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ORIGINAL PAPER

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Contradicting Barrier Reef relationships for Darwin's Evolution of reef types

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Abstract The Darwinian progressive subsidence model for the evolution of fringing reefs, barrier reefs and atolls has been generally accepted following the indisputable proof of subsidence provided by drilling results in the Pacific. Nonetheless, there are data that do not fit the expectations of the model, such as the similar lagoon depths of barrier reefs and atolls as opposed to the subsidence theory's implicit prediction that atolls should have significantly greater depths. In contrast, a great deal of evidence supports the influence of meteoric solution on barrier reef morphology. For example, the maximum lagoon depth of 56 modern barrier reefs is statistically correlated with the lagoon catchment area for modern annual rainfall. These modern rainfall patterns would seem to be a reasonable proxy for relative geographic differences in glacial lowstand rainfall, even though the absolute amounts of such rainfall are unknown. The correlation therefore suggests the importance of Pleistocene subaerial solution in contributing to barrier reef morphology. Further support for antecedent influence occurs in the form of barrier reef passes in which the depth of the reef pass is correlated with onshore drainage volumes. On a larger scale, the Cook Island of Mangaia provides evidence that solution can produce barrier reef morphology independent of reef development. In contrast, there are no examples of the subsidence-predicted lagoon transition of fringing reefs to barrier reefs to atolls. Moreover, the common occurrence of fringing reefs within barrier reefs negates subsidence as a causal factor in their 'presumed progressive evolutionary development. Consequently, the evidence to date suggests that a solution morphology template has been accentuated by reef construction to produce the diagnostic barrier reef morphology we see today. The importance of subsidence would seem to be in accounting for the overall thickness of the resulting carbonate caps of oceanic examples and in contributing to lagoon depth variation among the larger continental entities.

Keywords Barrier Reefs · Sea level · Karst · Subsidence

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Introduction

Darwin (1842) distinguished three reef types in his progressive subsidence developmental sequence of fringing reefs, barrier reefs and atolls and since then, these terms have been accepted by usage as descriptive terminology. Among these, atolls are the most clearly defined as more or less circular reefs enclosing a lagoon that has no internal volcanic or non-carbonate islands. The distinction between barrier reefs and fringing reefs is less clearly defined because it is generally based on the width of the lagoon separating the reef from one or more centrally located non-carbonate islands, or in the case of continental land masses from the mainland. Fringing reefs are essentially shoreline reefs usually associated with the relatively limited width and depth of an intervening lagoon, while barrier reefs are characterized by a significantly greater lagoon width separation from islands or mainland. There are no lagoon width criteria for the separation of the two; consequently, that distinction is largely subjective.

A number of minor additions have been made to this reef terminology. Among the more important is the Davis (1928) designation of almost-atolls for barrier reef lagoons that surrounded islands of such small areal extent that they were not far removed from being atolls. There are no precise limits to the size of the islands relative to that of the lagoon, but both Davis (1928) and Tayama (1952) cite the Pacific Caroline Island of Truk as an example (Fig. 1). It seems clear that subsidence in this and other almost-atoll examples would lead to the submer-

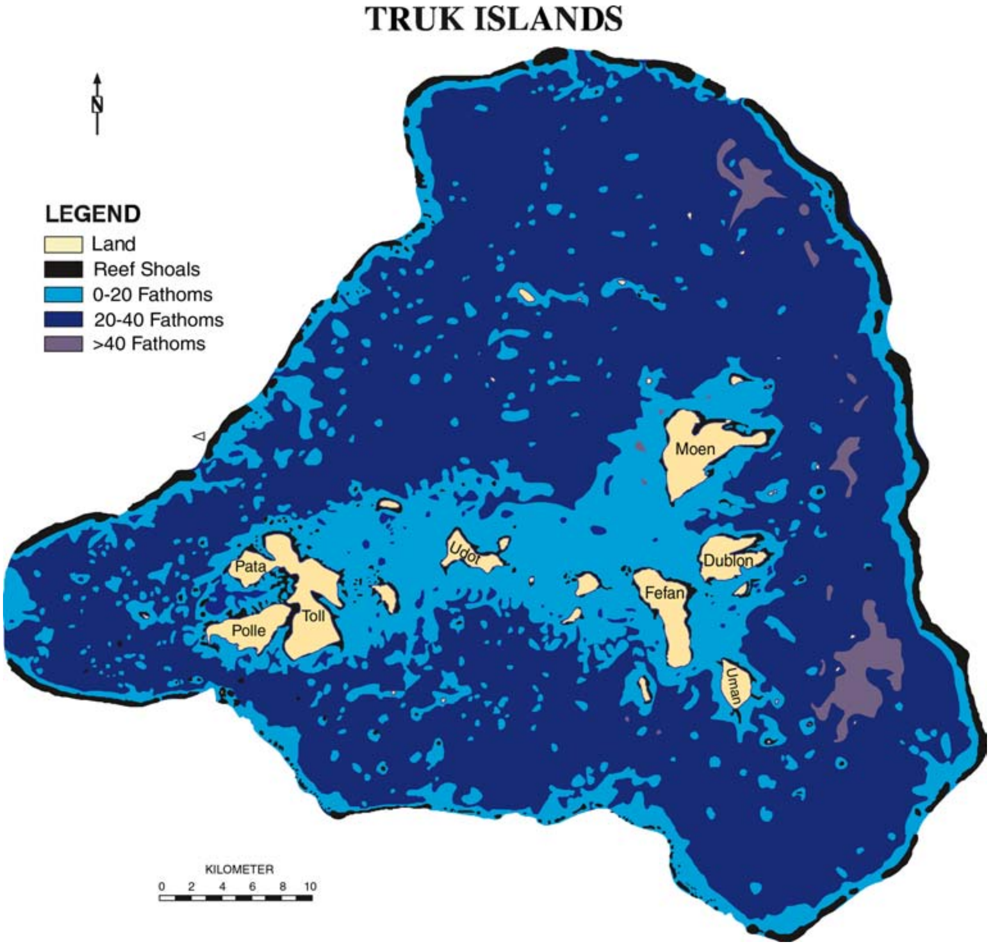

Fig. 1 Truk (now officially called Chuuk) Islands barrier reef. Modified from Shepard (1970). The land area is represented by almost 20 volcanic islands whose small size relative to the large size of the lagoon has given rise to the designation of Truk as an almost-atoll. Continued subsidence would certainly result in the disappearance of the small land areas below sea level and produce an atoll, but the problem of the original origin of the lagoon is unresolved. Moreover, one would anticipate that the resulting atoll lagoon would be deeper than its barrier reef predecessor, but contrary to expectations, Fig. 2 demonstrates the general similarity in depth between barrier reef and atoll lagoons and consequently calls into question whether atolls have generally evolved from subsidence of barrier reefs. Note also the occurrence of fringing reefs bordering many of the larger islands

gence of the islands and the consequent transformation to a *bona fide* atoll, thus supporting Darwin's idea that progressive subsidence leads to the development of atolls from barrier reefs. But while progressive subsidence would indeed lead to that transformation, the original origin of the lagoon is not resolved and this is the central problem in distinguishing fringing reefs, barrier reefs and atolls. With progressive subsidence, atoll lagoons should be deeper than barrier reef lagoons, but as Tayama (1952) has pointed out, this is not the case. It could, of course, be argued that the rate of sedimentation in the lagoon fortuitously kept pace with the rate of subsidence, resulting in no change in lagoon depth, but this seems unlikely as one of the sources of sedimentation, the non-carbonate islands, become progressively less important as a source of sediment with inundation.

The recently published analysis on the origin of atoll lagoons (Purdy and Winterer 2001) demonstrated, among other things, that the often-cited correlation between maximum atoll lagoon depth and atoll area was a reflection of the catchment area for rainfall. The present-day rainfall amounts used in that study were viewed as a surrogate for lowstand Pleistocene rainfall patterns in which the absolute amount of rainfall probably differed from the present, but paralleled the present day distribution in a relative sense. An identical approach was used in this study in accumulating data on the surface area, maximum lagoon depth and estimated annual rainfall for as many barrier reefs as one could find that provided these data.

Barrier Reefs

Measurements[1]

The initial goal was to accumulate data on a minimum of 100 barrier reefs, but it quickly became evident that this goal was difficult, if not impossible, to achieve because barrier reefs are nowhere near as abundant as atolls. Consequently, the barrier reef database is necessarily limited to 56 individual barrier reefs, the larger of which were subdivided for analysis to provide a total database of 81 barrier reefs (Table 1). Compared to the 301 atolls analyzed previously (Purdy and Winterer 2001), these figures suggest an approximate fourfold difference between the occurrence of barrier reefs and atolls. Indeed, if anything, this difference would be magnified by a tabulation of all atolls and all barrier

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[1] A compilation of all the basic data used in this paper is available, on line in the form of a spreadsheet, from http://www.springer.de

Table 1 Barrier Reefs database

A Group and Barrier Reef name	B Chart	C Latitude°	D Longitude°	E Lagoon area (km^2)	F Log$_{10}$ Lagoon area	G Land Area (km^2)	H Log$_{10}$ Land area	I Maximum land Elevation (m)	J Lagoon perimeter (m)	K Maximum Lagoon depth (m)	L Area, land elevation & Maximum depth comments	M Measured rainfall (mm/year)	N Gridded rainfall (mm/year)	O Catchment rainfall[1]
Comoro Islands														
Mayotte	BA 2741	−12.8	45.1	1286	3.11	372	2.57	592	205	74	Two soundings of 76 m + one each of 71, 73 & 74 m	2000 (Zinke (2000), Figs. 1.4)	1,108	3,446
Indonesia-Sulawesi														
Telek Tomori	BA 3240	−1.8	122.0	1280	3.11			2629	244	79	Maximum height from adjacent mainland		2,115	6,578
Teluk Bone West	BA 3616	−4.8	120.5	2188	3.34			750	288	50	Two soundings each of 49 and 51 m		1,946	6,500
Makassar Strait	BA 2637	−5.0	119.2	6488	3.81	45	1.65		503	55			1,965	7,487
Philippines														
North Bohol	BA 3825	10.3	124.3	16668	3.22				298	46	Maximum depth at either end of lagoon		2,343	7,544
North Palawan (Calamian- Nido area)	BA 967	11.7	119.5	10582	4.02				758	77	Area measured where reef is relatively continuous		2,326	9,351
Great Barrier Reef														
Cape York to Cape Weymouth	AUS 375	−11.0	143.5	21129	4.32				939	37	Area from Maxwell (1968, Fig. 16)	1600 (Hopley (1982), Figs. 2.12)	1,819	7,858
Cape Wemouth to Cape Melville	Aus 375-376	−13.0	143.8	11967	4.08				669	37	Area from Maxwell (1968, Fig. 16)	1200 (Hopley (1982), Figs. 2.12)	1,517	6,189
Cape Melville to Cape Tribulation	AUS 374- 375	−15.0	145.5	12965	4.11				736	37	Area from Maxwell (1968, Fig. 16)	1400 (Hopley (1982), Figs. 2.12)	1,304	5,359
Cape Tribulation to Magnetic Island	AUS 371,372, 373, 374	−18.0	145.5	25046	4.4				1249	40	Area from Maxwell (1968, Fig. 16)	1200 (Hopley (1982), Figs. 2.12)	983	4,325
Magnetic Island to Cape Palmerston	AUS 371- 372	−20.0	149.0	48679	4.69				1786	66	Area from Maxwell (1968, Fig. 16)	1000 (Hopley (1982), Figs. 2.12)	874	4,099
Cape Palmerston to Northeast Point	AUS 370-371	−21.5	151.0	62825	4.8				1932	91	Area from Maxwell (1968, Fig. 16)	1000 (Hopley (1982), Figs. 2.12)	802	3,850
Papua New Guinea														
Port Moresby to Round Point	AUS 380	−9.7	147.4	426	2.63				206	27			2,160	5,680

Table 1 (Contd.)

