Coral Reefs (2003) 22: 91–97
DOI 10.1007/s00338-003-0289-2

REPORT

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# Staghorn tempestites in the Florida Keys

Received: 8 March 2002 / Accepted: 31 December 2002 / Published online: 5 March 2003

**Abstract** Thirty-one samples of transported Holocene *Acropora cervicornis* “sticks” sampled from carbonate sand tempestite accumulations at 19 sites along a 180-km-long stretch of the Florida reef tract were dated using the radiocarbon ($^{14}$C) method. The “modern fossils” collected from just a few centimeters below the surface ranged in age from 0.5 to 6.4 ka. The majority lived between 3.5 and 5.5 ka. The time of transport and deposition is not known. There were no *A. cervicornis* samples centered around 4.5 ka. *Acropora cervicornis* is living on many Florida reefs, but the youngest tempestite sample was 500 years old. Two 500-year-long gaps in dated staghorn suggest that the documented decline in living *A. cervicornis* over the past 25 years may not be without precedent.

**Keywords** *Acropora cervicornis* · Bleaching · Carbon-14 · Coral · Growth rate · Holocene · Staghorn · Tempestite

## Introduction

Stick-like fragments of *Acropora cervicornis* (staghorn coral) are abundant in carbonate sand areas on the Florida reef tract. These skeletal sticks can be found a few centimeters below the sediment surface within a few kilometers landward of the outer reefs in the Florida Keys. Well-preserved 1- to 3-cm-diameter staghorn “sticks” range from a few centimeters to decimeters in length. The abundance of skeletal sticks compared to the small number of this species presently living in the area has puzzled coral researchers for many years. Scattered colonies of living staghorn coral could, over time, produce many fossil fragments that remain preserved once buried in sediment. Fossilization and burial processes may therefore account for the large ratio of dead to live corals but do not explain the abundance of sticks in areas far-removed from living stands.

Long-term observations since the late 1950s suggest that there were more living *A. cervicornis* colonies on the Florida Keys reef tract during the decades prior to the late 1970s than today. Decline in abundance was first noted in the late 1970s and early 1980s (Dustan and Halas 1987). However, the major period of modern acroporid death, including *A. palmata*, occurred in 1983 and 1984 both in Florida and throughout the Caribbean (Glynn 1988; Jaap 1998; Williams and Williams-Bunkley 1990; Shinn et al. 2000).

Axial growth rate of healthy *A. cervicornis* in Florida is approximately 10 cm/year, and transplanting experiments have shown that the species bleaches at water temperatures above 32 °C and dies below 14 °C (Shinn 1966). With its annual branching and rapid growth rate *A. cervicornis* is considered a prolific contributor to coral reefs (Shinn 1976).

Periodic cold-water outbreaks have been shown to kill *A. cervicornis* in the Florida Keys, and a cold front in 1977 killed many acres of staghorn at Dry Tortugas (Davis 1982). The dead staghorn, at Dry Tortugas and elsewhere, remained in growth position and formed an accumulation distinctly different from that described in this study. Staghorn coral was also decimated in 1878, by a so-called black-water event, at Dry Tortugas (Mayer 1903).

This study shows that the abundant acroporid “sticks” preserved in sand several kilometers landward from areas of staghorn growth most likely resulted from periodic storm transport and deposition during the past 6 ka. Whether *A. cervicornis* suffered catastrophic die-offs similar to those in 1983 and 1984 could not be determined.

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## Methods

Staghorn sticks were collected at 19 sites between Sand Key Reef off Key West, Florida, and Grecian Rocks reef off Key Largo, a distance of 180 km (Fig. 1). Selection of sites for the purpose of the study was limited to sandy areas far removed from areas of living specimens and selection of sites was purposely haphazard. Although sandy bottom areas were clearly visible from the boat, the presence or abundance of *A. cervicornis* sticks in the sand could not be determined without diving and digging. Divers collected samples at or within 30 cm of the seafloor surface by ''hand fanning'' the sand to expose buried *A. cervicornis*. Approximately 10 specimens were collected at each site. At a few sites, hand fanning revealed fewer than 10 specimens. Underwater photographs were taken at each collection site, and latitude and longitude determined by global positioning satellites (GPS) were recorded (Fig. 2).

