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Key Points:
- Evidence of Pacific reef island formation in latter stages of sea level rise
- Reef platforms accommodate the oldest coral reef islands in atoll archipelagos
- Islands formed at higher sea level have been stable for the past 2000 years

Supporting Information:
- Readme
- Text S1
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Evidence for coral island formation during rising sea level in the central Pacific Ocean

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Abstract The timing and evolution of Jabat Island, Marshall Islands, was investigated using morphostratigraphic analysis and radiometric dating. Results show the first evidence of island building in the Pacific during latter stages of Holocene sea level rise. A three-phase model of development of Jabat is presented. Initially, rapid accumulation of coarse sediments on Jabat occurred 4800–4000 years B.P. across a reef flat higher than present level, as sea level continued to rise. During the highstand, island margins and particularly the western margin accreted vertically to 2.5–3.0 m above contemporary ridge elevations. This accumulation phase was dominated by sand-size sediments. Phase three involved deposition of gravel ridges on the northern reef, as sea level fell to present position. Jabat has remained geomorphically stable for the past 2000 years. Findings suggest reef platforms may accommodate the oldest reef islands in atoll systems, which may have profound implications for questions of prehistoric migration through Pacific archipelagos.

1. Introduction

The evolution and controls on formation of mid-oceanic coral reef islands is the subject of considerable debate. Reef islands are coherent accumulations of sand and gravel deposited on coral reef platforms by the focusing effect of waves and currents. Studies to date have shown that most islands are 2000–3000 years in age. This age range coincides with the latter stages of the Holocene marine transgression when sea level stabilized or fell to present level from a highstand [*Woodroffe et al*., 1999; *Kench et al*., 2009]. As a consequence of this timing, sea level has been implicated as a first-order control on reef island evolution and stability.

Studies have suggested that sea level fall from the mid-Holocene highstand was an important trigger for the emergence of reef islands in the central Pacific [*Dickinson*, 2003, 2009]. In particular, the "cross-over" date, when mean high tide level fell below paleoreef flats constructed at the low tide level during the mid-Holocene highstand, is thought to be critical for island formation as emergent reef platforms became viable platforms for island accumulation [*Dickinson*, 2003]. This concept has been adopted in subsequent investigations of island geomorphology and anthropology. Evidence for island development associated with the falling sea level stage has been presented for a number of locations including Makin Island, Kiribati [*Woodroffe and Morrison*, 2001], Laura Island in Majuro atoll, Marshall Islands [*Kayanne et al*., 2011], and islands of Nadi Bay, Fiji [*McCoy et al*., 2010], in the central Pacific; Bewick Island, Great Barrier Reef [*Kench et al*., 2012]; Warraber Island, Torres Strait [*Woodroffe et al*., 2000, 2007], and Cocos (Keeling) Islands in the eastern Indian Ocean [*Woodroffe et al*., 1999]. However, a contrasting model of island formation has been proposed in the central Indian Ocean where islands in the Maldives formed earlier in the Holocene, over infilled lagoons, and during the latter stages of sea level rise [*Kench et al*., 2005]. Furthermore, observations from Utrok and Kaven islands in the Marshall Islands show they formed toward the end of the sea level highstand (~2750–2400 years ago), independent of sea level fall [*Weisler et al*., 2012]. This additional model and recent observations suggest that island formation is more complex than previously thought and relies on a number of factors that include sediment supply and the relative depth between reef platform development and sea level [*Kench et al*., 2005, 2012]. To date, no evidence has been reported from the Pacific region of coral island formation under rising sea level conditions. Indeed, the controls on island initiation and the modes and timeframes of island accumulation are poorly resolved, and the paucity of studies mean it is premature to discount this mode of development in the Pacific.

