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Coral Reef Morphogenesis: A Multidimensional Model

New data from coring and carbon-14 dating provide keys for unraveling some classical enigmas.

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Summary. Windward reef morphogenesis is a dynamic process directly controlled by the growth potential of dominant corals and coralline algae relative to wave energy and sea level rise. Moderate wave energy favors vertically rapid growth that is porous and uncemented; high wave energy favors slow but compact growth. Growth potentials of Caribbean and Indo-Pacific reefs are probably equivalent. Major differences are probably not due to biological or direct climatic factors but are in part related to differing patterns of sea level rise resulting from Holocene crustal adjustment. The nature and position of antecedent foundations developed by high interglacial and interstadial sea levels is especially critical and is largely controlled by regional tectonic factors, especially long-term subsidence.

In 1842 Charles Darwin published his subsidence theory for the origin and development of Indo-Pacific atoll reefs (*1*), and for over a century thereafter the "coral reef problem" remained the focus of attention for reef scientists (*2*). A serious alternative, the glacial control theory, was proposed later, in 1910, by R. A. Daly (*3*). Although all modern workers would certainly accept the critical effect of fluctuating sea levels on Pleistocene reefs, Daly's time scale and concept of erosional leveling of volcanic structures have now been shown to be incorrect. The deep drillings at Funafuti, Bikini, Enewetak, Murora, and Midway (*4*) have established the essential correctness of Darwin's logic as applied to most central Pacific atolls. A relatively new idea, attributing large-scale reef morphology to the development of karst terrane during Pleistocene low sea levels, has been developed primarily in the past several decades (*5, 6*). However, in view of the newer growth data discussed herein, it seems unlikely that this process has general applicability.

A corollary to Darwin's concept of subsidence was the idea that western Atlantic reefs were poorly developed fringes formed on banks of sediment. Davis (*7*), while disagreeing with Darwin with regard to the structure of the banks, concurred with him that modern "Lesser Antillean reefs are mere timid, postglacial novices belonging in the marginal belt of the Atlantic . . . " and "they are very unlike the vigorous veteran barriers of the Pacific coral seas." The geographic magnitude of the barrier and atoll structures and the much greater coral species diversity in the southwest Pacific, nearly eight times that found in the tropical west Atlantic, would seem to reinforce these conclusions. Although knowledge of Caribbean reefs has improved considerably since Darwin's time, that region is still considered depauperate and relatively barren in comparison to the Indo-Pacific, a condition historically attributed to lower temperatures (at present or at glacial maxima) in a continentally affected climate (*8, 9*). The presumed absence of algal ridge development in the western Atlantic (*10*) was considered another indication of inhibited reef development, and Newell (*11*) suggested "the absence of a protective algal ridge at the reef front in the surf zone prevents the development of a solid platform at low tide comparable to the reef flat of Indopacific reefs." Darwin's concept of western Atlantic reefs gained recent support with presentation of the idea that carbonate wall buildup in the Bahamas has resulted from submarine cementation of sediments and that reef framework is unimportant in its construction (*12*).

The belief that the Indo-Pacific atolls present the best examples of reef development, compounded by extensive scientific studies associated with atomic testing, led to much attention being devoted to that area by reef scientists. Indo-Pacific studies are cited more than four times as often as the tropical west Atlantic in Stoddart's 1969 review (*2*). Three modern studies of reefoid carbonate production cited 21 Recent field sites, 18 of which were in the central Pacific (*13-15*). The core of the tropical western Atlantic area was represented by a single site, and that from relatively deep water; yet, it was assumed that the results obtained were generally applicable not only to living reefs but also to the development of fossil reefs (*14*).

Western Atlantic Reef Growth More Vigorous Than Pacific?

During the past 5 years, new data on Holocene reef development have introduced a major element of uncertainty into these conceptions. Soon after wide-ranging field studies were initiated in the western Atlantic, algal ridges were found

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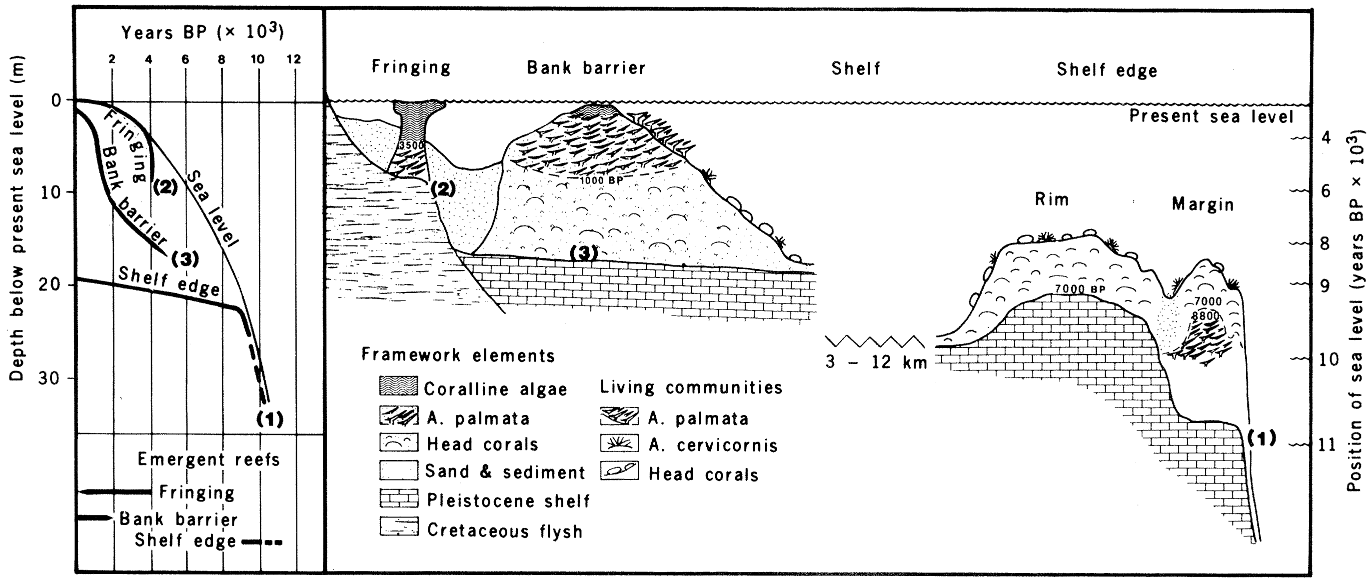

