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2015

Submerged fossil reefs discovered beyond the limit of modern reef growth in the Pacific Ocean

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Publication Details

Linklater, M., Brooke, B. P., Hamylton, S. M., Nichol, S. L. & Woodroffe, C. D. (2015). Submerged fossil reefs discovered beyond the limit of modern reef growth in the Pacific Ocean. *Geomorphology*, 246 579-588.

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Abstract

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Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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Submerged fossil reefs discovered beyond the limit of modern reef growth in the Pacific Ocean

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Abstract:

Balls Pyramid is the southernmost island in a linear island chain in the southwest Pacific Ocean, 24 km south of the limit of known coral reef formation at Lord Howe Island. This paper describes the geomorphometric structure of the shelf surrounding Balls Pyramid through the application of remote sensing data to create a high-resolution digital elevation model of the shelf (5 m cell size) and seafloor feature classification. Seafloor features were delineated using the bathymetry model together with slope, backscatter and sub-bottom profile data. The average depth of the 260.6 km² shelf was 55 m (± 21 m), with the majority of shelf area (77%) within 30-60 m water depth. Dominating the shelf is an extensive, mid-shelf reef at 30-50 m depth, dissected by basin and channel features. Outer-shelf reef and platform features surround the mid shelf, with terrace sequences marking the seaward outer-shelf rim in 65-100 m depth. Sub-bottom profiles and backscatter data demonstrate substantial accumulation (up to 16.5 m) of unconsolidated sediments within basin and channel features. The submerged mid-shelf reefs of Balls Pyramid are similar to the fossil coral reef system discovered on the Lord Howe Island shelf, implying origins as a drowned coral reef system. This paper reveals complex shelf topography with extensive submerged reefs on what was previously considered to be a planated volcanic shelf outside of reef-forming seas.

Keywords:

Submerged reefs, subtropical reefs, DEMs, fossil reefs, Balls Pyramid

1 Introduction:

Small oceanic islands provide valuable opportunities to study the processes that shape coastal evolution. Unlike mainland coasts, where relationships to the adjacent landforms are

geomorphologically complex, the isolated nature of oceanic islands offers a somewhat closed system, distal from surrounding depositional and erosional processes (Nunn, 1994). Under suitable conditions, extensive coral reefs form around tropical and subtropical oceanic islands, protecting the shoreline from erosion and contributing to carbonate production (Woodroffe, 2014).

Oceanic islands occur in three primary forms: volcanic or non-reefal islands; composite islands, where limestones overlay non-reefal foundations; and carbonate islands, where the non-reefal foundations are completely buried by limestones, such as the reef islands on atolls (Vacher and Quinn, 1997). An evolutionary model for the transition of oceanic islands into atolls was hypothesised by Darwin (1842), whereby coral reef accretion occurs around a subsiding volcano, progressing through the sequences of fringing- and barrier-reef stages, culminating in an atoll. The linear progression of the Darwinian sequence is exemplified by the Hawaiian Archipelago. Along this chain, active volcanic islands transition to atolls that in turn subside to form seamounts and guyots, which extend beyond the present-day latitudinal threshold of reef formation, referred to as the Darwin Point (Grigg, 1982). Current understanding of reef evolution acknowledges the contribution and interrelationships of processes shaping coral reefs, described in the various models of island evolution (Vacher and Quinn, 1997). The transition from fringing- to barrier- reefs, consistent with Darwinian concepts and modern understanding of glacio-eustatic fluctuations in sea level, has recently been demonstrated in the vertical accretionary history of Tahiti (Blanchon et al., 2014). These ‘classic’ examples, all within or moving out of reef-building seas, are characterised by island subsidence and the capacity for reef accretion to keep pace with a rising sea level.

An alternative evolutionary threshold of coral reef formation occurs when plate movement carries volcanic islands into reef-forming seas (Menard, 1983). Islands which do

not possess wave-attenuating reef structures can have their coastline eroded to form a near-horizontal shelf which may ultimately be truncated (Menard, 1983; Woodroffe et al., 2006). Reefless, truncated platforms may experience isostatic uplift to compensate for erosion, which counters subsidence (Menard, 1983). Such is the case in the subtropical southwest Pacific along the Lord Howe chain. Here, on the western margin of the Lord Howe Rise (Slater and Goodwin, 1973), there is a progressive sequence of islands to reefs to guyots that formed with the northwards movement of the plate over a hotspot, the volcanic islands slowly moving into tropical seas (Woodroffe et al., 2006).