Refining the timing, mode, and controls on reef island formation provides critical insights into two high-profile global research issues. First, how will reef islands respond to future sea level rise? Reef islands provide the only habitable land in atoll nations such as the Maldives (Indian Ocean), Tuvalu, Kiribati, and the Marshall Islands (Pacific). Projected sea level rise and climatic change are expected to promote widespread island inundation and

shoreline erosion, threatening the security of atoll nations and rendering them uninhabitable over the next century [*Dickinson*, 2009; *Kahn et al*., 2002; *Barnett and Adger*, 2003]. Resolving past relationships of sea level to island development therefore will allow development of a more complete understanding of the range of modes of island formation and provide critical insights to inform projections of landform trajectories over the next century. Second, refinement of the timing and modes of formation of reef islands provides a critical geomorphic framework for resolving an enduring debate concerning the prehistoric migration and colonization of the central Pacific [*Kirch*, 2010]. A number of studies have argued that the availability of land in the central Pacific may have been one factor constraining the colonization of atoll archipelagos and have also argued that relative sea level fall was essential in triggering the geological development of islands over the past two millennia [*Kirch*, 2010]. For example, recent evidence shows that human settlement was near contemporaneous with island formation in the Marshall Islands approximately 2000 years B.P. [*Kayanne et al*., 2011], while other studies in the region suggest human settlement prior to the sea level fall ~2000 was unlikely [*Weisler et al*., 2012; *Irwin*, 1992].

Here we present evidence of island formation and development during latter stages of the Holocene marine transgression that allows existing insights of island formation in the central Pacific to be reconsidered.

2. Field Setting and Methods

The Republic of the Marshall Islands consists of a double chain of 29 atolls and 5 reef platform islands oriented northwest-southeast in the central Pacific Ocean (Figure S1). This study examined the morphology, stratigraphy, and evolution of Jabat island (7°45′06″N, 168°58′36″E) situated on a reef platform located 16 km north of Ailinglalap atoll in the Ralik chain and in the southwest of the archipelago (Figure 1). The reef platform is triangular in shape, 2.04 km^2 in area, and has three distinct geomorphic units. The majority of the platform (57%) is subtidal (1–10 m depth) and maintains a living coral cover. In the center of the platform is an intertidal reef flat which occupies 43% of the platform area. The vegetated reef island fills a large proportion of the central reef flat surface (57.2%), though a much smaller proportion of the entire reef platform (~24.5%). The island is 0.5 km^2 in area with a longest axis of 1.2 km and varies in width from 300 m in the south to a maximum of 500 m in the north (Figure 1b). An impounded swamp is located in the northern sector of the island.

Topography of the reef flat and island was surveyed along five transects using a laser level, and surveys were connected using Real Time Kinematic GPS (Figure 1b). Subsurface stratigraphy was determined from six cores trenched, augured and drilled through the island (C1-6), along the central traverse (T3), and two cores from the northern transect (T5). Two additional and shallow reef flat cores were retrieved using a handheld diamond drill (Figure 1b). Sediment samples were collected every 0.25 m down each island core. The sediment grain size of 74 samples was analyzed using a settling tube, and skeletal composition of sediments greater than 1 mm in size was determined by point counts under a binocular microscope. Topographic surveys and elevations of all samples were reduced to mean sea level (msl) using the tidal predictions for Kwajalein (14.53°S, 144.87°E). Radiocarbon dates from 22 island sediment samples and from three in situ reef corals were used to develop a chronostratigraphy for the latter stages of reef development and island formation. Interpretation of the non-in situ nature of sediment samples is contained in the supporting information. Coral samples were tested for recrystallization and were largely unaltered and aragonitic (>95%). Radiometric ages discussed are the midpoint of the calibrated age range and are reported as cal years B.P. (Table S1).

3. Results and Discussion

3.1. Morphology and Stratigraphy

In cross section Jabat possesses a pseudo basin-shaped morphology with higher peripheral ridges and lower elevation central island surface (Figures 2 and S2). However, there is marked asymmetry to the basin-shaped morphology, and Jabat consists of a complex number of morphological units, which reflect temporal changes in process regimes that control island development. A striking topographic feature is the prominent western ridge, which is approximately 100 m wide and increases in elevation from 4.37 m above msl in the north to 5.73 m above msl in the south (Figure S2). Of note, the western ridge is 2.0–3.0 m higher than contemporary ridges (Figures 2 and S2).

The topography of the central island surface varies considerably. In the south the stepped morphology of the western ridge terminates in a small depression (+2.66 m msl) impounded by the eastern ridge (T1, Figure S2).

