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Response of coral reefs to climate change: expansion and demise of the southernmost Pacific coral reef

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Abstract

Coral reefs track sea level and are particularly sensitive to changes in climate. Reefs are threatened by global warming, with many experiencing increased coral bleaching. Warmer sea surface temperatures might enable reef expansion into mid latitudes. Here we report multibeam sonar and coring that reveal an extensive relict coral reef around Lord Howe Island, which is fringed by the southernmost reef in the Pacific Ocean. The relict reef, in water depths of 25-50 m, flourished in early Holocene and covered an area more than 20 times larger than the modern reef. Radiocarbon and uranium-series dating indicates that corals grew between 9000 and 7000 years ago. The reef was subsequently drowned, and backstepped to its modern limited extent. This relict reef, with localised re-establishment of corals in the past three millennia, could become a substrate for reef expansion in response to warmer temperatures, anticipated later this century and beyond, if corals are able to recolonise its surface. Citation: Woodroffe, C. D., B. P. Brooke, M. Linklater, D. M. Kennedy, B. G. Jones, C. Buchanan, R. Mleczko, Q. Hua, and J. Zhao (2010), Response of coral reefs to climate change: Expansion and demise of the southernmost Pacific coral reef, Geophys. Res. Lett., 37, L15602, doi: 10.1029/2010GL044067.

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Response of coral reefs to climate change: Expansion and demise of the southernmost Pacific coral reef

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[1] Coral reefs track sea level and are particularly sensitive to changes in climate. Reefs are threatened by global warming, with many experiencing increased coral bleaching. Warmer sea surface temperatures might enable reef expansion into mid latitudes. Here we report multibeam sonar and coring that reveal an extensive relict coral reef around Lord Howe Island, which is fringed by the southernmost reef in the Pacific Ocean. The relict reef, in water depths of 25–50 m, flourished in early Holocene and covered an area more than 20 times larger than the modern reef. Radiocarbon and uranium-series dating indicates that corals grew between 9000 and 7000 years ago. The reef was subsequently drowned, and backstepped to its modern limited extent. This relict reef, with localised re-establishment of corals in the past three millennia, could become a substrate for reef expansion in response to warmer temperatures, anticipated later this century and beyond, if corals are able to recolonise its surface.
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1. Introduction

[2] Coral reefs occur in shallow water with sea surface temperatures (SST) greater than 18°C, extending beyond the tropics where warm currents enable establishment [*Hopley et al.*, 2007]. The southernmost reef in the Pacific Ocean fringes 6 km on the western margin of Lord Howe Island (31° 30′S), with isolated reef patches to north and east. The island is a Miocene volcanic remnant on the western flank of the Lord Howe Rise (foundered continental crust). Basaltic cliffs rise to 875 m, flanked by Quaternary eolianites [*McDougall et al.*, 1981]. The reefs support 50–60 scleractinian coral species, whose rates of growth are only slightly slower than in more tropical locations [*Harriott and Banks*, 2002]. However, carbonate sediments with temperate biota, such as foraminifera and algal rhodoliths, dominate the surrounding shelf [*Kennedy et al.*, 2002]. A broad ridge-like feature, rising from water depths of 30–50 m, is prominent in mid shelf and represents a relict coral reef that formerly encircled the island [*Woodroffe et al.*, 2005, 2006]. We describe sonar swath mapping to determine the extent of the reef, and coring and dating that establishes its age and demise.

2. Methods

[3] Seabed topography was determined by sonar mapping using a Kongsberg Simrad EM 300 30 kHz multibeam echo sounder aboard *RV Southern Surveyor* in 2008 (voyage SS06). The sonar frequency of the system is 30 kHz, with signal resolved into 135 beams, corrected for vessel heave, roll and pitch. Vertical resolution is ± 0.2 m, with horizontal resolution of ± 5 m. High resolution data were acquired over the entire relict reef, but were supplemented with single-beam echosounder, and Laser Airborne Depth Sounder (LADS), data across the lagoon and the Admiralty Islands to the northeast, where the vessel could not be operated. Bottom sediments were examined using a Smith-Macintyre grab sampler and a Topas PS18 parametric 1.5 kHz acoustic sub-bottom profiler [*Brooke et al.*, 2010].