The southernmost island in the chain is Balls Pyramid (31°45' S, 159°15' E), a volcanic monolith considered to represent the penultimate stage of truncation in non-reef forming seas (Woodroffe et al., 2006). North of Balls Pyramid (24 km north), at the threshold of modern reef development is Lord Howe Island (31°33' S, 159°5' E), which supports a fringing coral reef system thought to be the modern-day limit for true coral reef formation in the Pacific Ocean (Veron and Done, 1979; Kennedy and Woodroffe, 2000). Progressing further north in the sequence are atoll-like reefs (Elizabeth and Middleton Reefs) and submerged seamounts and guyots (Gifford Guyot, Capel Bank, Kelso Reef and Nova Bank).

Although the fringing reef of Lord Howe Island was considered to be surviving at the environmental limits of coral reef growth (Kleypas et al., 1999), extensive past reef growth has been recently discovered on the shelf surrounding the island, where there is a fossil reef system 25 times larger in area than the modern fringing reef (Woodroffe et al., 2010). This fossil reef flourished during the Early- to Mid-Holocene (9-7 ka), before reef growth backstepped to form the modern fringing reef (Woodroffe et al., 2010). This finding expanded the known southerly extent of Holocene reefs in the South Pacific, which have been shown elsewhere to have shifted poleward under past favourable climate conditions (Greenstein and Pandolfi, 2008; Kiessling et al., 2012). Preliminary investigations of the

truncated platform surrounding Balls Pyramid revealed carbonate sediments across the shelf (Kennedy et al., 2002) and evidence of a complex topography (Brooke et al., 2010), implying that similar reef development might have extended further south in the past.

Recent mapping of the shelf around Balls Pyramid provided evidence of the further southerly extension of fossil reefs (Woodroffe et al., 2013). Drill cores extracted from the shelf surface revealed reef limestone, containing corals (Woodroffe et al., 2013). In this paper, we utilise remotely sensed data (acoustic and optical) of the Balls Pyramid shelf surface and sub-surface to quantitatively describe the geomorphometry of the limestone features. The aims of this study are to: 1) describe the morphology, depth distribution and spatial extent of submerged limestone reefs and surrounding shelf; 2) assess spatial patterns in sediment accumulation on the shelf; and 3) discuss the potential origin and evolution of key geomorphic features.

2 Regional setting:

Balls Pyramid (31°45' S, 159°15' E), the southernmost island in the Lord Howe chain, is located approximately 600 km east of the Australian mainland (Fig. 1). The region has been included on the World Heritage List since 1982 (UNESCO, 2015) and sits within the Lord Howe Island Marine Park (NSW MPA, 2010) and Lord Howe Commonwealth Marine Reserve (Department of Environment, 2015), which also encompasses Lord Howe Island, Elizabeth Reef and Middleton Reef.

Balls Pyramid is a volcanic rock pinnacle which rises 552 m from a submerged shelf. It formed from hotspot volcanism, active at a similar, though slightly younger (unpublished data) time to Lord Howe Island, which formed during the Miocene, 6-7 million years ago (McDougall et al., 1981). Post-eruption, marine and subaerial forces eroded the islands to an estimated 3% of their original size and planated broad shelves around the island remnants

(Dickson, 2004). The two shelves are connected by a trough of 400-1000 m depth, and have very steep flanks that plunge to abyssal depths of >3000 m (Kennedy et al., 2011).

Positioned at the tropical-temperate interface, this region experiences warm-water inputs from eastward flows of the East Australian Current (EAC, Supplementary Material 1), which interacts with cooler waters of the Tasman Sea, referred to as the Tasman Front (Denham and Crook, 1976). The warm-water in the EAC enables the growth of coral reefs further south than on the adjacent Australian mainland, and also results in a unique mix of tropical and temperate marine organisms (Veron and Done, 1979). The isolation from the mainland coast results in high endemism of marine species and high biodiversity (de Forges et al., 2000; Roberts et al., 2002; Anderson et al., 2013), with coral reefs around Lord Howe Island exhibiting lower diversity than tropical reefs with comparable coral cover (Veron and Done, 1979; Harriott et al., 1995). High energy wind and waves are experienced along the island coastlines (Supplementary Material 1), with the fringing reef attenuating energies along the western coast of Lord Howe Island (Dickson et al., 2004).

Preliminary seafloor characterisations have been undertaken for the Lord Howe Island shelf using bathymetric data, sub-bottom profiles, seabed drill core data and sediment data (Kennedy et al., 2002; Brooke et al., 2010; Mleczko et al., 2010; NSW MPA, 2010; Woodroffe et al., 2010; Kennedy et al., 2011). Sedimentological analyses of the Balls Pyramid and Lord Howe Island shelves show carbonates are characterised by tropical and temperate biota, with coralline algae dominant and smaller contributions from corals and *Halimeda* (Kennedy et al., 2002). Carbonate material recovered from the shelf flanks is inferred to have been shed from the shelf during times of lower sea level (Kennedy et al., 2011). Prolific Holocene coral reef growth occurred on the shelf around Lord Howe Island, with an extensive submerged fossil coral reef structure at 25-50 m depth dated to 9-2 ka BP (Woodroffe et al., 2010).