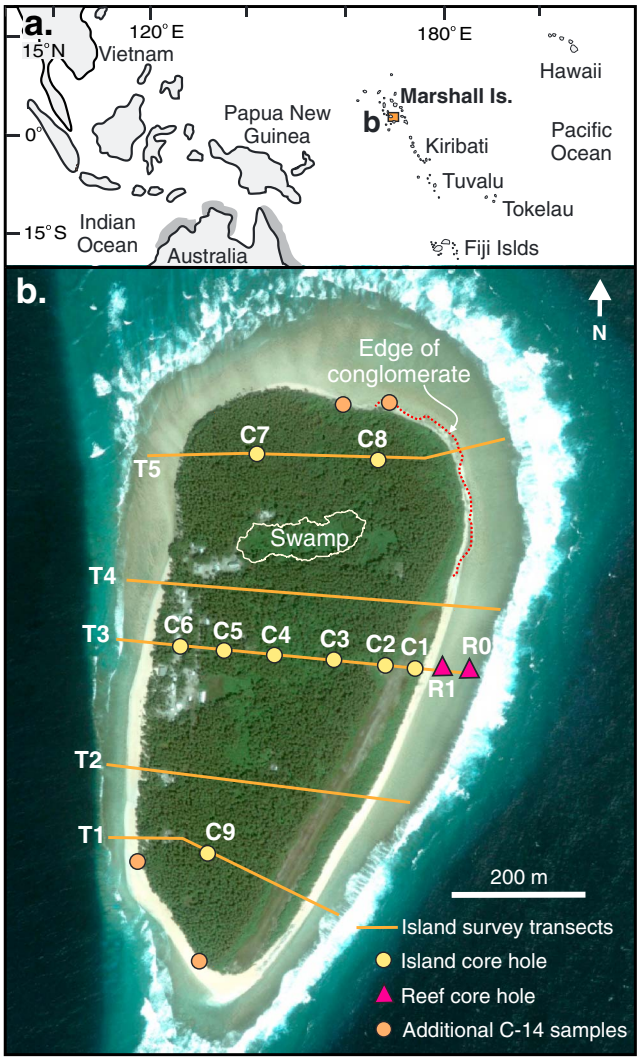

Figure 1. Location of Jabat Island, Marshall Islands. (a) Northwestern Pacific location of the Marshall Islands. (b) Jabat Island showing the location of field surveys and sampling.

Further north, the central island comprises a broad low-amplitude ridge that decreases in elevation from +3.63 m msl (T2, south) to +2.26 m msl (T4, north) and increases in width from 160 m (south) to ~200 m in the north (T4). A swamp is situated north of T4, which is impounded by a sequence of ridges on the west, north, and east, separating the central island core from the northern portion of the island (Figure 1b). The northern ridges comprise unconsolidated coral cobbles, overlying a cemented conglomerate surface and capped with a limited soil horizon. The ridges have maximum elevations ranging from +2.51 m (west), +3.06 m (center), and +3.02 m (east) (Figure 2a). The elevation and location of these northern gravel ridges indicate they were a discrete depositional phase in island development.

Eight trenches were excavated through the entire island sediment sequence, with five terminating on cemented conglomerate substrate. Island sediments can be separated into two distinct facies based on grade, composition, and location. First, the central core of the island, the northern sector (north of T4), and basal units of island ridges are dominated by very coarse gravel to cobble-size coral clasts (32–256 mm) with a subordinate matrix of coarse sand (Figure 2). The gravel content ranges from 60 to 90% and shows little stratification. Isolated large coral boulders (500 mm) and thin coarse sand units are present in some cores. The second facies forms the upper units of the marginal ridges (cores 1 and 6) and is dominated by poorly to moderately sorted gravelly coarse sands (Figure 2b). The mean size of sediments ranges from 0.3 Φ (coarse sand) to -2.6 Φ (pebbles). The granule and pebble-size range is comprised of coral (~72%) and coralline