[4] Composition of the relict reef was determined from short cores of 75 mm diameter recovered using a submersible rock drill lowered from the research vessel. The deepest core penetrated 2.72 m into reef limestone, with 1.2 m recovery. Samples of faviid coral and mollusc were selected for accelerator mass-spectrometry (AMS) radiocarbon dating at the Australian Nuclear Science and Technology Organisation (ANSTO) with a precision of 0.5–0.6%. Samples were cleaned, oven-dried, hydrolysed to CO_2, and then converted to graphite using the H_2/Fe method [*Hua et al.*, 2001]. Thermal ionisation mass-spectrometry (TIMS) uranium-series dating of older samples at the University of Queensland followed analytical procedures described by *Zhao et al.* [2001], except that a known $^{236}U/^{233}U$ ratio in a ^{229}Th-^{233}U-^{236}U mixed spike was used for mass fractionation correction. $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ activity ratios of samples were normalised and ages calculated using half-lives of 75,380 years (^{230}Th) and 244,600 years (^{234}U). Mineralogy of samples was established by X-ray diffraction. All those submitted for AMS dating were >98% aragonite. Traces of calcite were detected in some material used for TIMS analysis, but only those with >92% aragonite were dated. Initial $^{234}U/^{238}U$ values of samples are close to those of seawater and pristine coral, and their ^{230}Th ages are not significantly affected by this minor diagenesis. Paired TIMS and AMS ages for two samples enabled determination

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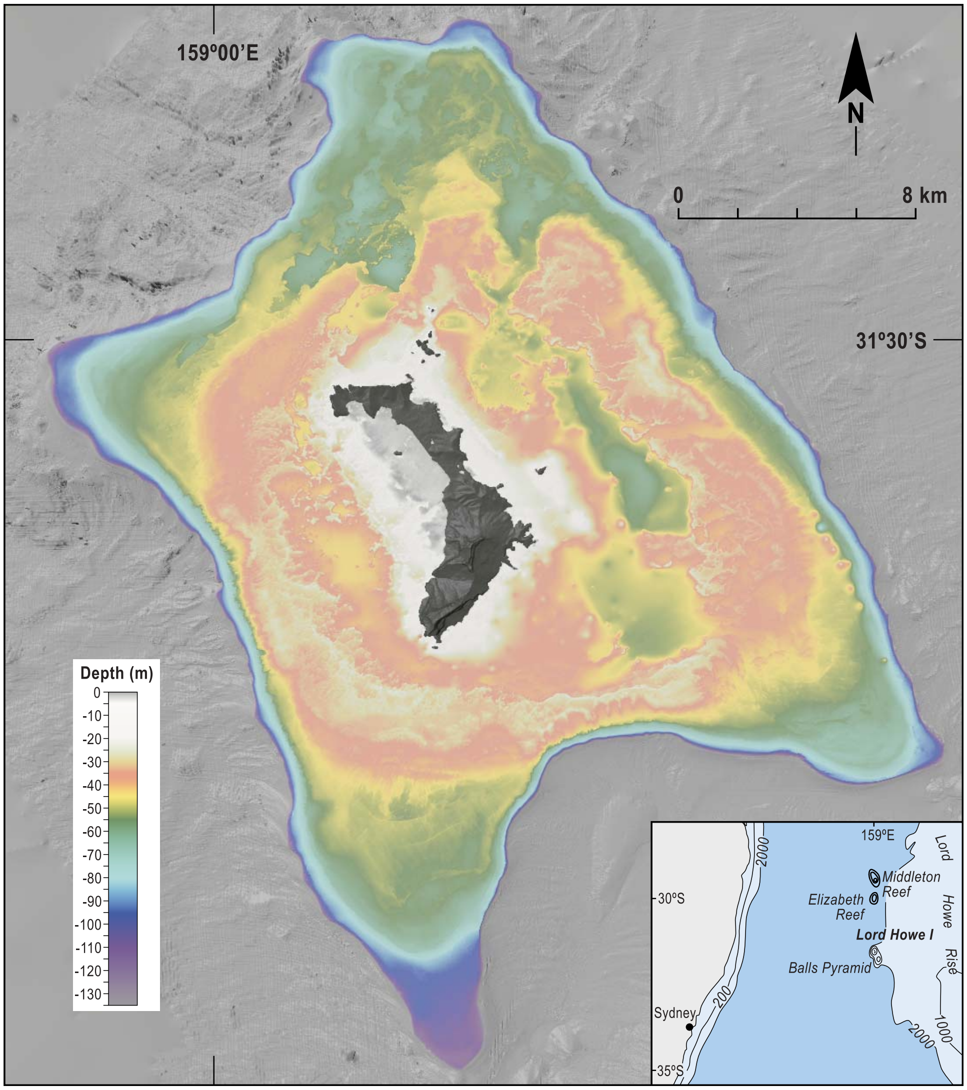