3 Methods:

3.1 Bathymetry model:

High resolution bathymetry acquired from multiple optical and acoustic platforms can be integrated to create seamless digital elevation models for geomorphometric analyses and interpretation (Reuter et al., 2009; Evans, 2012; Leon et al., 2013). To characterise the seafloor structure around Balls Pyramid, a seamless high-resolution bathymetric model was created using a combination of multibeam echosounder (MBES) data and empirically derived estimates of depth from satellite imagery (Fig. 2, 3a). MBES data provides near-continuous high spatial coverage and high resolution in a cost effective manner (Brown et al., 2011) and satellite imagery is useful to accurately estimate depth in areas inaccessible to mapping vessels (Lygenza, 1978; Stumpf et al., 2003).

MBES data was collected aboard the Marine National Facility Research Vessel Southern Surveyor (February 2013) using a Kongsberg EM300 30 kHz system and processed onboard using CARIS Hips & Sips software, gridded to 5 m using a cube surface (IHO II) with tidal corrections applied. Quickbird TM (4 spectral bands, 2.4 m cell size) imagery acquired in 2008 was used to estimate depth of the inner shelf of Balls Pyramid, supplementing the scarce MBES data available in shallower water, where vessel access was restricted. Pre-processing of the satellite image included corrections for atmospheric interference, applied using ENVI (v4.8) Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes algorithm (Berk et al., 1989; Matthew et al., 2000) with a Mid-Latitude Model (80 km visibility). Additionally, sun glint correction was undertaken on the atmospherically corrected image using the methodology of Hedley et al. (2005). Depth was derived down to 35 m (Mean Absolute Error 2.36) using the band ratio method of Stumpf et al. (2003,

Equation 9), which functions independently of bottom type by using a ratio transform to measure the relative attenuation of light through the water column for individual bands (Stumpf et al., 2003). Depth estimates were validated with a subset of MBES data and, although there is moderate inherent vertical error demonstrated in the dataset, the calculation is sufficient in delineating structural textures and broad scale geomorphic features across the shallowest areas of the shelf.

Near-complete coverage of the shelf was surveyed from the MBES instrument (272 km²) and depth derived from satellite imagery (11.7 km²). Both datasets were converted to points and interpolated to a 5 m grid using Natural Neighbour (ArcGIS v10.1), which was shown to generate the most appropriate surface from a range of interpolation approaches available (Li and Heap, 2008; Arun, 2013). The new shelf elevation model was mosaicked with an existing bathymetry model of the land and shelf slopes (Mleczko et al., 2010, Fig. 3a, b, c).

3.2 Seafloor feature classification:

Feature characterisation was undertaken using a visual interpretation of the broad seafloor structures whereby polygons delineating seafloor features were digitised in ArcGIS v10.1 (Nichol and Brooke, 2011; Evans, 2012), using terminology consistent with international nomenclature (Table 1). Inner-shelf features were defined at a 1:6,000 scale using satellite imagery.

Acoustic backscatter and sub-bottom profile data were used to inform the classification of mid- and outer-shelf features. Backscatter data differentiates hard substrates from unconsolidated areas using the relative measure of reflectivity of acoustic signal intensity, whereby hard surfaces reflect higher intensity backscatter (light areas in Fig. 3d) and soft surfaces reflect comparatively lower intensities (dark areas in Fig. 3d). Backscatter

data were collected concurrently with MBES bathymetry and processed using the CMST GA-MB Toolbox outlined in Gavrilov et al. (2005) and gridded to 5 m cell size (Fig. 3d). Sub-bottom profile data were captured as 2D profiles using a Kongsberg TOPAS 18 Parametric sub-bottom profiler (Base version v2.1) and were displayed and interpreted in Seisec (v2.6.2). These data were used to characterise sub-surface stratigraphy in areas of unconsolidated seabed. Sub-bottom profiles were collected continuously along MBES tracklines, totalling 2,003 km, for the duration of the cruise and processed onboard. These datasets, together with the drill and sediment core data collected by Woodroffe et al. (2013), provided information on surface and sub-surface composition.

Features from the mid shelf to shelf break were delineated at a 1:10,000 map scale using the bathymetry model overlain with slope (5 m cell size, 50% transparency), which was derived from the bathymetry model using ArcGIS Spatial Analyst (Fig. 3e). Slope effectively delineates landform boundaries without the bias of illumination direction that occurs with hillshading (Evans, 2012).

Zonal Statistics were extracted for each feature in ArcGIS, and a hypsometric curve was produced using the Zonal Histogram tool to show the depth distribution of each feature (depth binned at 1 m intervals).