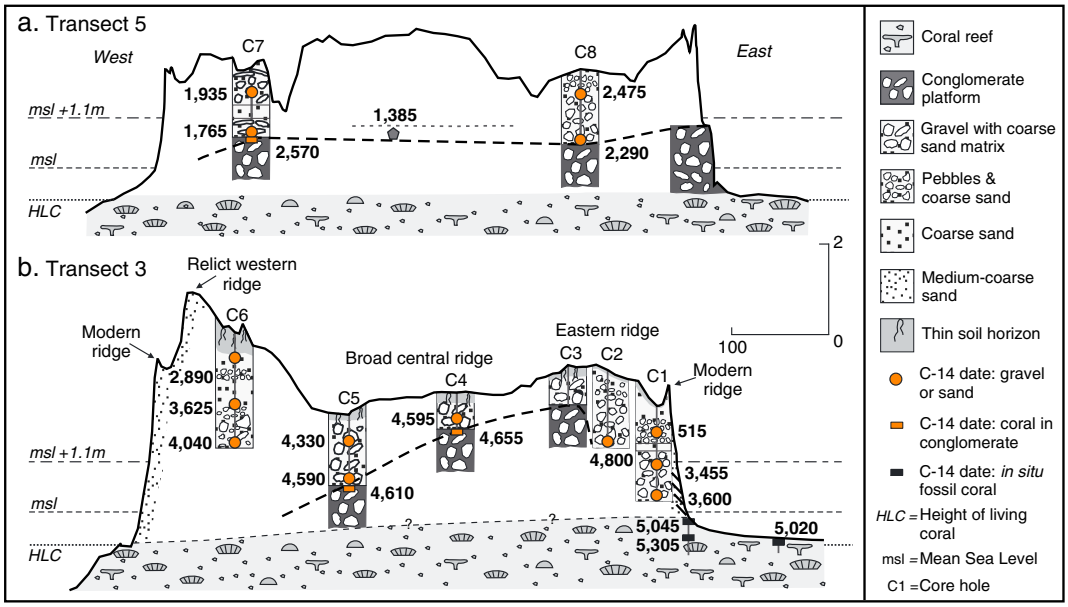

Figure 2. Topographic profiles from Jabat Island, Marshall Islands, showing stratigraphy in core holes. Radiometric ages are the midpoint of the calibrated age range. Location of profiles shown in Figure 1b. Radiocarbon ages presented in Table S1. All surveys reduced to mean sea level (msl).

algae (15%) with subordinate contributions of *Halimeda*, foraminifera, and molluscs. The skeletal composition of the coarse sand fractions is dominated by coral (~50%) and the foraminifera *Calcarina* sp. (~41%) with minor contributions of coralline algae, *Halimeda*, and molluscan fragments. Gravel layers are found throughout these cores, and isolated gravel clasts are common. The contemporary beach south of transect 4 (on the west and east) is composed of moderately to well-sorted, medium to coarse sands. These sands are compositionally indistinct from the sandy ridge units, but the better sorting and reduced size reflect abrasion in the littoral system.

Conglomerate, consisting of a cemented matrix of disoriented coral heads and cobble-size material, was encountered at the base of five cores in the center of the island and both cores in the north. Along the central transect (T3) the elevation of the conglomerate decreases in a westward direction from +2.40 m msl in core 3 to +0.7 m msl in core 4. In the north, conglomerate platform outcrops at the shoreline (Figure 1c) and has an elevation ~ +1.05 m msl. Conglomerate was encountered at depths of +0.62 m and +0.63 m msl in both northern cores indicating this surface is a continuation of the deposit that outcrops at the northern margin of the island and that it slopes from the island edge toward the swamp.

Three in situ fossil corals were sampled and dated from the reef flat cores adjacent to transect 3 (Figures 2b, S1, and S2). Based on the orientation of corallites, high quality of preservation, and gross structure, the corals are interpreted as in growth position. On the outer reef the 0.4 m core penetrated an in situ *Pocillopora sp*. colony (Figure S2c) which is a dominant shallow water reef framework builder in the northwest Pacific [*Hongo and Kayanne*, 2011]. On the inner reef the 0.83 m core penetrated two *Porites* microatolls (Figure S2b). Microatolls are excellent indicators that a reef has reached a confining sea level as they adopt a discoid morphology, when upward coral growth is constrained by prolonged subaerial exposure at low tides but lateral growth around submerged colony sides continues [*Smithers and Woodroffe*, 2000; *Woodroffe et al*., 2012].

3.2. Chronostratigraphy

Fossil *Porites* microatolls on the inner reef flat are 5305 and 5045 cal years B.P. in age (Table S1) and record the age of reef flat development with respect to sea level at this location [*Smithers and Woodroffe*, 2000]. Of note, these corals have elevations of −0.17 m and −0.52 m msl, respectively, which equates to +0.45 and +0.19 m above the modern height of living coral (HLC = −0.71 m msl). In the outer reef core the *Pocillopora* coral yielded an age of 5020 cal years B.P. This coral has an elevation of −0.73 m msl, which is comparable to

contemporary HLC and suggests the outer reef was still in vertical growth mode at this time. Elevations of the fossil microatolls provides evidence that at least the northeastern part of the Jabat reef flat grew to a higher sea level (+0.45 m) ~5000 years ago and subsequently became emergent in the late Holocene (~2200 years ago).

