Coral Reefs (1982) 1: 125–130

Coral Reefs
© Springer-Verlag 1982

Acropora Palmata Reef Framework: A Reliable Indicator of Sea Level in the Western Atlantic for the Past 10,000 Years

R. G. Lighty[1]. I. G. Macintyre[2], and R. Stuckenrath[3]

[1] Cities Service Company, Exploration and Production Research, Box 3908, Tulsa, Oklahoma 74102, USA
[2] Department of Paleobiology, Smithsonian Institution, Washington, D.C. 20560, USA
[3] Radiation Biology Laboratory, Smithsonian Institution, Washington, D.C. 20560, USA

Received 30 January 1982; accepted 16 June 1982

Summary. A minimum sea-level curve for the past 10,000 years has been constructed on the basis of radiocarbon dates of *Acropora palmata* (Lamarck) samples from the shallow-water framework of both relict and modern reefs of the tropical western Atlantic. *A. palmata* framework is a reliable reference for reconstructing the history of late Quaternary sea levels owing to its restricted depth range (< 1 to 5 m), the lack of postdepositional transport of *A. palmata* framework, the ease of obtaining uncontaminated samples, and the minimal compaction of *A. palmata* reef facies. The minimum sea-level curve constructed in this study is useful not only in evaluating the reliability of present and future Holocene sea-level curves for the western Atlantic, but also in estimating paleo-water depths in the study of Holocene reef history of this area.

Introduction

A notable change in emphasis from surface to subsurface studies is evident in recent geological investigations of Holocene reefs of the western Atlantic. This new approach has brought attention to the internal record of the stages of development leading to the present-day relief, community composition, and distribution of western Atlantic reefs (see, for example, Adey 1975; Adey and Burke 1976; Macintyre and Glynn 1976; Adey et al. 1977a; Lighty 1977; Shinn et al. 1977; Focke 1978; Lighty et al. 1978; Lighty et al. 1980; Shinn 1980; Macintyre et al. 1982; Shinn et al. 1982). As a result of these and other similar studies, enough data on the age of shallow-water *Acropora palmata* framework are now available to construct a minimum sea-level curve for the tropical western Atlantic.

The accumulation of tropical reef framework is generally limited to water depths less than 30 m. Communities that form the components of that framework live or have lived within even more restricted depths. This characteristic depth range of reef development has tracked the levels of the Holocene transgression, which have risen more than 100 m in the last 15,000–20,000 years (Curray 1965). Thus, the stages of reef development are controlled in large part by the position of pre-existing sea levels and by the topography of the continental or insular shelves on which the reefs have been established. It can now be assumed that a basic step in reef studies should be a thorough understanding of the history of post-Pleistocene sea levels in any area under investigation.

In relating the sequences of reef development in the western Atlantic to pre-existing sea levels, many investigators have had to refer to curves constructed from data collected outside their study areas. Another handicap has been that some widely used sea-level curves are based on unreliable controls such as unattached oyster shells. Significant postdepositional transport of relict unattached oyster shells off North Carolina indicates that sea-level histories based on radiocarbon dates of oysters, or on the dates of any other loose strandline deposits cannot be considered reliable (Macintyre et al. 1978).

Table 1. Reported maximum water depths for framework *Acropora palmata*

Reef location	Reference	Max. depth (m)
Bahamas, Andros reef	Newell and Rigby (1957)	7
Bahamas, Abaco reef	Storr (1964)	6
Bahamas, Eleuthera	Zankl and Schroeder (1972)	3
Belize, barrier reef	Rützler and Macintyre (1982)	5
Cuba reefs	Kuhlmann (1974)	3
Curacao reefs	Bak (1977)	4
Florida, Key Largo	Shinn (1980)	4
Grand Cayman reefs	Rigby and Roberts (1976)	7
Grenadines reefs	Lewis (1975)	5
Jamaica, north shelf	Goreau and Wells (1967)	5
Martinique reefs	Adey et al. (1977b)	5
Mexico, Yucatan shelf	Logan (1969)	9
Nicaragua atolls	Milliman (1969)	5
Puerto Rico, Vieques Is.	Macintyre et al. (1982)	4
St. Croix, west reefs	Adey and Burke (1977)	5
St. Croix, east reefs	Adey and Burke (1977)	12
St. Lucia reefs	Roberts (1972)	5

