Zonation of Uplifted Pleistocene Coral Reefs on Barbados, West Indies
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nonrandom rectangles, or the integral powers of 4, 5, 6, or 7 encountered in the curves built as in Fig. 2.) In case that the value of r is specified by choosing N, one can consider $-\log N/\log r$ a similarity dimension. More usually, however, given r, N will take different values for different figures of Ω. As one considers points "sufficiently far" from each other, the details on a "sufficiently fine" scale may become asymptotically independent, in such a way that $-\log N/\log r$ almost surely tends to some limit as r tends to zero. In that case, this limit may be considered a similarity dimension. Under wide conditions, the length of approximating polygons will asymptotically behave like $L(G) \sim G^{1-D}$.

To specify the mathematical conditions for the existence of a similarity dimension is not a fully solved problem. In fact, even the idea that a geographical curve is random raises a number of conceptual problems familiar in other applications of randomness. Therefore, to return to Richardson's empirical law, the most that can be said with perfect safety is that it is compatible with the idea that geographical curves are random self-similar figures of fractional dimension D. Empirical scientists having to be content with less than perfect inductions, I favor the more positive interpretation stated at the beginning of this report.

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4. B. Mandelbrot, *IEEE Inst. Elect. Electron. Eng. Trans. Commun. Technol.* **13**, 71 (1965) and *IEEE Inst. Elect. Electron. Eng. Trans. Inform. Theory* **13** (1967). Very similar considerations apply in turbulence, where the characteristic sizes of the "features" (that is, the eddies) are also very widely scattered, as was first pointed out by Richardson himself in the 1920's.
5. The concept of "dimension" is elusive and very complex, and is far from exhausted by the simple considerations of the kind used in this paper. Different definitions frequently yield different results, and the field abounds in paradoxes. However, the Hausdorff-Besicovitch dimension and the capacitary dimension, when computed for random self-similar figures, have so far yielded the same value as the similarity dimension.

14 November 1966; 27 March 1967

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Zonation of Uplifted Pleistocene Coral Reefs on Barbados, West Indies

Abstract. *The coral species composition of uplifted Pleistocene reefs on Barbados is very similar to Recent West Indian reefs.* Acropora palmata, Acropora cervicornis, *and* Montastrea annularis *are quantitatively the most important of the coral species.*

The island of Barbados in the West Indies emerged throughout the Pleistocene. During this emergence, fringing and barrier reefs formed from time to time around the island and resulted in the formation of a terraced "coral cap." Eighteen major reef tracts of different relative ages have been defined, the older reefs being located at the higher elevations (*1*).

Thirty road cuts through the reef terraces were examined to study the coral composition of these reefs. On traverses made perpendicular to the reef tract trends, from the base up to the crest of the terraces, a zonation of corals—largely in growth position—can be observed (Fig. 1). The zonation is composed of four major elements: (i) the coral-head zone, (ii) the *Acropora cervicornis* zone, (iii) the *Acropora palmata* zone, and (iv) the rear zone.

A distinct advantage in the study of uplifted reefs is that the deep-water communities can be examined in as great detail as those of the reef crest. Exposures at the base of the terraces are composed largely of coral species which tend to form massive coral heads. At several localities, *Montastrea annularis* makes up as much as 50 percent of the total exposure. However, at other localities, *M. annularis* composes only 10 to 15 percent of the total exposure and *Siderastrea siderea, Siderastrea radians, Diploria strigosa,* and *Diploria labyrinthiformis* are equally important. Numerous other coral species are also present in the coral-head zone, but they rarely exceed 5 percent of the total exposure. These include *Porites astreoides, Agaricia agaricites, Favia fragum, Meandrina meandrites, Meandrina brazilensis, Colpophyllia natans, Montastrea cavernosa,* and more delicately branched types such as *Porites porites, Eusmilia fastigiata,* and *Madracis* sp. The total coral content of some exposures in the coral-head zone exceeds 50 percent with the remainder being infilling matrix. The individual species occur in clumps with first one species being important and then another. Coralline algae are not abundant in this zone but at times form thick crusts on the upper surfaces of the coral heads.

Moving upward and back into the reef terrace, the zone of coral heads gives way gradually to a zone composed almost exclusively of *Acropora cervicornis* (Fig. 3). At times, *A. cervicornis* makes up as much as 75 to 80 percent of the total exposure. The average diameter of the individual branches is 2.0 to 2.5 cm although diameters in excess of 5 cm have been noted. Coralline algae often form thin coatings on the branches.