Dates on island materials indicate the formation of Jabat occurred rapidly shortly after, and near contemporaneously, with reef growth above current sea level in the mid-Holocene. The oldest ages of island material include coral gravel in core hole 2 at 4800 cal years B.P. and two corals dated from the conglomerate surface beneath the central island at 4610 and 4655 cal years B.P. The narrow age range of dates from unconsolidated sediments from the central island core and basal samples under ridges indicate the gravel/cobble core of the island was deposited by approximately 4000 years B.P (Figure 2b). Dates on samples underlying the eastern ridge indicate this feature was largely deposited by 3500 years B.P. and has remained relatively stable ever since. The younger date at the top of core 1 (515 cal years B.P.) indicates more recent sediment overwash and reworking. A single date from a core hole in the center of the southern transect (T1) at 3790 cal years B.P. is consistent with ages from the major phase of island deposition and suggests the footprint of the island south of the swamp had accumulated by 3500 cal years B.P. Following this rapid phase of accumulation, the most significant changes in morphology were on the western ridge where the decrease in ages up the core suggests vertical (and marginal lateral) development of this ridge of 3.28 m between 4000 and ~2500 years B.P. along the central transect (Figure 2b).

Radiometric dates from coral gravels and corals from conglomerate platform in the northern section of the island (T5) cluster between 2570 and 1765 cal years B.P., indicating a discrete phase of deposition approximately 2000 to 1500 years after the south. The complexity of ridges in this northern zone indicates multiple episodes of storm deposition (Figure 2a).

3.3. Model of Island Formation

Our morphological, sedimentological, and chronostratigraphic results provide new insights into the timing and mode of formation reef islands in the central Pacific with respect to Holocene sea level change and change in the type of island accumulation. A multiphase evolutionary model is presented that accounts for the depositional and morphological units of Jabat island and their temporal development with respect to established sea level change (Figures 3 and 4). The model shows that the reef flat first attained sea level and was actively developing ~5300 years B.P. (Figure 3a), implying parts of this small reef platform were in keep-up growth mode [*Neumann and Macintyre*, 1985] during the Holocene marine transgression.

Dates on microatolls provide evidence of higher reef platform development (and elevated sea level) ~0.45 m above present approximately 5000 years B.P. These dates provide critical evidence for the onset of the mid-Holocene highstand ~300 years earlier than previously reported, although consistent with the broad timing of the highstand in the Marshall Islands [*Tracey and Ladd*, 1974; *Kayanne et al*., 2011]. Of note, the mid-Holocene highstand is reported to have peaked at approximately +1.1 m above present and was sustained until approximately 2000 years B.P. in the Marshall Islands (Figure 4).

The onset of island formation on Jabat occurred ~4800 years ago across the elevated reef platform during the latter stages of the Holocene marine transgression. Initial island accumulation was characterized by deposition of coarse gravel/cobble sheets that define the footprint of the island and result from the focusing effect of wave process interacting with the reef platform [*Mandlier and Kench*, 2012]. The basal layers of the gravel sheets became cemented forming a conglomerate surface (Figure 3b). Ages on gravels from the island's central core lie within a narrow range from 4800 to 4000 cal years B.P. and indicate island deposition likely occurred shortly after reef flat development (and may have constrained further reef growth). The narrow age range and coarse grade of sediments are significant for interpretation of island formation. First, the narrow age range signifies a period of active reefal production that generated gravel-size sediments. Second, the coarse size range of sediment implies that sediment generation and deposition are likely to have occurred during high-energy storm events. This initial phase of island building occurred as sea level continued to rise to the mid-Holocene highstand (Figure 4).

The second phase of island development occurred 4000–2500 years B.P. during the sea level highstand. Notably, island accumulation during this phase was characterized by finer-sized materials (coarse sand to pebble size) dominated by coral and foraminifera constituents and resulted in two geomorphic changes.