4 Results:

4.1 Shelf geomorphometry:

High resolution (5 m cell size) bathymetric mapping of the Balls Pyramid shelf (16.2 km width; 22.8 km length) revealed a highly complex shelf predominantly comprised of reef structures with subordinate basins and channels (Fig. 3c). The shelf is predominantly 30-60 m deep, with little shallow (<30 m) substrate. Inclusive to the shelf break (maximum depth 243 m), the shelf averages 55 m (± 21 m) depth with <1 % in 0-30 m depth, 77% in 30-60 m

depth, 14% in 60-90 m depth and 8% in 90-220 m depth. Beyond the shelf break are steep flanks surrounded by abyssal plains >3000 m depth.

Seafloor feature classification and key attributes are shown in Fig. 4 (a, b), with depth distributions represented by a hypsometric curve (Fig. 4c). Inner-, mid- and outer-shelf reef features demonstrate greater relative relief, higher average slope (Fig. 4c), and higher backscatter intensity (Fig. 3d). Poor signal penetration of the sub-bottom profile data on the reef features indicates hard substrate surfaces. On the seaward rim of the outer shelf, a series of terraces extend to the shelf break. Dissecting the shelf reefs are basin and channel features, which are characterised by lower relative relief, circular to elongate morphologies, smooth surfaces (Fig. 4a, b), low intensity backscatter (Fig. 3d) and poor sub-surface penetration of sub-bottom profiler data. From the hypsometric curve, a peak in the distribution of the inner- and mid-shelf features occur at 35 m (Fig. 4c), followed by a minor peak at 42 m, attributable to the combined surface area of the mid-shelf reef structures. A distinct mode in the hypsometry at 48-53 m represents the outer-shelf platform and, to a lesser extent, mid-shelf basins and channels. The outer-shelf terraces are spread across a wide depth interval, forming a minor mode at 75 m.

4.1.1 Inner shelf:

Inner-shelf reefs encircle the Balls Pyramid pinnacle, extending from the island coast down to 40 m water depth (Fig. 4a, b), predominantly occurring in depths of 30-35 m (Fig. 4c). The island base steeply slopes to the surrounding seafloor, with gradients up to 67°. The inner-shelf reefs are separated from the mid-shelf reefs by distinct, linear channels 1-3 m deep. These are 2,830 m in length and up to 245 m wide on the western side of the shelf and 2,280 m in length and up to 380 m wide on the east. The channels transition to a basin morphology, reaching a maximum of 550 m in width. There was no backscatter or sub-

bottom profiler coverage of these features, though the substrates appear sandy based on the satellite imagery.

4.1.2 Mid shelf:

Mid-shelf reefs cover 87 km² of the shelf (33% of total shelf area) in depths of 20-56 m (Fig. 4b). They are most prominent on the southwest sector of the shelf, where they extend to the shelf break, reaching a maximum width of 5,221 m. The reefs are differentiated into upper and lower reefs, and inter-reef depressions based on differences in relative depth and surface complexity. The upper reef predominantly occurs in 30-40 m (average 35 m) and demonstrates greater structural complexity with broader distribution of slope angles (0-23°; average 2°, Fig. 4b, c). The lower reef largely occurs in 35-50 m (average 43 m depth) and exhibits less variability in slope (0-17°; average 1.6°, Fig. 4b, c). Within the upper and lower reef features there are smooth 'inter-reef depressions' (0-13°; average 1.2°), which primarily occur in 32-50 m (average 41 m, Fig. 4b, c).

The shallowest reef occurs 2,700 m south of South East Rock, where Sunken Rock rises to 20 m depth from a base of 34-42 m (Fig. 3c). This elongate feature (255 m length, 122 m width) has slopes up to 19°. It adjoins two smaller, mounded reefs to the north, which rise to 22 m and are 100-155 m in length and 66-67 m in width. A comparatively shallow peak at 23 m occurs 950 m west of South East Rock, where the reef rises, sloping up to 18°, from the eastern rim of the southern mid-shelf basin.

A series of linear, subparallel ridges are oriented southwest toward the south of the reef. The ridges range 1-2 m in height and up to 400 m in length, and further north the structures become more distinct reaching up to 600 m in length and 3 m in height (Fig. 5a). Similar structures appear on the seaward rim of the lower mid-shelf reef on the eastern shelf, where they reach up to 400 m in length and 0.5-2.5 m in height (Fig. 5b).

In contrast to the well-developed reefs of the southwest, the northeast shelf is characterised by a prevalence of basins and channels in depths of 31 to 57 m (Fig. 4b). Sub-bottom profiles reveal several prominent reflectors beneath the surface, with up to 16.5 m thickness of accumulated stratified material within the basins (Fig. 6a). Three prominent basins occur on the north, east and south of the shelf, in predominantly 42-50 m depth (average 46 m) and are characterised by expansive, smooth surfaces (average slope 0.7°) bordered by high elevation reef. The northern basin is the largest in area (11 km^2), up to 5,115 m in length and 1,455 m in width, and has continuous sediment cover up to 16.5 m thick (Fig. 3, 6). The eastern (8.6 km^2) and southern (5.7 km^2) basins, are smaller in area and show restricted spatial extents of unconsolidated material from the backscatter compared to the northern basin (Fig. 3, 6).