A Group and Barrier Reef name	B Chart	C Latitude°	D Longitude°	E Lagoon area (km^2)	F Log_{10} Lagoon area	G Land Area (km^2)	H Log_{10} Land area	I Maximum land Elevation (m)	J Lagoon perimeter (m)	K Maximum Lagoon depth (m)	L Area, land elevation & Maximum depth comments	M Measured rainfall (mm/year)	N Gridded rainfall (mm/year)	O Catchment rainfall[1]
Round Point to Hood Point	AUS 380	−10.0	147.6	288	2.46				96	18			2,122	5,219
Kailave Reef	AUS 380	−10.2	148.3	604	2.78				136	34	Two soundings of 33 m &one sounding of 35 m		2,123	5,904
West Reef to Batumata Point	AUS 380	−10.3	148.7	632	2.8				151	37			2,131	5,968
Orangerie Bay	AUS 380	−10.5	149.7	1084	3.04				181	55			2,156	6,544
Sunken Barrier to Rogea Island	AUS 381	−10.8	150.3	2629	3.42				496	57			2,155	7,377
Louisiade Archipelago														
Rosel	AUS 382	−11.4	154.0	704	2.85	272	2.43	838	201	49			2,288	6,520
Tagula	AUS 382	−14.3	153.0	6044	3.78	1948	3.29	806	513	64			1,708	6,457
Deboyne	AUS 382	−19.8	152.3	204	2.31	74	1.87	221	83	24			967	2,234
Solomon Islands														
Ghizo	US 82304	−8.1	156.8	167.6	2.22	36	1.56	180	63	82	ls. elevation; volc. core is higher (Stoddart 1969)		3,081	6,839
New Georgia	BA 3995	−8.4	157.7	1919	3.28	2486	3.40	1125	479	64	Land Elevation & Maximum depth from Stoddart (1969)	4452 (Stoddart 1969)	3,092	10,143
Caroline Islands														
Pohnpei	BA 981 & Atlas	6.9	158.2	31	1.49	662	2.82		105	42		4064 (13 year average, WC)	3,133	4,668
Truk	BA 982	7.3	151.8	2163	3.34	88	1.94	443	207	73		3525 (30 year average, WC)	3,122	10,588
Palau	BA 977	7.5	134.5	1844	3.27	445	2.65	242	365	42		3765 (748 months average, WC)	3,208	10,490
New Caledonia														
North	BA 935 & 936	−19.5	163.5	8281	3.92	801	2.9	283	682	45			1,383	5,421
Northeast	BA 935 & 936	−20.3	164.7	1562	3.19	319	2.5		356	22			1,334	4,255
Northwest	BA 935 & 936	−20.4	164.2	1558	3.19	2184	3.34		356	23	One sounding each of 22 and 23 m and two of 22.5 m		1,306	4,166
East Central Small	BA 935 & 936	−20.7	165.2	7	0.85	724	2.86		149	25	Two 25 m and one 24 m sounding		1,307	1,111
East Central Large	BA 935 & 936	−21.3	166.0	1948	3.29	3874	3.59		470	43			1,271	4,182
Southeast	BA 935 & 936	−21.9	166.8	836	2.92	1077	3.03		240	21	One sounding each of 21 & 20 m	3055 (576 nbsp;month average, WC)	1,235	3,606

Southwest	BA 935 & 936	−22.4	166.6	1398	3.15	2395	3.38		477	23		1134 (1378 nbsp;month average, WC)	1,186	3,736
South	BA 935 & 936	−22.7	166.8	4722	3.67	1189	3.08		616	56			1,166	4,279
Santa Cruz														
Utupua	US 82449	−11.3	166.5	184.5	2.27	63	1.80	365	61	74			3,061	6,948
Vanikolo	US 82449	−11.7	166.7	293.7	2.47	182	2.26	924	93	40			2,993	7,391
Fiji Islands														
Budd Reef	BA 440	−16.5	180.3	157.4	2.20	5.4	0.73		67	80			2,227	4,893
Vanua Levu: North	US 83570 & 83950	−16.5	178.8	6207	3.79	3137	3.50		701	77		2013 (Macfarlane, Fig.3)	2,222	8,420
Vanua Levu: Rambi Island/ Mbutha Bay	US 83570 & 83950	−16.6	179.9	431	2.63	272	2.43		184	59		2500 (Macfarlane, Fig.3)	2,209	5,811
Vanua Levu: Nukundrau Pass	US 83570 & 83950	−16.7	179.5	229	2.36	355	2.55		115	34	Two 33 m and two 35 m soundings	2500 (Macfarlane, Fig.3)	2,190	5,169
Vanua Levu: Savu Savu Bay	US 83570 & 83950	−16.8	179.2	371	2.57	590	2.77		127	50	Depths > 91 m assoc. with ? paleo-drainage channels	3750 (Macfarlane, Fig.3)	2,171	5,580
Vanua Levu: Yandua/ Namena/Wainunu Bay	US 83570 & 83950	−17.2	178.8	1668	3.22	895	2.95	105	318	60		2667 (Macfarlane, Fig.3)	2,102	6,768
Kimbombo	US 83590 & BA 416	−17.1	181.0	24	1.38	2	0.30	n.ht.	23	22	One sounding		2,135	2,946
Exploring Isles	US 83590 & BA 441	−17.2	181.2	765	2.88	76	1.88	290	145	84	169 m near pass; depths of 82, 84 & 86 m averaged		2,122	6,118
Kanathea	US 83590	−17.3	180.9	53	1.72	13	1.11	268	40	27	Two soundings		2,106	3,631
Makongai	US 83590	−17.5	179.0	188	2.27	7	0.85	267	90	35	Two soundings of 34 and 36 m, respectively		2,058	4,680
Katafanga	US 83590	−17.5	181.3	20	1.30	1	0.00	55	18	9	One sounding		2,081	2,707
Viti Levu: East	US 83570	−17.6	178.6	1446	3.16	1040	3.02		306	40		2500 (Macfarlane, Fig.3)	2,038	6,439
Nairai	US 83350	−17.8	179.4	128	2.11	23	1.36	336	63	31			2,017	4,251
Late-e-Vitti	US 83580	−17.9	181.7	85	1.93	1	0.00	3	37	34			2,030	3,917
Ngau (Gau)	US 83580	−18.0	179.2	175	2.24	141	2.15	713	74	36			1,984	4,444
Bacon I. (Vanua Masai)	US 83580	−18.0	181.6	107	2.03	1	0.00	24	45	31	Soundings of 36, 31 and 25.6 m		2,016	4,092
Lakeba	US 83580	−18.2	181.2	98	1.99	62	1.79	220	57	15	One sounding each of 18 & 12 m	1894 (643 month average, WC)	1,988	3,959
Mbenga	US 83580	−18.4	178.0	373	2.57	41	1.61	221	85	42			1,913	4,920
Oneata	US 83580 & BA 416	−18.4	181.5	96	1.98	3	0.48	48	49	37			1,968	3,902
North Astrolabe	US 83572	−18.7	178.5	37	1.57	1	0.00	20	23	20		2000 (Macfarlane, Fig.3)	1,882	2,951
Moala	BA 1252	−18.6	179.9	68	1.83	46	1.66	478	69	48	Soundings of 49, 47 and 47 m		1,920	3,518

Table 1 (Contd.)

A Group and Barrier Reef name	B Chart	C Latitude°	D Longitude°	E Lagoon area (km^2)	F Log$_{10}$ Lagoon area	G Land Area (km^2)	H Log$_{10}$ Land area	I Maximum land Elevation (m)	J Lagoon perimeter (m)	K Maximum Lagoon depth (m)	L Area, land elevation & Maximum depth comments	M Measured rainfall (mm/year)	N Gridded rainfall (mm/year)	O Catchment rainfall[1]
Komo	US 83580 & BA 441	−18.7	181.3	32	1.51	2	0.30	82	23	11	Sounding of 7.3 m on US 8350 & 11 and 14.5 m on BA 441		1,931	2,906
Ono (North Kadava, Great Astrolabe Reef)	BA 745	−18.9	178.5	334	2.52	35	1.54		123	33			1,860	4,693
Totoya	US 83580	−18.9	180.1	136	2.13	24	1.38	361	53	49	One sounding each of 48 & 49 m		1,886	4,023
Yangasa Cluster	US 83580 & BA 441	−18.9	181.6	90	1.95	6	0.78		47	27	Two soundings		1,912	3,736
Kadavu: Namalata	BA 745	−19.0	178.3	42	1.62				37	27			1,835	2,979
Kadavu: Galoa	BA 745	−19.1	178.3	126	2.10				94	35			1,830	3,845
Kadavu: Korolevu Bay	BA 745	−19.1	178.4	32	1.51				36	42	Maximum depth based on only two soundings		1,835	2,758
Fulanga	US 83580	−19.2	181.4	50	1.70	20	1.30	80	33	13	Soundings of 14.6 12.8 and 10.9 m		1,877	3,191
Ongea	US 83580 & BA 441	−19.2	181.6	77	1.89	17	1.23	90	39	16	Soundings of 18, 16.5 and 14.5 m on BA Chart 441		1,880	3,547
Vatulela	US 83570	−19.5	173.6	63	1.80	34	1.53	27	42	7			1,673	3,010
Wallis Islands														
Uvèa	F 64611	−13.6	185.8	201	2.30	79	1.90	145	82	58		2968 (21 year average, Taylor, 1973)	2,507	5,774
Sociey Islands														
Maupita	BA 1060 & F 7213	−16.4	207.2	35	1.54	4	0.60	380	24	7	Maximum land elevations from IUCN		1,731	2,673
Bora Bora	BA 1107 & F 6002	−16.5	208.2	87	1.94	21	1.32	727	42	31	Maximum land elevations from IUCN	2028 (21 year average, Taylor, 1973)	1,664	3,228
Raratea/Tahaa	BA 1103 & F6033	−16.7	208.6	262	2.42	257	2.41	1017	115	44	Maximum land elevations from IUCN		1,639	3,963
Huahini Niu	BA 1103 & F 6434	−16.7	209.0	58	1.76	72	1.86	669	59	44	Maximum land elevations from IUCN		1,614	2,846
Moorea	BA 1382	−17.5	210.2	54	1.73	134	2.13	1207	40	36	Two soundings of 36 m; 3 if drowned valley is added	1500 (Rougerie et al. 1997)	1,547	2,676
Tahiti & Taiarapu	BA 1382	−17.7	210.5	214	2.33	1006	3	2241	185	35	Depth greatest on east side.	1500 (Rougerie et al. 1997)	1,532	3,570

Gambier													
Gambier	BA 1112 & F 64611	−23.2	225.0	464	2.67	25	1.40	441	98	33	1932 (Chevre, 1974)	1,213	3,239
Belize													
South	US 1496 &1497	16.3	271.7	2866	3.46				244	46	3556 (Purdy 1974, Fig. 17)	989	3,419
Central	US 1497 & 1498	17.2	271.8	2346	3.37				252	24	2540 (Purdy 1974, Fig. 17)	960	3,236
North	Pusey (1975), Fig.6	17.8	271.9	1251	3.08				158	4	1524 (Purdy 1974, Fig. 17)	935	2,896
Cuba													
Anna Maria and Guacanayaro Gulfs	BA 2579	21.3	281.7	17588	4.25				912	23.8		683	2,903
East of Isle of Pines	BA 2579	22.0	278.0	9897	4.00				476	7.8		963	3,847
Bahamas													
Andros	BA 3912	24.6	282.3	297	2.47				291	3	1200 (Pierson and Shinn (1985), Fig. 12)	1,132	2,796

reefs rather than limiting the comparison to the ones that provide the comparable analytical data used in this and the previous atoll lagoon study.

Measurements of area, depth and rainfall were made in the same way as those of Purdy and Winterer (2001) in their study of atolls and it would serve no useful purpose to repeat those details here. Suffice it to state that lagoon surface area was taken as the area, in km^2, between the outer reef rim perimeter of the barrier reef and the coast of the major bordering island or mainland. The areas of high islands occurring within the lagoon were subtracted from the lagoon area but added to the total land area. Additionally, the maximum elevation of defining barrier reef islands was also tabulated. In all places the source of non-hydrographic data is identified on the accompanying spreadsheet.

In several instances individual barrier reefs were subdivided into segments dictated by one or more of several circumstances: (1) termination of the lateral extent of the barrier reef, (2) limitations of defining data (e.g., the poorly surveyed Table Reef segment of the Papuan Barrier Reef), (3) conspicuous plan-view changes in reef configuration among the larger barrier reefs (e.g., The New Caledonia barrier reef, the Australian Great Barrier Reef, the Papuan barrier reef and the Fijian Vanua Levu barrier reef).

Individual barrier reef lagoon depths were tabulated as the maximum depth recorded three or more times on the hydrographic charts identified on the database spreadsheet. Greater lagoon depths associated with the occurrence of reef passes were specifically avoided as they seemed an attribute associated with the development of the reef pass itself rather than being indicative of maximum depth development within the overall lagoon. In instances where three common maximum depth soundings were missing, averages were made of the three deepest soundings. These and other deviations are noted in the Comments column of the database spreadsheet. A depth distribution histogram for all database barrier reefs is illustrated in Fig. 2 where a comparison with that of 295 atolls demonstrates no significant depth differences between the two, confirming Tayama's 1952 conclusions.

Estimated annual rainfall for each barrier reef, in mm/year, was interpolated from the database previously illustrated and reported by Purdy and Winterer (2001). In contrast to the low relief of atoll islands, however, many barrier reef islands are characterized by considerable relief, resulting in a distinct orographic intensification of rainfall. For example, on the large Fijian barrier reef islands of Viti Levu and Vanua Levu, the southeast trade winds are the predominate rain-bearing influence on annual rainfall amounts that increase with altitude (Macfarlane 1998). The resulting areal difference in annual rainfall is as much as 3,500 mm/year with the western low relief coastal area receiving as little as 1,500 mm/year compared to the 5,000 mm/year annual rainfall values of the interior areas (Macfarlane 1998). The orographic influence on rainfall logically diminishes in an offshore direction from where the interpolated

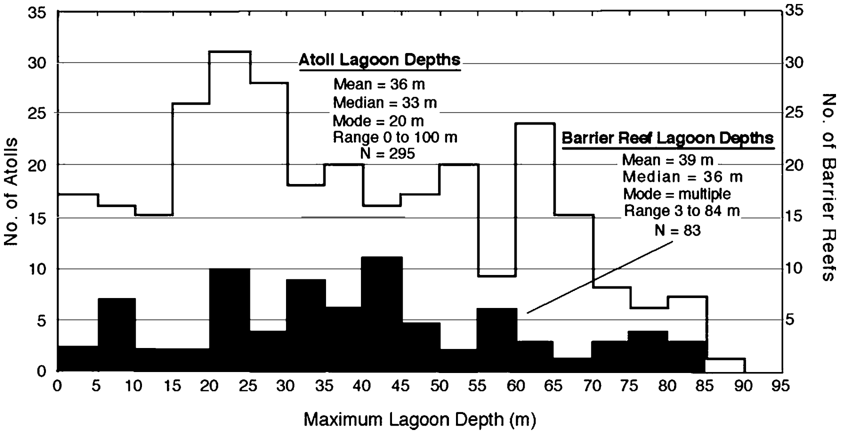


Fig. 2 Lagoon depth histogram comparing the frequency distribution of maximum lagoon depth for 87 barrier reefs and 295 atolls. In the interests of conserving graph space, three atolls with maximum lagoon depths in the 95–100 m range are not shown. Note that there is not much difference between the mean, median and range of barrier reefs compared to atolls. Indeed, if anything, the average and median maximum lagoon depths of barrier reefs would seem to be slightly greater than that of atolls

rainfall determinations were made, but some influence must remain because the original isohyetal chart used by Purdy and Winterer (2001) was based in part on rainfall measurements on islands.