0722-4028/82/0001/0125/$01.20

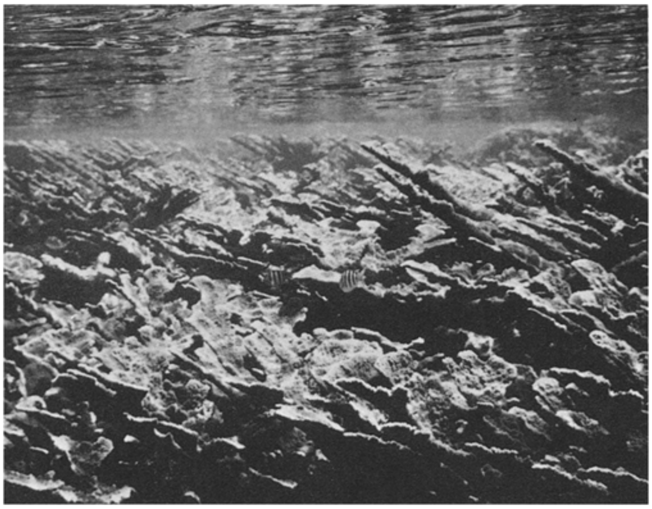

Fig. 1. *Acropora palmata* (Lamarck) framework community in shallow fore reef at Carrie Bow Cay, Belize Barrier Reef. Water depth is 0.5–2 m (Rützler and Macintyre 1982)

Table 2. Age and position of framework *A. palmata* used to construct sea-level curve

Location	Depth below present mid sea level (m)	^{14}C age (year BP)	Reference
Bahamas – Abaco Barrier Reef			
Fish Cays, H9-C2-1	6.8	4,515 ± 80	Lighty (unpubl.)
Umbrella Cay, H8-C1-1	5.5	3,985 ± 90	Lighty (unpubl.)
Umbrella Cay, H8-C3-1	6.4	3,795 ± 90	Lighty (unpubl.)
Umbrella Cay, H8-C4-1	7.0	3,685 ± 70	Lighty (unpubl.)
Umbrella Cay, H8-C4-2	7.3	3,580 ± 90	Lighty (unpubl.)
Florida – Shelf-Edge Reef 40 km North of Miami			
Vertical Sequence A	17.5	7,145 ± 80	Lighty et al. (1978)
Vertical Sequence A	20.5	7,595 ± 70	Lighty et al. (1978)
Vertical Sequence B	16.5	7,840 ± 65	Lighty et al. (1978)
Vertical Sequence B	17.5	7,740 ± 65	Lighty et al. (1978)
Vertical Sequence B	26.5	9,440 ± 85	Lighty et al. (1978)
Vertical Sequence C	18.0	8,295 ± 90	Lighty et al. (1978)
Vertical Sequence C	19.5	8,010 ± 80	Lighty (unpubl.)
Vertical Sequence C	24.5	8,900 ± 95	Lighty et al. (1978)
Vertical Sequence D	23.0	7,295 ± 70	Lighty et al. (1978)
Vertical Sequence D	27.0	8,405 ± 80	Lighty et al. (1978)
Martinique			
Pinsonelle Algal Ridge	4.0	2,110 ± 120	Adey and Burke (1976)
Rameville Reef, MR-2	2.0	1,980 ± 65	Adey (unpubl.)
Vauclin Reef, MV-1-1D	0.9	560 ± 110	Adey and Burke (1976)
Vauclin Reef, MV-3/4	4.0	1,670 ± 120	Adey and Burke (1976)
Vauclin Reef, MVH-2	1.0	805 ± 55	Adey (unpubl.)
Panama – Galeta Point Reef			
H3 C6 2/2	6.0	5,120 ± 65	Macintyre and Glynn (1976)
H3 C7 2/3	6.8	5,610 ± 95	Macintyre and Glynn (1976)
H3 C10 3/3	12.5	6,150 ± 95	Macintyre and Glynn (1976)
H6 C10 3/3	12.3	6,500 ± 100	Macintyre and Glynn (1976)
H7 C8 6/6	11.5	6,680 ± 110	Macintyre and Glynn (1976)
H8 C3 3/3	5.8	4,840 ± 85	Macintyre and Glynn (1976)
H10 C4 1/7	5.5	3,535 ± 80	Macintyre and Glynn (1976)
H11 C1 4/4	3.8	3,755 ± 85	Macintyre and Glynn (1976)
Puerto Rico – Bahia Salina Del Sur Reef, Vieques Island			
BSDS-1	1.1	190 ± 90	Macintyre et al. (1982)
BSDS-2	2.3	2,155 ± 80	Macintyre et al. (1982)
BSDS-3	2.8	860 ± 90	Macintyre et al. (1982)
BSDS-5	5.0	2,020 ± 70	Macintyre et al. (1982)