On the western rim of the eastern basin, a relatively steep slope (up to 22°) defines the basin rim and rises to the mid-shelf reef (Fig. 5c). Steep slopes also occur on the eastern rim of the southern basin (up to 12°) and southern rim of the northern basin (up to 16°). The southern basin is enclosed by mid-shelf reef, while the eastern and northern basins connect to the outer-shelf platform and reefs.

Sub-bottom profiles indicate one or several prominent reflectors within the first 5 m of the sub-surface, interpreted as layers of coarser or cemented materials. A cross-section through the eastern basin represents typical reflector patterns (Fig. 6a). Several widely spaced (4-6 m), sub-horizontal unconformity surfaces are preserved 2-10 m beneath the surface, overlain by 5 m of uniformly layered bedding (spaced 1-2 m) with a thin veneer of tightly spaced ($<1 \text{ m}$) uniform reflectors at the surface. The surface bedding appears closely related to the topography, onlapping onto exposed and semi-buried reef features.

4.1.3 *Outer shelf:*

Dominating the outer shelf is the outer-shelf platform (72.7 km²), which comprises 28% of total shelf area and largely occurs in 48-60 m depth (average 54 m, Fig. 4b, c). It typically has a smooth low gradient surface (slope average 1.1°), though the seaward rim steepens up to 73°. The width of the outer shelf is 45-3,612 m, narrowest on the western shelf and broadest to the south. The seaward rim of the outer-shelf platform is defined by a distinct terrace step, 1-5 m in height at an average of 60-70 m depth. On the western and eastern shelf, the terrace step is characterised by fore-reef buttresses, protruding up to 400 m in length and 1-2 m in height, with few other terrace steps observed. Numerous terraces and terrace steps are evident on the northern, southern and southeast shelves toward the shelf break (Fig. 4a). Substantial variability in the depth distribution occurs for the terrace features and shelf break due to the changes in gradient of the shelf break around the shelf (0.4°-84°, Fig. 4b, c). Outer-shelf terraces predominantly occur in 65-100 m depth (average 92 m) and the shelf break at 115-150 m depth (average 133 m).

Rising from the platform are patchy reef structures, primarily occurring in 45-56 m depth (average 53 m, Fig. 4b, c), intersected by basins and channels. The largest outer-shelf reef occurs on the northern shelf, reaching 4,310 m in length, 278-705 m in width and 3 m in height. On the southern outer shelf, a series of narrow, mounded ridges (typically < 1 m height) occur, including the longest reef at 8,300 m and 40-90 m in width. These ridges are sub-parallel to the adjacent seaward terrace steps. Other elongate and patch reefs occur on the south east and eastern shelf, with localised basins and channels positioned behind mounded ridges or adjoining the lower mid-shelf reef.

On the northern outer shelf, a dense network of basins and channels occurs. A northwest oriented channel connects the large northern mid-shelf basin to the outer-shelf terraces and flanks. The channel is 2,534 m long, 59-586 m wide, and is deepest at its

landward extent (6 m deep), shallowing seaward (1-2 m deep). The channel connects to a gently sloping terrace ($<4^{\circ}$ slope), adjacent to a series of terraces and terrace steps. Sub-bottom profiles reveal sediment accumulations (up to 5 m thick) overlaying buried reefs and sub-horizontal terrace surfaces (Fig. 6b). The upper terrace section (60-68 m depth) conceals three stepped reef structures and two phases of buried sub-horizontal terraces 3 m apart, while the lower terrace section (>68 m depth) is draped with sediments, with a slump-like mound apparent toward the terrace base at 80 m depth. Northwest-oriented bedforms, 1-2 m in height and 100-700 m long, occur at the terrace base.

Terraces and terrace steps are most numerous on the southern rim, where up to 12 clear sequential terrace steps are evident. These terraces appear to comprise harder substrate surfaces, as indicated by high intensity backscatter data (Fig. 3d) and poor signal penetration of the sub-bottom profiler, though unconsolidated sediments likely form a veneer. On the eastern and western rims, terraces converge to one or two distinct terrace steps (Fig. 4). Beyond the shelf break are the flanks and slopes of the shelf, which dip steeply into abyssal depths of $>3,000$ m, apart from the shelf section at 600 m depth that adjoins the Lord Howe Island shelf.