*Acropora cervicornis* in growth position was not encountered at any site. Constraints, or biases, in our protocol include locations of sample sites between 1 and 2 km landward of the outer coral reefs and/or ''hardbottoms'' where scattered small colonies of *A. cervicornis* are presently growing. There were no sampling transects normal to the reef tract. A second constraint was that sampling was conducted in a grass-free sandy area beneath the boat to avoid destruction of marine grass and for location of sites using GPS.

In the laboratory, specimens were scraped to remove encrustations and sawed with a diamond rock saw for examination. The prepared samples were then bathed in a 10% HCl solution until visually clean of encrustations. The degree of encrustation varied from none to moderate and there was no obvious indication of recrystallization or growth of aragonitic secondary pore filling. The latter, however, would be difficult to detect without petrographic examination using thin sections. Secondary aragonite precipitation would skew the $^{14}$C analyses toward younger dates but would not significantly change our conclusions. XRD and thin-section analyses were not performed because previous experience suggested little diagenesis in the backreef areas targeted for this investigation.

Thirty-one samples from 19 sites were submitted for commercial $^{14}$C analysis. Two duplicate samples were selected from site 10. At site 5, seven samples were picked and at site 18, six samples were selected (Fig. 1 and Table 1). The multiple samples from sites 5 and 18 were dated specifically to determine the degree of local mixing. Carbon-14 ($^{14}$C) ages were converted to calendar ages using the correction method of Stuiver et al. (1998) (Table 1).