Acropora palmata (Lamarck), the most prominent shallow-water framework builder in the western Atlantic, is commonly dated in geological studies of reefs in this area. Although *A. palmata* has been found living in depths as great as 17 m (Goreau and Wells 1967), this coral generally does not form an interlocking framework in depths greater than 5 m (Table 1, Fig. 1). This means that if samples of *A. palmata* framework are dated, they should provide a reliable indication of the positions of pre-existing sea levels inasmuch as these corals probably grew close to sea level and were part of a structural framework that experienced little, if any, postdepositional transport.

Thus, this paper proposes to reverse the commonly followed practice of comparing coral dates with previously established sea-level curves in order to interpret reef history. That is to say, we propose that a sea-level curve be constructed from the radiocarbon dates of the *A. palmata* facies in various reefs of the western Atlantic.

Methods

Forty-two radiocarbon dates were recorded from published and unpublished analyses of in situ *Acropora palmata* coral samples. We chose only the dates of samples from well-documented reef facies to insure that all samples were from an *A. palmata* framework and that no samples were from storm-ridge deposits. Furthermore, we concentrated on samples known to us from our earlier investigations (Table 2).

These radiocarbon-dated samples had been taken from unaltered sections of *Acropora palmata* that were free of boring, encrustation, and submarine cementation. X-ray diffraction techniques confirmed that the samples were pure aragonite. Approximately 50–80 g of skeletal aragonite were used in each age determination. All but three of the dates reported in this study were obtained at the Smithsonian Institution Radiation Laboratory (by R. Stuckenrath) using a Libby half life of 5,568 years and are uncorrected for ^{13}C/^{12}C ratios or for secular atmospheric variations. Dates for the three samples from Martinique (Pinsonelle Algal Ridge, Vauclin Reef MV-1-LD, and MV-3/4) were determined by Geochron Laboratories.

Because the aim of this study was to construct a minimum eustatic sea-level curve for the tropical western Atlantic, we chose samples from sixteen reefs in six widespread geographic locations (see Table 2). Be-

Location	Depth below present mid sea level (m)	^{14}C age (year BP)	Reference
St. Croix			
Boiler Bay, Shark Reef	2.8	315 ± 60	Adey (unpubl.)
Fancy Algal Ridge	2.0	355 ± 60	Adey (1975)
Hess Channel, Mid-Shelf	3.7	970 ± 95	Adey (1975)
Hess Channel, Shelf-Edge	13.0	7,240 ± 70	Adey et al. (1977a)
Issac's Algal Ridge	8.5	4,040 ± 95	Adey (1975)
North Shore Reef	2.7	1,850 ± 65	Adey (unpubl.)
Shelf-Edge Reef off East Pt.	23.5	9,075 ± 70	Adey et al. (1977a)
Tague Bay, Cramer Park, SCC-3	1.2	720 ± 80	Adey (unpubl.)
Tague Bay, Romney Pt., SCR-2	7.2	5,490 ± 85	Adey (unpubl.)
Tague Bay, Romney Pt., SCR-3D	10.4	6,135 ± 80	Adey (unpubl.)

cause of the wide variation in tidal ranges (35–125 cm) among these localities, as well as the difficulty of determining core depths relative to a specific tidal position in high-energy and swell-dominated environments, measured depths below sea level for each dated sample of *A. palmata* are referenced to mid (mean) sea level rather than mean low tide. Another factor taken into consideration is that *A. palmata* may occasionally survive subaerial exposure during extremely low spring or storm tides (Milliman 1969; Scatterday 1974).

