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Facies development model for emergent Holocene reef limestone: Southern Marianas Region.

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Abstract—Depositional and relative sea level histories of emergent ("two-meter") Holocene reef limestone along the shoreline of Rota (Mariana Islands) are reconstructed from detailed facies descriptions. Radiocarbon-dated corals and facies parameters are used to determine absolute timing and rates of developmental events. Major facies (I: Coral Framework; II: Algal Bindstone; III: Backreef Detritus) are exposed in the present reef flat as buttresses and algal ridges. The deposit is interpreted as a shallow-water fringing reef which began to develop on a pre-Holocene limestone substrate following a rise in sea level ca. 5500 BP. Facies I accreted vertically under moderate-to-high energy, rising sea level conditions until corals reached the water surface ca. 4700 BP; calcareous algae in Facies II then encrusted these corals under reef crest conditions as sea level approached highstand, which may have reached +3m to +5m (relative to modern MSL). During the subsequent relative sea level fall, which exposed buttresses by 2800 BP, younger corals and algal ridges developed seaward. These events produced a laterally adjacent pair of shallowing-upward facies sequences: an earlier, shoreward sequence (buttresses) corresponds to the rising sea level; a later, seaward sequence (algal ridges) corresponds to the subsequent fall. This is significant to carbonate depositional studies, because successive shallowing-upward facies in the geologic record are usually considered to develop in vertical order and only in conjunction with rising sea levels. The observed buttress-and-channel system probably represents incipient spur-and-groove development similar to those on living reefs.

Introduction

Emergent Holocene limestone (HLS) deposits crop out sporadically around several islands in the Marianas Group, located between 13 degrees and 21 degrees

N. Latitude in the Western Pacific. These are coral-algal framework deposits which reach 4m maximum thickness; similar deposits have been reported in other island groups in the Western and S.W. Pacific, e.g., Cook Islands (Ida et al. 1986). Geologically they are significant for at least two reasons: 1) their existence on three major islands at the southern end of the Marianas Arc—Guam, Rota, and Saipan—gives them a key role to understanding regional Holocene shallow marine sedimentation; 2) locally, their presence indicates a Holocene highstand of relative sea level above modern sea level position.

The HLS chosen for this study lies along the northern and northwestern coast of Rota, where Holocene-age outcrop coverage exceeds that of Guam and Saipan combined. Rota, located approximately 48 km NE of Guam, is the geologically least-known of these three islands. The objectives of this paper are to 1) describe depositional facies of the HLS on Rota in detail and interpret their environments of deposition, 2) reconstruct the probable sedimentary and relative sea level histories of the deposit in absolute chronological terms, and 3) discuss the significance of the facies sequences found. It is hoped that the findings provide a comparative model for the analysis of similar deposits elsewhere within and outside the Marianas Region.

This paper is based on M.S. thesis research by S. Bell (1988), carried out as part of a comprehensive program at the University of Maryland, College Park, to study reef limestone development in tectonically active basins such as those found in the Marianas. An extensive discussion of HLS marine diagenesis on Rota is planned for future publication. Descriptive limestone terms used in this paper are based on the classification systems of Dunham (1962) and Embray & Klovan (1971).

Geologic Background

SOUTHERN MARIANAS AREA

"High" islands (previously named) at the southern end of the Marianas Arc consist of Eocene- to Miocene-age cores overlain by younger reefal limestone sequences, now emergent up to several hundred meters (present Mean Sea Level (MSL) datum). The presence of multiple marine terraces on these islands implies that emergence occurred in stages which alternated with periods of to-sea level reef development. This has resulted in a "lateral" stratigraphic pattern which places younger limestones at lower elevations.

HLS in the Marianas has long been recognized from coastal outcrops along northern Rota (Sugawara 1934) and from southern Guam (Tayama 1936, 1952). Subsequently, Tracey et al. (1964), Curray et al. (1970), Easton et al. (1978), and Randall & Siegrist (1988) have identified and dated similar reef limestones from intertidal and supratidal outcrops scattered around Guam. Recently, Kayanne et al. (1988) and Matsumoto & Kayanne (1988) have detailed geomorphic features and compiled extensive radiocarbon analyses of the Holocene reefs on Rota. Seventy-four ^{14}C dates on corals, red algae, and *Tridacna*, collectively reported by Easton et al. (1978), Randall & Siegrist (1988), and Matsumoto & Kayanne

(1988) give an average estimated age of 3080 ± 1150 years BP for Holocene limestone of Rota and Guam. Estimates taken from the same coral genus at specific locations give an average age of about 3500 years per site.

ROTA ISLAND: HLS STRATIGRAPHIC FRAMEWORK

Rota is located at 145° 12′ 30″ E. Longitude and 14 ° 8′ 30 ″ N. Latitude and has a surface area of 82.4 km^2 (see Fig. 1). Its flat summit at 469m (MSL) elevation and seven to nine levels of terracing result in a "wedding cake" configuration; the lowest terrace level is the "two-meter surface".

In a reconnaissance-level geologic report of the island, Sugawara (1934) briefly described a unit under the name Mirikattan Limestone (see Fig. 3); this is probably the HLS of the current report, but Sugawara (1934) presented no formal type section, and Japanese place names have since been replaced by those of the local culture. In the current study, two different types of limestone appear to alternate along Rota's northern shoreline immediately beneath the HLS: a cobbly-weathering reefal unit and one consisting of well-cemented fossil debris of coarse sand size. These may be the same as Sugawara's (1934) Rota Limestone and Raised Beach Deposits, but their exact stratigraphic relationships were not determined. Dates by Ida et al. (1984) for corals from a notch in the underlying unit shown on Sugawara's (1934) map as Rota Limestone range from 16,000 to

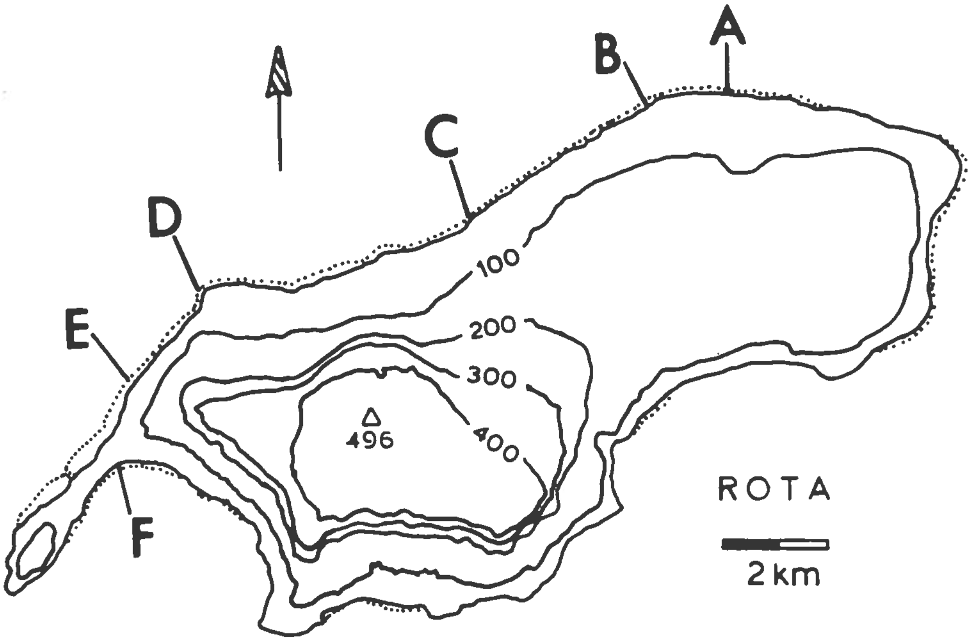


Figure 1. Rota Island, showing 100 m elevation contours (MSL datum), present reef margin (dotted lines), and sampling transect locations (lettered). Study area consists of the reef flat, where the Holocene limestone (HLS) is exposed, along the northern coastline and in the southwestern embayment (around Loc. F.). Scale is approximately 1:125,000.