5 Discussion:

Morphometric analyses of the Balls Pyramid shelf have revealed a complex network of reef systems and infilled basins on what had previously been considered to be a truncated volcanic platform beyond the limits of substantial reef growth (McDougall et al., 1981; Kennedy et al., 2002; Woodroffe et al., 2010). The broad spatial extent of the submerged, limestone reefs indicates that it is a composite island, with substantial limestone deposits atop a buried volcanic base (Vacher and Quinn, 1997; Woodroffe et al., 2013), inferred to represent multiple phases of reef accretion and shelf erosion throughout the Late Quaternary.

5.1 Origin of mid-shelf reefs:

The depths of mid-shelf reefs around Balls Pyramid (30-60 m depth) correspond to the Early Holocene marine transgression (10-8 ka) and interstadials of Marine Isotope Stages (MIS) 5, 7, 9 and 11 (Fig. 7), and occur at similar depths to the Lord Howe Island mid-shelf fossil reef (25-50 m depth) which accreted, in part, during the Holocene (9-2 ka, Woodroffe et al., 2010). Morphological attributes of the shelf reefs are also similar, with both shelves possessing complex surface topographies, elongate, protruding buttresses, and prominent basins intersecting the reef with channels connecting to the outer shelf (Woodroffe et al., 2010; Brooke et al., 2010). The orientation of fore-reef buttressing (Fig. 5b) and linear ridge formations (Fig. 5a) on the Balls Pyramid mid-shelf reef correspond to the alternating east-west wind patterns which established during the Early- to Mid-Holocene when the Tasman Front shifted to its current position at $\sim 34^{\circ}\text{S}$ (Bostock et al., 2006). Buttress morphologies on the reef rims are comparable to the large spur and groove features observed on the southern margin of the Lord Howe Island fossil reef, inferred to have been subject to high wave intensities (Woodroffe et al., 2010). The southwest shelf is interpreted as the windward shelf due to the orientation of reef formations and the larger spatial extent of mid-shelf reef growth. While the Lord Howe Island mid-shelf reef forms a distinctive barrier-type morphology, the Balls Pyramid mid-shelf reefs instead form a platform-type morphology.

The evidence presented for Balls Pyramid, including scale of reef development, the depth distribution of features and the morphological resemblance to the fossil coral reef around Lord Howe Island, suggests the mid-shelf reef surrounding Balls Pyramid is a fossil coral reef. It appears to be a drowned 'give up' reef (e.g. Harris et al., 2008), unable to accrete vertically to keep pace with sea level, as have the atoll-like Elizabeth and Middleton Reefs (Woodroffe et al., 2004), or backstep landward such as the Lord Howe Island reefs

(Woodroffe et al., 2010). Such drowning may be attributable to the lack of suitable topography on which to backstep (<1% of shelf area <30 m depth) and/or its more southerly position.

5.1.1 Evidence of basin erosion and deposition:

Basin and channel features are interpreted as paleolagoons and paleochannels, and occur most prominently on the northeast shelf, interpreted as the leeward shelf. The steep-sided rims of the basins (Fig. 5c) suggest shelf erosion during lower sea level, with topographies comparable to those observed on makatea islands (such as Ma'uke of the southern Cook Islands), where steep sided limestone rims, attributed to uplift and solution of reef limestone, surround a volcanic core (Stoddart et al., 1990; Nunn, 1994). The basin morphologies may therefore indicate dissolution as part of karst erosion of the shelf during times of exposure (Hoffmeister and Ladd, 1944; Purdy, 1974), followed by deposition of reefal material during periods of higher sea level.

Numerous reflectors observed from the mid-shelf basin sub-bottom profiles (5-16.5 m below the surface) indicate a dynamic sedimentary environment. The upper unit of closely-spaced, uniform bedding follows topographic contours, and is thus interpreted as likely Holocene post-transgressive deposits, with the strong unconformity reflector interpreted as the pre-Holocene surface. Similar stratigraphy patterns were observed in the modern lagoon of Lord Howe Island, where the Holocene-Pleistocene boundary occurred as a prominent reflector 5-20 m below the seafloor (Kennedy and Woodroffe, 2000). Elsewhere along the Australian coast similar pre-Holocene surfaces occur up to 25 m thick in the Great Barrier Reef (Hinestrosa et al., 2014) and up to 15 m thick along Ningaloo Reef (Collins et al., 2003).