The problem of rainfall variability is further compounded by the large size of some of the barrier reefs (e.g., the Australian Great Barrier reef and the New Caledonian barrier reef. In these instances, the initial thought was that a single interpolated rainfall value for the entire barrier reef lagoon would be a misleading over-simplification and for that reason the larger barrier reefs were subdivided into the barrier reef segments identified on the database spreadsheet. The basis for the identified subdivisions was a conspicuous change in the plan-view pattern of barrier reef morphology. Even so, the reader is cautioned that in some of the larger barrier reef subdivisions, there may still be an element of over-simplification with respect to representation of area with associated maximum lagoon depth and rainfall.

Notwithstanding these concerns, the interpolated rainfall values for individual barrier reef lagoons compare favorably with measured rainfall values on islands as illustrated by the scatterplot of Fig. 3 where the indicated correlation provides confidence that the interpolation methodology is a generally reliable indication of measured rainfall data. The absolute amount of rainfall in the lagoons undoubtedly differs from that of the surrounded high island or adjacent mainland, but it would seem that the results approximate reality in at least a relative sense.

Statistical Results

The 81 measured lagoon areas evidenced a log normal distribution that was converted to a linear relationship by using $\log_{10}$ of the measurement area. Initial scatterplots of maximum Lagoon Depth versus $\log_{10}$ Lagoon Area and Annual Rainfall demonstrated the conspicuous non-conforming nature of the Australian Great Barrier Reef relative to trends among the other barrier reefs for reasons discussed subsequently. In addition a multiple regression analysis of the remaining 75 barrier reefs with Maximum Lagoon Depth as the dependant variable and Lagoon Area and Annual Rainfall as the independent variables identified four outlier data points that fell more than 2.0 standard deviations from the standardized residuals (Table 2). Consequently, these four barrier reefs were eliminated from further collective statistical analyses.

A Multiple Correlation Coefficient of 0.75 documents the degree to which the independent variables, Log_{10} Area and Annual Rainfall, are related to the dependent variable of Maximum Lagoon Depth and is statistically significant at the $p < 0.000$ confidence level. The R^2 Coefficient of Determination indicates that the two independent variables explain 56% of the variability of Lagoon Depth. Partial correlation coefficients of 0.63 and 0.68 between the dependent variable and Log_{10} Area and Annual Rainfall, respectively, document the extent to which each independent variable contributes to the prediction of Maximum Lagoon Depth when the effect of the other independent variable is held constant.

A plot of $\log_{10}$ area versus maximum lagoon depth for the 72 barrier reefs is shown in Fig. 4. The linear association corresponds to a correlation coefficient of 0.41, a much weaker correlation than the 0.58 correlation value recorded for the same parameters in 295 atolls (Purdy and Winterer 2001), though still statistically significant at the $p < 0.000$ level. A graph of annual rainfall versus maximum lagoon depth for the same 72 barrier reefs is illustrated in Fig. 5 where a correlation of 0.53 is in evidence. This value is a considerable improvement over the 0.36 correlation value reported by Purdy and Winterer (2001) for identical parameters in 295 atolls. The reasons for these contrasts with the atoll database analyses are not obvious and perhaps simply record the imprecision of depth and rainfall determina-

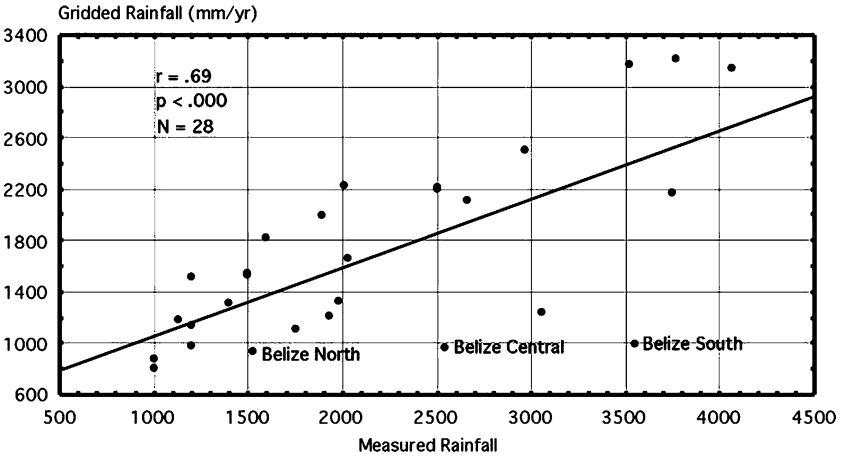


Fig. 3 Graph of measured annual rainfall on barrier reef mainlands versus annual rainfall calculated from the latitude and longitude position of corresponding barrier reef lagoons. The number of barrier reefs is limited by the number of cases for which one could find measured rainfall data. The correlation coefficient (*r*) is highly significant for the 28 (N) barrier reefs with less than one chance in a thousand (*p*) that the measured association is due to chance. Notwithstanding the obvious scatter of points at the lower and higher ends of the trend, the results provide confidence that the interpolation methodology is an overall reasonable indication of annual gauge-measured rainfall. The Belize data have been identified to illustrate a problem. The north to south annual rainfall distribution on the Belize mainland varies from approximately 1,500 mm in the north to 3,500 mm in the south. In contrast the lagoon calculated annual rainfall varies only from 935 mm to 989 mm in the same direction. Although a decrease in the amount of lagoonal annual rainfall is expected away from the orographic effect of the mainland Maya Mountains, the measured decrease seems much too excessive. Unfortunately, the data constraints upon which the original isohyetal chart of Xie and Arkin (1997) were based are unknown. Consequently, there was no way one could realistically re-contour the Yucatan Peninsula area without affecting large peripheral areas where data constraints were unknown; hence the large Belize discrepancy between measured and calculated annual rainfall values

Table 2 Deleted Barrier Reef outlier

Outlier Barrier Reef	Maximum Lagoon Depth (m)	Standard deviation of standardized regression residuals
Mayotte, Comoro Islands	74	2.81
Exploring Isles, Fiji	84	2.31
Budd Reef, Fiji	80	2.58
Palau, Caroline Islands	42	−2.19

tions, including the imperfect nature of using annual rainfall as a surrogate for paleo-rainfall.

The effect of including the four outliers is to decrease the area versus depth correlation from 0.41 to 0.39. Their inclusion also reduces the rainfall versus depth correlation from 0.53 to 0.46 with no change in confidence level for either from $p < 0.000$.

Interpretation

In their atoll analysis, Purdy and Winterer (2001) explained the relationships among Maximum Lagoon Depth, Lagoon Area and Annual Rainfall as reflecting a relationship in which Maximum Lagoon Depth was viewed as largely representing drowned solution relief developed during Pleistocene subaerial exposure through the combined effect of Lagoon Area and Annual Rainfall. In the case of atolls, multiplying these two independent variables together as catchment rainfall resulted in a significant increase in correlation with Maximum Lagoon Depth, not only with respect to the total atoll database but also with respect to individual atoll groups (Purdy and Winterer 2001). The same correlation improvement is apparent with barrier reefs where a correlation of 0.75 is evident for the 72 database barrier reefs (Table 3 and Fig. 6).

With one exception, barrier reefs in individual areas are too few to demonstrate whether a comparable correlation improvement is apparent in specific geographic areas. The exception is Fiji in that 29 or 41% of the 72 barrier reefs in the database occur there. This increases to 31 or 44% when the two Fijian outliers of Exploring Isles and Budd Reef are added. The distinction between Fijian and non-Fijian barrier reefs provides sufficient numbers to compare relationships between the two. These are presented in Table 4 and Figs. 7 and 8 where the correlations between Maximum Lagoon Depth and the combined variable of Annual Rainfall multiplied by Log_{10} of Lagoon Area document a considerable increase in the strength of the correlation compared to separate correlations with these variables, even with the inclusion of the outlier data points.

In essence the multiplied variables of Annual Rainfall and Log_{10} of Lagoon Area imperfectly reflect annual volume of rainwater. This has been referred to as Catchment Rainfall by Purdy and Winterer (2001) and it is in this sense that the term is used throughout the present paper. The statistically highly significant regression equation for lagoon depth predicted by catchment rainfall for the 72 barrier reefs is:

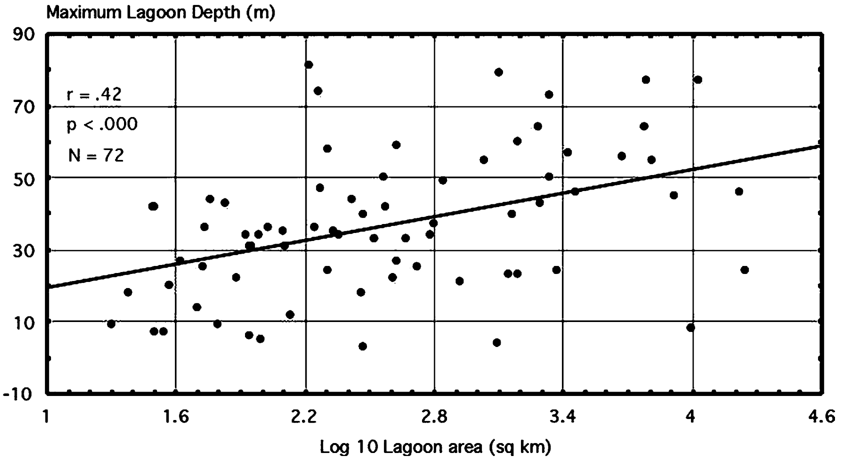
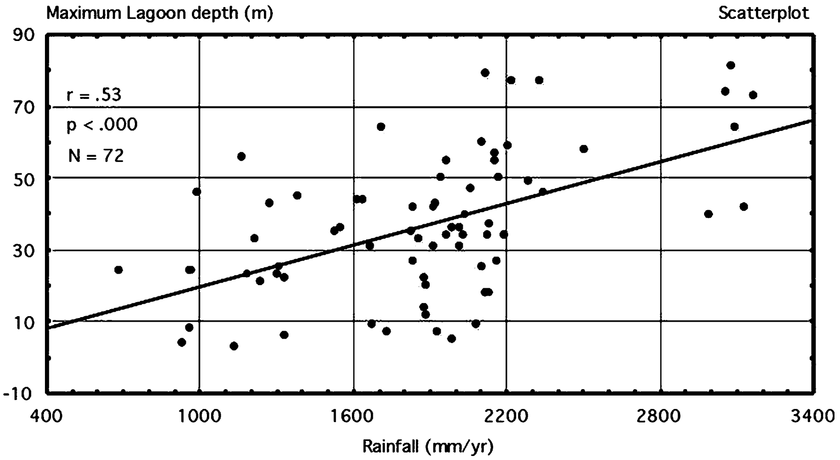


Fig. 4 Graph of barrier reef lagoon area versus maximum lagoon depth for 72 barrier reefs. Lagoon area was measured as the area in km^2 between the outer reef perimeter and the inner defining land area. Areas of islands within the lagoon were subtracted from the lagoon total. The resulting net lagoon area was converted from a log normal to linear relationship by using $\log_{10}$ of the measured area. Maximum lagoon depth is generally that recorded by three or more atoll lagoon soundings on hydrographic charts. The 0.42 correlation between maximum lagoon depth and lagoon area is not particularly strong, but nonetheless is highly significant statistically

Fig. 5 Graph of annual rainfall versus maximum lagoon depth for barrier reefs. The 0.53 correlation coefficient is stronger than that of the area versus depth graph of Figure 4, and like that correlation, is also highly significant statistically



$$\text{Maximum Lagoon depth(m)} = 0.463 + 0.008(\log_{10} \text{Area in km}^2 \times \text{Rainfall in mm/year})$$

The intercept differs from that of atolls (9.385 vs. 0.463), but the barrier slope coefficient of 0.008 approximates the atolls value of 0.007.

Collectively these relationships provide strong circumstantial evidence that maximum barrier reef lagoon depths are a function of subaerial solution. Additionally they suggest that lagoon depths in general are, at least in part, a function of subaerial solution, otherwise it is difficult to see how solution would be limited in its expression to the relatively few areas represented by maximum lagoon depth.

One further point should be noted with respect to the subdivision of the larger barrier reefs. Although the initial decision to subdivide these was based on the areal variability of rainfall, the areal rainfall differences among most of the individual barrier reef subdivisions proved, in retrospect, too small to be of any consequence. The significance of the subdivisions seems to lie in the observation that in the case of large barrier reefs such as that of New Caledonia, it is unrealistic to think of the entire lagoon as a catchment area for maximum lagoon depths that may be recorded in only a small area of that lagoon. Instead, smaller catchment subdivisions would seem to be more applicable to the maximum lagoon depth recorded within their limits. The reader should note that this relationship is probably also applicable to the barrier reef lagoon areas that have not been subdivided, thereby contributing to the scatter of data points, particularly in the area versus maximum lagoon depth graph (Fig. 4).