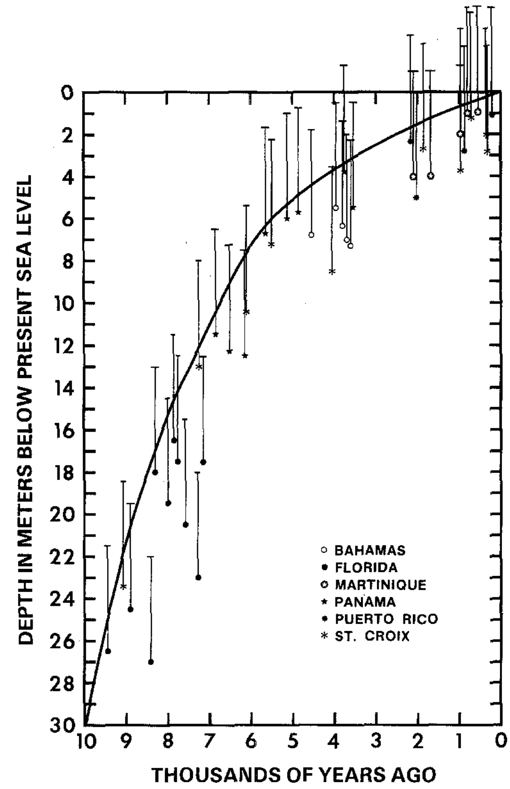

Fig. 2. Minimum sea-level curve for past 10,000 years based on age and location of forty-two in situ *Acropora palmata* framework samples from around the tropical western Atlantic (Table 2). Note the close agreement in the distribution of data producing a smooth linear trend. Vertical bars represent paleo water-depth intervals of 0–5 m for each sample. Width of horizontal bars indicates possible error in dating

Results

The sea-level curve in Fig. 2 was constructed from plots of age versus depth below sea level. The vertical bars above each plot were made to represent a paleo-water depth interval of 0–5 m because almost all present-day *A. palmata* reef framework is constructed in water depths less than 5 m (Table 1). Because these corals must have lived below sea level, a minimum sea-level curve for the past 10,000 years can be constructed by positioning a line a short distance above the coral time-depth plots (Fig. 2).

The possible error in radiocarbon age determinations is indicated in Fig. 2 by the width of the horizontal bars located atop the vertical bars. Note that the ranges of possible error in dating appear to have little effect on the positioning of the minimum sea-level curve. Errors in sample location within core holes were estimated to be less than ± 15 cm in depth and therefore are not considered significant in the sea-level diagram. These errors are mainly the result of poor core recovery, or of inadequate tidal data.

Discussion

Our approach of using only shallow-water framework corals has several advantages over previous attempts at dating shallow-water or strandline deposits. First, owing to its rigid framework, *Acorpora palmata* is not easily transported or compacted upon burial, as are other sea-level indicators, which can also undergo soft sediment deformation during coring. Second, *A. palmata* facies are the dominant reef facies of the tropical western Atlantic and are recognized easily in reef cores and sections. Third, the in situ growth position of a sample is readily determined from the distinctive asymmetrical growth form displayed in the skeletal banding of *A. palmata* (Fig. 3). Finally, the branching shape of this coral leaves little doubt as to its growth orientation; in contrast, hemispherical coral heads can be transported by storms and flipped back into a stable flat-bottom position that simulates normal growth orientation.

If we consider that corals must live below sea level and that *Acropora palmata* has a narrow optimum depth range (< 1–5 m), then it should give an indication of "absolute" minimum sea level. Depth of origin can be confirmed in some cases by the presence of crustose coralline algae that have well-established shallow-water depth ranges (for example, *Lithophyllum congestum*; see Steneck and Adey 1976). Depth of origin is also reflected in the characteristic growth form of *A. palmata*'s skeleton, which varies as a function of water depth and energy level (Shinn 1963).

Acropora palmata samples are particularly suitable for radiocarbon dating because they generally consist of well-preserved original skeletons. Owing to the high rate of ac-