Fig. 1. Idealized section across the St. Croix windward platform showing Holocene reef development relative to sea level rise. (**1**) Sea level reaches bench on shelf edge prior to 10,000 years before present (*BP*). (The exact position of this bench is not known. It is assumed that it coincides with a marked slope break at 33 m, but it may be deeper.) (**2**) Initiation of fringing reef system on shoreline benches approximately 4000 years ago. (**3**) Initiation of bank-barrier reef system on coral head and detrital bars approximately 5000 years ago. [After (*18, 19, 26*)]

in abundance (*16–19*), their distribution being related to the strength and constancy of the trade wind (*20*). Their existence was previously overlooked apparently because of the firmly held belief that they were not to be found. Some small examples had been described in the literature prior to 1971 (*21–23*); however, the structures were always referred to by different terms—terraces, cup reefs, boilers—or by suggesting that they were veneers overlying fossil dunes.

Previously ignored bank-barrier reefs in the Lesser Antilles have now been described and cored (*19*). Another major barrier system, approximately 150 kilometers long, has been identified at 27°N on the northern side of Little Bahama Bank (*24*), an area generally considered devoid of extensive reef development (*12*). The single largest reef complex in the Caribbean area, found on the Nicaraguan Rise (*24*), remains even now undescribed by scientists. Many of these western Atlantic reefs are indicated as elongate shoals on navigational charts that have been available for a century or more, and most of them are clearly visible from the air; yet they have often been dismissed as veneers over older geological structures by the scientific community (*1, 11, 23*).

Recent coring has exposed the fallacy of this judgment, for total vertical Holocene reef accretion in all areas of the Caribbean (*6, 19, 25–30*) has now been shown to be generally more than twice that reported for the Pacific atolls (*31, 32*). The thickest Holocene reef structure now dated (23 to 33 meters) has been recorded at Alacran reef in the southwestern Gulf of Mexico (*30*). These data coincide with the new CLIMAP findings (*33*) indicating little climatic deterioration in the Caribbean, even during the glacial maximum 18,000 years ago (*34*).

Recent estimates of carbonate production rates in modern Indo-Pacific reefs, based on water chemistry, indicate a maximum potential for upward growth of about 3 to 5 m per 1000 years (*14, 15*). Smith and Kinsey (*14*) considered this figure a constraint to reef growth and stated that "It therefore appears from biological, geological, and chemical evidence that coral reef communities as presently comprised would be unable to persist as three dimensional structures if sea level were rising more rapidly than about 3–5 mm per year." A reef now emergent would thus be limited to a total possible accumulation of 12 to 15 m in the Holocene period (*35*), allowing a 500- to 1000-year lag period for establishment on a newly submerged basement. Thus, the actual cored thicknesses of 6 to 15 m in Pacific atoll reefs would seem to fit within this limitation. However, reef growth in the Atlantic, as documented by carbon-14 dating, contrasts markedly: rates of 9 to 15 m per 1000 years have been recorded at a number of Caribbean sites.

It is possible that the atoll systems are not the epitome of Holocene reef accretion in the Indo-Pacific. Although a very extensively cored and dated reef in Hawaii (*36*) has provided data which largely agree in thickness and growth rate with the atoll data cited above, much more limited studies made in other areas of the Indo-Pacific do suggest the possibility of higher rates and accumulations, similar to those found in the Caribbean. A modern reef 20 m in thickness has been reported from a single boring at Reunion Island in the Indian Ocean, and early Holocene growth rates of 10 m per 1000 years have been calculated (*37*). Chappell and Polach (*38*) report an accretion rate of 8 m per 1000 years for an uplifted reef in New Guinea, and the maximum Holocene thickness for the Great Barrier Reef of Australia has recently been suggested to be at least 20 m (*39*).