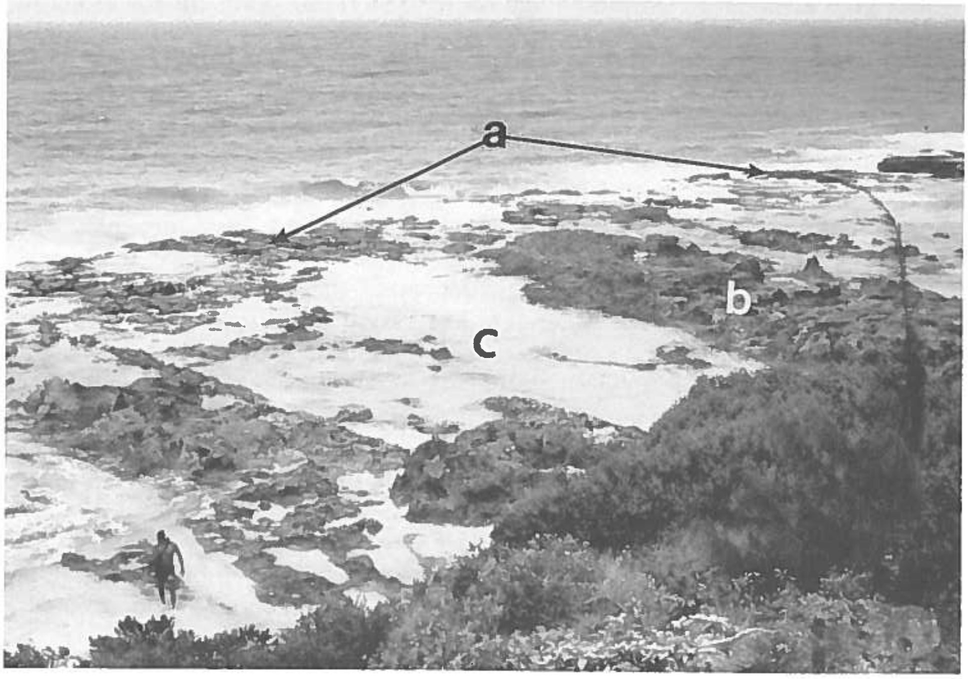


Figure 2. Oblique view of a typical portion of the reef flat within the study area. Shown are examples of a buttress (b), channel (c), and the algal ridge (a) (on the reef margin). Reef flat is 100 m wide here. (Near Loc. F.)

32,000 BP. Thus, the underlying rock in the current report is referred to as simply "older substrate limestone" (of later Pleistocene age?). Shoreline cliff remnants of this rock at many locations within the study area contain a pair of horizontal marine notches centered at ca. 2.5m and 5.0m (MSL) elevation, respectively; each appears to average ca. 1.0m high by deep. Sugawara's Recent Limestone consists of beachrock, considered in the present study to be a shoreward facies of the HLS.

Most of the HLS on Rota appears concentrated along the northwestern coastline, where it crops out semicontinuously from NE to SW ends of the island and into the SW embayment shown on the map; this constitutes the current study area (see Fig. 1). The study is limited to the supra- and intertidal portions of the HLS, which may well extend beneath present sea level and the living coral cover on the modern fringing reef. Radiocarbon ages reported by Ida et al. (1984) for corals from these outcrops range from 2640 ± 140 BP to 5010 ± 100 BP; this shows the deposit to be of middle-to late Holocene age.

Overall Description of the Deposit

OUTCROP DISTRIBUTION AND MORPHOLOGIES

HLS and substrate limestone, both irregularly veneered with patches of modern coral, algae, or bioclastic sediment, form the ca. 100 m-wide reef flat complex

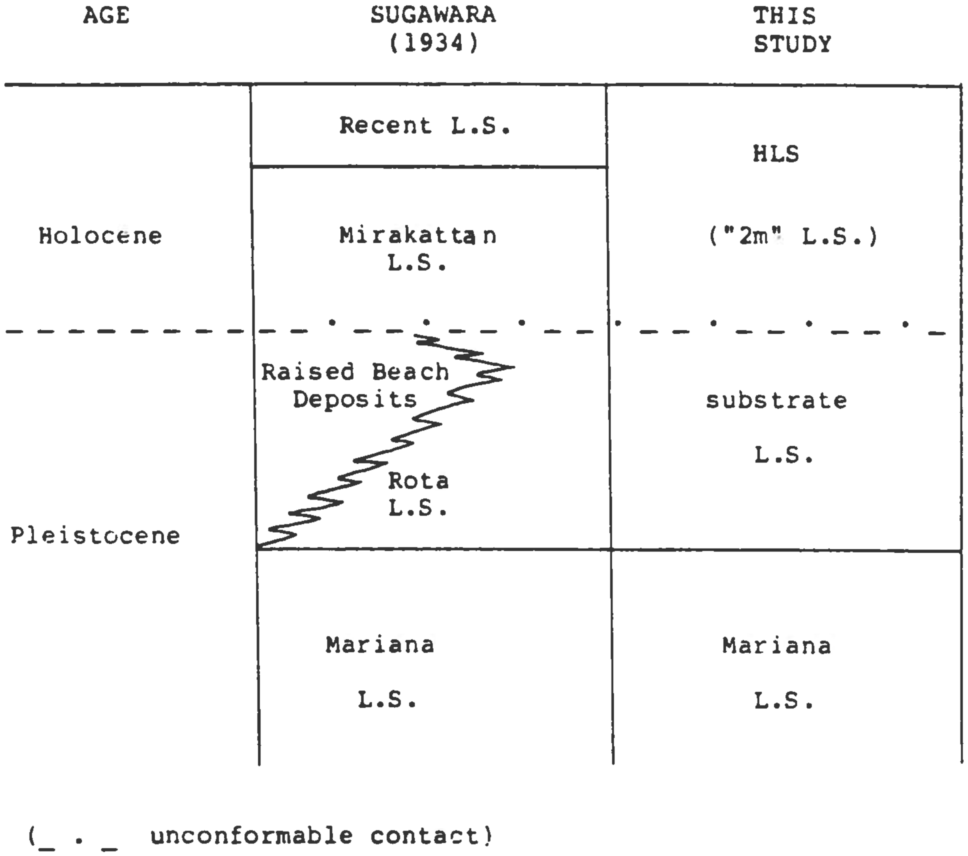


Figure 3. Stratigraphic framework in the study area: Sugawara's (1934) nomenclasure *vs.* that used in the present study. (HLS: Holocene Limestone)

in the study area (see Fig. 2). The HLS crops out in two distinct topographic forms: buttresses, usually located toward the landward margin of the reef flat, and in an algal ridge seaward of the buttresses in the modern wave impact zone. The buttresses are presently erosional, although they probably formed by other processes; intervening channels are sub- or intertidal and expose the substrate limestone. Scattered Holocene corals are attached to the substrate limestone surface between seaward ends of buttresses and the algal ridge at many locations.