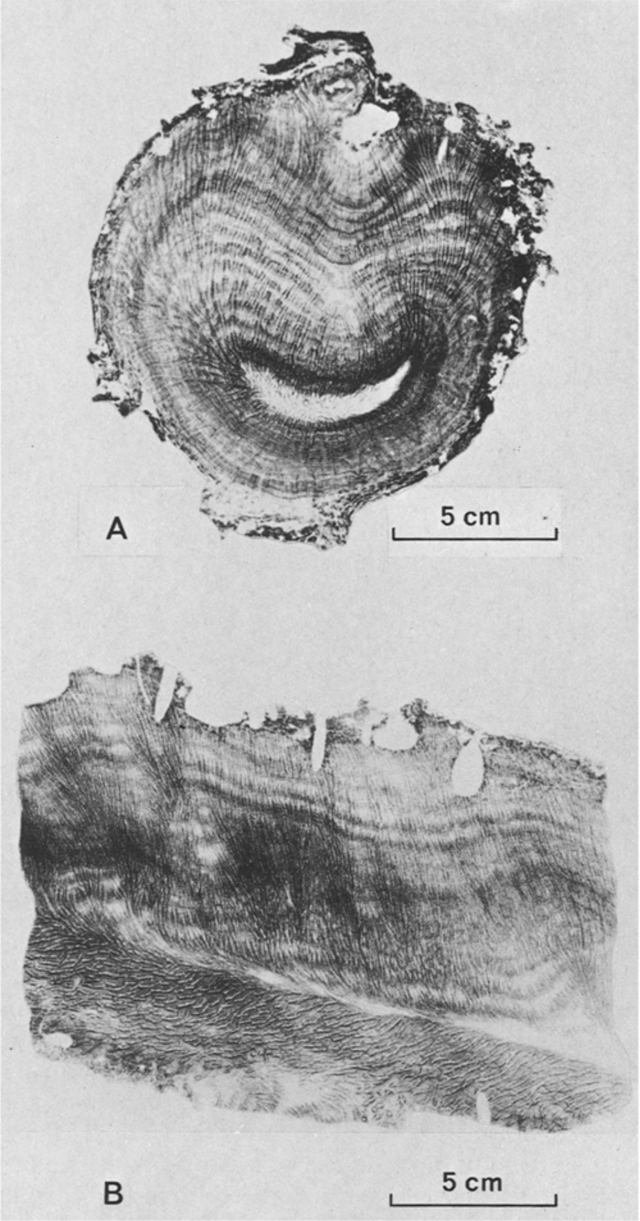

Fig. 3 A, B. X-radiograph of (**A**) transverse section and (**B**) longitudinal section through *Acropora palmata* framework sample. Asymmetry of skeletal growth bands may be used as right-side-up indicator to determine if sample is in situ. Typically, only outer surface areas are altered by borings, encrustations, and submarine cements, providing abundant unaltered internal-skeletal material for radiocarbon dating

cumulation in the *A. palmata* reef facies, submarine diagenesis (contamination) is limited to the outer surface of the coral (Macintyre 1977), and this material (magnesium calcite) is easily recognized (Fig. 3) and can be removed prior to dating. Sample purity, as noted, can then be confirmed by X-ray diffraction mineralogy. In contrast, sample purity is difficult to establish for other sea-level indicators because of undetectable contaminations, as in the case of peats penetrated by overlying roots.

Table 3. Radiocarbon dates on living *Acropora palmata* (Lamarck)

Location	Collector	Water depth (m)	^{14}C age
Tortugas, Florida	Palmer (1884)	≦3	195+50 years BP
Golding Cay, Bahamas	Mayer (1912)	≦3	205±65 years BP
Umbrella Cay, Bahamas	Lighty (1979)	3	121.7% modern
Umbrella Cay, Bahamas	Lighty (1979)	3	122.8% modern
Spanish Cay, Bahamas	Lighty (1979)	4	128.9% modern
Green Turtle Cay, Bahamas	Lighty (1979)	2	130.6% modern
Great Guana Cay, Bahamas	Lighty (1979)	3	132.5% modern

Acropora palmata skeletons are believed to contain an accurate record of past radiocarbon levels. Recent studies have shown that *Montastrea annularis* (Ellis and Solander), another common Atlantic reef coral, is a reliable recorder of isotope concentrations in dissolved inorganic carbon (DIOC) in surrounding oceanic waters, the main source of carbon for skeletal aragonite (Weber 1974; Druffel 1980). Isotopic carbon in zooplankton, the primary constituent of coral diet, is the same as that for DIOC in seawater, and metabolic CO_2 from coral polyps is but a minor source of carbon (Williams and Linick 1975; Linick 1978). To check the reliability of *A. palmata* as a recorder of carbon isotope concentrations characteristic of modern seawater, we dated five samples of living *A. palmata* from the Abaco Barrier Reef, Bahamas, as well as two pre-bomb samples collected off Florida and the Bahamas in 1884 and 1912, respectively. Results are shown in Table 3.

As expected, the two pre-bomb samples provide ages somewhat earlier than the dates of collection, quite in line with the 5% depletion in surface seawater radiocarbon concentrations engendered by the accelerated burning of fossil fuels (Druffel 1980). Because of the incorporation of bomb-produced radiocarbon, the modern living specimens provide the expected "future" dates, which are similar to the values obtained by Druffel (1980) and lower than terrestrial levels of ca. 140+ % (M. Rubin, personal communication). Although irregular fractionation of carbon isotopes has been noted in crustose coralline algae (Adey 1975), there seems to be no excessive fractionation in these *A. palmata* skeletal carbonates, and we may assume that *A. palmata*, like *M. annularis*, retains a reliable radiocarbon history.