In any event, these findings seem to reveal a paradox: geographically and morphologically spectacular Indo-Pacific atoll reefs have been growing slowly with little recent increase in thickness, while less extensive systems in the Caribbean are growing rapidly and have achieved greater vertical accumulation. Wainwright (*40*) and Stoddart (*2*) both stressed the importance of differentiating between structural reefs [perhaps best referred to as bioherms (*5, 41*)] and coral communities producing relatively little structure. It appears that there is a major problem in studies of carbonate genesis in reef systems that lies in failure adequately to separate Tertiary or Pleistocene from Holocene structures, in attributing most situations or processes not immediately understood to vague factors of climate, and in the romanticization of the Indo-Pacific and atoll reefs.

Reef Complex on St. Croix: Effect of Shelf Morphology

Studies of an excavated ship channel and over 70 core holes make the extensive late Pleistocene-Holocene reef complex of the Caribbean island of St. Croix one of the better known in the world and a convenient focal point for developing this discussion (*18, 26, 42*).

The reefs on the eastern end of the island consist of three more or less parallel series (Fig. 1): (i) an extensive outer system on the shelf edge, now submerged; (ii) an intermittent series of fringing reefs close to shore; and (iii) a consistent emergent central series, now referred to as the bank-barrier system.

These three reef systems dominated the St. Croix shoreline at different times during the late Pleistocene-Holocene. As sea level rose up the wall of the St. Croix platform prior to 9000 years ago, an extensive *Acropora palmata* reef on the outer margin maintained an accretion rate of 8 to 9 m per 1000 years (*26*). As the rising water broke over the island shelf about 9000 years ago, the rapidly growing upper portion of this reef died. It has been suggested that deteriorating water quality (sediment load, temperature extremes, and eutrophic conditions), resulting from the rapid drowning of a long-exposed shelf, reduced the rate of growth below the rate at which sea level was rising and was ultimately responsible for its demise (*26, 43*). From about 9000 to 5000 years ago, apparently very little reef development occurred on the island of St. Croix. The drowned shelf-edge reef became veneered with deeper water coral species, but major emergent reefs were absent for this interval. As water depth over the shelf increased with the continued rise in sea level, water quality would have gradually improved allowing more rapid reef growth. Numerous shallow benches along the island were inundated from 5000 to 3000 years ago, and fringing reefs dominated by *A. palmata* developed. As yet unprotected by the bank-barrier system, these areas were exposed to the full force of the waves and, as the rate at which the sea level was rising decreased, many eventually developed algal ridge caps. These ridges are now more or less degenerate depending on the degree of protection provided by the younger outlying reefs.

At the same time that fringing reefs were developing, detrital rubble entrapped by a head coral community on the inner shelf contributed to the formation of extensive barlike structures with

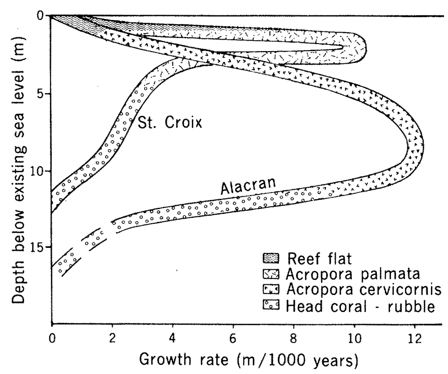

Fig. 2. Upward growth rates of two windward Caribbean reefs as a function of depth at time of growth, dominant frame-building elements, and wave energy. The St. Croix curve represents a medium-high energy reef (dominated by coralline, *Millepora* and *A. palmata*) and is based on 12 carbon-14 dates (*18, 19, 26*). The Alacran curve represents a medium-low energy reef (dominated by *A. cervicornis*) and is based on the data of Macintyre and Burke (*30*).

accumulation rates of 1 to 2 m per 1000 years. From about 2000 to 5000 years ago, with the further slowing of sea level rise and the continued upward growth of this submerged coral bank, an *A. palmata* community became established on the crests and rapidly developed the present emergent bank-barrier reef system (*44*).

While the history of Holocene reef development on St. Croix is complex, and vigorous growth intermittent, no tendency toward climatic inhibition appears. Vertical growth rates that exceed by two to three times the apparent theoretical limit based on water chemistry are recorded from early and late Holocene. The period of least reef development is the mid-Holocene, the time of the "climatic-optimum" (*34*).

Effects of Wave Energy

Complicating the relation between sea level rise and reef development is the effect of sea and swell conditions on the major framework elements. It has been shown for the Caribbean that the crustose coralline algae *Porolithon* and *Lithophyllum* and the scleractinian corals *Acropora palmata* and *Acropora cervicornis* dominate as framework elements in accordance with the degree of wave energy (*19, 20, 45, 46*). Coralline algal communities, often mixed with *Millepora*, are most favored in high-energy zones, but are slower builders of framework [3 to 6 m per 1000 years (*47*)] than the acroporids. Areas subject to the greatest wave energy would therefore show less total accretion than the medium energy acroporid reefs. If one allows for a lag in initiation, accretion of a dominantly coralline reef could only have matched sea level rise for the last 4000 to 5000 years, and maximum thickness should generally be limited to less than 10 m. This has been true on the outer Lesser Antillean islands (*19*) and apparently is so on some Pacific atolls today (*15*).