Near the upper portions of the *A. cervicornis* zone, *Montastrea annularis* along with *Siderastrea* sp. and *Diploria* sp. frequently are seen scattered in among the rich *A. cervicornis.* The *M. annularis* here has the growth form of heads and tall, thin columns or "pipes." At a few localities, thick developments (6 to 9 m) of *M. annularis* heads and pipes occur at the position normally occupied by the upper portions of the *A. cervicornis* zone. Such occurrences appear to be analogous to the "buttress zone" reported for Recent West Indian reefs along the north coast of Jamaica (*2*).

Near the crest of the reef terraces, the *A. cervicornis* zone grades rather rapidly into a zone which is composed almost exclusively of *Acropora palmata* (Fig. 4). Some of the reef terraces on Barbados, however, do not show the development of an *A. palmata* zone. The *A. palmata* increases in size and overall abundance towards the central portions of the zone where it reaches a maximum development, often making up to 70 percent of the exposure. For the reef terraces examined, the zone averages 75 m wide. Coralline algae are most abundant in this zone, and they often form heavy crusts on the massive branches of *A. palmata.* The algal crusts are particularly thick on the upper surface of the branches with crusts 5 to 8 cm thick not being unusual.

Moving back from the crest of the reef terrace, *A. palmata* gradually decreases in importance and is replaced by a wide variety of corals. This variety is comparable to that found in the

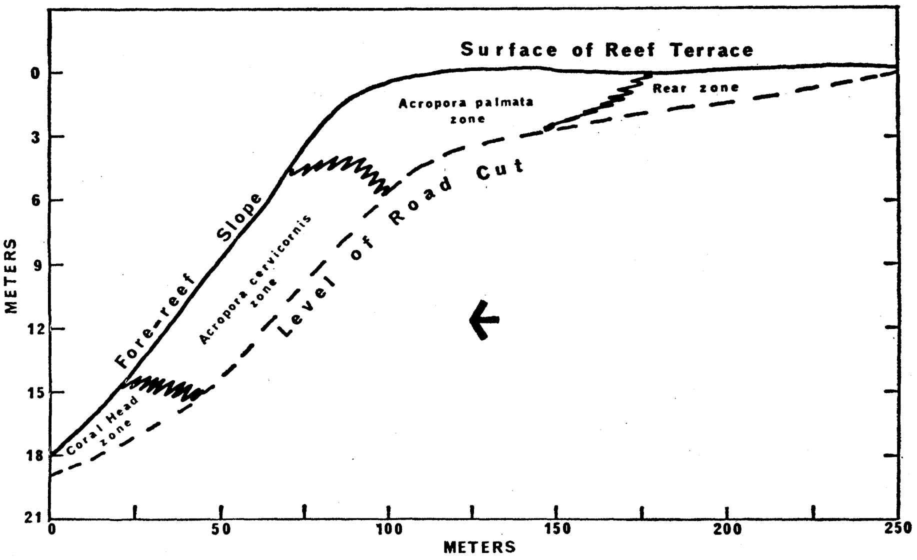

Fig. 1. Schematic coral reef zonation model constructed from an average of measurements taken in 19 exposures through uplifted Pleistocene reefs on Barbados, West Indies. Arrow points seaward.

coral-head zone with many of the same species recurring. *Montastrea annularis, Acropora cervicornis, Diploria* sp., *Siderastrea* sp., and *Porites porites* are quantitatively the most important. Of lesser importance are *Agaricia agaricites, Eusmilia fastigiata, Favia fragum, Meandrina meandrites, Colpophyllia natans, Porites astreoides, Montastrea cavernosa, Madracis* sp., and *Oculina diffusa*. Bladed colonies of *Millepora alcicornis* as well as coralline algae crusts and molluscan debris are locally abundant. The term "rear zone," as used by Goreau (*2*) for the reef community behind the *A. palmata* crest zone, is applied to these similar occurrences in the Barbados Pleistocene reefs.

An estimation of the depth of water in which the various coral zones developed has been made from measurements of the uplifted reefs. However, before any considerations of depth can be attempted, a reference datum must be established. By analogy with Recent West Indian reefs, it is assumed that the crest of any reef terrace with a well-developed *A. palmata* zone can be taken to represent mean low tide level as related to that particular reef. Inferences about depth based upon such a datum would be minimum figures since a reef crest could exist in deeper water. Table 1 shows measurements taken in 19 exposures through reef terraces with well-developed *A. palmata* crests. A figure followed by a single asterisk indicates a locality where the base of the particular zone being measured is not exposed; it is therefore a minimum figure.