Considering that the samples in this study are from tectonically stable areas throughout the western Atlantic, the continuous, uniform nature of this curve and the close agreement of all time-depth points seem to indicate eustatic control on sea-level rise rather than variation in local or regional history of transgression. It should be noted, however, that *A. palmata* – like any dated sample of an in situ coral – is not an absolute indicator of sea-level position. Rather, it is only an absolute indicator of the

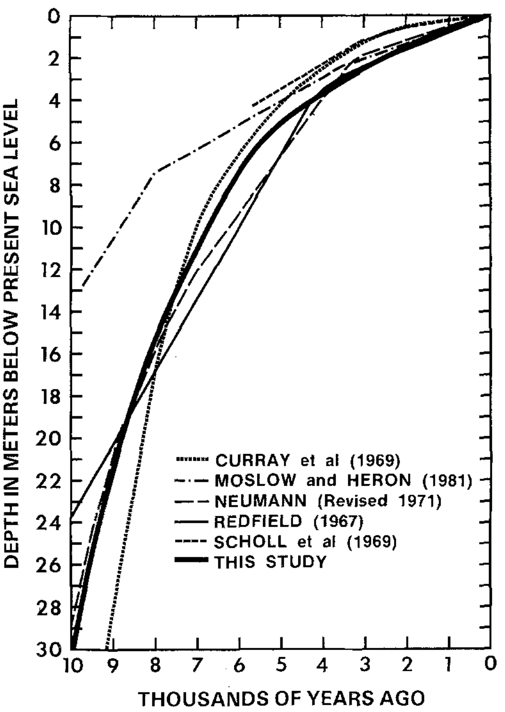

Fig. 4. Sea-level curves for the western Atlantic compared to the minimum sea-level curve proposed in this study

conditions of submergence (that is, the coral had to be submerged in order to grow), and as such may indicate a minimum position of sea level. Even though colonies of *A. palmata*, as noted, have been reported from water depths of 17 m, modern *A. palmata* framework is generally restricted to much shallower depths, as shown in Table 1.

Our minimum sea-level curve (Fig. 2) places all *Acropora palmata* framework samples under water, the lower limit dictated by the position of the shallowest samples. Only four time-depth plots do not allow the construction of a sea-level curve within the 5 m optimum depth limit. That these plots are located well below the minimum sea-level curve is understandable, because the samples were collected from deeper water sections of a submerged relict barrier reef off the east coast of Florida (Lighty et al. 1978). These deeper plots may also reflect the survival of *A. palmata* communities in deeper waters during the rapidly rising seas – approximately 5 m/1,000 years (Neumann 1971) – from 9,000 to 7,000 years BP.

The sea-level curve described in this study differs from other curves in that it represents a lower limit for the position of pre-existing sea levels rather than their actual depth with respect to present sea level. As such, our curve should be considered a tool for evaluating other sea-level curves thought to represent the Holocene sea-level history of the western Atlantic. Some curves, for example, have sections that plot below the minimum limits established by our data (Fig. 4): the Neumann (1971) and Redfield (1967) curves are below the suggested lower limits for the period 4,000–8,000 years BP, while the Curray et al. (1969) curve appears to be below acceptable limits for the time interval between 8,000 and 10,000 years BP.

It should be noted, however, that the validity of curves (or sections of curves) that are shallower than our minimum sea-level curve can be questioned only when they differ by more than 12 m – the reported maximum depth for *A. palmata* framework construction (Adey and Burke 1977). Because optimum development of *A. palmata* communities is restricted to water depths of < 1–5 m, it is not unreasonable to expect the position of pre-existing sea levels for the past 10,000 years to occur within 5 m above the minimum *A. palmata* curve.

If the position of our curve is accurate, it is possible to predict the minimum paleo-water depth in which an *A. palmata* sample lived by reading the value of the interval on the vertical bar between the time-depth plot and the intersection with the sea-level curve. This method of comparison has considerable potential as a paleoecologic tool in interpreting reef growth history.

Conclusions

1. The coral *Acropora palmata* commonly builds a rigid framework in shallow-water reef environments which, when identified within the internal facies of a reef build-up, can be used as a reliable indicator of sea-level history.
2. Radiocarbon dates for forty-two in situ samples of *A. palmata* reef framework from reefs throughout the tropical western Atlantic were used to construct a minimum eustatic sea-level curve for the past 10,000 years.
3. The distribution of *A. palmata* time-depth plots used to construct this sea-level curve shows a uniform and continuous trend with a relatively close pattern of time-depth plots.
4. New eustatic sea-level curves for the tropical Atlantic, or new individual sample dates, should be compared with our minimum sea-level curve as a first check on reliability because our minimum values are lower boundary limits in that corals cannot live above sea level.
5. Similarly, new dates obtained for *A. palmata* framework samples may be compared with our curve to confirm whether they are in situ samples and to estimate paleo-water depths at the time of reef growth.