Barrier Reef Passes

Description

Reef passes provide further evidence of solution modification of antecedent Holocene topography. These are distinguished as channels or passages through perimeter

Table 3 Barrier Reef correlation matrix $N = 72$

	Log_{10} Lagoon area	Lagoon depth	Rainfall/year	Area×rainfall
Log_{10} Lagoon area	1.000 $p < 0.000$	0.423 $p < 0.000$	−0.19 $p < 0.107$	0.571 $p < 0.000$
Lagoon depth	0.423 $p < 0.000$	1.000 $p < 0.000$	0.534 $p < 0.000$	0.751 $p < 0.000$
Rainfall/year	−0.191 $p < 0.107$	0.534 $p < 0.000$	1.000 $p < 0.000$	0.67 $p < 0.000$
Area×rainfall	0.57 $p < 0.000$	0.751 $p < 0.000$	0.670 $p < 0.000$	1.000 $p < 0.000$

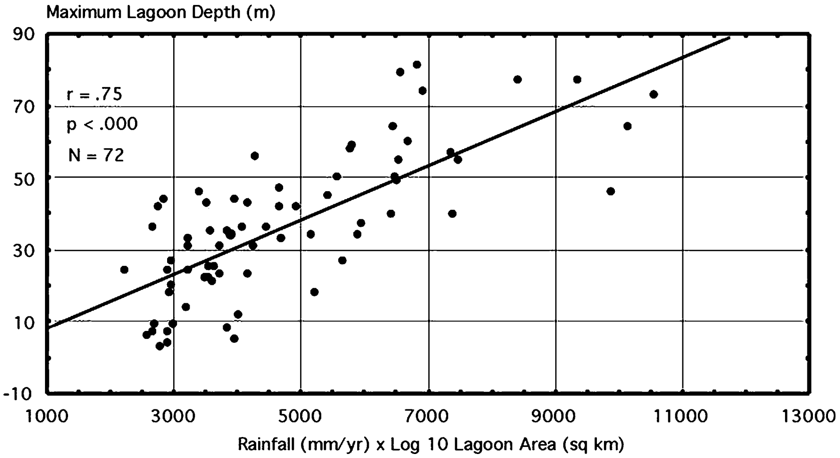


Fig. 6 Graph of catchment rainfall (rainfall in mm per year multiplied by $\log_{10}$ of atoll area) versus maximum lagoon depth of barrier reefs. The correlation coefficient of 0.75 is an improvement over that of maximum lagoon depth correlations with area and annual rainfall, respectively, as shown individually in Figs. 4 and 5 and in Table 3, suggesting the importance of rainfall collection area in contributing to the magnitude of solution relief

reefs and range from shallow depths that barely allow the passage of shallow draught boats to deeper entities that are sometimes navigable by large oceangoing vessels. Stoddart (1969) provided evidence of the modern erosional origin of the shallower ones in Rangiroa Atoll and Purdy (1974) speculated that in general they might have originated through reef destruction by storms, but it is the deeper ones that provide evidence of solution.

Among these, Darwin (1842) recognized the frequent occurrence of passes in front of land valleys, and further observed that they were seldom as deep as the adjacent lagoon, an observation repeated by Tayama (1952) and Purdy (1974). Davis (1928) commented that reef passes in the Moorea, Society Islands barrier reef were all situated opposite valleys on the island, but also observed that there were many valleys without opposite passes. Guilcher (1988) concurred that deep barrier reef passes were located opposite the mouths of main rivers and added the belief that they were remnants of sea level lowstand Pleistocene valleys that drained the lagoon into the surrounding sea.

There is a depth distinction between deep passes in which the depth of the contiguous lagoon increases consistently through the reef pass toward the open sea, and those in which pass depth increases in both open sea and lagoon directions (Fig. 9). The two have been confused in the literature with Darwin (1842) and Purdy (1974), emphasizing the partially blocked, plugged or "choked" reef passes and Davis (1928) and Guilcher (1988), unknowingly, emphasizing the "unblocked" variety.

Drowned valleys

Among the unblocked examples, Tayama (1952), Shepard (1970) and Guilcher (1988) all mention the association of reef passes with drowned valleys in the Pacific, Caroline Islands, Pohnpei barrier reef. This association is illustrated in Fig. 10 where reef passes appear to be drowned extensions of land valleys. In these instances it seems reasonable to suppose that the depth of the reef passes might reflect the amount of corresponding land drainage. A difficulty in testing that hypothesis is the paucity of hydrographic chart soundings within unblocked passes that could be considered as representative of maximum pass depth. Even so, data considered representative were tabulated for Pohnpei and the Society Islands of Moorea and Tahiti and are shown in Table 5 along with opposite river drainage areas and interpolated rainfall values for each island. The drainage areas evidenced a log normal distribution and were converted to Log_{10} values to facilitate calculation of product moment correlation coefficients. These correlations are shown in Table 6 where it is evident that multiplying the Log_{10}drainage areas by present-day annual rainfall improves the positive correlation with reef pass depth for each barrier reef. In essence, the Log_{10}area × annual rainfall product is a proxy for annual volume of catchment meteoric water. Two of the Tahiti passes are suspect with respect to the accuracy of depth soundings and in any event constitute outliers that fell more than 2.0 standard deviations from the standard-

Table 4 Correlations between maximum barrier reef lagoon depth and indicated variables

Barrier Reef Group	Log 10 Lagoon area (sq km)	Annual rainfall (mm)	Log_{10} Lagoon Area × annual rainfall
Fiji ($N = 31$)[a]	$r = 0.71$ $p < 0.000$	$r = 0.55$ $p < 0.002$	$r = 0.74$ $p < 0.000$
Non-Fiji ($N = 45$)[b]	$r = 0.23$ $p < 0.131$	$r = 0.57$ $p < 0.000$	$r = 0.64$ $p < 0.000$

[a] Includes Budd Reef and Exploring Isles Outliers
[b] Includes Mayotte and Palau Outliers

ized residuals. Their removal from the correlation database improves the correlation from 0.62 to 0.74, both of which, however, are highly significant statistically at the $P < 0.000$ level (Table 6). These data strongly suggest that the depth of unblocked passes is largely a function of catchment area rainfall during Pleistocene lowstands of sea level.

Blocked passes

The partially blocked, plugged or "choked" reef passes are certainly far more numerous than the unblocked variety and have the common characteristic of being shallower than contiguous lagoon depths, in keeping with the observation first made by Darwin (1842). In some instances, the shallower depth is represented by an isolated sounding, presumably reflecting the occurrence of a local shoal within the pass. In other cases, the outline of a shoal is shown on hydrographic charts, and in still others, a bathymetric sill is illustrated as occurring across the width of the pass (Fig. 9). In all these cases, the pass obstruction occurs approximately on trend with the barrier reef on either side of the pass but is significantly deeper than the depths of those reefs.

In some cases there is an indication that the choked pass developed within a drowned valley. The western Pacific Yap Islands are one of the best examples of this phenomenon (Fig. 11). Tayama (1954) refers to this as an "almost barrier reef", but while it is not a barrier reef in the strict sense, the reef passage marking the position of the drowned valley is choked, as in the case of barrier reefs. The presence of a large drowned drainage pattern in Tamil Harbor is beyond dispute (Fig. 11), but the paradox of a drainage pattern that evidences distinct shoaling before discharging into the open sea remains, duplicating the relationship for choked barrier reef passages in general. The shoaling is obviously contrary

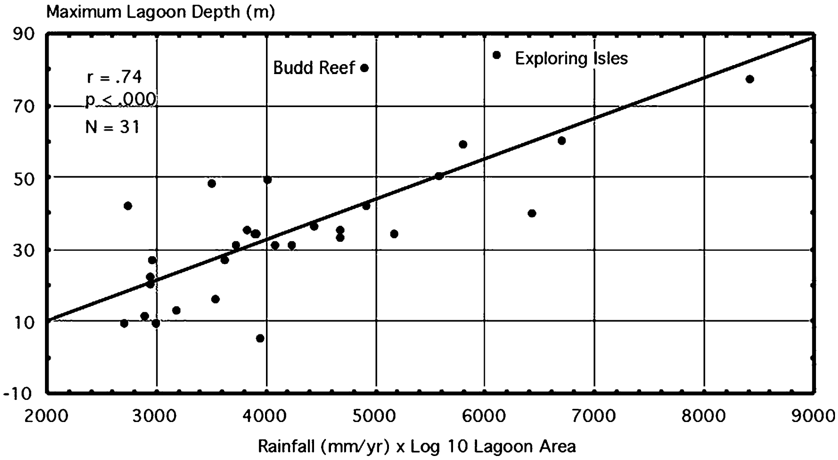


Fig. 7 Graph of catchment rainfall versus maximum lagoon depth for Fiji barrier reef lagoons. The Budd and Exploring Isles statistical outliers are included in the correlation coefficient of 0.74, which is highly significant statistically, $P < 0.000$, even with their inclusion

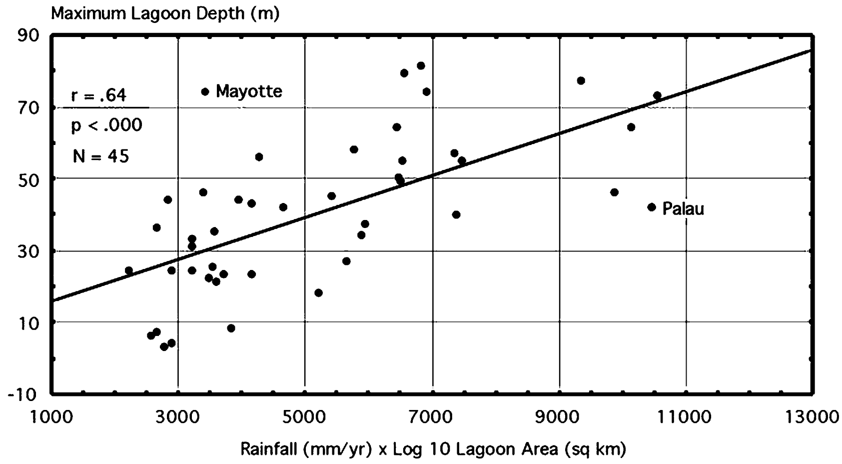


Fig. 8 Graph of catchment rainfall versus maximum lagoon depth for non-Fijian barrier reefs. The correlation coefficient of 0.64 is less than that of Fijian barrier reefs but still highly significant statistically with $P < 0.000$ even though the outlier data points of Mayotte and Palau are included

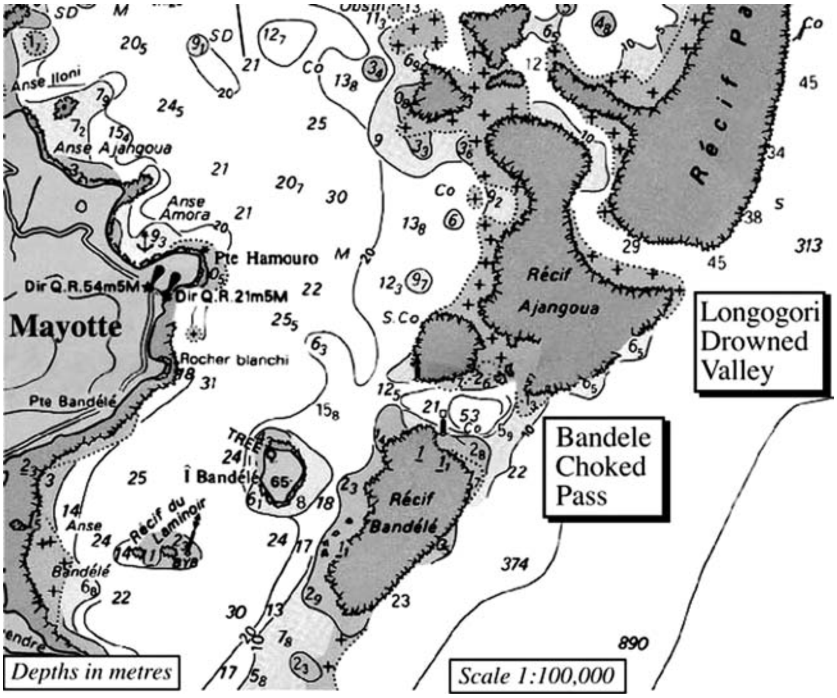


Fig. 9 Barrier reef passes on the eastern side of the volcanic island of Mayotte, Comoro Islands, western Indian Ocean. Modified from British Admiralty Chart 2741. The Longogori pass has depths that increase in a seaward direction and has been interpreted by Guilcher (1988, his Fig. 85) as a drowned Pleistocene valley. In contrast, water depths within the Bandélé pass are similarly deeper than those of the adjoining lagoon but separated from the still deeper water of the open ocean by a shallow rim that is on strike with the barrier reef on either side. The 53 m deep depression within the pass is said to be an expression of karst solution (Bernard Thomassin, personal communication), but there are many examples of partially or completely choked passes that have no distinctive depression immediately lagoonward of the blocked area. In these, the origin of the blocked pass is unknown

to expectations of progressive deepening of the stream channel toward the open sea.

Darwin (1842, p. 100) believed that these passes were inherited from original breaches in fringing reefs adjacent to shoreline drainage and that they became plugged by reef growth as lagoon width increased with subsidence and the fringing reef became a barrier reef. This is difficult to accept because an initially deeper breach should have resulted in a lagoonward depth shift of reef colonization within that breach relative to that of the barrier reef on either side, but this is not the case. The same objection applies to Guilcher's (1988, p. 127) conclusion that reef pass obstructions in some Tahiti examples are simply drowned Holocene reefs developed during the early rise of post-glacial sea level.