Individual buttresses are elongate perpendicular to shore and have gently seaward-sloping profiles; average elevation of their tops is around +2.5m, they range in width from one to ten meters, are as much as 100m long, and coalesce laterally at some locations. Intervening channels are parallel to long axes of buttresses and frequently traverse the reef flat to intersect the algal ridge and open to the sea (see Fig. 2). Where the substrate limestone rises into a cliff at the shoreward end of the reef flat, buttresses "patch into" the cliff and fill voids, including horizontal marine notches.

GENERAL LITHOLOGIC CHARACTER AND SUBSTRATE CONTACT

The HLS consists mainly of massive, in-situ coral and algal framework limestone which is well-preserved and filled with varying amounts of bioclastic detritus. Only the beachrock shows good stratification. Fresh surfaces are consistently spotted red with *Homotrema rubrum* tests.

Substrate limestone appears in two varieties: 1) well-sorted foraminiferal-*Halimeda* grainstone and 2) molluskan-coral rudestone/floatstone. Fresh surfaces usually show calcite cleavage sparkle, indicating recrystallization. The HLS-substrate contact is difficult to discern in weathered outcrop; red spotting and lack of crystalline sparkle distinguish HLS from substrate in the field. The contact surface undulates upward under buttresses and downward in channels. Substrate grains clearly truncated at the contact and incorporated in the HLS matrix several cm above it (see Fig. 4) indicate deposition on a mechanically eroded platform—probably a wave-cut bench.

Materials and Methods

Field work was carried out during July and August of 1985 and 1986. HLS and substrate were first mapped on the Rota 1:25,000 topographic base (USGS, 1983). Forty outcrop stations were described in the study area; six of these were chosen for detailed study and sampling (see Fig. 1). A landward-to-seaward transect line was constructed across the reef flat to the present reef margin at each of these locations. Elevations and locations of points on transects were surveyed by rod-and-chain and stadia methods using U.S. Naval coastal markers for control; datum is present-day MSL. Continuous vertical sampling was performed in columns every 20m along each transect by hand-quarrying on open faces; several 2cm drill cores were also taken at transect E. Elevations of samples were recorded to the nearest 0.1m.

Over 200 samples were slabbed, polished, and described with the aid of a low-power binocular microscope. Approximately seventy-five thin sections were prepared from marked slabs and stained with Feigel's Solution and Titan Yellow for petrographic analysis.

In-situ corals selected for age dating were first cleaned in dilute HCl, then determined by thin section and XRD analysis to have an all-aragonite composition and be essentially free of cement and fill. Geochron, Inc., Cambridge, Mass. carried out dating procedures using standard carbonate techniques; age calculations were based on a ^{14}C half life of 5700 years.

Selected examples of whole skeletal material, bioclastic detritus, and carbonate cements were analysed on the University of Maryland's JOEL840-A microprobe for Ca and Mg content using a 20KEV beam voltage. Multiple points measured on larger samples were averaged.

Depositional Facies

Three major lithofacies were identified in the HLS: Facies I: Coral Framework Limestone; Facies II: Algal Bindstone; Facies III: Detrital Limestone.

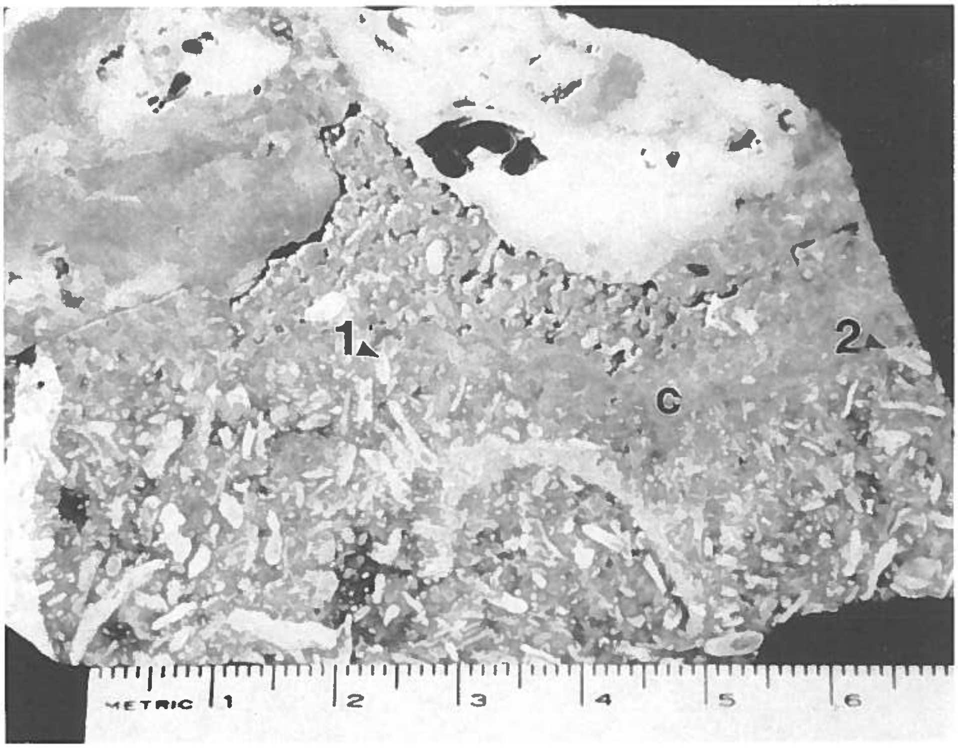


Figure 4. Polished slab of HLS/substrate contact: truncated oval *Halimeda* grains (1., 2.) in substrate surface lie at base of narrow contact zone (C). Granular detritus above 1. is Facies I matrix; large, white coralline algal clast at upper right contains red *H. rubrum* colonies (fuzzy gray patches) and conspicuous vermetid test (dark); gray area left of clast is algal framework encrusting substrate. Other substrate grains include mollusk fragments and foraminifers. Individual scale marks (bottom) are mm. Sample was collected from the base of a buttress at Location A.