Under conditions of moderate energy, potential rates of accumulation of framework dominated by acroporid species are considerably greater (8 to 15 m per 1000 years) and could match Holocene rates of sea level rise. However, *A. palmata* can build rapidly only at depths of less than 4 to 6 m, depending on water clarity and light transmission. If one assumes that a marked slowing in reef growth occurred at the time of shelf-flooding, a moderate to high-energy area dominated by *A. palmata* could have become a modern emergent reef only where the antecedent shelf or bank depth is now less than about 15 m (*25, 26*). *Acropora cervicornis* requires less light and can grow at rapid rates at depths of 4 to 12 m. However, it is a fragile coral and can form massive reef structures only where unaffected by destructive wave energy. Under conditions most favorable to *A. cervicornis* growth (light but consistent trade winds or reduced fetch, no extratropical swell, and protection from storm destruction), potential Holocene reef thickness appears to be 20 to 30 m (*46*). Rates of upward growth of reef surfaces relative to energy conditions, as documented by coring of two Caribbean reefs, are shown as a function of water depth in Fig. 2.

Similar coralgal (coral and coralline algae) associations relative to wave energy occur on Pacific reefs (*48*). Although the comparable building rates are not known, the basic similarity of coralgal morphologies in corresponding zones suggests that their accretion potentials are probably similar. Tracey (*34*) states that vertical reef growth at Enewetak reached 10 m per 1000 years from 7000 to 6500 years ago, and that the framework was dominated by coral. The position of these corings suggests that this growth probably occurred in a back reef area behind an algal-dominated reef crest that was about 5 m below present sea level and growing at 4 m per 1000 years, the rate of sea level rise at that time. This interpretation appears to agree with the recent work of Smith and Harrison on Enewetak (*15*) showing a much lower accretion rate for the upper windward

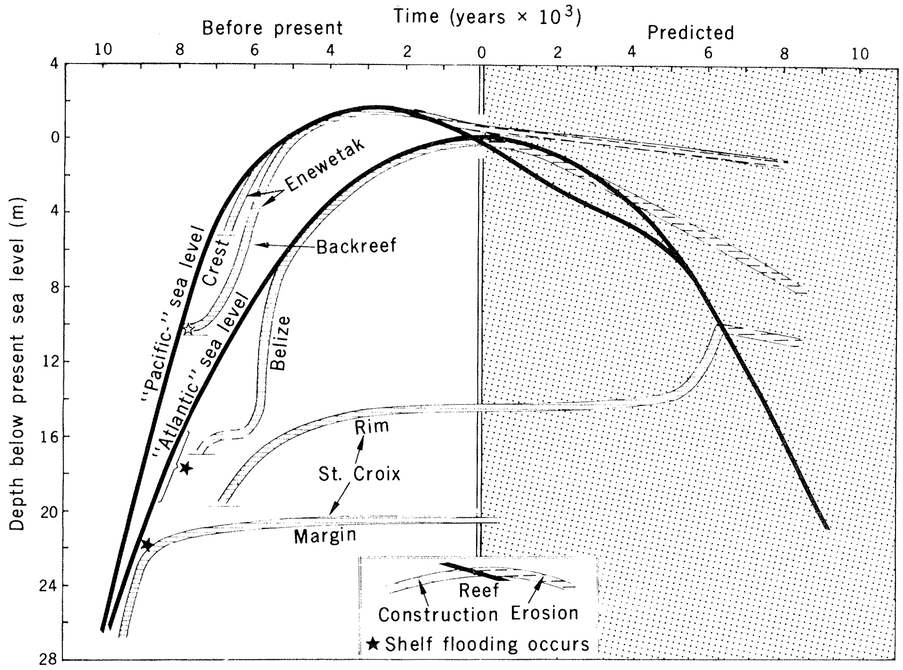

Fig. 3. Growth in Holocene time of "type" reef surfaces relative to their associated sea level curves (*53*). The growth patterns for the Belize and St. Croix reefs are derived from the curves for growth rate, wave energy, and depth given in Fig. 2 and from coring [(*6, 27, 28*) and (*18, 26, 42*), respectively]. The Enewetak reef growth pattern is derived primarily from Tracey and Ladd (*31*) [see also (*49*)].

slope having an acroporid coral cover of only 10 to 15 percent [see also (*49*)].

Some shelf environments, lacking marginal reefs, favor the formation of banks of coral and detritus. These provide foundations raised above the surrounding platform and, at least in the more protected western Caribbean, *A. cervicornis* can develop on such banks, ultimately producing reefs as much as 25 to 33 m in thickness (*30*), with or without succession by *A. palmata* nearer the surface.

Effects of Deglaciation

Massive framework production by reef-building corals and coralline algae requires light and is restricted to a relatively narrow band close to the sea surface. Under a regime of fluctuating sea levels extensive growth can occur only during periods of rising sea level. Thus, the intervals of deglaciation during the 3 to 5 million years of the latest Neogene and Pleistocene are most critical to reef development.

During deglaciation, shorelines are subject to a complex process involving both eustatic change (sea level relative to the earth's center) and crustal adjustment because of the shift in ice and water loading. It has generally been accepted that ice cap melting caused significant crustal readjustment in high latitudes and the eustatic pattern of sea level rise was greatly modified relative to certain shorelines. However, in spite of evidence to the contrary [for example, see (*50*)] it has often been tacitly accepted that the tropical Atlantic and Pacific should have similar relative sea level rise.