Hopley (1982) attributed Great Barrier Reef passes to successive periods of Pleistocene emergence, but suggested that partial or complete blocking of the channels was the result of "rock falls" from the valley sides in a manner similar to that described by Jennings and Sweeting (1963) for the rock falls blocking valleys in the Limestone Ranges of Western Australia. He also suggested that the saddle shaped sills that Veron (1978) described as terminating the seaward edge of passes in the northern part of the Australian Great Barrier Reef might be analogous to the 3 m high calcrete ridges developed on pediments adjacent to channel exits in the Limestone Ranges. The calcrete ridge explanation for the silled passes fails to explain their generally depositional strike coincidence with the barrier reef on either side and additionally would seem to require a semi-arid climate for development (Jennings and Sweeting 1963) that would have to be too widespread globally to be acceptable as a general explanation for similar choked passes elsewhere. Rock falls from lowstand valleys are certainly a possibility, but leave unanswered the question of why such falls should be prevalent at the seaward end of reef passes. Perhaps stress release fractures along valley walls are maximized at the "cliff" edge of the subaerially exposed barrier rim in the manner postulated for valley walls in general by Sasowsky (1998), leading to preferentially located rock falls through fracture solution enhancement and subsequent wave dislodgement of blocks as sea level rose.

Blockage may also result from erosional lowering, and in some cases breaching, of a lowstand subaerial drainage divide that continued on either side of the pass as a higher antecedent surface beneath the modern reef (Purdy 1974). Certainly there are indications of lagoonward directed drainage from the position of a barrier rim, and it does not take much imagination to presume differential erosion and occasional breaching of a rim, no matter what its origin.

There is little doubt that the shoals within the passes and the sills that extend across some of them support a

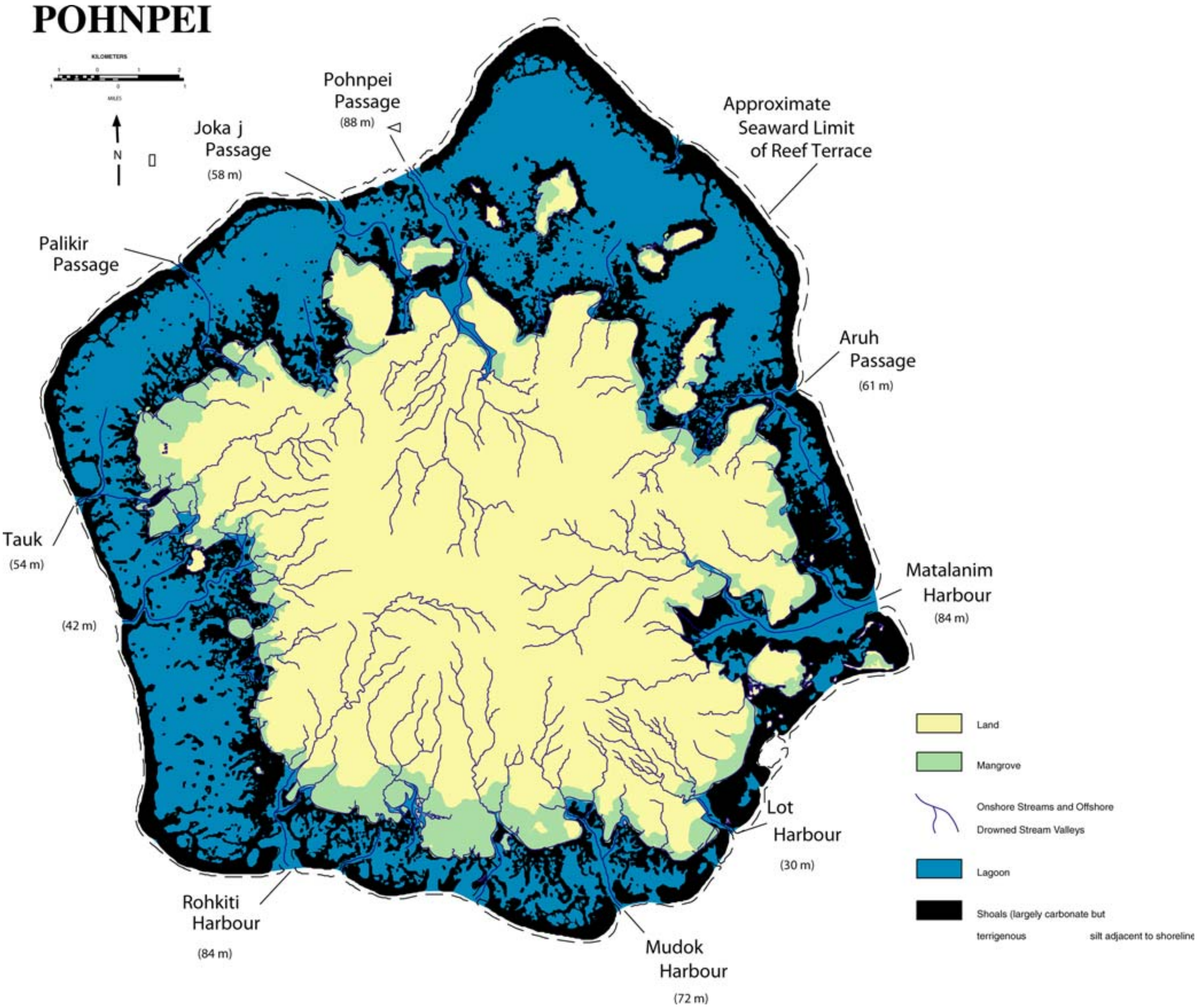


Fig. 10 Association between onshore river drainage and barrier reef passes in the volcanic island of Pohnpei, Caroline Islands. Pass depths are from British Admiralty Chart 981. All other data are based on the exceptional detail recorded in the Pohnpei Coastal Atlas (1985). Maximum land elevation is 790 m. Identified reef pass depth is positively correlated with the $\log_{10}$ area of the associated drainage system of Tables 5 and 5. Note the offshore lagoon drainage between Aruh Passage and Matalanin Harbour that parallels the reef front and seems to reflect tributary drainage development into the main Aruh Passage drainage during glacial low stands of sea level. Note also that not all the river drainage systems are associated with reef passes

rich variety of modern corals, but that in itself does not account for relationships that are suggestive of colonization of antecedent relief.

The Great Barrier Reef exception

Unlike all the other analyzed barrier reefs, the Australian Great Barrier Reef shows no positive correlation between catchment rainfall and lagoon depth. In fact, the opposite is the case (Fig. 12) for the six subdivisions defined by the lateral changes in reef configuration shown in Fig. 13. Additional subdivisions could have been made (e.g., between the Pompey Complex and the Swains Reefs of Fig. 13) but would have made no difference in the results of the analysis. Depth and shelf area both increase toward the south but annual rainfall increases in the opposite direction. Purdy (1974) tried to explain the opposing depth versus rainfall relationship in terms of the marked difference in the amount of land drainage reaching the coast. In the north the main drainage divide is located close to the coast; in the south it occurs at a considerable distance inland (Fig. 13). Correspondingly, no major river discharges into the sea north of the latitude of 19°30′ whereas to the south, the Fitzroy and Burdekin rivers are, respectively, the second and third largest river basins in Australia (Hopley 1982). The point emphasized by Purdy (1974) was that the amount of freshwater reaching the shelf through river discharge was associated with increasing water depth on

Table 5 Reef Pass DataBase

Barrier Reef	Reef pass name	Reef pass depth (m)	Land drainage area (sq km)	Log_{10} land drainage area	Gridded rain (mm/year)	Log_{10} drainage area×rainfall
Moorea	Tareu	50	21.6	1.33	1,547	2,058
	Avorea	42	12.2	1.09	1,547	1,686
	Irikonu	23	6.3	0.80	1,547	1,238
	Valare	23	6.8	0.83	1,547	1,284
	Teruaupu	32	11.4	1.06	1,547	1,640
	Avamotu	25	6.4	0.81	1,547	1,253
Tahiti	Taunoa	46	43.1	1.63	1,532	2,497
	Unamed	50	25.7	1.41	1,532	2,160
	Mahakonu	40	12.8	1.11	1,532	1,701
	Papenoo	67	87.3	1.94	1,532	2,972
	Faaurumai	50	5.4	0.73	1,532	1,118
	Onoheha	72	18.4	1.26	1,532	1,930
	Mahaena	66	36.1	1.56	1,532	2,390
	Unamed	39	8.1	0.91	1,532	1,394
	Tamatoe[a]	91	31.1	1.49	1,532	2,283
	Faaone	33	14.1	1.15	1,532	1,762
	Taharoa	50	8.4	0.92	1,532	1,409
	Teafa	50	30.5	1.48	1,532	2,267
	Vaiau	22	6.2	0.79	1,532	1,210
	Hotumatuu[a]	72	6.7	0.83	1,532	1,272
	Rautirare	50	14.6	1.16	1,532	1,777
	Maraa	41	10	1.00	1,532	1,532
	Paea	20	35	1.33	1,532	2,038
Pohnpei	Pohnpei	86	52	1.72	3,133	5,389
	Aruh	61	4.9	0.69	3,133	2,162
	Matalanin Harbour	84	42	1.62	3,133	5,075
	Lot Harbour	30	10.7	1.03	3,133	3,227
	Mudok Harbour	72	16.1	1.21	3,133	3,791
	Rohkiti	84	24.4	1.39	3,133	4,355
	Unamed	42	15.1	1.18	3,133	3,697
	Tauk	54	17.1	1.23	3,133	3,854

[a] Reef pass outliers greater than 2.0 standard deviations from standardized residuals

the shelf and speculatively overrode the southerly decrease in annual rainfall, thereby accentuating solution relief in a southerly direction during Pleistocene lowstands of sea level.

These interpretations require comment and modification. With one exception the maximum observed depths in the six barrier reef sections consistently occur in the outer-shelf reef complex area and not in the mid-shelf areas that Purdy (1974) thought were analogous to barrier reef lagoons. The exception is the 76 m depth of the Capricorn Channel adjacent to the 64 m depth of the Swains Reefs in the southernmost barrier reef section (Fig. 13). Even so, there is an approximate 30 m increase in outer shelf maximum depth from north to south and this is more likely to reflect subsidence than subaerial solution. Holocene hydro-isostatic subsidence would only account for an approximate 1 m difference in outer shelf subsidence toward the south assuming continental crust lay beneath the shelf (Hopley 1982). The assumption of underlying oceanic crust would increase the amount to perhaps as much as 3 m (Hopley 1982), which still falls far short of the approximate 30 m difference in observed maximum depth. Significantly, Hopley (1982) mentions various indications of additional differential shelf subsidence including the possible occurrence of as much as 20 m of downwarping in the outer shelf area between Cairns and Townsville. He suggests that differential subsidence of various parts of the Great Barrier Reef may be associated with major structural features and may have continued throughout the Quaternary and earlier. Among other things, Hopley (1982) notes the structural continuation of the Cape York Peninsula northward into the area of the Warrior Reefs and cites the occurrence of granite on the Cockburn and Sir Charles Hardy islands (Fig. 13). More speculatively, he notes that the limits of the Pompey Complex are suggestive of structural control and to a lesser extent suggests that this may also be the case for

Table 6 Correlation: Reef pass depth (m) versus rainfall (mm/year) × Log_{10} drainage area (sq km)

Barrier Reef name and No. of Reef passes (N)	Reef pass depth correlation coefficient
Moorea ($N=6$)	0.97 $p<0.002$
Tahiti ($N=17$)	0.40; $p<0.109$
Tahiti ($N=15$)	0.55; $p<0.032$
Pohnpei ($N=8$)	0.73 $p<0.041$
All Reef passes	
$N=32$	0.62; $p<0.000$
$N=29$	0.74; $p<0.000$

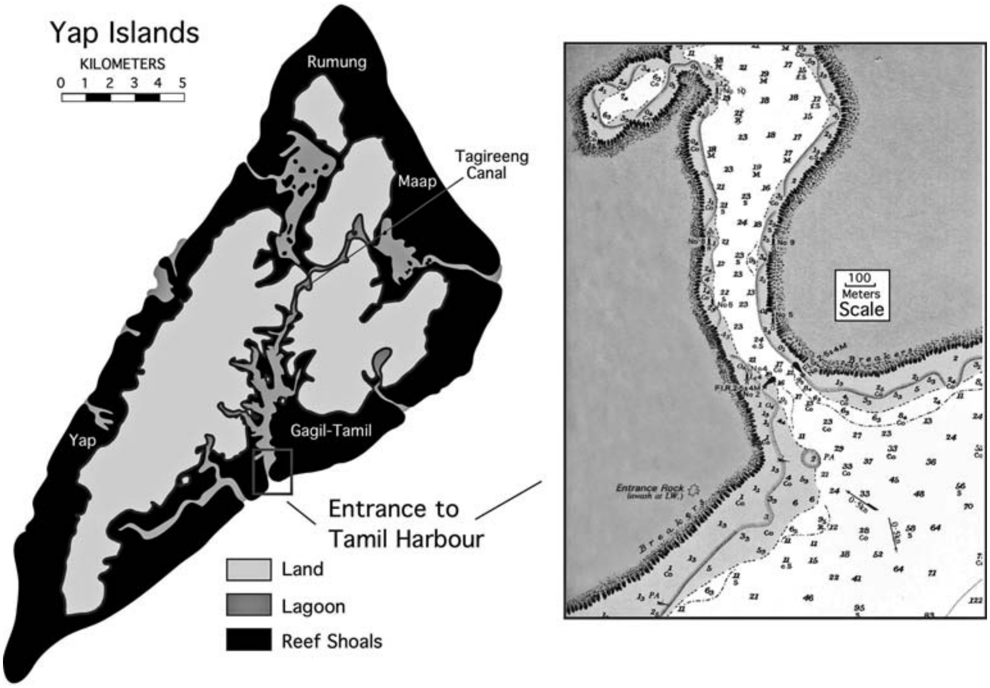


Fig. 11 Yap Islands, Caroline Islands. **a** Distribution of reef shoals and land area of the four main Yap Islands. Modified from British Admiralty Chart 1485. Onshore geology is represented by outcrops of peridotite, greenschist, amphibolite and volcanics with no raised coral reefs. For the most part, the lagoon areas evidence a distinct dendritic drowned valley pattern that is particularly well-displayed in Tamil Harbor. **b** Detailed bathymetry of the entrance to Tamil harbor. Note that the depths in fathoms do not increase progressively toward the open sea, but shoal adjacent to the reef on either side. This suggests that the shoaling phenomenon is post-drowned valley in origin, since otherwise the drowned valley should progressively increase in depth toward the open sea. If the shoaling represents reef occlusion of the pass, it is difficult to understand why that shoaling occurred in the deeper part of the original drowned valley rather than farther upstream at depths comparable to that of antecedent surfaces beneath the reefs on either side of the pass. The adjoining Yap Harbor entrance shows a similar shoaling relationship. The Yap reefs are considered to be fringing reefs or almost-barrier reefs (Tayama 1952); nonetheless choked passes are a common barrier reef attribute, although relationships are seldom as clear as in the Yap example

some of the other reef segments. Consequently, subsidence is probably not completely progressive toward the south. Indeed the shallower 64 m depth of the Swains Reef area compared to the 77 m of the adjacent reef section to the north (Fig. 13) would seem to suggest a depth trend reversal. This possibility is further sup-