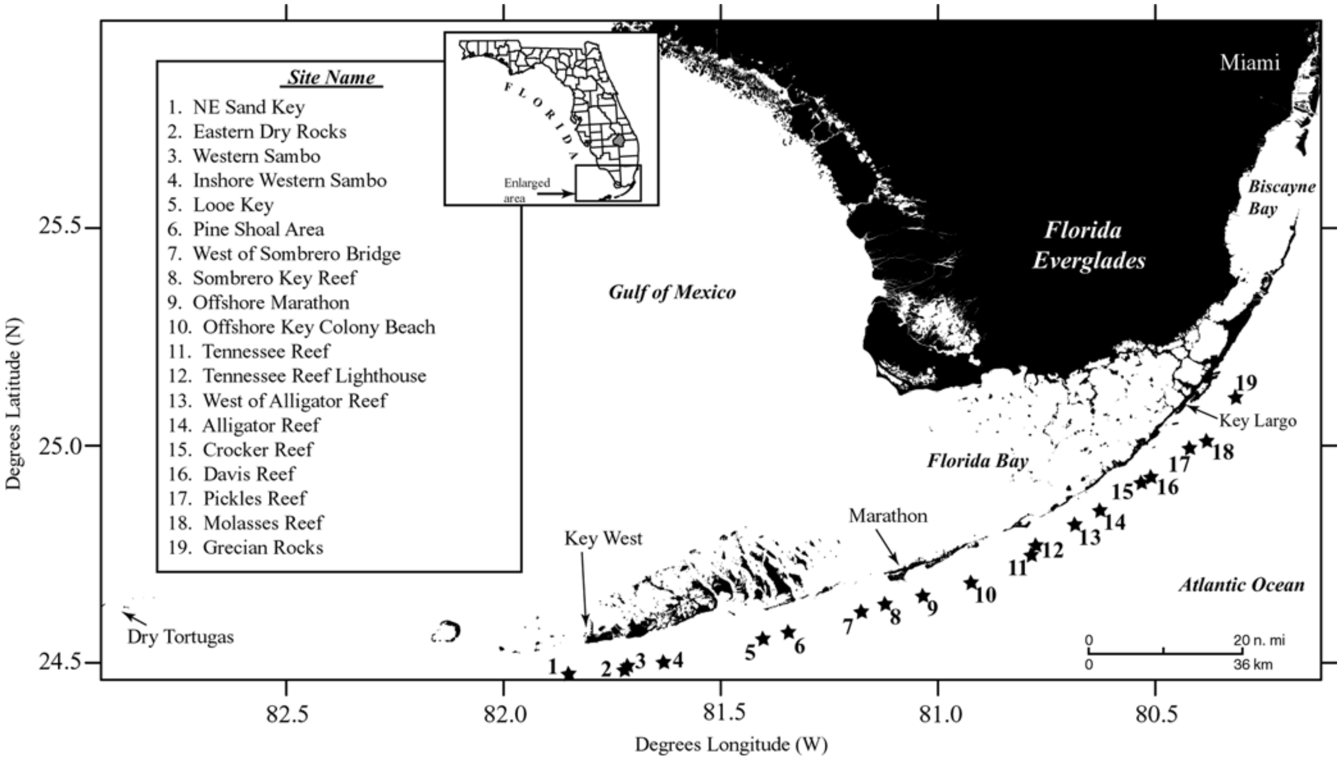
## Results

The $^{14}$C data plot (Fig. 3), arranged by site location in the lower, middle, and upper Keys, shows a wide scatter of ages ranging from around 0.5 ka to over 6 ka. The frequency histogram (Fig. 4), depicted in 500-year intervals, shows that the bulk of samples ranges between 3.5 and 5.5 ka with two gaps centered around 3 and 4.5 ka.

## Discussion

The $^{14}$C data show a wide range of ages with more than half greater than 3 ka. The ages do not clearly support our initial hypothesis that $^{14}$C ages would cluster around a common date and thus suggest a period of proliferation and death over a large area similar to that observed over the past 20 years. Previous $^{14}$C coral data from reef cores (Shinn et al. 1977; Shinn 1980; Shinn et al. 1989), dredge holes, and sediment cores (Enos 1977) show a systematic upsection reduction in age. Dates from the bottom of such cores also indicate that the earliest Holocene coral growth on Florida Keys reefs began about 6 ka. Cores drilled at Grecian Rocks, Looe Key,

**Fig. 1** Locations and sample station numbers along the 180-km-long sampling transect



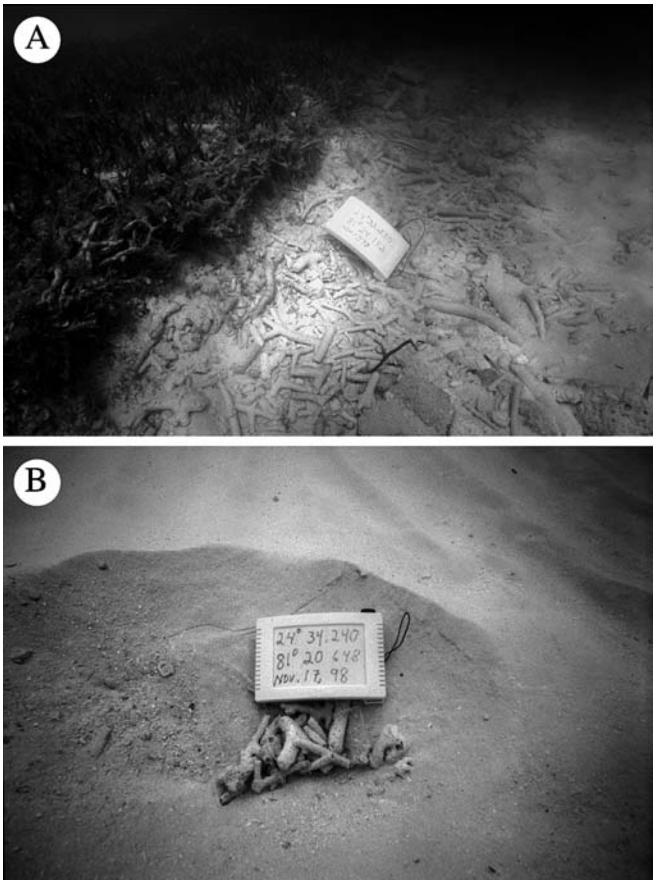


**Fig. 2** **A** Underwater photograph showing staghorn sticks in sand adjacent to marine grass bed at Looe Key site 5. **B** Underwater photograph showing samples collected and latitude and longitude at Pine Shoal area site 6. See Table 1 for location and water depth. Diving tablet in both photos is 20 cm long

and at Southeast Reef in the Dry Tortugas revealed 6-ka corals beneath several meters of younger coral accumulation (Shinn et al. 1989). Radiocarbon analyses of peat collected on the reef tract also indicate that the Florida shelf flooded between 6 and 7 ka (Robbin 1984). Farther north, in water deeper than that generally found in the Keys ($>20$ m versus 10 to 15 m), *A. palmata* was dated at around 7 ka (Lighty 1977). In addition, sea-level curves (Robbin 1984; Fairbanks 1989; Lidz and Shinn 1991; Shinn 2001) indicate that flooding of the shallow limestone platform where reefs are presently accumulating occurred between 7 and 6 ka.