FACIES I: CORAL FRAMEWORK LIMESTONE

Description: The coral framework facies constitutes 60–70% of the deposit and forms the bulk of each buttress. It consists mainly of coral bafflestone with lesser coral framestone and algal bindstone identical to Facies II. (see Figs. 5 and 6). In situ colonies of corymbose *Acropora* species dominate the framework and are distributed in an outward-fanning pattern about the long axis of each buttress. At numerous locations, including transects A, B, and D, the lower portion of each buttress just above the substrate is blanketed by framestones of low-convex encrusting corals (usually *Porites* or *Montipora*). Important variations in Facies I framework are: 1) at some locations—including transects A and B—patches showing a greater apparent diversity of corals extend tens of meters shoreward of buttresses; 2) Algal laminites identical to Facies II sometimes occur as mm-

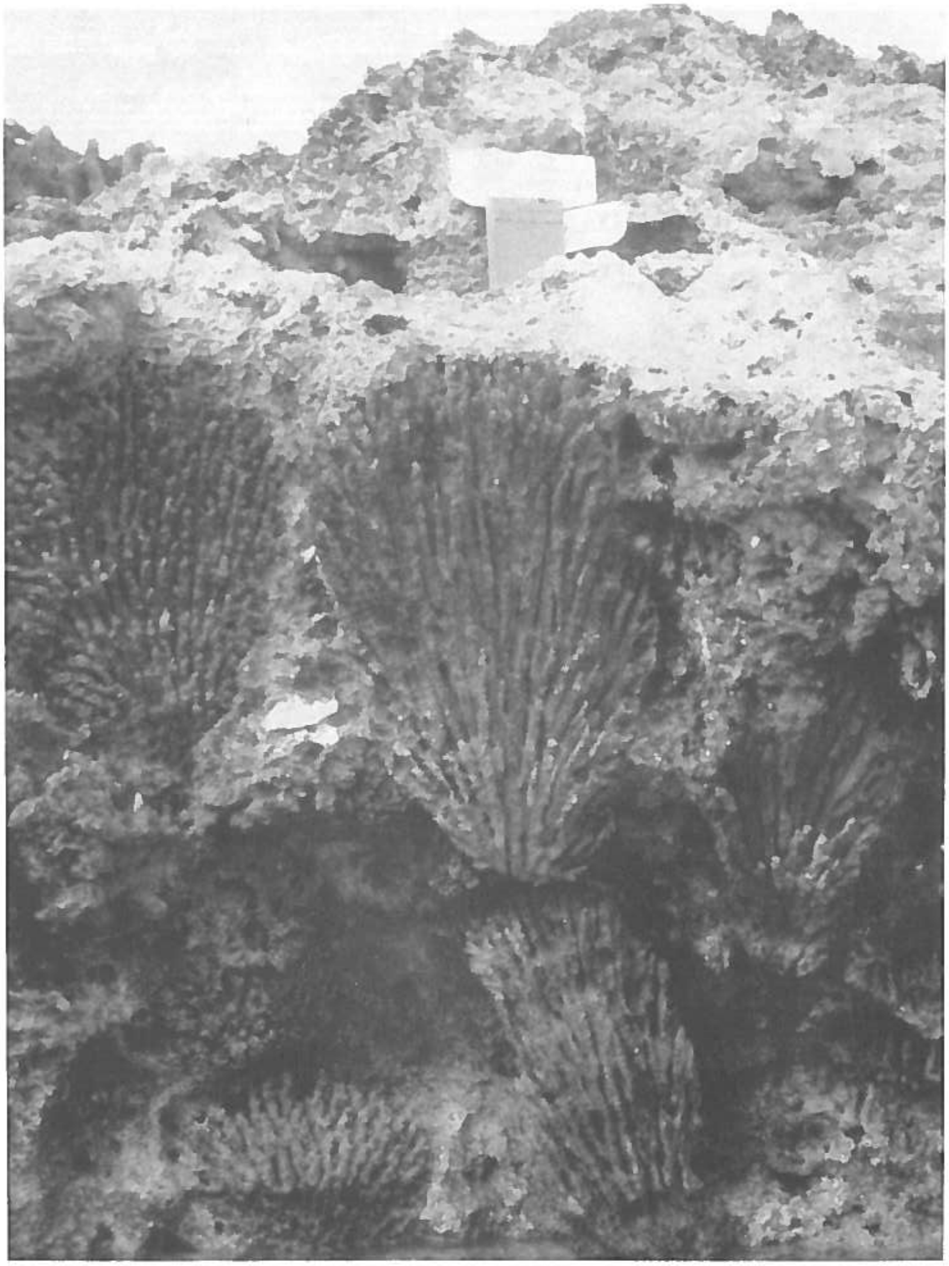


Figure 5. Facies I (coral framework) bafflestone (below) and Facies II (algal bindstone) "cap" appear in the side of a buttress. Bafflestone framework appears dominated by acroporan corals; interstices are filled by well-cemented bioclastic matrix. White rectangle at Facies II level is 22 × 30 cm. (Loc. E., approx. halfway between backreef margin and algal ridge.)