Figure 1. Digital terrain model of the shelf around Lord Howe Island, showing the relict reef compiled from multibeam sonar supplemented inshore by other data sources [see *Brooke et al.*, 2010].

of a ΔR value of −11 ± 39 yrs used to calibrate radiocarbon ages (with Marine04 data using CALIB 5.01), and TIMS and AMS ages are reported in years prior to 1950 AD (cal BP).

3. Relict Reef Morphology

[5] Figure 1 shows 3-dimensional morphology around Lord Howe Island, mapping the relict reef based on multibeam sonar. The shelf around Lord Howe Island comprises three zones: outer shelf (55–70 m water depth); relict reef (rising from 50 m depth with an upper surface, encrusted by coralline algae at 24–40 m depth); and inner shelf (~40–50 m depth, with sandy substrate and sedimentary reflectors in sub-bottom profiling). The reef ranges between 0.5 and 5.8 km wide; it lies close to land to the northeast, but its steep inner flank lies >6 km offshore to the east. It has an area of at least 145 km^2, covering 28% of the shelf. Three former reef passages dissect north, northeast and eastern margins, and prominent spur and groove features indicate the southern margin was exposed to considerable wave energy.

4. Stratigraphy and Chronology of Relict Reef

[6] Six rotary drill cores were recovered from water depths of 24 to 34 m (Figure 2), penetrating almost 3 m into the relict reef, with variable recovery. Cores contain corals and molluscs, in a matrix of coralline algae. Visual description of cores 13, 14, 21 and 22 indicated reddish-brown discoloration, micritization, borings and cavities in the lower sections characteristic of interglacial limestone. However, TIMS and AMS dates indicate that the major phase of growth was early Holocene (Tables 1 and 2). A hiatus in reef growth occurred during mid-Holocene in several cores, with some late Holocene re-establishment of coral, especially at site 15 (34 m water depth).

[7] The extensive relict reef underwent significant vertical accretion during the early Holocene. A TIMS age of 9079 ± 52 cal yrs BP on coral in core 22, from a depth of almost