Holocene sediments, in contrast to coral reefs, have accumulated to a thickness of 2 m to several meters on the Florida reef tract during the past 6 ka (Enos 1977; Lidz et al. 1997; Lidz et al. 2003) and there are large areas of no sediment or coral accumulation (Shinn et al. 1989; Lidz et al. 1997). Coral reefs that have kept pace with rising sea level during the past 6 ka cover less than 1% of the reef tract, but those that have kept pace are between 10 and 15 m thick. Although superficially resembling coral reefs, there are many areas of non-deposition that are best described as hardbottom communities.

The $^{14}C$ age distribution (Figs. 3 and 4) shows that *A. cervicornis* grew on the reef tract for the past 6.4 ka years but less so during the past few hundred years. Surprisingly, most (70%) coral sticks are more than 3 ka even though they are often $>2$ km from outer reefs and present just a few centimeters beneath the sediment surface (Fig. 2), indicating relatively long-distance transport. The most likely causes of transport are tropical storms and hurricanes. Whether the "sticks" were transported by a single event or by a combination of events combined with vertical reworking from deeper accumulations is not known. Upward reworking of old sticks buried several meters below the sediment/water interface implies processes not observed. We have seen no burrowers capable of such translocation and, for the most part, the water depth at the sample sites is too shallow for sand tile fish *Malacanthus plumeri*. *Malacanthus plumeri* generally live in water deeper than 10 m and their burrows extend less than 1 m below the sea floor (Clifton and Hunter 1972).

Rays foraging for mollusks produce craters up to 30 cm deep and 1 m or more in diameter, and a lag of coarse shell and coral fragments generally lines the bottom of feeding craters (Clifton and Hunter 1973). Rays feeding over a long period of time could have affected every centimeter of the bottom and created a semi-continuous layer of coral and shell debris 10 to 30 cm below the sediment/water interface. This process, however, would not likely concentrate coral fragments with ages ranging from 0.5 to 6.4 ka unless the coral sticks had already been transported laterally several kilometers. We are left to conclude that a combined process of storm transport and some exhumation by winnowing was responsible for these accumulations even though other types of debris, such as mollusk shells, are not commonly associated with the sticks.

If the presence of old fragments near the surface is the result of storm mixing and/or concentration, then a period of more frequent and severe storms in the past may be indicated. Alternatively, or in combination, cold water, warm-water bleaching, or microbial disease may have periodically killed many *A. cervicornis* on time scales too brief for resolution by $^{14}C$ dating. It should be pointed out that the two 500-year gaps (Fig. 4) do not necessarily indicate periods of no growth but could simply be periods when there were few storms and thus no lateral transport.

The process that created these possible tempestites is decidedly different from that which produces in-place accumulations. The process of death and in-situ collapse should be clearly distinguishable from the tempestite accumulations described in this paper. Death and in-place collapse are documented in long-term serial underwater photographs (Fig. 5). The 1977 cold front at Dry Tortugas (Davis 1982) and the Florida Keys (Hudson 1981a, 1981b; Roberts et al. 1982) and the black-water event in 1878 (Mayer 1903), including more recent disease outbreaks (Fig. 5), all produced in-place accumulations.

**Table 1** Sample location information, conventional radiocarbon age (*CRA*) and calibrated age (marine corrected) in years Before Present (CAL B.P.) of fossil *Acropora cervicornis* sticks