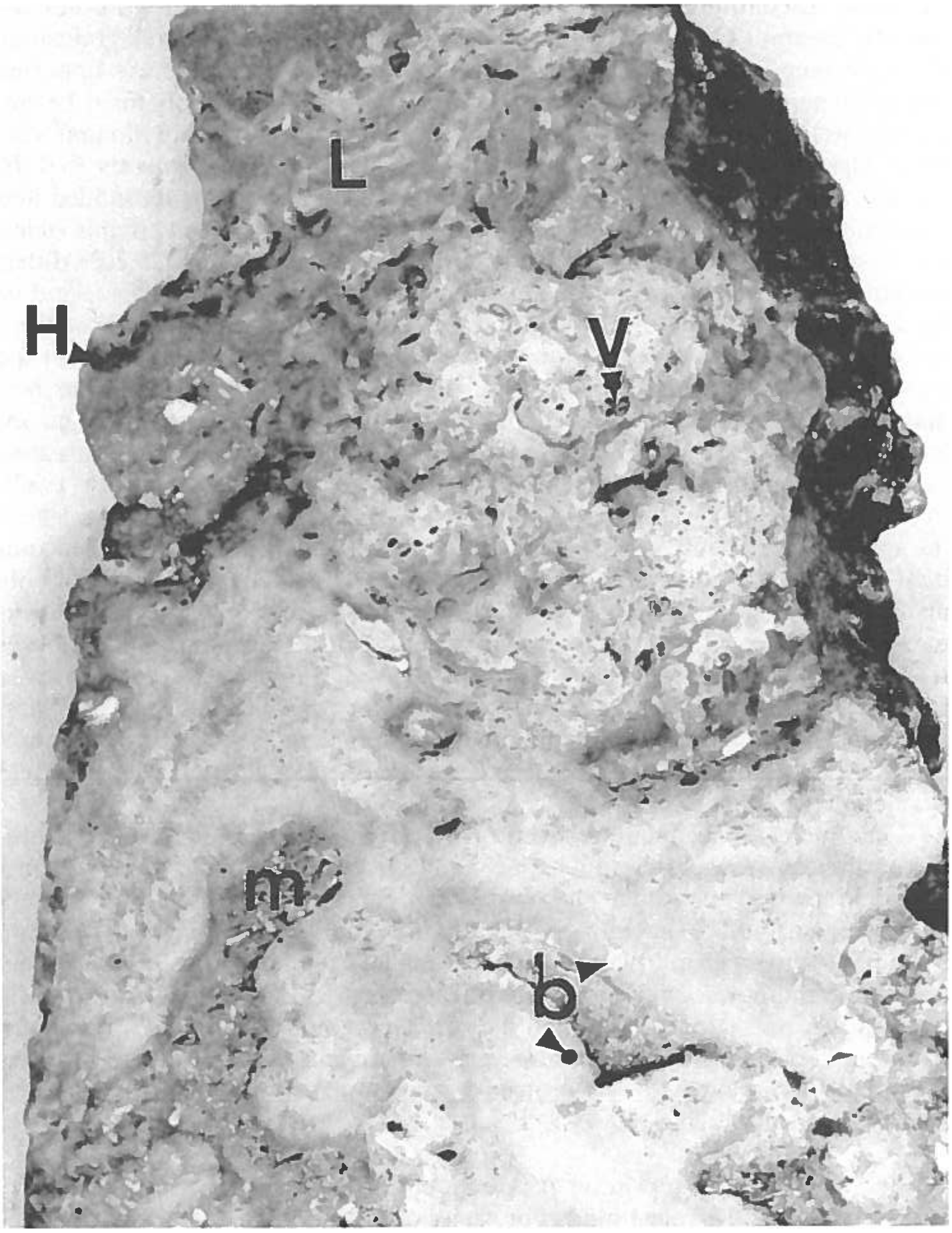


Figure 6. Polished slab showing oblique view through Facies I–II contact: branches of the coral *Stylophora mordax* appear as massive, light areas in the lower half of the photo and are encrusted above by convolute framework of Facies II. Shown in Facies II are examples of alternating light and dark, mm-scale laminae (L), which form stromatolite-like heads at uppermost left, lensatic *Homotrema rubrum* colonies (H) (appear black), and vermetid gastropod tests (V) (small, dark figure "8" shapes). Facies I matrix appears between coral branches (see text for description). Circular, filled and unfilled borings just inside outer growth surfaces of coral appear at and below b. Middle of slab is 10 cm wide (Sample from Transcect Loc. E; collection point is 50 m from backreef margin and +2.3 MSL.)

cm thick, discontinuous crusts; 3) meter-scale domes of encrusting *Porites* apparently preempt buttresses at Location F. The matrix ranges from a grainstone to a rudestone/floatstone (see Fig. 6); intraskeletal fill shows both mud-supported and grain-supported textures. Petrographic examination shows both to be frequently well-cemented. Sand-size and larger grains consist mainly of coral, coralline algal, mollusk, echinoid, or encrusting foraminiferal fragments (red *H. rubrum* tests are particularly noticable). Grains are angular to subrounded and randomly oriented; no compaction evidence was observed. Porosity in this facies, due mainly to unfilled coral skeletal cavities, may reach as high as 20%. Interpretation: Widespread, in situ organic framework continuous with the island is, by definition, a fringing reef. According to Chappel (1980), the corymbose form and relatively low (*Acropora*-dominated) diversity prevalent in this facies indicate a regime of medium-to-high energy and shallow depths. These conditions best match the upper (i.e. maximum depth 5–8m) reef front environment. This interpretation is supported by 1) frequent report of abundant *Acropora* in this zone in Holocene-modern reefs of the Pacific and Australia (e.g. Hopley 1982), 2) observations that Acropora dominates this zone in modern reefs throughout the southern Marianas, 3) extreme scarcity of *Halimeda* fragments and concomitant abundance of coral and red algal fragments in the matrix—which reportedly distinguishes margin- from backreef facies (Boss & Liddell 1987), 4) detrital texture of the matrix, and 5) the presence of red algal crusts (see interpretation:Facies II). The term "reef core" thus applies to this facies. Lower parts of some buttresses are comprised of the low convex and encrusting forms, which indicate shallowest depths and highest energy possible for corals on Chappel's (1980) continuum. This suggests that corals developed under at-sea level conditions when buttress development began.

The increased population diversity reported in patches shoreward of buttresses indicates, according to Chappel (1980), a more moderate energy regime. Together, lowered energy and shoreward position suggest that these were moated areas, similar to those on Rota's reef flat today. The *Porites* mounds at Location F are high-convex forms, which indicate Chappel's (1980) lowest energy regime. *Porites* mound development is reported in protected backreef areas in Polynesia (Davies & Montaggioni, 1985), and they are a common landward feature in the Holocene reefs described on Guam (Siegrist & Randall 1985). These observations suggest that this location was protected from intense wave action during the development of the HLS.

FACIES II: ALGAL BINDSTONE

Description: The algal bindstone facies constitutes 20–30% of the HLS, directly overlies Facies I., and is present in two main geomorphic forms: 1) the algal ridge and 2) buttress caps. It also directly veneers shoreline outcrops of substrate limestone at some locations up to 4m elevation. Measured thicknesses on buttresses range from 0–1.3m. The framework consists mainly of a three-part assemblage: encrusting coralline algae, which dominate the assemblage, *H. rubrum*, and vermetid gastropods (see Fig. 6). It also contains encrusting foraminifers other than *H. rubrum* and encrusting corals and hydrocorals; the latter two occur as submm-mm lenses or strips surrounded by the more continuous algal and foraminiferal layers (as seen in thin section). As seen on slab surfaces, the framework is crustose, dense, hard, and well-laminated on the mm-submm scale; laminae are wavey and sometimes sharply flexed into mm-dm scale domes or convolutions.

Primary porosity appears extremely low and consists mainly of spaces beneath arched laminae. These range in scale from microscopic to cm; they frequently contain a submicroscopic (< 1–$4 \mu m$) to silt-textured fill of marine carbonate cement, bioclastic detritus, or both.

Interpretation: The three-part assemblage dominating the framework is regarded as a reliable indicator of high-energy, at sea-level conditions (Davies & Montaggioni 1985). The conformable occurrence of Facies II directly above the main coral framework therefore leaves little doubt that this facies developed in a reef crest environment. Framework and other components nearly identical or directly comparable to those of Facies II were reported in algal cup reefs presently developing near sea level under intense hydraulic conditions on the Bermuda Platform (Ginsburg & Schroeder 1973).

FACIES III: DETRITAL LIMESTONE

Description: 10–20% of the HLS consists of a detrital facies, which is distributed in patches along the shoreward margin of the reef flat and ranges lithologically from pure beachrock to coral rudestone-floatstone. The most frequent variety is a partly- to well-cemented rudestone/floatstone with coarse sand- to pebble-size framework clasts representing a wide biological constituency, including frequent *Halimeda* and *H. rubrum* grains. It is "patched into" depressions on horizontal and vertical shoreline surfaces and interfingers with the coral framework facies. Interpretation: Backreef detrital deposits—including beachrock—are common on mature fringing reefs. Material eroded from the "carbonate factory" of the reef and transported shoreward during storms (and, perhaps to a lesser extent, on a daily basis) is the apparent source.

Facies Analysis, Chronology, and Deposition Rates

COMPOSITE FACIES DIAGRAM

A composite profile of the HLS (Fig. 8) was reconstructed from measured transect profiles A–E (Fig. 7); it shows averaged elevations of facies contacts and thicknesses. Time lines were drawn from elevations and radiocarbon dates of selected in situ corals from the most complete transect (A).

RESULTS OF RADIOCARBON DATING

The distribution of coral dates in the present study (see Fig. 9) compares closely with that established by Ida et al. (1984) (range = 5010 ± 200 BP to 2460 ± 140 BP, mean = 3786 BP) for Holocene corals within the study area.