In a series of papers over the past decade, starting with Bloom (*51*), Walcott (*52*), and Chappell (*53*) and culminating in the numerical, multipoint loaded viscoelastic model of Clark *et al.* (*54*), it has been shown that sublatitudinal differences in apparent sea level patterns are to be expected. While the fit of actual curves to the model (*54*) indicates that further refinement is required, the basic differences between tropical western Atlantic and southwestern Pacific, as shown in Fig. 3, have now been predicted by a theoretical approach.

Bloom, Walcott, Chappell, and Clark *et al.* (*51-54*) also postulated a relatively long-term crustal adjustment (continental hydroisostasy) which should express itself primarily in postglacial elevation of continents relative to adjacent ocean areas. According to this theory, the sea level curves of lower latitude continental shores should show several meters of late Holocene emergence, whereas oceanic islands should show a curve largely dependent on their latitudinal position. However, irrespective of their continental or oceanic association, all well-documented curves of the southwestern North Atlantic (outside of rebound areas), Caribbean, and Central America are of the continually submergent (Atlantic) type, whereas most curves from the southwest Pacific [however, see (*55*)] are of the "Pacific" type, showing late Holocene emergence. This suggests that continental hydroisostasy is not operating within the Holocene time frame.

Irrespective of the problems remaining to be solved in modeling patterns of sea level change due to ice cap formation and melting, it seems clear that major portions of the two predominant reef building regions of the earth, the Indo-Pacific and the Caribbean, have different relations to sea level resulting from deglaciation. These differences are probably consistent throughout the Pleistocene and probably have considerable significance with regard to reef and carbonate platform construction.

A Model for Late Cenozoic Reef Building

The dynamic process of reef growth, governed by the height and form of the antecedent carbonate surfaces, the growth potential of the coralgal biota, and wave energy is interpreted in Fig. 3 for three representative platform rims relative to their associated sea level curves: (i) a relatively deep shelf rim (22 m below present sea level) under moderately high-energy conditions (St. Croix); (ii) a shelf rim of intermediate depth (16 m) under moderately low-energy conditions (Belize); (iii) a shallow shelf rim (10 m or less) under high-energy conditions (Enewetak). The form of the reef growth curves has been estimated from the community growth rates shown in Fig. 2. Figures 2 and 3 together constitute a model for Holocene reef morphogenesis. The major difficulty in application of the model to specific cases lies in the determination of the lag time or inhibition of reef growth resulting from shelf flooding. At depths greater than 10 to 20 m, a major shelf rim is likely to experience a significant period of minimal reef growth (1000 to 2000 years). High rims or those on narrow shelves under less than 10 m of water should show no appreciable lag if conditions are otherwise suitable for reef growth. Other cases should show intermediate lag times.

The model explains why the volume of Holocene reef accretion on the Belizean outer barrier under medium low energy conditions has been 5 to 6 times greater than that on the St. Croix submerged shelf rim. However, it appears that much of the Belizean accretion is poorly consolidated and weakly cemented sediment

(27, 28) compared to the very solid and often heavily cemented St. Croix rim (26). When exposed by falling sea level, the rate of degradation under subaerial conditions will probably be greater in the Belizean barrier compared to the St. Croix rim. An attempt is made to show that difference in the predicted interval of falling sea level in Fig. 3. Although the volume of accretion at Enewetak (allowing a crest width of roughly twice that at Belize) is about equivalent (49), this high-energy reef is likely to be much more resistant to erosion and a slower rate of subaerial degradation expected following exposure.

The model presented herein for reefoid carbonate rim development during the Holocene has been extended through the latest Pleistocene in Fig. 4. Climatic fluctuations of the Pleistocene are now regarded as cyclic and probably caused by characteristics of the earth's orbit and axial tilt (56), and the most recent interglacial cycle (from about 120,000 years ago to present) should approximate the repeated fluctuations of the Pleistocene. Thus, it is now possible to begin the formulation of testable hypotheses for the development of carbonate platforms during the entire Pleistocene.

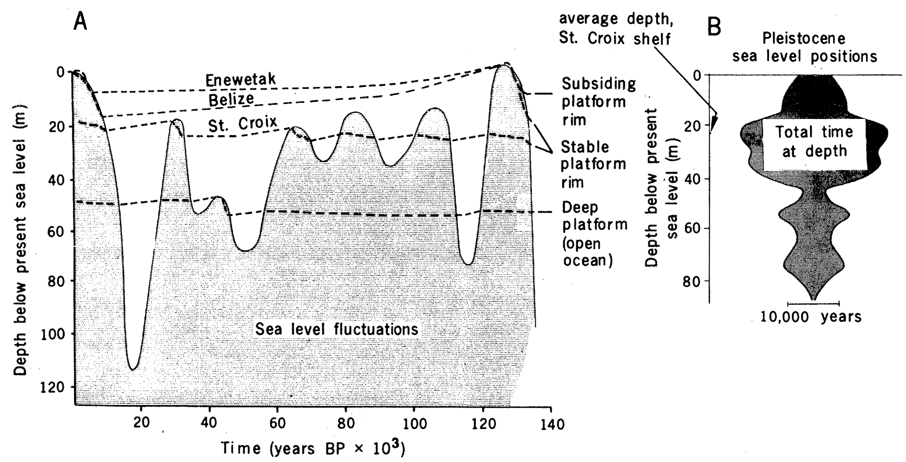

Fig. 4. (A) Patterns of reef accretion on "type" reef-platforms for one interglacial-interglacial cycle (56). (B) Cumulative sea level curve [based on (A)]. The total time that sea level has been 5 m above any given position. The "stable" platform designation applies to geological situations that have not experienced long-term subsidence rates greater than 15 to 20 m per million years.