| Site location | Sample no. | Water depth (m) | $^{13}$CPDB (parts per mil) | CRA 2 sigma (years B.P.) | CAL 2 sigma (95%) (years B.P.) |
|---|---|---|---|---|---|
| NE Sand Key | FL Keys 01 | 5.8 | −1.1 | 985 ± 105 | 580 ± 170 |
| E. Dry Rocks | FL Keys 02 | 3.9 | 1.5 | 2,445 ± 115 | 2,075 ± 275 |
| Western Sambo | FL Keys 03 | 4.5 | 0.6 | 4,110 ± 140 | 4,150 ± 400 |
| Inshore W. Sambo | FL Keys 04 | 6.4 | −0.1 | 1,340 ± 110 | 885 ± 225 |
| Looe Key | FL Keys 05 | 4.5 | −0.7 | 4,800 ± 90 | 5,065 ± 225 |
| Looe Key | FL Keys 05 | 4.5 | 0.7 | 4,680 ± 85 | 4,975 ± 275 |
| Looe Key | FL Keys 05 | 4.5 | 0.2 | 5,570 ± 90 | 5,950 ± 220 |
| Looe Key | FL Keys 05 | 4.5 | 0.5 | 4,790 ± 80 | 5,060 ± 220 |
| Looe Key | FL Keys 05 | 4.5 | 0.6 | 3,980 ± 70 | 3,975 ± 205 |
| Looe Key | FL Keys 05 | 4.5 | 0.1 | 4,070 ± 70 | 4,100 ± 210 |
| Looe Key | FL Keys 05 | 4.5 | 0.3 | 4,890 ± 60 | 5,150 ± 180 |
| Pine Shoal Area | FL Keys 06 | 6.1 | 0.4 | 4,580 ± 140 | 4,800 ± 400 |
| W of Sombrero | FL Keys 07 | 7.6 | 0.8 | 5,880 ± 160 | 6,275 ± 375 |
| Sombrero Key Reef | FL Keys 08 | 6.7 | 0.7 | 1,820 ± 110 | 1,385 ± 235 |
| Off Marathon | FL Keys 09 | 6.4 | 0.9 | 3,655 ± 85 | 3,560 ± 210 |
| Off Key Colony Beach | FL Keys 10 | 5.2 | 0.9 | 2,360 ± 115 | 2,000 ± 300 |
| Off Key Colony Beach | FL Keys 10 | 5.2 | 0.4 | 2,450 ± 120 | 2,100 ± 300 |
| Tennessee Reef | FL Keys 11 | 6.1 | 0.6 | 5,280 ± 100 | 5,660 ± 220 |
| Tennessee Reef Light | FL Keys 12 | 7.3 | 0.9 | 5,460 ± 110 | 5,840 ± 250 |
| W Alligator Reef | FL Keys 13 | 5.8 | −0.4 | 1,240 ± 70 | 790 ± 130 |
| Alligator Reef | FL Keys 14 | 4.5 | 1.2 | 3,975 ± 95 | 3,975 ± 275 |
| Crocker Reef | FL Keys 15 | 4.8 | 1.1 | 1,210 ± 70 | 800 ± 350 |
| Davis Reef | FL Keys 16 | 5.5 | 1.6 | 4,010 ± 95 | 4,025 ± 275 |
| Pickles Reef | FL Keys 17 | 4.5 | 1.1 | 3,500 ± 90 | 3,380 ± 220 |
| Molasses Reef | FL Keys 18 | 5.5 | 0.7 | 5,750 ± 95 | 6,130 ± 210 |
| Molasses Reef | FL Keys 18 | 5.5 | −0.2 | 5,360 ± 80 | 5,740 ± 160 |
| Molasses Reef | FL Keys 18 | 5.5 | 0.6 | 4,910 ± 80 | 5,210 ± 230 |
| Molasses Reef | FL Keys 18 | 5.5 | 0.2 | 3,970 ± 70 | 3,960 ± 200 |
| Molasses Reef | FL Keys 18 | 5.5 | 0.4 | 5,970 ± 70 | 6,400 ± 150 |
| Molasses Reef | FL Keys 18 | 5.5 | 0.6 | 3,850 ± 70 | 3,800 ± 190 |
| Grecian Rocks | FL Keys 19 | 3.3 | 1.9 | 2,630 ± 75 | 2,320 ± 220 |
| Median | | 5.5 | 0.6 | 4,010 | 4,025 |
| Mean | | 5.3 | 0.5 | 3,855 | 3,875 |