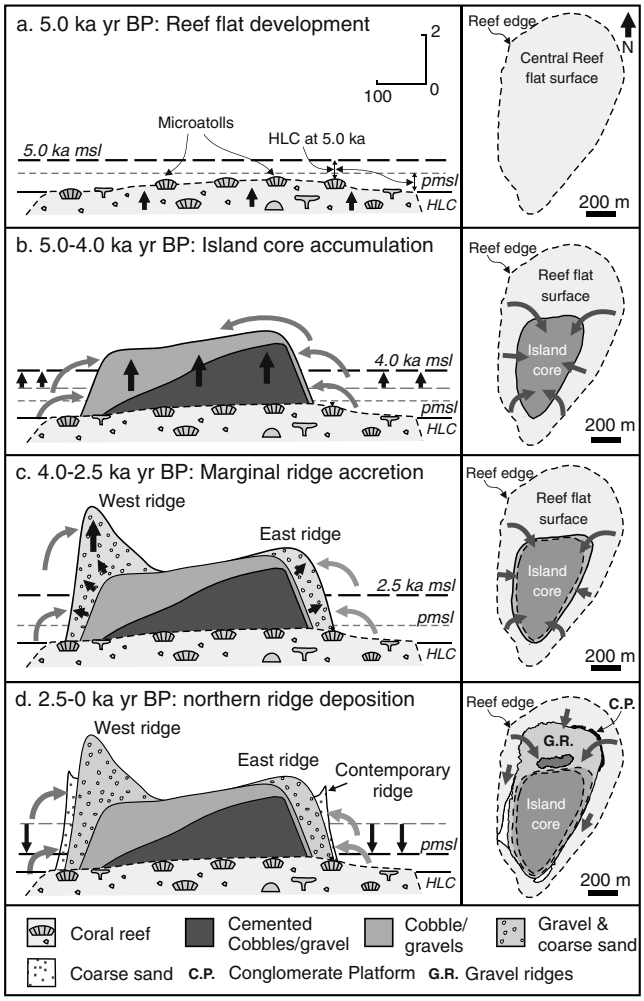

Figure 3. Formation of Jabat Island, Republic of the Marshall Islands, in relation to middle late Holocene sea level change and reef flat development. Dark arrows show direction of movement of the reef, sea level, and island building. Gray arrows convey direction of sediment flux. pmsl = present mean sea level.

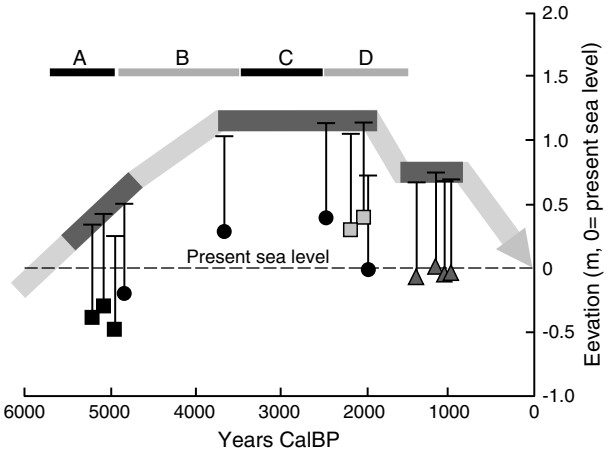

Figure 4. Middle late Holocene sea level change in the Marshall Islands. Black squares are in situ microatolls dated from Jabat Island (this study). Black circles are microatolls and in situ corals from Enewetak [*Tracey and Ladd*, 1974]; grey triangles are microatolls from Arno atoll [*Kayanne et al.*, 2011]; Grey squares are microatolls at Majuro [*Kayanne et al.*, 2011]. (a–d) Phases of development of Jabat Island shown in Figure 3.

First, small-scale lateral progradation of shoreline ridges by approximately 3500 years cal B.P. Second, marked vertical accretion of the western ridge to an elevation of 5.73 m above msl, or 2.5–3.0 m above the elevation of contemporary ridges (Figures 2b and 3c). The high elevation of the western ridge may be explained by two possible factors. First, deposition of finer (sand-size) materials under continued rising sea level conditions (to the mid-Holocene highstand) which incrementally raised wave runup processes above contemporary levels. Second, superelevation of wave runup process on the leeward side of the reef platform due to greater incident wave energy at the shoreline as a consequence of the narrower and deeper leeward reef surface and complete refraction of ocean swell that produces higher runup levels [*Yeh et al*., 1994; *Mandlier and Kench*, 2012]. Significantly, this phase of island development occurred during the latter stages of sea level rise and throughout the highstand.