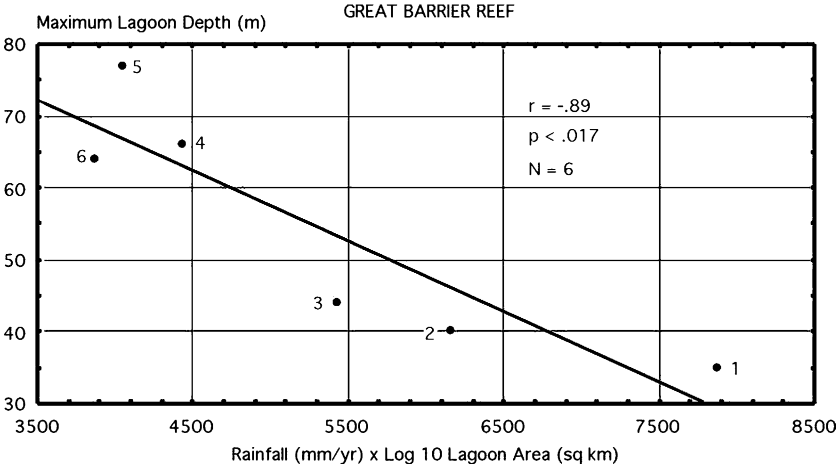


Fig. 12 Graph of catchment rainfall (rainfall in mm per year multiplied by $\log_{10}$ of atoll area) versus maximum lagoon depth for the Great Barrier Reef. The numbers identifying the data points refer to the six subdivisions of the Great Barrier Reef shown in Fig. 13 and are numbered consecutively from north to south. The negative product moment correlation of 0.89 is significant at the 5% confidence level, notwithstanding the limited number of data points. This negative trend contrasts markedly with the positive correlation for the same variables in all the other analyzed barrier reefs (Fig. 6) and results from the contrasting increase in area toward the south and decrease in annual rainfall in the same direction

ported by the moderate Holocene antecedent platform depths reported by Hopley (1982, p. 284) for parts of the Pompey Complex. Even so, the important point from the standpoint of the present analysis is that subsidence is likely to be the major contributory factor in the observed increase in maximum water depth toward the southern end of the Great Barrier Reef. Differential subsidence may have occurred prior to carbonate deposition in the Pleistocene, or possibly even earlier, as a cumulative expression, but in any event was certainly not an exclusive Holocene product as the 30 m of north to south relief difference is too great to be accommodated by known subsidence rates even though differential subsidence may have continued through the Holocene.

Manifestations of solution topography are superimposed on this subsidence expression. In the North, largely unmodified antecedent platforms occur in the generally reefless area immediately to the west of the continuation of the linear pattern of shelf edge reefs north of 15°S (Hopley 1982). These continue northward at least to the approximate latitude of the Great Detached Reef (Fig. 13), where the bottom topography west of the linear shelf edge reefs is said to be reminiscent of undeniably karst-eroded surfaces (Hopley 1982). In the south, blue holes on Molar and Cockatoo reefs (Fig. 13) are classified by Backshall et al. (1979) as collapsed dolines resulting from solution during the last glacial low stand of sea level. Mid-way between these northern and southern examples are the relatively attenuated reef expressions between Truck Reef and Darley Reef (Fig. 13). Here, seismic profiling has been successful in delineating the filled Pleistocene channels of the Herbert and Burdkin Rivers (Johnson and Searle 1984; Fielding et al. 2003). The Burdekin River channel has been traced farthest seaward, becoming progressively smaller as it traverses the outer reef shelf until disappearing over the outermost 10 km of the shelf (Fielding et al. 2003). The preferred explanation offered by Fielding et al. (2003) for the disappearance is that erosion removed channel infill during the initial stages of postglacial transgression. There seems to be circumstantial evidence for a similar seaward disappearance of some of the offshore Belize Pleistocene channels illustrated by Esker et al. (1998). There, the draft of their seismic boat was too great to trace the channels into the shoal waters bordering the barrier reef, but nonetheless the apparent absence of barrier reef passes anywhere in the vicinity would seem to suggest a comparable disappearance. One wonders whether the explanation for these disappearances might be the sapping of channel drainage through underground solution in the underlying carbonate substrate.

Be that as it may, it seems more than a coincidence that the reduction in the areal extent of reef shoals between Truck and Darley reefs (Fig. 13) is associated with the Pleistocene channel drainage of the third largest river basin in Australia. The suggestion is that solution associated with drainage within and into the Burdekin and to a lesser extent, Herbert rivers reduced the areal extent of antecedent relief to something less than that characterizing the adjacent areas and hence offered only limited opportunities for subsequent colonization by reefs.

The important point, however, is that the usual association between maximum lagoon depth and rainfall catchment area apparent in other barrier reefs is negated in the Great Barrier Reef by the controlling influence of subsidence on depth that opposes the direction of increasing annual rainfall. Subsidence is probably also a factor in some of the other large barrier reefs where cross-trends between the two may be less apparent. Differential subsidence may also be a factor in instances in which increases in rainfall and lagoon depth parallel each other, as for example on the Belize shelf (Purdy et al. 2003). These examples of subsidence control on lagoon depth seem to be more obvious in the relatively few large continental crust supported barrier reefs than on the more numerous, smaller oceanic examples. Even so, karst topography is certainly evident in the antecedent topography of the Great Barrier Reef (Fig. 14), although the karst marginal plain concept proposed by Purdy (1972) for the origin of the mid-shelf "lagoon" is untenable and rightly rejected by Hopley (1982) for the reasons cited by him.

Antecedent Depositional Relief

Aggradation

The tendency of carbonates to accentuate antecedent relief is well established, but with the single exception of Tahiti, the less than 25 m thickness of Holocene reefs in Table 7 is insufficient to account for the 36 m and 39 m average depth of atolls and barrier reef lagoons shown in Fig. 2. Moreover, the 17 m and 14 m minimum difference between the two is generally too great to attribute to known rates of Holocene subsidence. Consequently, one is left with the possibility of antecedent erosional or depositional relief or both. The degree of pre-existing antecedent depositional relief is unknown, but certainly a significant amount of erosional relief is demonstrated by the data from some atolls (Purdy and Winterer 2001). The Table 7 Tahiti reef thickness of 90.6 m does not necessarily conflict with this interpretation as that thickness may reflect the fact that Tahiti lies within the cone of flexural subsidence surrounding the growing volcanic load of Mehetia (Dickinson 2001 and personal communication). Alternatively, it may in part represent penetration of prograding deposits with consequent exaggeration of true stratigraphic thickness. The need for seismic geometry in this and other borehole locations is obviously necessary, not only for comparison purposes but also in locating the borehole position likely to provide the maximum amount of significant data.

Holocene reefs, or for that matter reefs in general, are not always localized on positive antecedent relief. There are, for example, pinnacle-like lagoon reefs called "bommies" in the Australian Great Barrier Reef that appear to have no underlying positive antecedent seismic expression (Purdy, personal observation). An explanation for these and other instances of reefs with no apparent antecedent relief control may well be the storm transportation of corals onto substrates inimical to settling by coral planulae larvae but attendant by sufficient light and nutrients to encourage subsequent asexual budding of the transported coral and in so doing to ultimately provide a hard substrate for colonization by other coral and reef contributing organisms (e.g., Highsmith et al. 1980).

It also seems clear that the relatively rapid initial rise of post-glacial sea level would have favored vertical accumulation of carbonates over antecedent shelf-edge topography whereas the slower rates that occurred as sea level approached its present position would have promoted an increased rate of progradation as the limited vertical accommodation space was rapidly filled. It follows from this that the relative importance of antecedent topography in localizing reefs, or for that matter, carbonate facies in general, will be maximized during sea level transgressions but diminished as sea level approaches a still-stand position. It is this phase of facies development that has begun its Holocene expression (see examples cited by Purdy and Bertram 1993).

Arrested vertical accretion during rapid seal level rise as at Barbados (Macintyre et al. 1991) and Hawaii (Webster et al. 2004) leaves drowned reefs.

Progradation

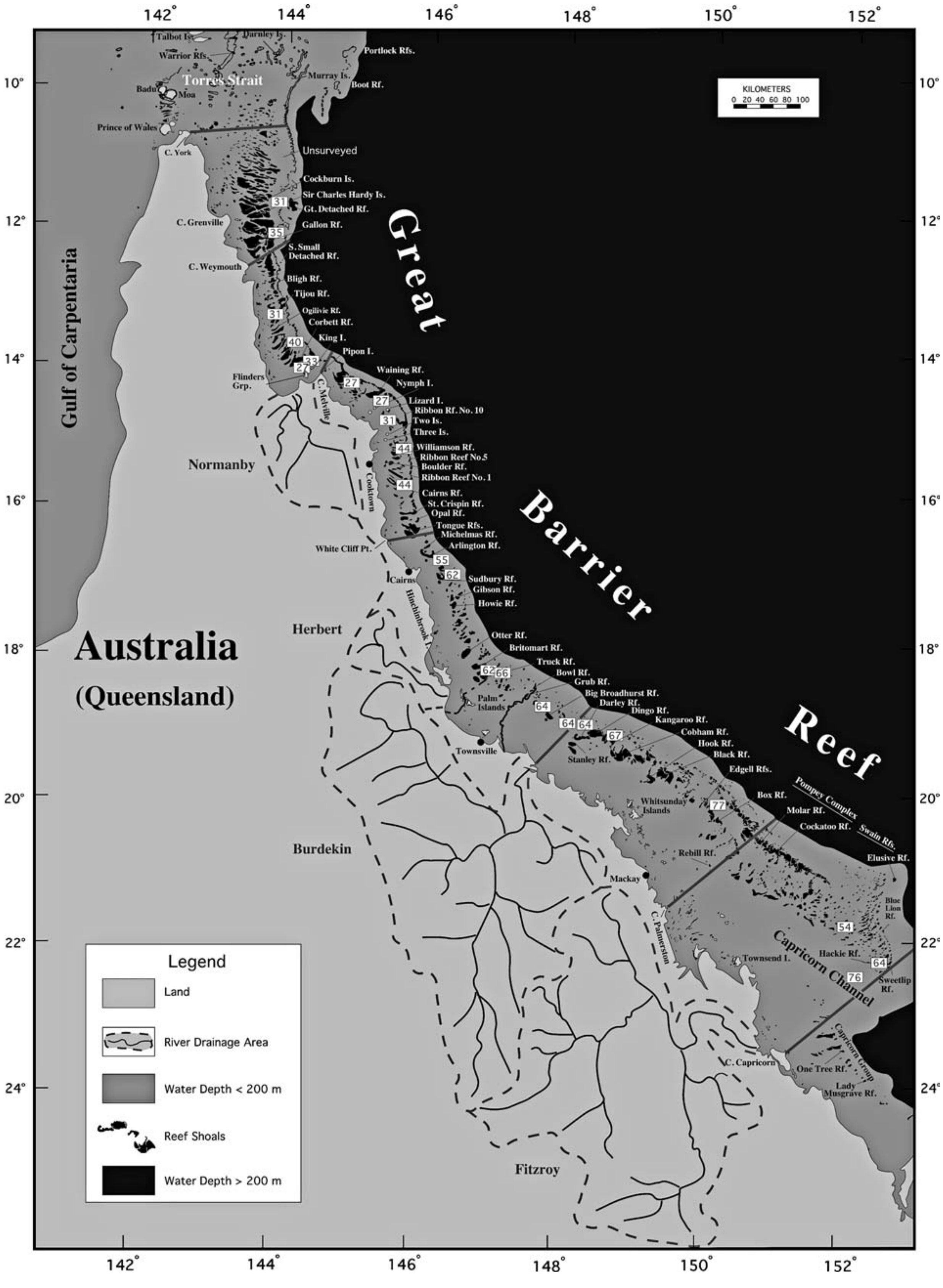
While vertical accentuation of antecedent relief is widely recognized, the significance of lateral filling of the lagoon by reef-derived sediment is sometimes overlooked, perhaps because of the current tendency to regard modern reef lagoons as unfilled accommodation space that will never be filled (e.g., Eberli and Grammer 1996; Gischler 2003). This is a mistaken belief based on the anthropocentric point-of-view that the unfilled lagoons of modern rimmed carbonate platforms are an end-member product rather than a stage in the evolution of a lagoon filling process that is apparent on aerial and satellite photographs of many barrier reefs and atolls. Waves breaking on a reef front create an ephemeral hydraulic head that is dissipated in both a seaward and lagoonward direction with resulting progradation in both a seaward and landward direction. Examples of landward-directed lagoon infilling occur in the Kabira fringing reef of Ishigaki Island, southwest Japan (Yamano et al. 2001), in the Lord Howe, Tasman Sea fringing reef (Kennedy and Woodroffe 2000), and in the Mauritius, Indian Ocean fringing reef (Montaggioni and Faure 1997) as well as in the Hayman Island fringing reef of the Great Barrier Reef (Hopley 1982) and the Hanauma, Oahu, Hawaii fringing reef (Easton and Olson 1976). In most cases, seaward progradation is greater than landward, but in all these cases there is no evidence of widening of the unfilled lagoon separating the island from the fringing reef and therefore no evidence of the initial stage of transition to a barrier reef lagoon. Moreover, it seems clear that the rate of seaward progradation relative to landward would ultimately be slowed down by the increasingly large volumes of sediment that would be required for seaward progradation into progressively greater water depths, thus insuring an eventual greater landward than seaward progradation extent. Admittedly, seaward reef progradation would enlarge the under-water lagoonal area immediately behind it, but it is clear that Darwin (1842) regarded lagoon infilling as diminishing lagoon area.

