II. Local distribution. *Atoll Research Bulletin* 221: 71-97

Maragos, J, Jokiel, P.
1978. Reef corals of Canton atoll: I. Zoogeography. *Atoll Research Bulletin* 221: 55-69

Obura, D, and G. Stone.
2003. Phoenix Islands. Summary of marine and terrestrial assessments conducted

in the Republic of Kiribati, June 5-July 10, 2002. Primal Ocean Project, New England Aquarium, Boston.

Obura, D., G. Stone, G., S. Mangubhai, S. Bailey, A. Yoshinaga, C. Holloway, and R. Barrel

2011 (this volume). Baseline Marine Biological Surveys of the Phoenix Islands, 2000. *Atoll Research Bulletin* No. 589, p. 1-61

Obura, D. and S. Mangubhai

in review. 'Catastrophic bleaching' in the Phoenix Islands, Central Pacific in 2002. Spatial variability of impacts and recovery.

Shultz, L.P.

1943. Fishes of the Phoenix and Samoan Islands collected in 1939 during the Expedition of the U.S.S. "Bushnell". Smithsonian Institution, United States National Museum, Bulletin 180. 315 pages.

Smith, S. V., and P. L. Jokiel.

1978. Water composition and biogeochemical gradients in the Canton Atoll lagoon. *Atoll Research Bulletin*. 221, p. 17-53

Smith, S. V., and R. S. Henderson (eds.)

1978. An environmental survey of Canton Atoll Lagoon, 1973. *Atoll Research Bulletin* No. 221 192 pp.

Stone, G., D. Obura, S. Bailey, A. Yoshinaga, C. Holloway, R. Barrel, and S. Mangubhai.

2000. Marine Biological Surveys of the Phoenix Islands. Report of the New England Aquarium, Primal Oceans Project. 106 pp.

APPENDIX I - SURVEY SITE DETAILS

The appendix shows the names, codes latitude/longitude and exposure type for each survey site shown in the maps. Also shown is the year(s) in which the each site was visited, and numerical site codes used in 2002 that correspond to sites listed in the fish distribution paper (Allen and Bailey, this volume).

Code	Site Name	Exposure	Longitude (W)	Latitude (S)	2000	2002	2005	CODE 2002
	Birnie							
B1	Puff Magic	Lee	171°31.093'	3°35.363'		y		67
B2	Rock 'n' Roll	Wind	171°30.936'	3°34.597'		y		66
B3	Prognathus Point	Wind	171°31.404'	3°34.754'		y		65
	Enderbury							
E1	Shark Village	Lee	171°5.517'	3°6.312'	y	y	y	59
E2	Obs Spot	Lee	171°5.549'	3°8.539'	y	y	y	62
E3	Lone Palm	Lee	171°5.564'	3°7.06'	y	y	y	61,64
E4	Mystery Wreck	Wind	171°4.723'	3°7.469'		y		63
E5	Southern Ocean	Wind	171°4.761'	3°8.855'	y	y	y	60
	Kanton							
K1	Nai'a Fly'a	Cha	171°43.002'	2°48.821'	y	y	y	24,50
K2	Lagoon End	Lag	171°37.227'	2°51.697'		y		35a
K3	Back Reef A	Lag	171°38.031'	2°51.102'		y		35b
K4	Back Reef B	Lag	171°38.506'	2°50.558'		y		35c
K5	Line Reef B	Lag	171°39.837'	2°49.694'		y		36
K6	Line Reef A	Lag	171°40.395'	2°48.113'		y		29a
K7	Rocks & Pole	Lag	171°40.395'	2°48.966'		y	y	29b, 37
K8	Coral Castles	Lag	171°41.743'	2°48.814'		y		26,45,53,55
K9	Lagoon Pass Zone B	Lag	171°41.835'	2°48.729'		y		56
K10	Lagoon Pass Zone A	Lag	171°42.378'	2°48.289'		y	y	30
K11	Coral Castles	Lag	171°42.388'	2°48.314'	y	y	y	
K12	Degraded Zone C	Lag	171°42.432'	2°46.691'		y		28c
K13	Degraded Zone B	Lag	171°42.457'	2°46.84'		y		28b
K14	Degraded Zone A	Lag	171°42.491'	2°47.384'		y		28a
K15	Guano Alley	Lag	171°42.56'	2°48.77'		y	y	54,58
K16	Kanton Wharf	Lag	171°42.69'	2°48.86'		y		52
K17	British Gas	Lee	171°42.924'	2°49.263'	y	y		27
K18	President Taylor	Lee	171°42.987'	2°48.959'	y	y	y	34,38,47,48
K19	Weird Eddie	Lee	171°43.047'	2°48.723'	y	y	y	32,39
K20	Six Sticks	Lee	171°43.24'	2°48.337'	y	y	y	25,40,51
K21	Crash Landing	Lee	171°43.35'	2°45.639'		y	y	42
K22	Satellite Beach	Lee	171°43.51'	2°46.802'	y	y	y	43
K23	Rolly Coaster	Wind	171°38.523'	2°47.978'		y		31,41,43,44,49
K24	Oasis	Wind	171°41.149'	2°50.098'		y		46,57
K25	Steep To	Wind	171°42.511'	2°49.986'	y	y	y	33
	Manra							
M1	Northern Lee	Lee	171°15.128'	4°26.475'	y	y	y	14
M2	Harpoon Corner	Lee	171°15.901'	4°27.315'	y	y	y	15,17,18,20
M3	Northern Exposure	Wind	171°14.634'	4°26.164'	y	y		16
M4	Wild Side	Wind	171°14.431	4°28.186		y		19