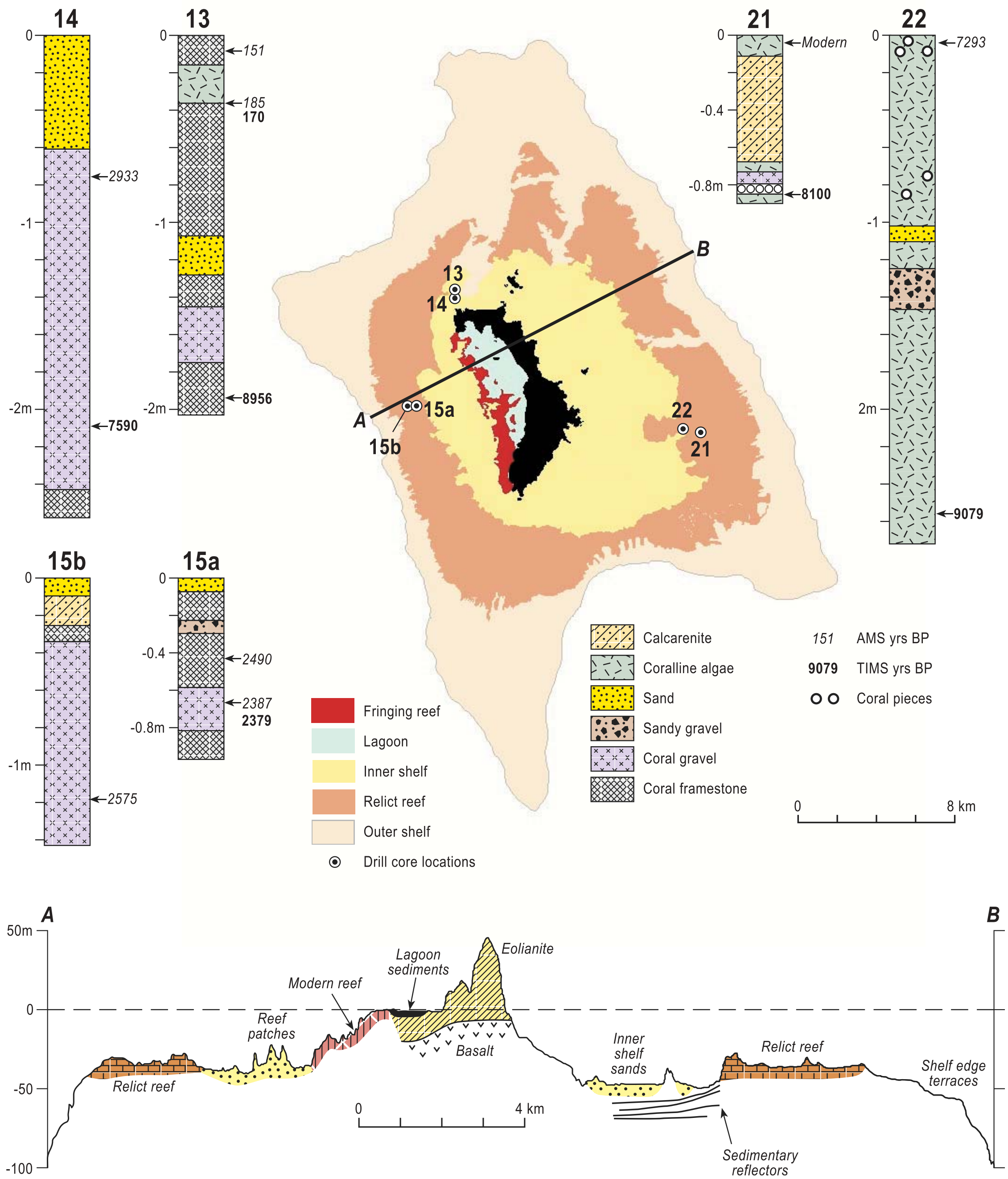

Figure 2. Distribution of relict and modern reef around Lord Howe Island and location, stratigraphy, and chronology of cores. The schematic cross-section (A–B) shows the relict reef and the location to which it backstepped on the west of the island, forming the modern reef and lagoon.

3 m below the surface, and AMS age at the surface almost two millennia younger (7169–7407 cal yrs BP) indicates that the upper part of the reef accreted at an average vertical rate of 1.5 mm/yr until growth ceased around 7000 years ago (Figure 2). A similar phase of early Holocene accretion preceding reef demise is implied by a basal date in core 21; the upper part of this core contained a modern *Tridacna* clam, indicating that the relict reef still forms substrate for some benthic organisms. On the western and northern margins of Lord Howe Island, the early Holocene age for the reef is substantiated by dates from cores 13 and 14; however, more recent reef growth (around 2400 cal yrs BP), occurred at site 15.