5.2 *Origins of outer shelf features and implications for sea level:*

Submarine terraces mark phases of past sea-level lowstands, and can form as erosional structures where wave action planates a horizontal bench and sea cliffs (Menard, 1983), or as accretionary structures, such as dunes or coral reefs (Abbey et al., 2013; Ramalho et al., 2013). The depth distribution and morphology of terrace steps around Balls Pyramid indicate the terraces are eroded sea cliffs, formed during periods of low sea level, with evidence of accretionary processes acting to form the adjacent outer-shelf reefs. The terraces occur at a broad depth range, most commonly at 65-100 m depth, which corresponds to sea-level lowstands during the last glacial (MIS 2-4, Fig. 7). At this time, the East Australian Current had shifted north to 26°S along the Lord Howe Rise, associated with conditions of weakened easterly Trade Winds, strengthened Westerlies, and cooler sea surface temperatures (Martínez, 1994; Nees, 1997; Kawagata, 2001; Bostock et al., 2006;). The prevailing alternating east-west winds correspond to the morphology of the steeper-gradient eastern and western rims, which are characterised by buttressing formations. Adjoining the terraces on the gentler-gradient northern and southern rims are elongate, sub-parallel outer-shelf reefs which appear to represent accretionary paleoshoreline features, with possible origins as dunes (e.g. Nichol and Brooke, 2011) or coral reefs (e.g. Abbey et al., 2013).

On the northern shelf, sub-bottom profiling revealed buried sub-horizontal terraces (Fig. 6b), attributed to shelf-derived sediments transported off-shelf by seaward flowing channels. Sediments recovered by Kennedy et al. (2011) from a core in the trough between the Balls Pyramid and Lord Howe Island shelves (750 m depth) showed the deposition of carbonates primarily sourced from shelf erosion during the last glaciation, with negligible Holocene carbonates. Surficial reflectors in the sub-bottom profiles are therefore inferred as Holocene to modern deposits, with the first strong sub-horizontal reflector likely representing the pre-Holocene surface.

5.3 Implications for reef evolution at the latitudinal limit:

The broad spatial magnitude of fossil reefs discovered on the Balls Pyramid shelf provides evidence of extensive coral reef production at the limit of reef formation. The evolution of the Balls Pyramid shelf appears to have undergone a complex erosional and depositional history, and represents a post-erosional stage of island evolution, which has not reached the stage of an emergent reef (Ramalho et al., 2013). Had the island-reefs around the Balls Pyramid shelf developed in tropical seas on a rapidly subsiding surface, their morphologies might have been expected to fit into the Hawaiian or Tahitian examples of island-reef sequences (Webster et al., 2009; Blanchon et al., 2014). However, since they developed in a tectonically stable setting at the margin of reef-forming seas, they have experienced significant erosion before substantial reef accretion occurred, and thus developed a characteristic morphology unique to this setting (Fig. 8).

In a time of rapid change to ocean processes as a result of global warming (IPCC, 2014), there is a need to better understand the distribution of coral reef ecosystems at their environmental and physiological limits (Kleypas et al., 1999; Perry and Larcombe, 2003). Coral reefs are shown to have expanded their ranges poleward under past conditions of warming (Kiessling et al., 2012) and understanding the nature of such expansions can provide insights into how reefs may respond under changing climate pressures (Perry and Larcombe, 2003, Riegl, 2003; Pandolfi and Kiessling, 2014). The evidence of extensive submerged reef systems around the remote island platform of Balls Pyramid demonstrates substantial carbonate production despite its location at the modern limits of hematypic coral growth. Morphological attributes suggest the dominant reef features have origins as a drowned coral reef, implying the platform lies within reef-forming seas. As the southernmost island in the chain, 24 km south of the known limit of Holocene and modern coral reef growth in the

Pacific Ocean, the discovery of substantial reef growth at this locality has important implications for understanding the limits of past coral reef expansions, and the potential capacity of the shelf to support modern coral reef expansion under warming conditions.

5.4 Conclusions:

The key findings of this study are:

1. The discovery of an extensive network of submerged fossil reef systems on the shelf around Balls Pyramid, dominated by a large mid-shelf reef at 30-50 m depth
2. Evidence of a dynamic, high energy sedimentary environment indicated by accumulations of unconsolidated sediments in basins and channels
3. Identification of erosional terrace-step sequences marking the outer-shelf rim at 65-100 m depth
4. Correlation of features to the mid-shelf fossil reef around Lord Howe Island, suggesting the mid-shelf reef features discovered are drowned coral reefs

6 Acknowledgements:

Research cruise SS2013_v02 on RV Southern Surveyor was facilitated through the Marine National Facility. We are grateful to the captain, crew and technical staff from Geoscience Australia (GA) and CSIRO for all their support. Many thanks to Voyage Manager Bruce Barker, Deputy Voyage Manager Brett Muir, boatswain Tony Hearne, swath technicians Tara Martin and Rick Smith (CSIRO) and the scientific crew aboard the voyage, including Kim Picard, Stephen Hodgkin, Matthew Carey, Mark Sharah, Craig Wintle, Tanya Whiteway (GA) and Christopher Gallen (NSW Department of Primary Industries). Thank you to Alan Jordan (NSW DPI) for project support and manuscript review, Justy Siwabessy (GA) for post-cruise processing of the backscatter. We thank the Lord Howe Island Marine Park

Authority (LHIMPA) (Permit LHIMP/R/2012/013), NSW DPI (Permit P12/0030-1.0) and the Department of the Environment (Permit 003-RRR-120918-02). This research was made possible through funding by GA through the National Environmental Research Program Marine Biodiversity Hub (Department of Environment, Australian Government), with additional funding from NSW DPI, LHIMPA and the University of Wollongong (UOW) Research Partnerships Grant. ML acknowledges the support from the Australasian Hydrographic Society Education Award. BPB and SLN publish with permission of the Chief Executive Officer, Geoscience Australia.