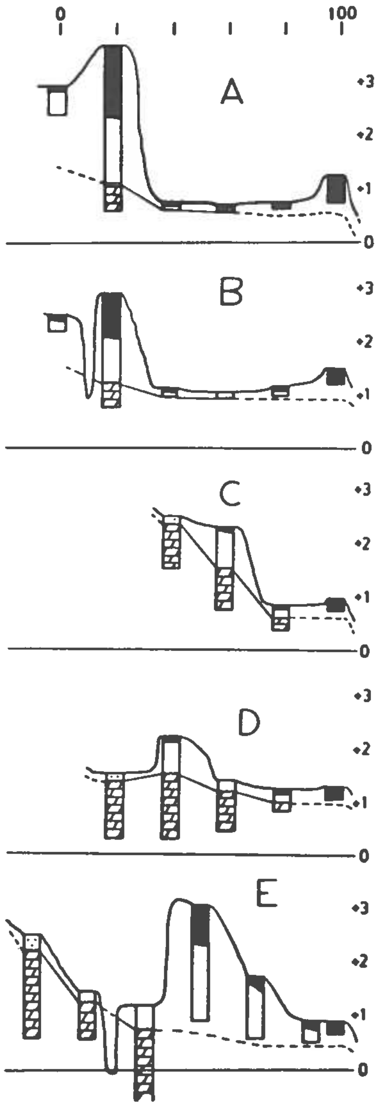


Figure 7. Profile diagrams of measured transects A–E (see Fig. 2). Top scale shows horizontal distance (m) from shoreward reference points to modern reef margin (with algal ridge) (far right). Vertical scales show elevations (m) above datum (modern MSL). Shown are: topographic surfaces, 20 m sampling columns, and HLS-substrate contact. Key to column patterns: plain = Facies I (coral framework LS.); solid black = Facies II (algal bindstone); dotted = Facies III (detrital LS.); brick pattern = substrate LS. Vertical exaggeration = 20.

DEPOSITION RATES

If the average 1.1 m thickness of Facies I in buttresses (see Fig. 8) is constrained within the dates shown (5530 BP–4745 BP = 785yrs.), the average ver-

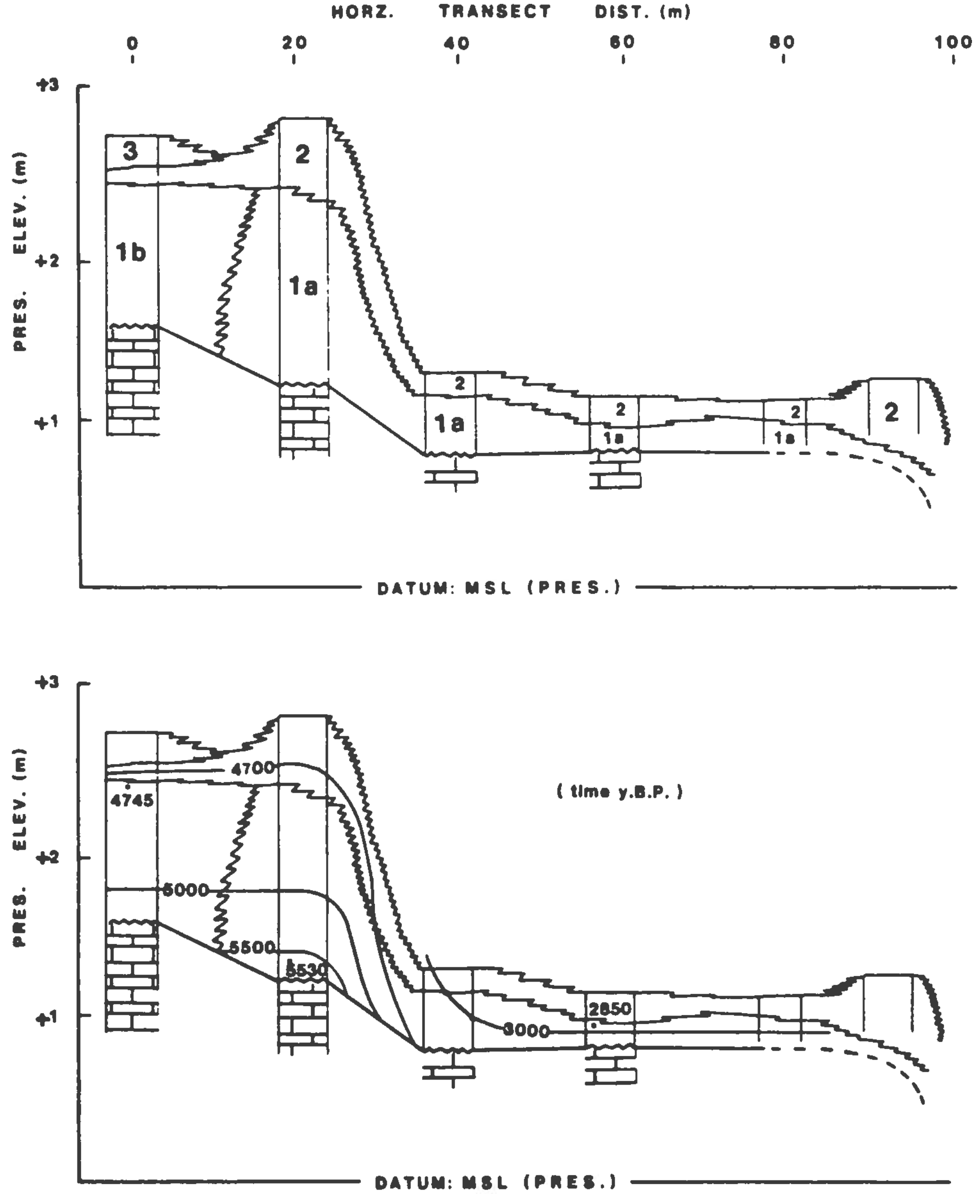
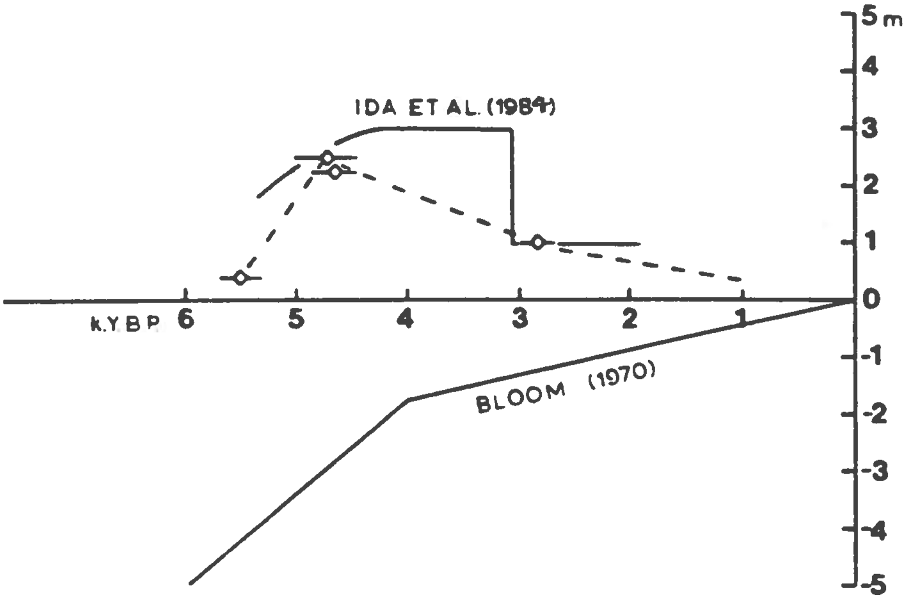


Figure 8. Idealized facies profile of the HLS on Rota. Upper diagram is an averaged composite of measured transects A–E, shown in Fig. 8; 1a = Facies 1, *Acropora*-dominated portion; 1b = Facies I, diverse coral portion; 2 = Facies II; 3 = Facies III; brick pattern = substrate LS. Horizontal scale shows distance (m) from the position of the modern backreef margin (left) to that of the seaward margin (and algal ridge) (right); buttress outline appears centered around the 20 m column. Vertical scales show elevation (m) above datum (modern MSL). The same profile appears in the lower diagram; time lines, which represent isochronous deposition surfaces, are drawn on the basis of the coral date points shown (see chart, Figure 10., for information).