►

Fig. 13 Great Barrier Reef showing the distribution of reef shoals, river drainage systems and the six subdivisions into which the Great Barrier Reef was subdivided for analysis. Reef shoal configurations were digitized from maps 11c, d and e of Spalding et al. (2001). Onshore river drainage areas were digitized from Maxwell 1968 (his Fig. 12). Subdivision limits are identified by thick black lines and based on the illustrated changes in reef shoal configurations. These are numbered 1–6 from North to South in Fig. 12. Maximum depths in meters are identified by numbers in the general area in which they occur in each of the subdivisions. These depths were taken from Australian Hydrographic charts 367, and 370 through 375. With the illustrated exception of the Capricorn Channel and the 57 m deep channel separating the Cockburn and Sir Charles Hardy reef shoals, all mid-shelf depths are less than those shown for the outer shelf reef shoals. The pattern of mid-shelf shoals in the northernmost subdivision is suggestive of a drowned antecedent shoreline. The occurrence of granite on Cockburn and Sir Charles Hardy islands further suggests the shallow occurrence of non-carbonate antecedent topography. In the succeeding subdivision to the south, water depth deepens and the seaward extent of mid-shelf shoals is attenuated, though still retaining the northern mid-shelf shoal pattern. This pattern is absent from the next adjoining reef subdivision to the south. The offshore paleo-channels of the Herbert and Burdekin rivers are from Johnson and Searle 1984 and Fielding et al. in press, respectively. Note the paucity of shoals in the outer shelf area associated with the position of the paleo-channels and the disappearance of the well-surveyed Burdekin paleo-channel toward the outer shelf edge. The limits of the Herbert and Budekin drainage areas do not correspond to the onshore position of their respective offshore paleo-channels. This may reflect either error in scaling from Maxwell's original figure or possible shift in the position of those divides from the time of formation of the paleo-channels

Problem of coexisting fringing and barrier reefs

Contradictions with subsidence theory expectations are not only presented by the comparable depths of barrier reef and atoll lagoons, but also by the commonplace occurrence of fringing reefs within enclosing barrier reefs (e.g., Figs. 1, 9). Darwin recognized that this was a problem with respect to his evolution of reef types and supposed that these fringing reef occurrences were associated mainly with stationary or rising coasts on the apparently theoretical grounds that otherwise subsidence would have converted them to barrier reefs. He relegated these occurrences of fringing reefs within barrier reefs to periods of sea level stillstand following the subsidence that, theoreti-


142°
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KILOMETERS
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Darnley Is.
Warrior Rfs.
Portlock Rfs.
Torres Strait
Murray Is.
Boot Rf.
Badu
Moa
Prince of Wales
C. York
Unsurveyed
Cockburn Is.
Sir Charles Hardy Is.
31
Gt. Detached Rf.
Gallon Rf.
C. Grenville
35
S. Small Detached Rf.
C. Weymouth
Great
Gulf of Carpentaria
Bligh Rf.
Tijou Rf.
31
Ogilivie Rf.
Corbett Rf.
40
King I.
Pipon I.
33
27
Flinders Grp.
C. Melville
Waining Rf.
27
Nymph I.
27
Lizard I.
Ribbon Rf. No. 10
31
Two Is.
Three Is.
44
Williamson Rf.
Ribbon Reef No.5
Boulder Rf.
Ribbon Reef No. 1
Normanby
Cooktown
44
Cairns Rf.
St. Crispin Rf.
Opal Rf.
Tongue Rfs.
Michelmas Rf.
Arlington Rf.
White Cliff Pt.
Barrier
55
62
Cairns
Sudbury Rf.
Gibson Rf.
Howie Rf.
Hinchinbrook I.
Herbert
Otter Rf.
Britomart Rf.
Australia
(Queensland)
Truck Rf.
62
66
Bowl Rf.
Grub Rf.
Big Broadhurst Rf.
Palm Islands
Darley Rf.
64
Dingo Rf.
Kangaroo Rf.
64
64
67
Cobham Rf.
Hook Rf.
Townsville
Stanley Rf.
Black Rf.
Reef
Edgell Rfs.
Whitsunday Islands
77
Box Rf.
Pompey Complex
Molar Rf.
Cockatoo Rf.
Swain Rfs.
Burdekin
Rebill Rf.
Elusive Rf.
Mackay
Blue Lion Rf.
C. Palmerston
54
Capricorn Channel
Hackie Rf.
Townsend I.
64
76
Sweetlip Rf.
Capricorn Group
C. Capricorn
One Tree Rf.
Lady Musgrave Rf.
Fitzroy
Legend
Land
River Drainage Area
Water Depth < 200 m
Reef Shoals
Water Depth > 200 m

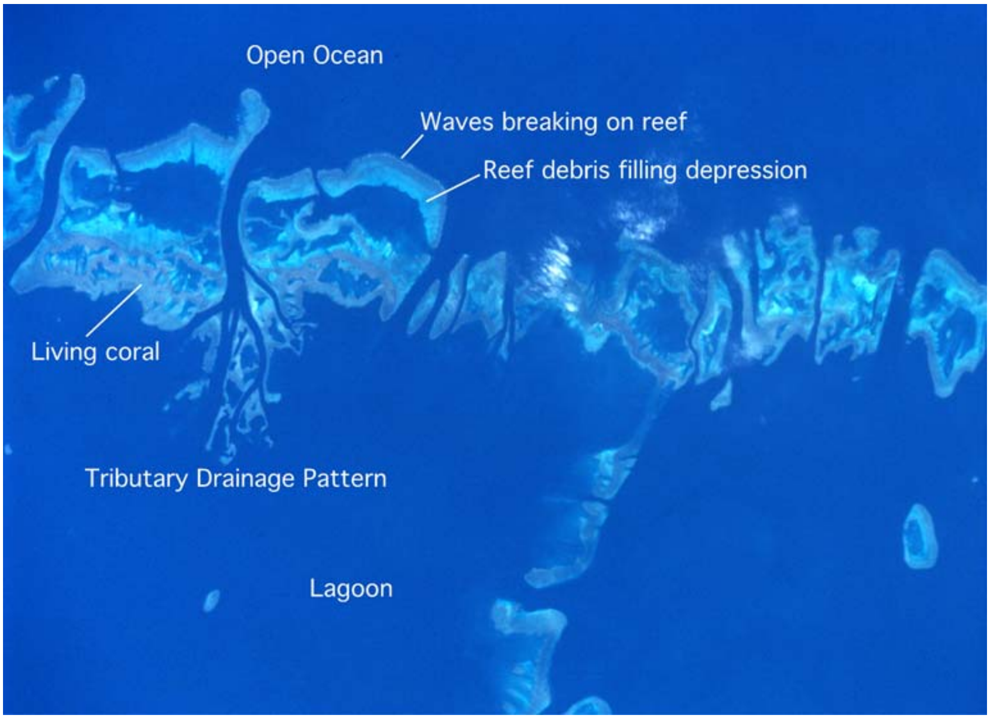

Fig. 14 Modified astronaut photograph of the "hard line" Pompey Reef Complex, Great Barrier Reef (Image STS111_STS11 Courtesy of Earth Sciences and Image Analysis Laboratory NASA Johnson Space Center). Hard line refers to that part of the Pompey Reef Complex that faces the open ocean. Tributary drainage pattern apparent on the left side of the illustration is highly suggestive of antecedent drainage developed during glacial low stands of sea level from the shallower lagoon toward the deeper open sea. Maxwell (1968) interpreted such features as constructional rather than destructional in origin, but the obvious drainage pattern as well as the occurrence of a drowned blue hole doline in the adjacent Pompey Complex Cockatoo Reef (Backshall 1979) makes this seem unlikely (see Fig. 13 for location relationships). Reddish-brown areas are living coral. The bathymetric depressions apparent within the separate carbonate platforms are currently being filled in largely from reef-derived debris transported by waves breaking on the reef front. These depressions also seem logically attributed to antecedent morphology; otherwise, why would reefs grow in such a pattern

cally, had transformed the initial fringing reef into the enclosing barrier reef. Steers and Stoddart (1977) refer to Darwin's interpretation of the occurrence of fringing reefs within barrier reefs as second-generation fringing reefs. Table 7, however, demonstrates, that there is no appreciable difference between the thicknesses of fringing reefs within barrier reefs (e.g., Australia and New Caledonia) relative to those that are not so enclosed (e.g., Mauritius and Hawaii). Consequently, these fringing reef thicknesses are difficult to explain within the framework of the Darwinian subsidence model because they necessitate a subsidence rate, or alternatively, a rising sea level rate, that was never great enough in the Darwinian sense to create the wider lagoon of a barrier reef.

The faster rate of Holocene sea level rise relative to the rate of subsidence also poses problems for the theoretical transformation of fringing reefs into barrier reefs. Compare for example, the fast rate of subsidence of 5 cm/ka postulated by Hein et al. (1997) for Rakahanga Atoll, Cook Islands with the approximate 600 cm/ka average calculated from the Bard et al. (1990) or Lambeck et al. (2002) sea level curve for the last deglaciation. The rate of lagoon infilling would presumably be greater if subsidence were the only factor in creating accommodation space because of the greater amount of time available for lateral filling of lagoon space relative to that of filling the vertical accommodation space created by subsidence. Consequently, the absence of evidence of fringing reef lagoons widening to become barrier reef entities during the relatively fast Holocene sea level rise would seem to demonstrate the inadequacy of the subsidence theory to produce the desired vertical transition of fringing reefs to barrier reefs.

Another difficulty for the subsidence theory is the frequent transformation of barrier reefs into fringing reefs around the same island. For example, in the Caroline island of Palau, an east coast fringing reef is zreplaced by a barrier reef along the west coast of the several islands. Davis (1928) viewed this as a reflection of "gentle tilting", but later work by Easton and Ku (1980) casts doubt on this interpretation by concluding that the series of blocks underlying the islands have only moved independently of each other in a vertical sense. Even so, there are instances in which independent evidence of tilting does approximate the plan-view transition between barrier and fringing reefs around the same island. One such example is recorded by Nunn (1994, p. 237, and his Fig. 7.5b) for the Fiji island of Gau.

Table 7 Holocene Fringing Reef, Barrier Reef and Atoll Rim thickness comparisons

Fringing Reef	Thickness (m)	Reference
Mauritius	19.3	Montaggioni and Faure (1997), Fig. 4
Reunion	> 19.3	Camoin et al. (1997), Fig. 2
Ryukyu Islands		
Okierabu Island	11.0	Kennedy and Woodroffe (2002), Fig. 12
Kume Island	11.0	Kennedy and Woodroffe 2002, Fig. 13
Kikai Island	18.0	Kennedy and Woodroffe (2002), Fig. 14
Australian Great Barrier Reef		
Hayman island	20.0	Hopley (1982), Fig. 12.6
Orpheus Island	6.7	Hopley (1982), Fig. 12.7
Fantome Island	12.0	Kennedy and Woodroffe (2002), Fig. 5
Coolgaree Bay, Great Palm Island	1.5–2.7	Hopley (1982)
Hammond Island, Torres Strait	6.0	Kennedy and Woodroffe (2002), Fig. 6
Lord Howe Island, Tasman Sea	> 10.0	Kennedy and Woodroffe (2002), Fig. 10
New Caledonia		
Ricaudy	3.0–6.0	Cabioch et al. (1995), Table 2
Tara	8.5	Cabioch et al. (1995), Table 2
Mamié-Ounia	7.0	Cabioch et al. (1995), Table 2
Thio	4.8	Cabioch et al. (1995), Table 2
Poindimié	5.5	Cabioch et al. (1995), Table 2
Popuébo	3.0–11.0?	Cabioch et al. (1995), Table 2
Poum	3.5	Cabioch et al. (1995), Table 2
Poya	13.5	Cabioch et al. (1995), Table 2
SW Espirito Santo, New Hebrides	20.0–25.0	Cabioch et al. (1998)
Hanuama Bay, Hawaii	14.0 (core 10)	Easton and Olson (1976), Fig. 3
Punta Islotes, Golfo Dulce, Costa Rica	2.5–9.0	Macintyre et al. (1994), table 1
Galeta Point, Panama	1.0 (core 5)–14.3 (core 11)	Macintyre and Glynn (1976), Fig.4
Curacao & Bonaire, Netherlands Antilles	> 16.0	Focke (1978)
	Range: 2.5–25.0	
	Mean: 10.9 ($N=29$)	
Barrier Reef		
Mayotte, Comoro Archipelago	21.4	Camoin et al. (1997), Fig. 2
Palau, Caroline Islands	14.6	Kayanne et al. (2002), Fig.3
New Caledonia Amédée	14.0	Cabioch et al. (1999),
Aitutaki, Cook Islands	10.0	Hein et al. (1997), Fig. 16-4
Papeete, Tahiti	90.6 (P8 core)	Camoin et al. (1999), Fig. 3
Central and Southern Belize	5.0 to > 22.0	Gischler (2002), unpublished data
	Range < 5.0 to > 22.0	Excludes Tahiti
	Mean: 14.5 ($N=6$)	Excludes Tahiti
Atoll		
Cocos Keeling, E. Indian Ocean	15.6	Searle (1994)
Enewetak, Marshall Islands	15.0	Wardlaw and Quinn (1991); Buddemeier and Oberdorfer 1997
Pukapuka, Cook Island	23.0	Hein et al. (1997), Fig. 16-5
Rakahanga, Cook Islands	20.0	Hein et al. (1997), Fig. 16-6
Mururoa, French Polynesia	15.0	Buigues (1997)
Turneffe, Belize	3.8	Gischler and Hudson (1998)
Lighthouse Reef, Belize	7.9	Gischler and Hudson (1998)
Glovers Reef, Belize	11.7	Gischler and Hudson (1998)
	Range: 3.8–23.0	
	Mean = 14.0 ($N=8$)	

Reef crest (core 5) to fore reef (core 11)

Nonetheless, it beggars belief to attribute the many worldwide examples of this transition to tilting. An equally plausible explanation is lateral relief variability of the underlying pre-Holocene substrate.