Reefoid Carbonate Platforms

It is generally accepted that mid to early Tertiary climate was warmer than that in the Pleistocene or Holocene, that continental glaciation was absent, and that sea levels were 60 to 100 m higher than at present (57–59). The major ice sheets that developed in the late Miocene-Pliocene (60) apparently formed swiftly and sequentially, resulting in a stepwise drop in sea level with the progressive glaciation of East Antarctica, Greenland, and West Antarctica. The alternate formation and breakup of the Laurentide, Scandinavian, and perhaps West Antarctic ice sheets was apparently responsible for the more or less regular oscillatory patterns of the Pleistocene.

The rate of sea level fall in the Pliocene is not known, but the scarcity of Pliocene reef deposits suggests that the drop was probably rapid (61). If the east Antarctic ice sheet formed at a rate comparable to that of the Laurentide ice sheet, the 60-m sea level drop in the latest Miocene or early Pliocene probably occurred on a scale of tens of thousands of years, or effectively at a rate of one or two orders of magnitude faster than the subsidence rates of atolls and other major carbonate platforms (4). Early Tertiary carbonate platforms that were subsiding at 20 to 30 m per million years would initially have been exposed by the generally falling sea levels of the late Neogene. However, by late Pliocene time, these surfaces would have subsided to the then existing sea levels, permitting additional vertical growth on the rims. Although some lateral growth on these platforms might have occurred, these marginal areas would gradually have been submerged. Vertical rim building on such platforms during the Pleistocene would have been intermittent, occurring only at the highest (interglacial) sea levels, and subject to erosion during the long intervals of exposure. We now live in an interglacial period, during one of the less frequent periods when subsiding atolls are adding a small increment of growth. During much of the Pleistocene, however, most atolls would have stood above the sea, barren of active reefs except for minor amounts of marginal growth on their steep flanks.

In the case of carbonate platforms formed in nonsubsiding areas, the early Tertiary accretion would have remained above all subsequent transgressions, with new carbonate building proceeding peripherally around the platform flanks. During the sea level oscillation of the Pleistocene, carbonate building in high-energy areas would coincide with mean high sea level, because of the slower growth of reef-building organisms in those areas and the inhibiting effects of shelf flooding. As shown in Fig. 4B, the mean of the highest sea levels at each interstadial would lie about 22 m below its present position (at about the present depth of the St. Croix shelf).

In areas experiencing medium to low wave energy, nonsubsiding platform rims could potentially grow to the height of interglacial sea levels. However, the resultant structures are probably not as resistant as high-energy structures to subaerial degradation during periods of lowered sea level. Whether these rims, by repeated interglacial addition, will eventually build a "solid" foundation at interglacial levels or prograde seaward to create a multiple system of crests (such as the Belize Barrier?) probably depends largely on adjacent water depth (61).

The apparent correlation between deep lagoons and the "Pacific" type sea level curve is striking. There is a direct relation between atoll size in the southwest Pacific and lagoon depth, small atolls tending to be "filled in" (62). However, mean lagoon depth does not continually increase with size for atolls larger than approximately 25 km, but levels out at about 65 m, the maximum known depth being about 110 m. Although the total carbonate accretion of many atolls is apparently 400 m in thickness, similar lagoon depths are not known. Calculating from a mean subsidence rate of 20 to 30 m per million years (4) for a period of 3 million years (59) the rims of larger atolls would consist largely of Pleistocene accretion. Subsiding carbonate platforms and atolls at least as old as their Pacific counterparts are known in the western Atlantic. However, lagoons are not deep. Possibly the very broad reef flats that develop under the sea level pattern of the "Pacific" type reduce lagoonal circulation and carbonate accretion.

MacNeil (5) and Purdy (6) developed the concept that modern reef relief, particularly the raised platform rims, is derived primarily from the karst topography of antecedent surfaces exposed to subaerial solution at each drop of sea level. Not only would the magnitude of the features discussed here require considerable erosion, there would seem to be no obvious difference between the character of the limestone foundation or rainfall of the Caribbean compared to the deep lagoons of the Indo-Pacific, or between the emergent rims of Caribbean atolls and the submerged rims of Caribbean banks. The documented rates of reef growth for the Holocene are sufficient to have produced virtually all reefoid rims, even with subsidence and erosion of the rim between intervals of high sea level. Macintyre and Glynn (*25*), in a series of holes across a mature reef system in Caribbean Panama, were able to show that the typical Holocene biohermal structure had "completely masked the relief" of the rock basement. While the position, orientation, and surface expression of a modern reef may have been initially determined by the erosional surfaces of older structures, this is not a necessary condition to development of the classical bioherm configuration.