Table 1. AMS Dating of Core Samples[a]

Sample	Lab Code	Sample Depth[b] (cm)	Material	δ ^{13}C (‰)	^{14}C Age (yr BP) ± 1σ	Th Age (cal BP ± 2σ)	Calibrated ^{14}C age (cal BP) 1σ Lower	1σ Upper	2σ Lower	2σ Upper	Median Calibrated Age[c]
13RDC01 a-6	OZL208	R = 6; I = 22	Coral	0.3	510 ± 40	n/a	87	244	0	260	151 (0–260)
13RDC01 b-16	OZL209	R = 16; I = 40	Coral	−0.2	545 ± 35	170 ± 2	132	262	0	291	185 (0–291)
14RDC01 a-17	OZL210	R = 17; I = 62	Mollusc Operculum	3.4	3135 ± 50	n/a	2842	3017	2768	3111	2933 (2768–3111)
15RDC01 a-27	OZL211	R = 27; I = 23	Coral	−0.3	2750 ± 45	n/a	2363	2572	2336	2669	2490 (2336–2669)
15RDC01 c-40	OZL212	R = 40; I = 60	Coral	−1.3	2670 ± 45	2379 ± 13	2305	2457	2225	2605	2387 (2225–2605)
15RDC02 -32	OZL213	R = 32; I = 120	Coral	0.5	2815 ± 40	n/a	2499	2678	2390	2717	2575 (2390–2717)
21RDC01 a-2	OZL214	R = 2; I = 8	Clam shell Genus *Tridacna*	1.9	430 ± 40	n/a	-	-	-	-	Modern
22RDC01 b-9	OZL215	R = 9; I = 10	Coral	−0.5	6750 ± 50	n/a	7235	7364	7169	7407	7293 (7169–7407)

[a]Calibrated ^{14}C ages reported in years prior to 1950 AD.
[b]R, Recovered; I, Interpreted.
[c]Values in parentheses are 2σ.

[8] The relict reef was immense (>20 times the area of modern reefs), but it was drowned prior to establishment of the modern reef. Upright branches of *Acropora* encountered in vibrocores 4–6 m beneath the lagoon floor and dated around 7000 cal yrs BP [*Kennedy and Woodroffe*, 2000] indicate that the modern reef formed at a similar time to other Indo-Pacific reefs (which established over antecedent topography at around 10–25 m depth around 8000 cal yrs BP [see *Harris et al.*, 2008, Table 3]). However, this mid-late Holocene reef growth, associated with stabilization of sea level close to present, was preceded at Lord Howe Island by a much more extensive phase of early Holocene reef establishment which flourished for 2000 years, before being drowned as the reef backstepped to its modern foundations (see cross-section A–B in Figure 2).

5. Drowning by Sea-Level Rise and Reef Demise

[9] This relict reef is particularly significant for several reasons. First, it demonstrates that reefs were much more extensive 9000 years ago than they are at present at this latitudinal limit to reef growth. This is contrary to the view that reef distribution contracted during glaciations and were slow to recolonise mid-latitude seas that were marginal for corals [*Daly*, 1934]. Second, a phase of reef establishment occurred across the shelf flanking Lord Howe Island prior to, and in water depths deeper than, the foundations of most modern reefs, presumably because a broad shelf provided suitable substrate at this depth. Third, this reef, at the southern limit to reef development, was drowned during the early Holocene, extending into the Holocene the record of episodes of reef drowning documented for the late Pleistocene [*Beaman et al.*, 2008].