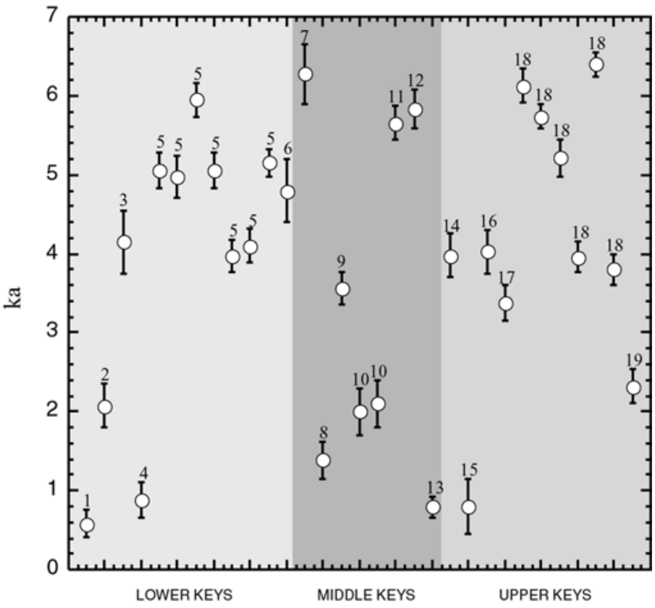


**Fig. 3** Distribution of corrected $^{14}$C ages. Note similarity of ages of multiple samples at sites 5 and 18 and paucity of sample ages around 3.0 and 4.5 ka. *Error bars* represent 2 sigma (95% confidence interval) standard deviation. See Fig. 1 and Table 1 for location, water depth, and both corrected and uncorrected $^{14}$C ages

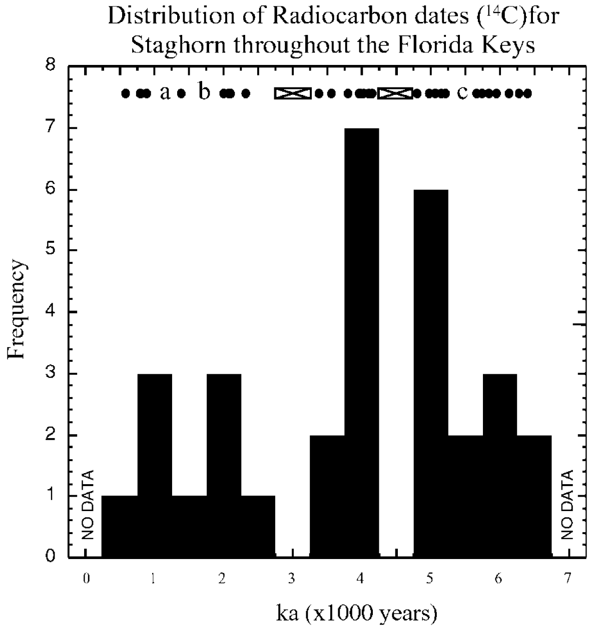
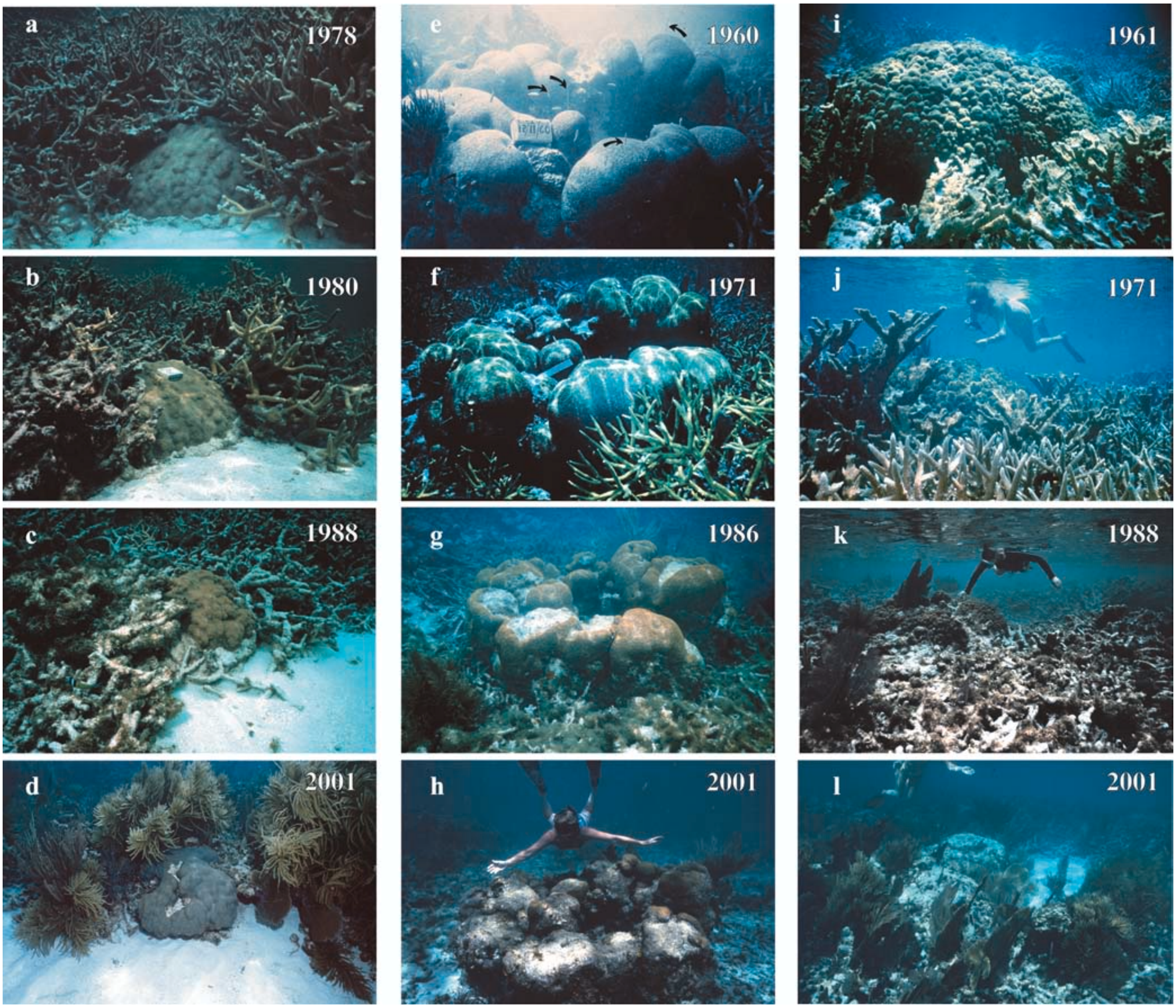