Conclusions

Massive reef accretion occurs primarily with rising sea level and is dependent on the ability of light-dependent coralgal communities to pace the rate of rise. On the basis of data from reefs on three representative carbonate platforms a model is proposed for reef-building on tropical shores that relates antecedent topography and geology, the growth potential for dominant organisms as related to wave energy, and the local pattern of sea level rise.

Inundation of surfaces of carbonate platforms during deglaciation results in deterioration of water quality, impeding growth of marginal reefs. Where such shelf margins lie more than 10 m below maximum interglacial sea levels in high-energy conditions, coralgal communities are not generally able to reestablish or build rapidly enough to form mature reef structures. It is hypothesized that non-subsiding carbonate platforms generally cannot build marginal reefs to interglacial sea levels when they are subjected to medium to high wave energy. Such platforms are restricted to building seaward during interstadials and are tuned to a position 20 to 30 m below present sea level.

Windward reefs subjected to medium to low wave energy favor species of coral that can build reef framework rapidly from greater depths. In such cases, rims of antecedent platforms lying as much as 30 m below present sea level are able to build to the surface during interglacials. However, the erodability of this reef type prevents the establishment of a permanent carbonate surface related to interglacial sea levels.

Typical subsiding pre-Pliocene carbonate platforms sink only 2 to 3 m during an interglacial cycle. Where high-energy conditions prevail, the dense shelf edge reefs formed in such environments lose little to erosion. Growth of such reefs, typified by the Pacific atolls, would proceed primarily during interglacials, and form a rim 10 to 20 m above the position of interstadial sea levels. Under the "Pacific" type sea level rise, with mid-interglacial emergence, this rim becomes a wide and solid intertidal feature.

Data are rapidly becoming available on reef accretion rates and the controlling biological, environmental, and geological factors, as well as the thickness and structure of reefoid platforms and the patterns of Pleistocene sea level oscillations. It is time to begin a synthesis of these new data, to develop new hypotheses and new directions and to leave behind some of the century-old axioms that account for much existing confusion.

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35. J. I. Tracey [*U.S. Geol. Surv. Prof. Pap. No. 1050* (1977), p. 146] states that work at Enewetak has revealed accumulations of reef material reaching 15 m in thickness in back reef areas, the result of coral and sediment buildup on the back part of the reef. This explanation cannot be used to account for the thicker Holocene accumulations measured in the Caribbean: in some of the cases cited above (*25, 42*) a series of holes was taken in a transect across the reef axis, including fore reef areas; in others, because of the relatively shallow basement found in the associated lagoons, significantly deep accumulations of off-reef drape would not be possible.
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43. A similar *Acropora palmata* barrier reef of about the same age has been described for the east Florida shelf (*29*). Its demise has also been attributed to deteriorating water quality associated with shelf flooding (R. G. Lighty and I. Macintyre, in preparation). A major submerged barrier reef on the southeast side of the Puerto Rican–northern Virgin Islands shelf shows the same relationship, the upper surface coinciding with shelf depth. Numerous similar "shelf edge features" [I. Macintyre, *Am. Assoc. Pet. Geol. Bull.* **56**, 270 (1972)] have been described in the Lesser Antilles, and remain to be examined in this regard. The role of turbidity and natural eutrophication in altering reef community struc-