An average depth range for the individual zones has been calculated with only the values where the particular zone being measured was fully exposed. The average depth ranges of the Barbados Pleistocene reefs agree particularly well with depth ranges reported for the various coral zones of Recent West Indian reefs of Jamaica (*2*).

The coral zonation of the uplifted Pleistocene reefs on Barbados is comparable in many respects to the coral zonation observed in various Recent West Indian reefs such as those of Jamaica (*2*), South Florida (*3*, *4*), the Bahamas (*5*, *6*) and British Honduras (*7*). In particular, some exposures through Barbados reef terraces exhibit a coral zonation nearly identical to that reported by Goreau for Recent coral reefs along the northern coast of Jamaica (*2*).

Some discussion has arisen concerning the relative importance of various corals in the overall biomass of the reef structure. Ginsburg (*3*) and Shinn (*4*) report that the primary structural element of the bank reefs of the Florida reef tract is *A. palmata*. In the Jamaican reefs, *M. annularis* is the dominant contributor to the framework of the reefs with *A. palmata* being of secondary importance (*2*). While *M. annularis* and *A. palmata* are major contributors to the Barbados Pleistocene reefs, *A. cervicornis* is equally important as a framework builder.

The coral zonation shown in Fig. 2 or some variation of that scheme occurred numerous times during the Pleistocene in the Barbados reefs. Thus, similar zonations in Recent West Indian reefs are not solely Recent phenomena. Perhaps the idealized Barbados reef zonation model shown in Fig. 2 is the climax zonation for West Indian fringing and barrier reefs in

Table 1. Depth range of coral zone below reef crest; n.e., not exposed; n.d., not developed.

Section	*A. palmata* zone (meters)	Buttress zone (meters)	*A. cervicornis* zone (meters)	Coral-head zone (meters)
BD	0–6.8	n.d.	6.8–17.8*	n.e.
CZ	0–4.0	n.d.	4.0–12.0*	n.e.
BT	0–6.8	n.d.	6.8–18.2	18.2–27.7*
BS	0–2.8	n.d.	2.8–10.2*	n.e.
BE	0–3.7	n.d.	3.7–13.8	13.8–15.4*
AEO	0–4.0	4.0–9.5	9.5†–17.8*	n.e.
DM	0–3.1	n.d.	3.1–13.5	13.5–20.3*
BF	0–5.5	n.d.	5.5–13.5*	n.e.
BY	0–4.0	n.d.	4.0–13.2	13.2–21.2*
EH	0–9.2	n.d.	9.2–26.5	26.5–33.2*
EW	0–5.2	n.d.	5.2–23.7*	n.e.
AFM	0–6.2	n.d.	6.2–16.9	absent
D	0–4.6	4.6–12.3*	n.e.	n.e.
IF	0–4.9	n.d.	4.9–15.1	15.1–23.7*
AEU	0–3.7	n.d.	3.7–7.7*	n.e.
E	0–2.2	n.d.	2.2–7.1	7.1–20.3*
QU	0–4.6	4.6–10.2*	n.e.	n.e.
HG	0–5.5	n.d.	5.5–10.2*	n.e.
BV	0–3.7	n.d.	3.7–10.8	10.8–12.6*
Average	0–4.8	4.4–9.5	4.8–15.0	14.8
Recent Jamaican reefs (Goreau) 1959	0.5–6.0	1–10	7.0–15.0	15.0

* Minimum figure; base not exposed. † Lowered due to presence of buttress zone.

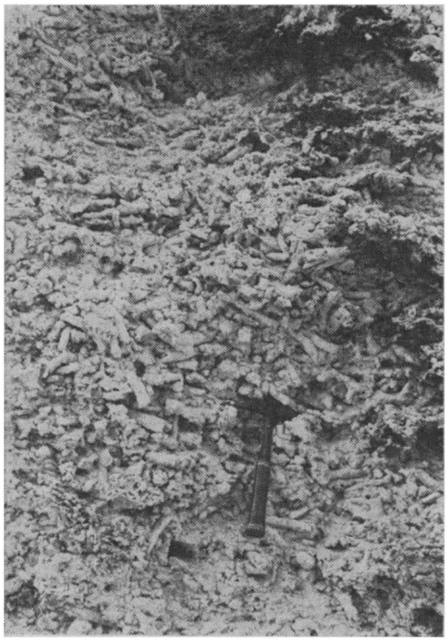

Fig. 2. An exposure within the *A. cervicornis* zone. Skeletons of *A. cervicornis* compose over one-half of this exposure; the remainder is infilling matrix. Hammer is 32 cm long.