Acknowledgements: W. H. Adey and R. B. Burke graciously provided unpublished data for inclusion in this study. Radiocarbon dates on samples from Bahamas were obtained by NSF funding to A. C. Neumann. All other dates were sponsored by the Smithsonian Institution. R. G. Loucks, T. F. Moslow, and D. R. Stoddart kindly reviewed this report. The manuscript was typed by J. S. Kline.

References

Adey WH (1975) The algal ridges and coral reefs of St. Croix: their structure and Holocene development. Atoll Res Bull 187

Adey WH, Burke R (1976) Holocene bioherms (algal ridges and bank-barrier reefs) of the eastern Caribbean. Geol Soc Am Bull 87:95–109

Adey WH, Burke RB (1977) Holocene bioherms of Lesser Antilles – geologic control of development. Studies in geology, no 4, Am Assoc Petrol Geol pp 67–81

Adey WH, Macintyre IG, Stuckrath R, Dill RF (1977a) Relict barrier reef system of St. Croix: its implications with respect to late Cenozoic coral reef development in the western Atlantic. In: Proc 3rd Int Coral Reef Symp Miami, vol 2, pp 15–21

Adey WH, Adey PJ, Burke R, Kaufman L (1977b) The Holocene reef systems of eastern Martinique, French West Indies. Atoll Res Bull 218

Bak RP (1977) Coral reefs and their zonation in Netherlands Antilles. Studies in geology, no 4. Am Assoc Petrol Geol pp 3–16

Curray JR (1965) Late Quaternary history, continental shelves of the United States. In: Wright HE, Frey DC (eds) The Quaternary of the United States. Princeton Univ Press, Princeton, pp 723–735

Curray JR, Emmel FJ, Crampton PJS (1969) Holocene history of a strand plain, lagoonal coast, Nayarit, Mexico. In: Coastal lagoons, a symposium – UNAM-UNESCO, Mexico, DF, 1967. Mexico Univ Nac Autonoma, pp 63–100

Druffel EM (1980) Radiocarbon in annual coral rings of Belize and Florida. Radiocarbon 22:363–371

Focke JW (1978) Holocene development of coral fringing reefs, leeward off Curacao and Bonaire (Netherlands Antilles). Mar Geol 28:M31–M41

Goreau TF, Wells JW (1967) The shallow-water Scleractinia of Jamaica: revised list of species and their vertical distribution ranges. Bull Mar Sci 17:442–453

Kuhlman DHH (1974) The coral reefs of Cuba. Proc. 2nd Int Coral Reef Symp, Brisbane. vol 2, pp 69–83

Lewis JB (1975) A preliminary description of the coral reefs of the Tobago Cays, Grenadines, West Indies. Atoll Res Bull 178

Lighty RG (1977) Relict shelf-edge Holocene coral reef: southeast coast of Florida. Proc 3rd Int Coral Reef Symp Miami, vol 2, pp 215–221

Lighty RG, Macintyre IG, Stuckenrath R (1978) Submerged early Holocene barrier reef, southeast Florida shelf: Nature 276:59–60

Lighty RG, Macintyre IG, Neumann AC (1980) Demise of a Holocene barrier-reef complex, northern Bahamas. Geol Soc Am 12:471 (abstracts with programs)

Linick TW (1978) La Jolla measurements of radiocarbon in the oceans. Radiocarbon 20:333–359

Logan BW (1969)Coral reefs and banks, Yucatan shelf, Mexico (Yucatan reef unit) In: Carbonate sediments and reefs, Yucatan shelf, Mexico. Am Assoc Petrol Geol Mem 11, pp 129–198

Macintyre, IG (1977)Distribution of submarine cements in a modern Caribbean fringing reef, Galeta Point, Panama. J Sediment Petrol 47:503–516

Macintyre IG, Glynn PW (1976) Evolution of a modern Caribbean fringing reef. Galeta Point, Panama. Am Assoc Petrol Geol Bull 60:1054–1072

Macintyre IG, Burke RB, Stuckenrath R (1982) Core holes in the outer fore reef off Carrie Bow Cay, Belize: A key to the Holocene history of the Belizean barrier reef complex. Proc 4th Int Coral Reef Symp Manila (in press)