C14 Age* (yBP)	Elev. (m) (MSL)	Loc.	Taxon
2850 ± 160	1.0	A	Acropora monticulosa
4700 ± 200	2.25	E	Acropora monticulosa
4745 ± 285	2.50	A	A. humilis
5530 ± 215	1.4	A	Acropora sp.

*N = 4; $\bar{X}$ = 3813.8 yBP in the present study.

Figure 9. Minimum relative sea level (RSL)/coral growth curve for Rota's northern coastline from the present study (dashed) (table below graph gives information on the four coral date points shown), and from Ida et al. (1984). S.L. curve for Micronesia by Bloom (1970) (as shown in Ida et al. 1984) appears below date scale for comparison.

tical accumulation rate is calculated at 1.4m/1000y. This was the average coral framework growth rate, but it can be used as a crude estimate of the overall rate of deposition for the HLS, because that framework constitutes the bulk of the deposit.

Diagenesis

Thin sections and slabs showed an abundance of well-preserved features associated with marine diagenesis in all three major facies; these features fell into the categories of cement, borings, and infillings. Microprobe analyses of skeletal material and cements revealed no evidence of fresh- or mixed-water alteration in the HLS. Cements are either aragonite or Mg calcite (>4 mole% Mg as $MgCO_3$) in composition. Borings range from microscopic- to cm-scale and frequently contain infill. Infill material, found in both primary cavities and borings, was described in the section on Facies II; this includes material whose chemical/detrital origin has been debated in other reef studies (e.g. submicroscopic (<4μm) carbonate and "peloidal cements" (Macintyre 1977,1985). Complex, multiple-generation boring-and-fill patterns appeared concentrated in a narrow zone at the top of Facies I in buttresses and in Facies II on the algal ridge.

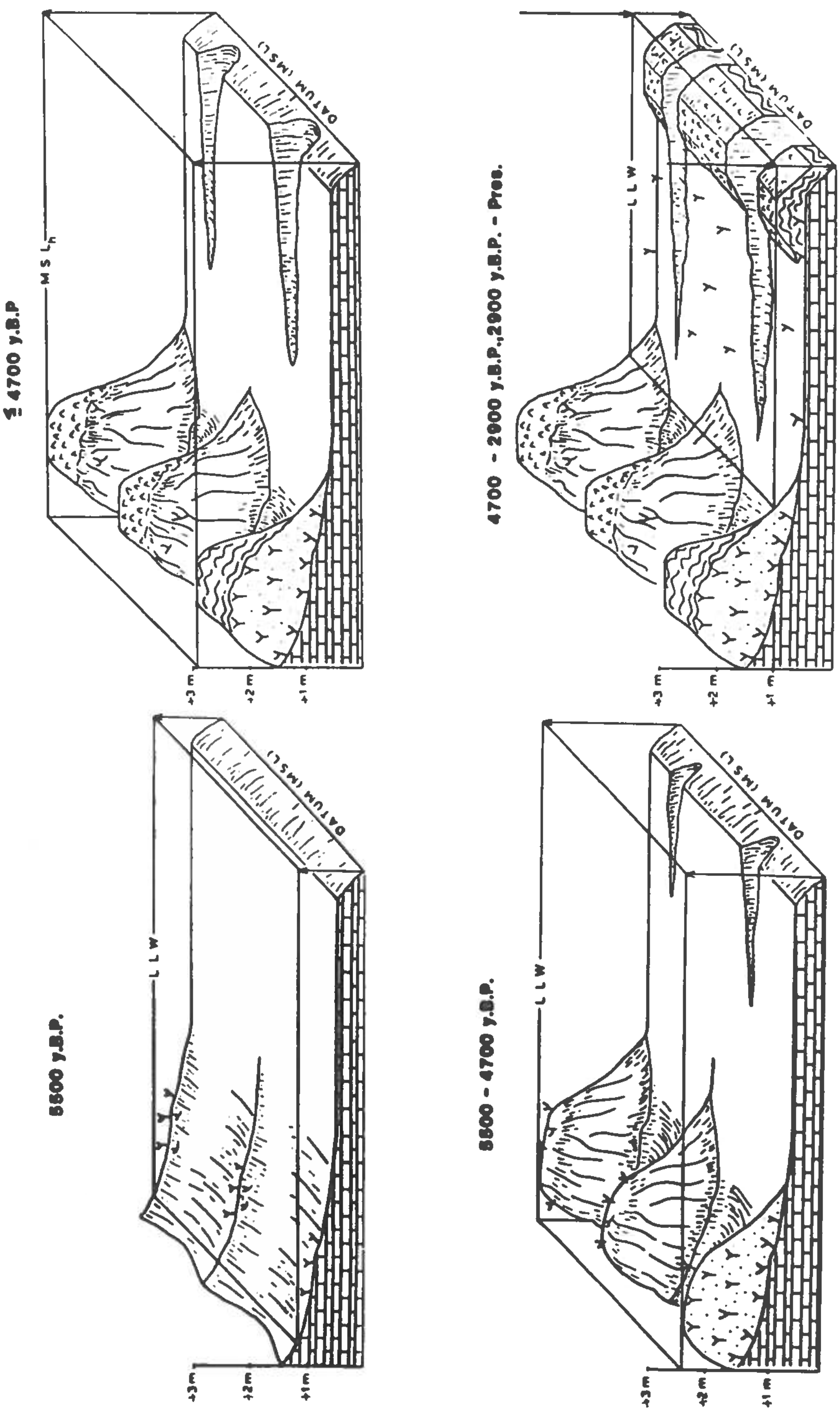
Integrated Depositional Model

The following model is based on information in the previous sections and proposes the sequential depositional development of the HLS and associated RSL activity. Figure 10 depicts the major stages; Figure 9 shows the RSL (Relative Sea Level) curve. RSL direction and estimated position in each stage are based on: 1) Low Low Water level (LLW) as the upper growth limit of corals, and 2) the organic assemblage described in Facies II framework as a reliable indicator of conditions at sea level. Present-day MSL is the vertical datum. Stages are grouped under two major phases: the Transgressive (to-highstand) Phase and Regressive (post-highstand) Phase.

STAGES IN THE TRANSGRESSIVE PHASE

1) By 5500BP, sea level had transgressed a preexisting (Pleistocene?) limestone surface, and corals had begun to colonize on pre-existing highs about 80m behind the present reef margin (Fig. 10a).