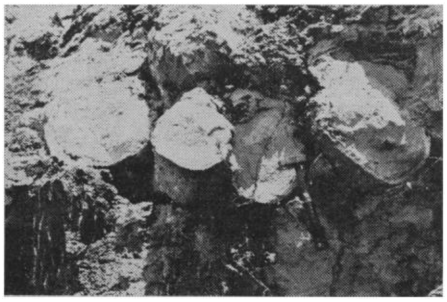

Fig. 3. Circular cross-sections of massive branches of *Acropora palmata* near the reef crest. Branches are oriented perpendicular to the trend of the reef tract. Hammer is 32 cm long.

general. Variations of a Recent West Indian fringing or barrier reef from this model might well be, in part, a function of its developmental history.

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Variation in Atmospheric Carbon-14 Activity Relative to a Sunspot-Auroral Solar Index

Abstract. *Radiocarbon activity was negatively correlated* ($P < .01$) *with a sunspot-auroral index during 25 designated solar activity periods from 129 B.C. to A.D. 1964. Change in carbon-14 activity during these periods was inverse to change in solar activity in 22 of 24 instances* ($P < .001$)*. Contamination from carbon-14 formed during previous solar cycles may lessen the value of carbon-14 as a climate or solar index.*

A negative correlation between atmospheric radiocarbon activity and solar activity was suggested by Stuiver (*1*) on the basis of carbon-14 data of Willis *et al.* (*2*) which covered a 1300-year period. Subsequent analysis by Stuiver (*3*), Suess (*4*), and Bray (*5*) supported this suggestion. Bray found a significant negative correlation between C^{14} and solar activity over the period 200 B.C. to A.D. 1860, but the relationship was uncertain at the higher solar activity levels. Below I present a further analysis of this relationship, using a combined sunspot and auroral index of solar activity and an augmented set of radiocarbon activity data.

Sunspots and auroras are the only aspects of solar activity for which direct observations are available over a long-term historical interval. Since both these features indicate level of solar activity, a combination of sunspot and auroral data into a single solar activity index appeared feasible. The index was based on compilations by Schove of sunspot activity from 522 B.C. to A.D. 1947 (*6*) and of auroral activity from 500 B.C. to A.D. 1960 (*7*). Since some periods were represented by measurements of only one of these features, the relationship between the Schove sunspot and auroral indices was examined to allow representation by either feature if the other were missing. The mean auroral value was found to equal nearly half (.48) the mean sunspot activity value. An index was constructed, therefore, in which solar activity equalled (i) the sum of the auroral value and one-half the sunspot value, (ii) the sunspot value if auroral data were missing, (iii) twice the auroral value if sunspot data were missing. The result of this compilation gave indices of solar activity for every sunspot cycle from 527 B.C. to A.D. 1964 with the exception of the periods 378 to 355 B.C., 333 to 250 B.C., 239 to 220 B.C., and A.D. 203 to 283. These missing periods were tentatively assumed to represent low solar activity periods, since it is easier to discover historical records of high sunspot or auroral activity than of lower activity (*8*). As noted by Schove (*6*), historical observations of solar activity before A.D. 1600 are of less reliability, especially as to the exact year of observation.

A total of 361 C^{14} activity values from 12 laboratories were summarized from published data (*2, 4, 9–11*) by the criteria previously outlined (*5*). All C^{14} values were converted to the 5730-year half-life, thus allowing a more accurate representation of the older measurements and reducing their magnitude of variation relative to the more recent values. Such variation, due to the less correct half-life of 5568, partly accounted for the higher C^{14} values before around 100 B.C. summarized in Bray (*5*).

Examination of the sunspot-auroral index values from 527 B.C. to A.D. 1964 showed the same pattern of higher activity alternating with lower activity that was summarized for the period A.D. 1656 to 1964 (*12*). Intervals of three or more solar cycles with all or nearly all sunspot-auroral index values above 100 alternated with intervals in which all or nearly all index values were below 100. A division of the sunspot-aurora index data was made, therefore, into periods of alternating "high" (>100) and "low" (<100) values by the following criteria: (i) if a period was interrupted by one cycle of a different value, the period was continued; (ii) if the period was interrupted by two cycles of different value the period was continued if the next two cycles were within the period; (iii) if the period was interrupted by three successive cycles of different value, these cycles constituted the beginning of a new period. Application of these criteria over the interval 527 B.C. to A.D. 1964 resulted in the designation of 31 solar activity periods which varied in length from 28 to 189 years (Table 1). The mean solar index for the "low" periods varied from 60 to 89; that of the "high" periods, from 107 to 137.

Variation in C^{14} activity is shown