[10] Figure 3 shows postglacial sea-level rise, and an envelope within which reef growth was considered possible in the southwest Pacific [*Andréfouët et al.*, 2009]. Around 9000 cal yrs BP, there was a barrier reef around Lord Howe Island, at or close to sea level. The reef accreted at rates insufficient to keep pace with sea-level rise and had drowned by 7000 cal yrs BP. Its demise may have been accelerated by an abrupt sea-level rise [*Blanchon and Shaw*, 1995]. Independent evidence for a sea-level jump in early Holocene has recently been described from southeast Asia [*Bird et al.*, 2007; *Hori and Saito*, 2007; *Tamura et al.*, 2009], the Baltic Sea [*Yu et al.*, 2007], and the eastern USA [*Cronin et al.*, 2007], perhaps associated with rapid melt of the Laurentide Icesheet [*Carlson et al.*, 2008]. Shelf-edge reefs are common throughout the Caribbean [*Hubbard et al.*, 2008], and backstepped to modern reef locations 7000-6500 years ago. Complex early Holocene shelf reefs flourished 9000-7000 years ago in southeast Florida, at the northern latitudinal limit to reef growth, ceasing growth before 6000 cal yrs BP [*Toscano and Lundberg*, 1998; *Banks et al.*, 2008]. The demise of some shelf-edge reefs has been attributed to environmental degradation associated with sedimentation or eutrophication as the adjacent shelf was flooded, rather than abrupt sea-level rise [*Toscano and Macintyre*, 2003]. This interpretation seems less likely for the mid-shelf Lord Howe reefs as there are not horizontal substrates that would have been inundated at elevations coincident with the surface of the relict reef. Around Lord Howe Island, some reef growth occurred during late Holocene when sea level was at its present level, implying potential for recolonization of the relict reef when environmental conditions are favourable. Human activities have imposed stresses, such as eutrophication, pollution and sedimentation, which impede expansion of reefs in many parts of the world. Protection of marine environments around this World Heritage site is intended to minimise these additional stresses. However, the extent to which the relict reef may be able to support vigorous coral communities in future will depend on a range of environmental factors, as it is now in water depths that are largely beyond those optimal for coral growth.

6. Conclusion

[11] Evidence that coral reefs extended beyond their present latitudinal limits during the Holocene and previous interglacials [*Veron*, 1992; *Greenstein and Pandolfi*, 2008], is significant as human-induced climate change impacts tropical reefs [*Precht and Aronson*, 2004]. Deeper water (>10m) reefs and non-framework corals on shelves, such as the Lord Howe shelf, may represent important refugia from increases in SST [*Riegl and Piller*, 2003]. We demonstrate that an enormous early Holocene reef flourished around Lord Howe Island, and that it was drowned with

Table 2. TIMS Dating of Core Samples

Sample ID	Sample Depth (cm)	Material	Aragonite (%)	U (ppm) ± 2σ	^{232}Th (ppb)	^{230}Th/^{232}Th	^{230}Th/^{238}U ± 2σ	^{234}U/^{238}U ± 2σ	Uncorrected ^{230}Th Age (yr) ± 2σ	Corrected ^{230}Th Age[a] (yr) ± 2σ	Corrected ^{230}Th Age[b] (cal BP) ± 2σ
13RDC01-016	R = 16; I = 40	Coral	>99	4.3918 ± 0.0068	0.3466	93.8	0.002441 ± 0.00002	1.1488 ± 0.0014	231 ± 2	229 ± 2	170 ± 2
13RDC01c-085	R = 85; I = 190	Coral	98.5	2.7683 ± 0.0038	2.3752	323.7	0.091547 ± 0.00027	1.1501 ± 0.0020	9037 ± 32	9015 ± 34	8956 ± 34
14RDC01b-055	R = 55; I = 200	Coral	96.8	2.6819 ± 0.0025	2.6086	244.7	0.078430 ± 0.00028	1.1528 ± 0.0011	7674 ± 30	7649 ± 32	7590 ± 32
15RDC01-040	R = 40; I = 60	Coral	98.6	4.0243 ± 0.0064	0.5404	574.8	0.025438 ± 0.00013	1.1455 ± 0.0014	2438 ± 13	2438 ± 14	2379 ± 14
21RDC01c-079	R = 79; I = 115	Coral	93.9	2.8866 ± 0.0049	0.9895	735.5	0.083091 ± 0.00045	1.1502 ± 0.0019	8168 ± 48	8159 ± 48	8100 ± 48
22RDC01d-117	R = 117; I = 270	Coral	92.6	4.1408 ± 0.0066	0.6595	1768.3	0.092813 ± 0.00049	1.1531 ± 0.0017	9142 ± 52	9138 ± 52	9079 ± 52