**Fig. 4** Frequency distribution of $^{14}$C ages. Note absence of corals during roughly 500-year time spans centered around 3.0 and 4.5 ka (rectangles). *Markers (solid circles) along top of plot* represent actual data points of *A. cervicornis* dates. There are at least three other gaps in data (*a*, *b*, and *c*), but the 500-year gaps are the largest

Although many questions cannot be answered without further study, our study confirms that the geology, age, habitat, and preservation of these fragments are very different from the situation recently described at Channel Key, Belize (Aronson and Precht 1997, 2001). Channel Key bank is a >20-m-thick patch reef where waves and tides are minimal and the matrix consists mainly of carbonate silt and mud. Channel Key is similar to Rodriguez Key bank in the Florida Keys except that Rodriguez Key bank is only 4 m thick and the corals are *Porities furcata* rather than *A. cervicornis* (Turmel and Swanson 1977). Cores from both places show little evidence of reworking or transportation prior to burial. Encrustation of coral sticks entombed in fine-grained gray muddy sediment in both banks is considered evidence of in-situ preservation.

Carbon-14 data presented here indicate two 500-year-long interruptions in *A. cervicornis* growth (Fig. 4). The 500-year hiatus centered at 3 ka is possibly the result of insufficient sampling. There is only one sample represented for the 500-year period before the gap at 3 ka and just two samples for the 500-year period after 3 ka. Had more samples been collected, that gap in our