The last major phase of island development occurred ~2500–1800 years ago with formation of multiple gravel ridges that welded to the island core and impounded the northern swamp (Figure 3d). This phase was coincident with sea level fall from the mid-Holocene highstand to present level and is likely to have resulted from higher-energy episodes interacting with the emerging reef material on the broader subtidal reef platform and generating fresh supplies of gravel and cobble-size material to the reef flat surface. Small age reversals of the gravel within the northern ridge are consistent with reworking during higher energy deposition events. Subsequent to this phase of deposition, the island footprint appears to have remained stable, except for the formation of contemporary marginal island ridges, at lower elevation than mid-Holocene highstand counterparts (Figures 2b and 3d). The contemporary beach on the west and east now actively transfers sand-size material toward and off the southwest tip of the platform. The relative geomorphic inactivity over the past 1800 years is attributed to the reduced supply of coarse sediment on the emergent reef platform, the fact the island occupies a large proportion of its platform surface which constrains further progradation, and the emergence of the reef platform, which has reduced the depth window for wave propagation and effectively closed down the process regime under which the island was formed, thus "fossilizing" the island.

4. Conclusions

Our data presents the first evidence of coral reef island formation in the Pacific during the latter stages of sea level rise in the mid-Holocene and which continued during the period of the highstand (5000–2000 years B.P.). A multiphase model of island development is presented which accounts for discrete stages of morphological development with respect to sea level change and changes in the grade and composition of sediments. Initial construction occurred during latter stages of sea level rise (~4800 cal years B.P.) and comprised sheets of coral gravel/cobble-size material forming the footprint of the island. Phase two occurred during the mid-Holocene sea level highstand with development of the high western ridges composed of coarse sand to pebble-sized sediments. The third phase occurred at, or following sea level fall to present level (~2500 cal years B.P.), abandoning the high island ridge and with deposition of multiple gravel ridges at the northern end of the island.

Our findings are contrary to prevailing theory and show that sea level fall in the late Holocene was not a necessary trigger for island formation in the central Pacific, although it was coincident with island accumulation in a number of examples. Indeed, Jabat Island formed approximately 3500 years before the proposed cross-over date, which has been suggested as a necessary condition for island development [*Dickinson*, 2003]. This new evidence from the Pacific is consistent with evidence from the central Indian Ocean [*Kench et al*., 2005] and combined with other studies indicates that reef islands can form at various stages of sea level change. Our findings suggest that island formation is complex and is likely dependent on the site specific temporal relationship between reef growth and sea level (which controls the depth window for effective wave entrainment and transport of sediments) and available sediment supply as previously proposed from evidence in the other reef regions [*Kench et al*., 2005, 2012]. Our data further suggest that smaller reef platforms such as Jabat may have been the first islands to form in the Holocene as their smaller areal extent may have been more favorable for keep-up growth mode and attainment of sea level earlier than larger reef and atoll systems that adopted a catch-up growth strategy, and more efficient at retaining sediment on the platform surface due to the focussing effect of waves around the entire platform surface. Subsequent sea level fall around Jabat has shut down the process regime, and Jabat has been geomorphically stable for the past 2000 years. The results also imply Jabat should remain stable in the face of projected sea level rise over the next century as (i) the conglomerate platform provides a resistant core to the island and (ii) rising sea level

will raise the elevation of the process regime to levels at which the island was formed during the mid-Holocene highstand.

Our results also have significant implications for anthropological investigations of human migration and colonization of mid-ocean atoll archipelagos. Jabat is the oldest island yet dated from the Marshall Islands, with supratidal deposits forming as early as 4500 years ago. It is possible that islands on smaller reef platforms consistently predate island formation on larger atoll systems and provide the first pedestals for habitation in atoll archipelagos. This observation implies that the temporal window in which reef islands formed in the Pacific may be broader than previously proposed, raising new questions about the patterns and constraints on human migration through the Pacific. Examination of reef platform islands in particular may provide fruitful repositories of anthropological evidence in order to refine the chronology of human colonization of archipelagic regions in the Pacific.

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