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Table 1: Definitions of terms used within this study.

Feature	Definition	Reference
Reef	A mass (or group) of rock (s) or other indurated material lying at or near the sea surface that may constitute a hazard to surface navigation	IHO (2008)
Coral reef	A tract of corals growing on a massive, wave resistant structure and associated sediments, substantially built by skeletons of successive generations of corals and other calcareous biota	Done (2011)
Basin	A depression, in the seafloor, more or less equidimensional in plan and of variable extent	IHO (2008)
Channels	Relatively elongated, low lying areas that dissect shallower seafloor	Abbey et al. (2011)
Depressions	Closed-contour, low-lying areas surrounded on all sides by shallower seafloor	Abbey et al. (2011)
Platform	Low-gradient, low-relief surface of extensive horizontal dimensions	Beaman et al. (2008)
Terrace (s)	An isolated (or group of) relatively flat horizontal or gently inclined surface(s), sometimes long and narrow, which is(are) bound by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.	IHO (2008)
Step	A narrow area on the continental (or island) shelf that has a distinctive steep gradient	Beaman et al. (2008)
Shelf break	The line along which there is marked increase of slope at the seaward margin of a continental (or island) shelf	IHO (2008)
Slope	The deepening sea floor out from the shelf-edge to the upper limit of the continental rise, or the point where there is a general decrease in steepness.	IHO (2008)

Figure 1 a) Lord Howe chain, including submerged Capel Bank and Gifford Guyot, atoll-like Middleton Reef and Elizabeth Reef, Lord Howe Island and Balls Pyramid. Geoscience

Australia National Bathymetry Grid. Inset: Regional location; b) Middleton Reef (M Hallam); c) Lord Howe Island (M Legge-Wilkinson); and d) Balls Pyramid (M Linklater).

Figure 2 Process diagram of steps undertaken during processing satellite imagery and producing bathymetry model.

Figure 3 a) Source of input datasets integrated to produce bathymetry model; b) Detailed bathymetry model for Lord Howe Island and Balls Pyramid shelves (5 m cell size). Colour scheme stretched from 0 to -100 m depth, white dashed lines represent 1000 m contour intervals; c) Hillshaded bathymetry of Balls Pyramid (5 m cell size) with colour scheme as in b). Inset boxes A-E represent locations of Fig. 5, 6; d) Backscatter data for the Balls Pyramid shelf (5 m cell size) with the location of drill cores and vibrocores collected aboard R.V. Southern Surveyor SS2013_V02 (Woodroffe et al., 2013); e) Slope map (5 m cell size).

Figure 4 a) Seafloor geomorphic feature classification for Balls Pyramid shelf; b) zonal statistics; and c) zonal histogram. Abbreviations: R. = range; Av = average, sd = standard deviation. Inset boxes A-E represent locations of Fig. 5, 6.

Figure 5 Hillshaded bathymetry, slope map and profile cross-section of: a) mid-shelf linear reef features; b) mid-shelf reef fore-reef buttresses; and c) steep rimmed mid-shelf basin (Inset and legends in Fig. 3, 4).

Figure 6 Hillshaded bathymetry, seafloor feature classification, slope map and sub-bottom profile cross-section of: a) the mid-shelf basin and channel feature; and b) outer-shelf terraces (Inset and legends in Fig. 3, 4).

Figure 7 Quaternary sea-level curve modified from Grant et al. (2014) with generalised depths of mid-shelf reef features, terrace upper and lower boundaries. The Holocene Thermal Maximum (HTM) and Marine Isotope stages 1-12 are indicated.

Figure 8 a) Darwinian sequence of island-reef evolution in reef-forming seas; b) Planation of volcanic islands in non-reef forming seas; and c) the Lord Howe chain showing the sequence of the southerly Balls Pyramid (BP) shelf with fossil reefs, Lord Howe Island (LHI) with

fossil and fringing reefs, and atoll-like Elizabeth and Middleton Reefs. LHI and BP bathymetry clipped to 1000 m depth, north-facing oblique angle with 8 x vertical exaggeration. Modified from Woodroffe et al. (2006).

Supplementary Material 1 a) MODIS derived Summer (January); and b) Winter (June) sea surface temperature (SST) 2011 (Huang et al. 2013); Averaged Wave Watch III wave direction (TDir) and significant (sign.) wave height for c) Summer (January); and d) Winter (June) 2011 (Tolman, 2014).