ture from coral to fleshy algal domination on the high island of Martinique is described by W. Adey, P. Adey, R. Burke, L. Kaufman, *Atoll Res. Bull. No. 218* (1977).
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49. J. I. Tracey (personal communication) states that early reef growth at Enewetak was predominantly coral and occurred from 7500 to 6000 years ago [see also (*31, 34, 35*)]. However, the outermost cores were taken in the back reef and the Holocene-Pleistocene unconformity showed an upward slope to seaward. Since the wave energy levels were probably as high then as at present, it seems likely that a basement as shallow as 4 to 6 m below present sea level exists to seaward. If this is the case, the predecessor of the present-day algal ridge would have been established on the shallowest part of the outer rim 6000 to 7000 years ago.
50. The "Atlantic" sea level curve is a mean of the following published curves: C. Neumann, Bermuda (*18*); A. C. Redfield, Louisiana [*Science* **157**, 687 (1967)]; D. W. Scholl, F. C. Craighead, Sr., M. Stuiver, Florida [*ibid.* **163**, 562 (1969); W. Newman *et al.*, eustatic curve based on east coast North American data [*Congres INQUA* **8**, 795 (1971)]; Curray *et al.*, Pacific Mexico after I. Macintyre and P. Glynn (*25*); and J. Milliman, Atlantic U.S., also after (*25*). The "Pacific" curve is a mean of the following: F. Baltzer, New Caledonia [*C.R. Acad. Sci.* **271**, 2251 (1970)]; J. Schofield, Gilbert and Ellice Islands, New Zealand [*J. Geol. Geophys.* **20**, 3 (1977)]; R. Pickrill, New Zealand [*N.Z. Geogr.* **32**, 17 (1976)]; B. Thom and J. Chappell, Australia [*Search* **6**, 90 (1975)]; C. Lalou *et al.*, Tuamotos (*32*); J. Tracey and H. Ladd, Enewetak (*31*). Most of these curves have been collected together by A. Bloom, *Atlas of Sea-Level Curves* (International Geological Correlation Program, Project 61, Ithaca, N.Y., 1977). The extension of the curves into the future presumes a symmetrical Holocene rise and fall of the sea level around the present. This would be an apparent maximum length for the Holocene interglacial, since at that length it would be somewhat longer than the interglacial 125,000 years ago.
51. A. L. Bloom, *Geol. Soc. Am. Bull.* **78**, 1477 (1967).
52. R. I. Walcott, *Quat. Res. (N.Y.)* **2**, 1 (1972).
53. J. Chappell, *ibid.* **4**, 429 (1974).
54. J. Clark, W. Farrell, W. R. Peltier, *ibid.* **9**, 3 (1978).
55. A. L. Bloom, *Geol. Soc. Am. Bull.* **81**, 1895 (1970). Three samples in coastal swamp deposits from Micronesia ranging from 1 to 2 m below present sea level have given dates of approximately 1000 to 4000 years, apparently consistent with the eustatic curve. Bloom has argued that oceanic islands should show the eustatic curve (see text); however, data from the Tuamotos, Gilbert and Marshall Islands (*53*) seem to contradict this theory. The eventual resolution of this problem is not, however, critical to the basic discussion.
56. The sea level curve is after N. Morner [*Can. J. Earth Sci.* **8**, 132 (1971)], with maxima and minima based on Barbados [R. P. Steinen, R. Harrison, R. Matthews, *Geol. Soc. Am. Bull.* **84**, 63 (1973)]; the position of the peak at 29,000 years ago is based on studies in progress, St. Croix [Macintyre *et al.*]. It is not the intention of this diagram to fix precisely the shelf margin buildup at the localities cited. Although some sea level positions are becoming better established (and these are most critical to the discussion) others are only guesses, for example, the position of sea level below 50 m and especially that of the "miniglacials." The diagram is intended to show the type of processes that must have been operating to control reef and carbonate shelf development in tropical seas. Understanding of the details of late Pleistocene climate and sea level was greatly enhanced by the study of the Barbados reef cap. However, it seems very unlikely that the present growth of *A. palmata* on Barbados is climate-limited as suggested by K. Mesolella *et al.* [*J. Geol.* **77**, 250 (1969)]. There is a strong possibility that the submerged ridge along the west and southwest of the island, as yet undrilled, is an early Holocene *A. palmata* reef, perhaps overlying another formed 30,000 to 40,000 years ago. These factors, together with the differing elevations attached to concurrent date sets, and the possibility of an irregular rate of uplift suggest the likelihood of a greater complexity of events than considered by the Barbados workers. A reevaluation in the light of newer data on Caribbean reef development would probably improve our insight into Pleistocene sea level events.
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59. W. Tanner, *ibid.* **5**, 1 (1968).
60. J. Mercer, *ibid.*, p. 1.
61. W. Adey and R. Burke, *Am. Assoc. Pet. Geol. Stud. Geol.* No. 4 (1977), p. 67.
62. H. J. Wiens, *Atoll Environment and Ecology* (Yale Univ. Press, New Haven, Conn., 1962).
63. I thank L. Hickey, I. Macintyre, and J. Tracey, as well as my students and colleagues P. Adey, S. Brawley, R. Burke, C. Rogers, and R. Steneck for carefully reading and criticizing the original manuscript.

Energy and Labor in the Construction Sector

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Efforts to evaluate the potential for energy conservation in the construction industry have usually focused on reducing operational energy consumption, with little concern for the energy cost of the construction activity itself (*1*). A study of energy use in both building and nonbuilding construction indicates that construction activity accounts for a significant amount of national energy consumption (*2*). Knowledge of how energy is used in the construction process and of energy expenditures during construction that reduce operational energy consumption could contribute significantly to programs designed to diminish the nation's overall energy demand.

In our study we considered the employment generated by the construction industry as well as the labor impacts of various energy-saving construction options. We also investigated the possible inverse relation between total energy and labor requirements for construction (*3*).

The basis for the study was an energy and employment input-output model of the construction industry (*2, 4-7*). The model describes energy flows through the U.S. economy in 1967. The data for 1967 are the most recent available through the Bureau of Economic Analysis in regard to completeness and comprehensiveness. Although there have been some changes in the kinds and extent of construction activity as well as some changes in manufacturing and construction methods, the general information is still applicable.

The power and versatility of the model come from two sources. First, the model is comprehensive. It includes nearly 400 sectors, 49 of them in the construction industry (Fig. 1), and covers the entire U.S. economy. Second, the model makes it possible to determine the total direct and indirect energy requirements, as well as the labor requirements of various industrial activities (*8*).

Direct inputs to an activity are those actually consumed by the industrial sector engaged in the activity. For example, the refined petroleum needed to operate construction equipment represents direct energy use. Indirect inputs to an activity, on the other hand, represent consumption (or employment) in sectors not engaged in the given activity but which supply inputs to it via the chain of production.

For example, the use of a steel beam in construction represents an indirect use

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