Macintyre, IG, Pilkey OH, Stuckenrath R (1978) Relict oysters on the United States Atlantic continental shelf: a reconsideration of their usefulness in understanding late Quaternary sea-level history. Geol Soc Am Bull 89:277–282

Macintyre IG, Raymond WF, Stuckenrath R (1982) Recent history of a fringing reef, Bahia Salina del Sur, Vieques Island, Puerto Rico Atoll Res Bull (in press)

Milliman JD (1969) Four southwestern Caribbean atolls: Courtown Cays, Albuquerque Cays, Roncador Bank and Serrana Bank. Atoll Res Bull 129

Moslow TF, Heron SD Jr (1981) Holocene depositional history of a microtidal cuspate foreland cape: Cape Lookout, North Caroline. Mar Geol 41:251–270

Neumann AC (1971) Quaternary sea-level data from Bermuda: Quaternaria 15:41–43. The sea-level curve used in this report is Neumann's revision of his curve, and has been published in Adey (1975) and Macintyre and Glynn (1976)

Newell ND, Rigby JK (1957) Geological studies on the Great Bahama Bank. In: Regional aspects of carbonate deposition. Soc Econ Paleontol Mineral Spec Pub 5:15–72

Redfield AC (1967) Postglacial change in sea level in the western north Atlantic ocean. Science 157:687–691

Rigby JK, Roberts HH (1976) Geology, reefs, and marine communities of Grand Cayman Island, British West Indies. Brigham Young Univ Geol Studies Spec Publ no 4, pp 1–95

Roberts HH (1972) Coral reefs of St. Lucia, West Indies. Caribbean Sci 12:179–190

Rützler K, Macintyre IG (1982) The habitat distribution and community structure of the barrier reef complex at Carrie Bow Cay, Belize. In: Rützler K, Macintyre IG (eds) The Atlantic barrier reef eco-system at Carrie Bow Cay, Belize. Scientific Reports 1, Smithsonian Contributions to the Marine Sciences no 12, Smithsonian Institution Press, Washington DC, pp 9–46

Scatterday JW (1974) Reefs and associated coral assemblages off Bonaire, Netherlands Antilles, and their bearing on Pleistocene and recent reef models. Proc 2nd Int Coral Reef Symp Brisbane, vol 2, pp 85–106

Scholl DW, Craighead FC, Stuiver M (1969) Florida submergence curve revised: its relation to coastal sedimentation rates. Science 163:562–564

Shinn EA (1963) Spur and groove formation on the Florida reef tract. J Sediment Petrol 33:291–303

Shinn EA (1980) Geologic history of Grecian Rocks, Key Largo Coral Reef Marine Sanctuary. Bull Mar Sci 30:646–656

Shinn EA, Hudson JH, Halley HR, Lidz B, Robbin DM, Macintyre IG (1982) Geology and sedimentology accummulation rates at Carrie Bow Cay, Belize. In: Rützler K, Macintyre IG (eds) The Atlantic barrier reef ecosystem at Carrie Bow Cay, Belize. Scientific Reports 1, Smithsonian Contributions to the Marine Sciences no 12, Smithsonian Institution Press, Washington DC, pp 63–75

Shinn EA, Hudson JH, Halley RB, Lidz B (1977) Topographic control and accumulation rate of some Holocene coral reefs: south Florida and Dry Tortugas. Proc 3rd Int Coral Reef Symp Miami, vol 2, pp 1–7

Steneck RS, Adey WH (1976) The role of environment in control of morphology in *Lithophyllum congestum*, a Caribbean algal ridge builders. Bot Mar 19:197–215

Storr JF (1964) Ecology and oceanography of the coral-reef tract, Abaco Island, Bahamas. Geol Soc Am Spec Papers no 79

Weber JN (1974) $^{13}C/^{12}C$ ratios as natural isotopic tracers elucidating calcification processes in reef-building and non-reef-building corals. Proc 2nd Int Coral Reef Symp Brisbane, vol 2, pp 289–298

Williams PM, Linick TW (1975) Cycling of organic carbon in the ocean: Use of naturally occurring radiocarbon as a long and short term tracer. In: Isotope ratios as pollutant source and behaviour indicators, IAEA, Vienna, pp 153–167

Zankl H, Schroeder JH (1972) Interaction of genetic processes in Holocene reefs off North Eleuthera Island, Bahamas. Geol Rundschau 61:520–541