Outcrop solution analogue of Barrier Reef morphology

Glacial lowstands of sea level would have eroded the infilled edge of the barrier reef lagoon to some extent. The vehicle for this erosion would seem to be mainly mainland runoff that was not directed into the valleys that subsequently became reef passes. In this regard, the work of Stoddart et al. (1985) on the Cook island of Mangaia is particularly enlightening. The island consists of an elevated rim of reef limestone surrounding a higher central volcanic core (Fig. 15). The inner slopes of the carbonate rim facing the volcanics are essentially vertical and up to 60 m high (Stoddart et al. 1985). Drainage from the volcanic core terminates as swamps at the foot of the cliffs and there are no through-going stream passages through the rim. Water passage through the rim occurs in the form of conduits, some of which make the inner rim slope resemble a giant slab of Swiss cheese (Stoddart et al. 1985, their Fig. 6). Natives on the less steep outer seaward slope of the rim wash their clothes in the fresh water passing through the conduits. A number of lines of evidence convinced Stoddart et al. (1985) and Dickinson (1998) that the limestone topography is erosional rather than constructional. Among the more important erosional indications were: (1) limestone outliers on the volcanics that are separated by erosion from the rim; (2) thick volcanic soils on the surface of the limestone that must have predated the development of the positive relief on which they are found and (3) deep karst dissection of the upper surface of the rim (Stoddart et al. 1985). Aerial photographs (Wood and Hay 1970; Dickinson 1998) and a satellite photograph (ISS002-ESC2-9925) provide further evidence of erosion in that the limestone rim can be seen to consist of a series of seaward-added increments in which the separating surfaces are clearly truncated in places by the inner rim slope. These separating surfaces presumably represent the steeply seaward dipping limestone joints that Stoddart et al. (1985) suggested might be depositional in origin.

With these relationships in mind, it would seem reasonable to suppose that erosion during glacial low stands of sea level not only attenuated the lagoonward depositional limit of lateral lagoon infilling but also allowed the passage of large amounts of mainland drainage through the infilled lagoon sediment to the open sea via solution conduits. The amount of such drainage would be dependant upon the volume of mainland drainage discharged into the open sea via the subsequently drowned valleys that became reef passes.

The Role of Subsidence

Volcanic islands subside very rapidly when they are young and still adding to their height. During this stage, the lithosphere flexes isostatically under the load. The rate and amount of flexing is a function of the flexural rigidity of the lithosphere (soft when young, stiff when old) and the size of the load. Under the large accumulating load of Hawaii, for example, the present rate of subsidence is about 2.5 mm/year (Ludwig et al. 1991). After the end of up-building, the volcano subsides because of the cooling of the lithosphere, generally at a much lower rate, of the order of 0.1 mm/year. In neither case is the rate of subsidence sufficient to drown acroporid dominated reefs in which the maximum growth rate approximates 8 to 15 m/ka (Adey 1978). In contrast, measured Holocene pulses of glacially controlled sea level rise is as much as 20 m/ka (Purdy and Bertram 1993, their Fig. 22), clearly outstripping maximum reef accumulation rates With this in mind, it seems clear that the chief role of subsidence is in providing a continuum of vertical accommodation space that accounts for the thickness of carbonate deposits and further that that this thickness is modified by variations in glacially controlled sea level that alternately magnify and reduce subsidence accommodation space.

For example, consider a volcanic island with slopes of 15°. At a distance of 1.5 km from the shore, the depth of the volcanics would be approximately 400 m, much too deep for the 10–20 m depth limit of reef development and yet many oceanic barrier reefs lie at distances greater than this. Given an interglacial high stand of sea level, however, a fringing reef surrounding the volcanic island, could, and indeed would prograde in both a seaward and landward direction. The result would be a carbonate platform extending essentially from the shoreline to the former depth of 400 m. Progradation into water depths of this magnitude is not hypothetical in that it occurs on a large scale in the Maldives (Purdy and Bertram 1993). Moreover, the extent of progradation may not be a single event phenomenon but may be composite, representing more than one nucleus of seaward extension. Additionally, reefs may not be involved, as demonstrated by some of the Lau Fiji limestones, although reefal platform expansion would certainly seem to be the norm.

Sea level low stands would result in the subaerial exposure of limestone platforms with attendant solution modification by rainfall and runoff from the volcanic island. Mainland drainage not ponded on the platform would find its way to the deep sea through subsequently drowned valleys opposite the main mainland streams. Carbonate platforms, would develop again during the following sea level rise, the seaward extent of the platform being dependant upon the extent of seaward progradation. The subsidence continuum, however, would insure that the optimum 10–20 m depth range for shallow water and/or reefal carbonate production would consistently shift landward. The extent of the shift could be appreciable. In the case of the 2.5 mm/year subsidence rate, the increase in water depth would be 250 m for the approximate 100 ky duration of a glacial-interglacial cycle. For the slower 0.1 mm/year subsidence rate, the increase in water depth over the same time period would be only 10 m. In both cases the water depth over the edge of the previous carbonate platform would have increased beyond the 10–20 m limit for reef development and consequently the location of that optimum would have shifted landward. The extent of the landward shift would obviously be intermediate between these two subsidence rate extremes, but in all cases the result would be a back-stepping staircase of drowned carbonate platforms with associated barrier reefs, each barrier reef drowned in turn as sea level rose on the next deglaciation. In the case of Hawaii, the staircase descends to about 1,400 m subsea where it is about 700 ka old with the youngest drowned platform succeeded by the current fringing reefs (Clague et al. 2002).

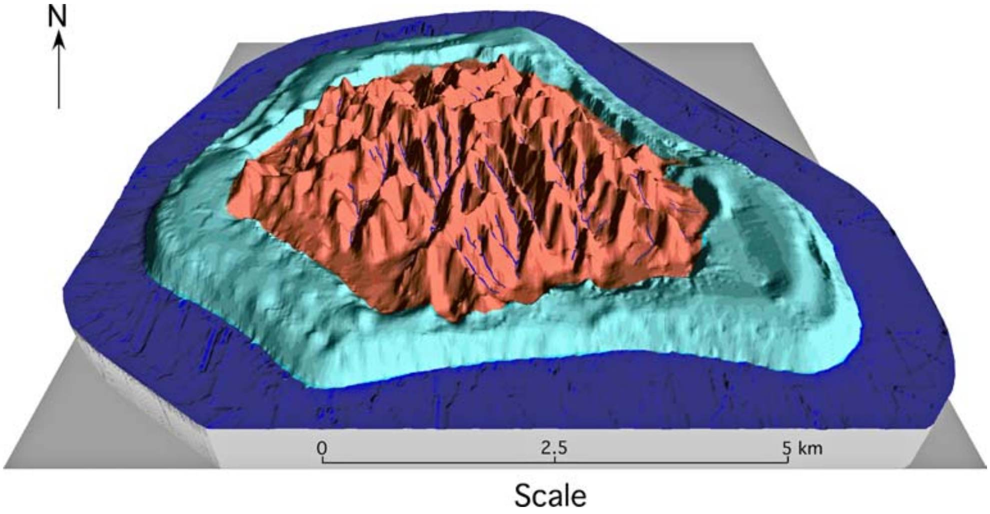

Fig. 15 Topography and geology of the island of Mangaia, Cook Islands, based on the topographic contour relief of a 1986 New Zealand Department of Lands and Survey map and the geology recorded by Stoddart et. al. (1985, their Fig. 2) The centrally located basalts are colour-coded reddish-brown and have a maximum height of 169 m. The maximum height of the surrounding limestone is 70 m. Five K–Ar determinations provide an age range of 16.6 ± 0.2 to 18.9 ± 0.7 Ma (*fide* Stoddart et al. 1985). Surrounding the volcanics is a rim of limestone dated paleontologically as Oligocene to Miocene in age (*fide* Stoddart et. al. 1985). The absence of volcanic debris within the limestone in conjunction with the age determinations of the basalts, however, suggests a limestone age that is probably no older than Miocene (Stoddart et al. 1985). The rim itself has steep cliffs that are as much as 60 m high facing the volcanics and these slopes descend locally into swamp depressions fed by the streams draining the volcanics. There are no stream valleys through the rim. Instead, water draining the volcanics finds its way into the open ocean through innumerable limestone conduits (Stoddart et. al. 1985). Not illustrated are the erosional outliers of limestone that apparently occur in places on the volcanics. These, together with other evidence, convinced Stoddart et al. (1985) and Dickinson (1998) that the rim constituted an erosional remnant rather than the fossilized reef lagoon morphology that had been assumed by other workers. Additional confirmation of that conclusion is provided by a satellite photograph in which lines of separation within the rim, that are presumably bedding planes, can be seen to be truncated by cliff development. It requires no great stretch of the imagination to see that submergence of the Mangaia rim would transform an erosional topography into typical barrier reef morphology

Over the past ca. 800 ky, eustatic sea level has fluctuated up and down by about 100 m every 100 ky, but prior to that time, sea level fluctuations were at a dominant frequency of only about 40 ky, and of considerably less amplitude. The implication is that the height and distance between the lowermost "steps" of the drowned platforms should decrease and shorten, respectively, relative to those that follow. It remains to be seen whether this theoretical conclusion is verified by future information.

Given a constant amount of carbonate production, volcanic slopes lower than 15 degrees would result in further seaward extension of prograding carbonates, and conversely. Given a constant volcanic slope, older volcanic islands have a greater chance of seaward progradation and consequently a greater probability of having a larger lagoon, other factors being equal. With this in mind, the difference between volcanic islands with fringing reefs as opposed to similar aged islands with barrier reefs should reflect differences in volcanic slope. Whether or not this is the case remains to be demonstrated by seismic reflection techniques. Regardless of this point, the essential role of subsidence is in determining the thickness of carbonate caps. The back-stepping geometry of the drowned deposits results from the interaction between continued subsidence and glacially induced variations in sea level accommodation space.

Conclusions

The subsidence theory is elegant in its simplicity in explaining the presumed genetic association of fringing reefs, barrier reefs and atolls, but is based on the unproven assumption that the combination of subsidence and reef growth can produce this succession of reef types. More importantly, it ignores the influence of glacially-controlled fluctuations of sea level that were unknown to Darwin. Part of the supposed transition is disproved in the Maldives where subsurface evidence demonstrates that the modern atolls were not preceded by a barrier reef stage of development (Purdy and Bertram 1993). Moreover, outcrop evidence indicates that subaerial solution has produced atoll-like morphology in a number of the Fiji Lau Archipelago islands (Ladd and Hoffmeister 1945; Nunn 1994; Ferry et al. 1997) and has also produced barrier reef-like morphology in the Cook Island of Mangaia (Stoddart et al. 1985). There is also the evidence that maximum lagoon depths of both atolls (Purdy and Winterer 2001) and barrier reefs (this paper) are a function of rainfall catchment area, implicating solution as a causal agent. Additionally, the depth of some barrier reef passes is positively correlated with the onshore rainfall catchment area of adjacent river systems. In all these instances the importance of solution in creating antecedent Holocene relief is strongly indicated. Nonetheless, the solution rates reported by Purdy and Winterer (2001) are insufficient to have produced the observed lagoon depths of either barrier reefs or atolls in the time available for subaerial exposure during the last glacial low stand of sea level. Similarly, the well-know ability of carbonate deposition in general and reef deposition in particular to accentuate antecedent topography seems insufficient to account for the relief of reef rims relative to overall lagoon depths in most instances, although here it must be noted that the data available are limited (Purdy and Winterer 2001). Collectively, these attributes lead to the conclusion that existing lagoon relief is a product of more than one glacial stage of subaerial exposure and submergence. Subsidence has determined the thickness of the carbonate caps, which include multiple stages of subaerial exposure, but it is the combination of antecedent solution and deposition that has produced the overall relief of reef lagoons, including not only those of barrier reefs and atolls but also some fringing reefs.

It is an interesting paradox that the great number of atolls and barrier reefs in existence today stands in marked contrast to their relative scarcity in the geologic record. Part of the reason may be the necessity of having repeated glacial fluctuations of sea level to produce the observed patterns. But even more important would seem to be the fact that the large majority of present-day atolls and barrier reefs occur on Pacific subsiding volcanic foundations that are slated to disappear in subduction zones. Perhaps this is the reason that barrier reefs, and particularly atolls are rare in the geologic record compared to their abundance today.

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