**Fig. 5** Time series set of underwater photos at **a–d** Grecian Rocks reef, **e–h** Carysfort reef, and **i–l** Grecian Rocks reef showing disappearance of *A. cervicornis* and *A. palmata* from the 1970s to 2001. **a** At Grecian Rocks reef site (**a–d**), abundant staghorn encroached on a *Montastraea* sp. head in 1978. **b** By 1980, much of the staghorn was dead. Note live colonies to right of *Montastraea* sp. **c** In 1988, all of the staghorn adjacent to the head coral was dead. **d** By 1992 (photo not shown), the thicket had collapsed, and by 2001, gorgonians were established. **e** At Carysfort Reef, sparse staghorn grew to the right of and behind a *Diploria* sp. head in 1960. *Arrows* show 10-cm-long pins that were part of a growth-rate experiment. **f** Abundant staghorn coral surrounds the *Diploria* sp. head in 1971. **g** and **h** Photos from 1986 and 2001 demonstrate progressive disappearance of living staghorn coral. **i** and **j** At Grecian Rocks reef both *A. palmata* and *A. cervicornis* surround the *Montastraea* sp. from 1961–1971. **k** and **l** Note disappearance of both *A. palmata* and *A. cervicornis*, their collapse, and replacement by sea fans and other gorgonians. Prominent *Montastraea* sp. died after 1988 and is being bioeroded



data might not exist. However, the gap centered at 4.5 ka is statistically more plausible because there are many more samples on either side of the gap. We believe it is significant that this time interval roughly coincides with the worldwide change from rapid early Holocene sea-level rise to the present slow rate. This period of time is also after the creation of tidal passes to Florida Bay and a general reduction in coral cover opposite these passes (Ginsburg and Shinn 1964; Shinn et al. 1989). The creation of Florida Bay, the tidal passes and flux of bay waters may have led to a general reduction of *A. cervicornis* growth throughout the Florida reef tract, which could explain why there are so many samples older than 3 ka. It is also possible the relative lack of younger sticks is because we purposely did not sample near "source areas" where *A. cervicornis* is presently living.

Studies of the effects of hurricanes on reefs generally have not included adjacent sandy environments like those targeted in this study. Exceptions are Ball et al. (1967) and Perkins and Enos (1968), who examined several non-reef areas in the Florida Keys affected by Hurricanes Donna and Betsy in 1960 and 1965, respectively. Ball et al. (1967) documented 10 to 15 m of lateral carbonate sand accretion along a portion of the steeply dipping western edge of White Bank off Key Largo. Staghorn sticks were not a noticeable component of the accreted sand wedge.

Another possibility is that the layer of staghorn sticks represents a lag deposit resulting from removal of 1 m or more of overlying sediment, thus exposing older buried sticks. This explanation seems unlikely because sandy sediment is continually being produced and most is probably transported onto the shelf, whereas muddy sediment remains in suspension longer and most is transported off the shelf (Ball et al. 1967). Our observations also indicate that sediment thickness is increasing in these backreef areas. Thus, organically derived carbonate sand is for the most part being produced on, rather than removed from, the Florida reef tract. We are led to speculate that staghorn growth, storm transport, and reworking of sediment were more frequent during the middle Holocene possibly due to climate change and a series of closely spaced very intense hurricanes. These tempestite accumulations are distinctly different from those formed by in-place collapse and burial as described from Belize by Aronson and Precht (1997) and as seen in reef areas in Florida (Fig. 5). We hope that the information provided by this small study will help geologists recognize similar but different accumulations in older limestone sections. Similar principles of growth and sedimentation should apply to the geologic record regardless of age and reef-building species.

Future studies that include transects of samples extending from areas of living staghorn to tempestite-derived fossil sticks might confirm or close the 500-year growth gaps found in this study.

## Conclusions

1. The 31 samples of *Acropora cervicornis* sticks from the Florida Keys reef tract range in age from 0.5 to 6.4 ka with a mean age of 3.9 ± 1.8 ka.
2. The actual process that deposited old staghorn sticks near the surface has not been observed but is most likely related to lateral storm transport rather than bioturbation.
3. The $^{14}$C data suggest a 500-year widespread *A. cervicornis* mortality or non-recruitment event centered around 4.5 ka.
4. The accumulations described here are considered to be evidence of storm transport and deposition and provide criteria and clues for distinguishing between in-place reef accumulation and tempestite deposition in ancient limestones. Such distinction might aid in the interpretation of depositional environments and paleoclimates.

**Acknowledgments** We thank Robert and Linda Halley and Robert Rowland for participating in the collection phase of this study. The paper was greatly improved by reviewers Terence Edgar and Ginger Garrison. We thank Robert N. Ginsburg, Peter Swart, and two anonymous reviewers for refining and focusing the paper. We also thank the owner and Captain of the M/V *Papa-San* for donating use of the vessel for this research.

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