Code	Site Name	Exposure	Longitude (W)	Latitude (S)	2000	2002	2005	CODE 2002
	McKean							
Mc1	Rush Hour	Lee	174°7.65'	3°35.52'	y			
Mc2	Guano Hut	Lee	174°7.69'	3°35.86'	y			
	Nikumaroro							
N1	Nikumaroro channel	Cha	174°32.238'	4°40.137'		y		10
N2	Nikumaroro lagoon	Lag	174°32.1'	4°40'.0		y		11
N3	Amelia's Lost Cswy	Lee	174°32.616'	4°40.477'	y	y	y	7,9,84
N4	Nai'a Point	Lee	174°32.697'	4°39.335'	y	y	y	1,83
N5	Kandy Jar	Lee	174°32.724'	4°39.409'	y	y		2
N6	Norwich City	Lee	174°32.847'	4°39.652'		y		87
N7	Ameriki	Wind	174°29.407'	4°41.619'		y		3
N8	Turtle Nest Beach	Wind	174°30.905'	4°40.008'		y	y	4,82,85
N9	Electra Landing	Wind	174°31.302'	4°41.19'		y	y	6
N10	SW Corner	Wind	174°32.41'	4°40.87'	y		y	
N11	Windward Wing	Wind	174°32.552'	4°39.048'	y	y	y	5,8,12,13,86
N12	Landing	Lee	174°32.59	04°40.54	y			
	Orona							
O1	Orona Lagoon A	Lag	172°10.302'	4°29.701'		y	y	72
O2	Orona Lagoon B	Lag	172°08.712	4°29.878		y		73
O3	Orona Lagoon C	Lag	172°10.509'	4°30.341'		y	y	74,78
O4	Orona Lagoon D	Lag	172°11.502'	4°30.86'		y		77
O5	Orona Lagoon E	Lag	172°09.31	4°29.83	y			
O6	Orona Lagoon F	Lag	172°10.15	4°29.49	y			
O7	Algae Corner	Lee	172°13.616'	4°31.112'	y	y	y	68,75,79
O8	Dolphin Ledge	Lee	172°10.932'	4°29.487'	y	y	y	69,81
O9	Small Channels	Lee	172°12.962'	4°30.285'		y		80
O10	Transition Reef	Lee	172°13.531'	4°30.683'		y		70
O11	Aerials	Wind	172°12.953'	4°31.961'	y	y		71
O12	Backdoor	Wind	172°10.243'	4°31.815'			y	
O13	Far Side	Wind	172°8.241'	4°29.468'		y	y	76
O14	Farther Side	Wind	172°7.738'	4°29.816'			y	
O15	North Side	Wind	172°9.422'	4°28.942'			y	
	Rawaki							
R1	Clearwater	Lee	170°42.79'	3°43.6'	y		y	
R1	Deepwater	Lee	170°43.054'	3°43.222'	y	y	y	23
R1	Farwater	Wind	170°42.711'	3°42.927'		y	y	22
R1	Stillwater	Lee	170°43.017'	3°43.26'	y	y	y	21