[a]Ages reported in years prior to analysis in 2009 AD.
[b]Ages reported in years prior to 1950 AD.

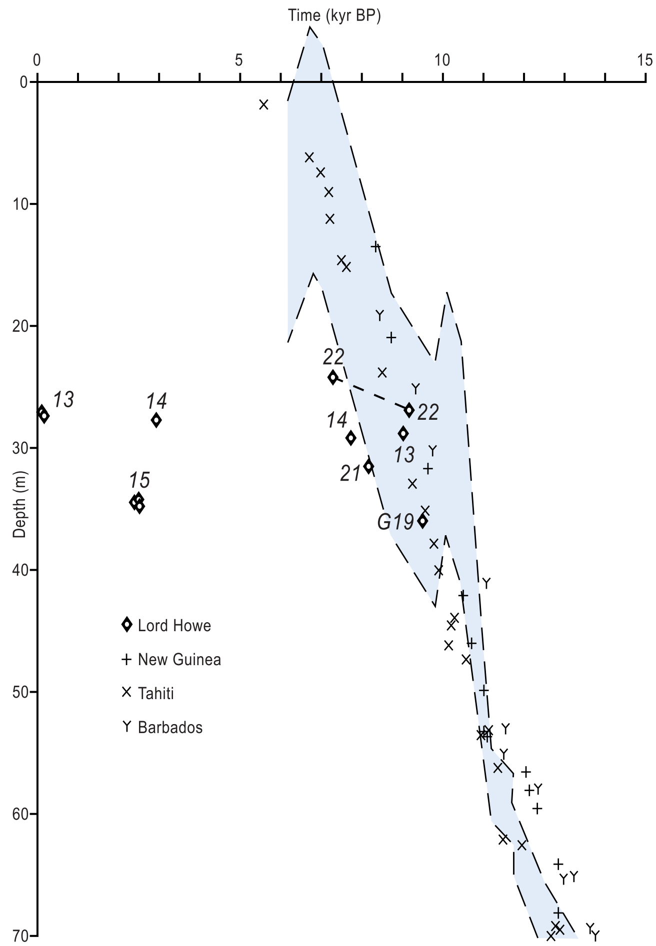

Figure 3. Age-depth plot of dated coral samples recovered from the relict reef (G19 is fossil branching coral recovered in grab sampler from 36 m water depth [see *Kennedy et al.*, 2002]), plotted in comparison with sea-level curves reconstructed for the early Holocene and an envelope within which coral growth is considered possible for the southwest Pacific. (Following *Andréfouët et al.* [2009]: Barbados data based on *Fairbanks* [1989] sampling as reported in the work of *Bard et al.* [1990]. Tahiti data are from *Bard et al.* [1996], and New Guinea Huon Peninsula data are from *Chappell and Polach* [1991] and *Edwards et al.* [1993]. The sea-level envelope represents upper and lower limits to the depth range in which living coral can grow as inferred from a rapidly uplifting island, Urélapa Island, southern Vanuatu, (average uplift 3mm/year) after *Cabioch et al.* [2003].)

reef growth backstepping to its modern position. This new record from the southern Pacific indicates the complex interaction of environmental processes that control coral reef growth.

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