2) Between at least 5500BP and 4700BP, coral framework built vertically under constantly rising sea level conditions over those populated highs to produce buttresses (Fig. 10b). Low encrusting corals in the bottoms of buttresses imply that framework initially developed at or near sea level under the highest-energy conditions allowable for corals. Corymbose *Acropora*-dominated framework above indicates that buttress development later continued under the moderate-high energy conditions of the upper reef front environment; algal laminites in the framework indicate proximity to the sea surface. The more diverse coral populations at some locations grew under slightly more protected, perhaps


≤ 4700 y.B.P
M S L
DATUM (MSL)
+3 m
+2 m
+1 m
4700 - 2900 y.B.P.,2900 y.B.P. - Pres.
L L W
DATUM (MSL)
+3 m
+2 m
+1 m
5500 y.B.P.
L L W
DATUM (MSL)
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5500 - 4700 y.B.P.
L L W
DATUM (MSL)
+3 m
+2 m
+1 m

moated conditions behind buttresses. Under more fully protected conditions at Location F, *Porites* mounds grew instead of buttresses.

3) Sometime around 4700BP, sea level rise slowed significantly and Facies I framework on buttresses reached LLW at around +2.5m (Fig. 10b). The dense laminites of Facies II encrusted the top surface of the coral framework under high-energy, sea level conditions, thus forming buttress "caps" (Fig. 10c) which tracked sea level to highstand. Based on the average elevation of these caps, a maximum estimate of Holocene highstand, which probably occurred shortly after 4700 BP, is +3.0m; the presence of the upper of a pair of marine notches in shoreline cliffs (described in the Geologic Background section) suggests the possibility that it may have reached as high as +5m, but it was not determined whether that notch was related to the highstand discussed here. Facies III began to form during this time from bioclastic debris eroded from Facies I and II.

STAGES IN THE REGRESSIVE PHASE

1) Between 4700BP and 2900BP, sea level began to fall from highstand; buttresses became exposed and, by 2850BP, corals had developed on the present reef flat surface seaward of buttresses. Also by that time, the algal ridge began to develop on the present reef margin. (See Fig. 10d).

2) Finally, sometime after 2850BP, sea level fell to its present position. The algal ridge is still under construction, as indicated by its living veneer of Facies II organisms. Facies III continues to prograde.

Discussion

The following observations strongly support the origin of buttresses as constructional forms on topographic highs in the antecedent surface: 1) the contact between the HLS and underlying substrate limestone undulates upward under buttresses and downward under channels; 2) growth axes of corals on buttresses form a radial pattern above the substrate contact in a plane perpendicular to longitudinal axes of buttresses.

Circumstantially, the likeness of their mounded morphology to rounded coral growth clumps presently covering spurs in the upper reef front off Rota

Figure 10. Integrated model depicting the four major steps of HLS deposition on Rota outlined in the text. Block diagrams depict an area ca. 100 m shoreward from the present reef margin position (on right); fronts of diagrams are based on the facies model (Fig. 8.). Vertical scales show elevation in m above datum (modern MSL); arrows show RSL direction. LLW = lowest low water position (at date range shown); MSLh = lowest estimated Holocene highstand MSL; stick figures = corals; knobby/wavy pattern = algal bindstone; brick pattern = substrate LS. Figure 10a. (ca. 5500 BP)—initial RSL rise and coral development. Figure 10b (ca. 5500–4700 BP)—Facies I buttresses reach S.L. Figure 10c (ca. 4700 BP)—algal bindstone encrusts Facies I during highstand. Figure 10d (ca. 4700–2900 BP: 2900 BP–present)—regressive stage: algal ridge development and present S.L. Detrital Facies (III) not shown. See text for details.

(and many other modern reefs) also supports this (compare with Longman 1981, p. 26, Fig. 12A). Thus it is suggested that buttresses and channels of the HLS represent incipient spur and groove structures, respectively. It is conceivable that channels developed by erosion along joints oriented perpendicular to the present shoreline in the substrate limestone prior to initial RSL rise, leaving minor intervening highs available for coral nucleation. A dominant joint set so oriented was observed in substrate exposures at numerous locations in the study area.

Vertically continuous framework in buttresses indicates continuous RSL rise during the transgressive phase. Slightly deeper (maximum 5–8m) conditions interpreted for the upper part of Facies I suggest that RSL rate outpaced accretion rate just prior to 4700BP. Contact with Facies II, interpreted as the truncation of coral development at S.L. (i.e. LLW), represents the horizon at which framework accretion and RSL rates equilibrated. Equilibration must have been initiated by significant deceleration in RSL rise, because there is no reason for an increase in coral growth rate; this supports the shape of the RSL curve (Fig. 9) to highstand.

Therefore, the most important conclusion concerning the Facies I–II transition in buttresses is that it constitutes a shallowing-upward carbonate facies sequence which developed under transgressive conditions. The vertical parameters of this sequence were controlled by the interaction between RSL rates and framework accretion rates preceeding highstand. The same vertical sequence beneath the algal ridge indicates that the same environmental change to reef crest conditions occurred seaward of buttresses; however, younger corals dictate that the transition proceeded there under falling S.L. conditions. The progradation of Facies III onto buttress tops is also a consequence of regressive conditions.

Thus, the HLS on Rota can be visualized as two laterally adjacent shallowing-upward facies sequences. One, situated shoreward, averages ca. 2m thick and represents mid-Holocene RSL rise; the second, situated seaward, averages ca. 1m thick and represents the subsequent RSL fall to present S.L. position. Shallowing-upward sequences in carbonate deposits are usually considered to represent rises in relative sea level, because carbonate production rates (i.e. by calcareous organisms) in warm, shallow sea water under optimal conditions are able to pace meter-scale vertical sea level jumps. Such sequences are frequently described in vertical succession in ancient limestone deposits. The association of a shallowing-upward sequence with falling sea level conditions and the lateral relationship of the sequences in the present study therefore raises the possibility that a portion of those reported in ancient limestones could have formed similarly under the same set of conditions in the past. This is significant to the interpretation of older carbonate deposits and to the history of shallow marine deposition in the Marianas Region.

Conclusions

1. The ca. 2m (average), emergent limestone on Rota's northern coast is a mid- to late-Holocene (5500BP–present) age fringing reef deposit containing: 1) a medium- to high-energy coral framework facies (ca. 1.0–1.5m average thickness)

overlain conformably by 2) a high-energy algal bindstone facies (ca. 0.5–1.0m average thickness) and 3) a detrital backreef margin facies (ca. 0.3m average thickness).

2. Deposition occurred in two successive stages; each coincided with a separate stage and direction of RSL activity and produced different geomorphic forms. In the first stage (5500BP–4700BP), coral framework developed buttresses over shoreward highs on the substrate surface during initial RSL rise; upon reaching S.L., buttresses were encrusted by algal bindstone as highstand (+3 to +5m, modern MSL) approached. In the second stage (4700BP–present), new coral framework developed on the substrate surface seaward of buttresses as RSL fell from highstand; algal bindstone encrusted these corals in the form of an algal ridge as they were exposed.

3. The resulting depositional facies pattern consists of two laterally (shoreward to seaward) adjacent, meter-scale shallowing-upward sequences (coral framework limestone succeeded vertically by algal bindstone). The thicker, shoreward sequence was deposited during rising sea level conditions, while the seaward, thinner sequence was deposited during relative sea level fall. It is thus possible that some shallowing-upward sequences in ancient marine limestones may have developed under falling sea level conditions.

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