THE CORAL RECORD OF LATE GLACIAL SEA LEVEL RISE

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ABSTRACT

Each new improvement in radiometric dating has provided new insights into the growth history of coral reefs during the latest deglaciation. High precision U-series dates on corals now serve to calibrate the ^{14}C time scale beyond the range of dendrochrology. Corrected ages incidentally show distinct fluctuations in the late glacial rate of sea level rise, which have useful implications for reef growth.

INTRODUCTION

This is an exciting decade for the field of Quaternary research. As a recent manuscript reviewer noted, "One has the distinct feeling that with the necessary time control now nearly in hand, a crucial breakthrough in our paleoclimatic understanding is just on the horizon". Corals are more than ever before providing radiometric dates and isotopic ratios that integrate sea level change, atmospheric and ocean circulation, and late Quaternary climate history into a single subject. This "case study" is a review of recent research by others, much of which will be familiar to participants in this colloquium and forum. My purpose is to record my personal admiration for, and amazement at, the quality of research now in progress on the history of the late glacial rise in sea level, with emphasis on its record in coral reefs, and to ask some questions that may already be in the process of being answered.

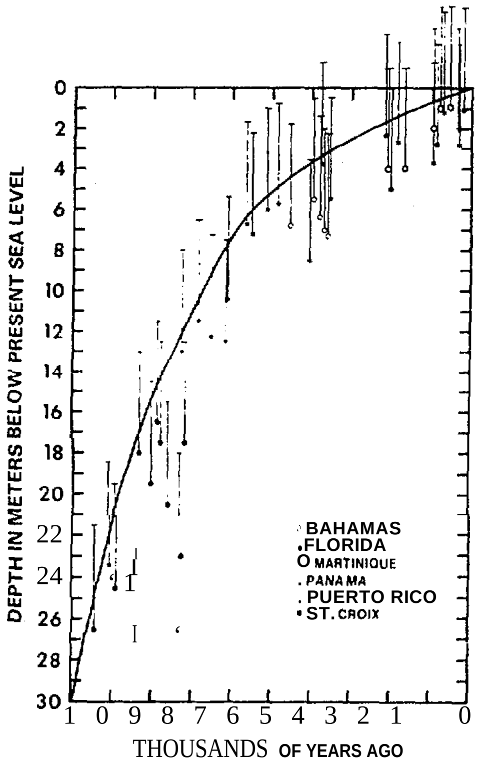
IMPROVED DATING METHODS

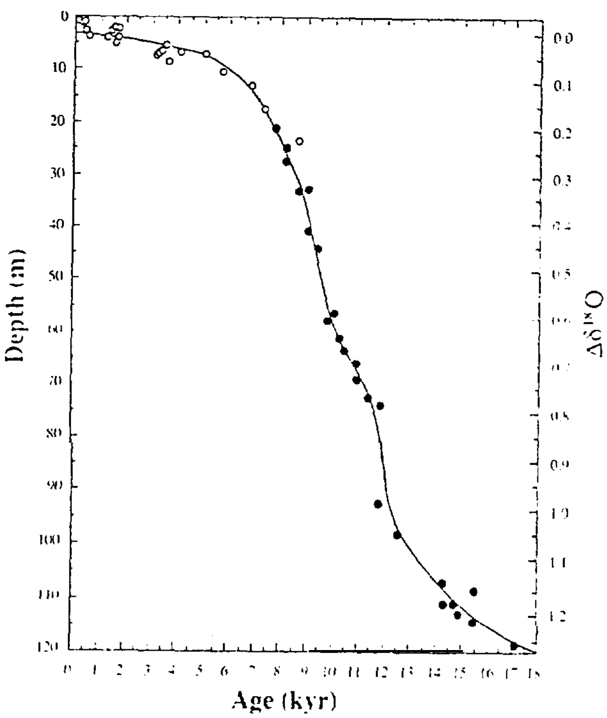
During the nearly 50 years that radiocarbon dating has been revolutionizing Quaternary studies there have been repeated examples of great promises suddenly tempered by new problems, only to have those problems resolved in unexpected ways that lead to more great promises. Within two decades after the discovery of radiocarbon dating in 1947 by Willard Libby, the impact of the industrial revolution on recent radiocarbon dates was recognized by Hans Suess. Soon thereafter, atmospheric nuclear testing introduced new problems of ^{14}C productivity and mixing rates, but almost immediately, one person's contaminant became another's tracer. In rapid succession, sunspots and the fluctuating secular magnetic field of the earth were shown to perturb the classic concept of 14C dating with its assumptions of constant generation and decay. In each case, the "problem" became an exciting and fruitful research topic, touching on broader issues such as the sun as a variable star, the origin and history of the earth's magnetic field, and mixing rates in the atmosphere and ocean.

New and improved equipment and techniques continued to revolutionized radiometric dating. By 1966, Veeh had dated emerged coral reefs of last interglacial age at many locations in the Pacific and Indian Ocean by U-series alpha spectrometry, with ages ranging from "90,000 ± 20,000 to 160,000 ± 40,000 years" and from "80,000& 50,000 to 180,000 ± 60,000 years". By 1970, the Milankovitch theory was finding support in U-series dates from Barbados (Broecker et al., 1968), Papua New Guinea (Veeh and Chappell, 1970), and elsewhere, with Emiliani's isotope stage 5 subdivided into intervals centered at about 80,000,105,000, and 125,000 years, all with 26 counting errors reduced to the range of ±10%.

Reef corals, by virtue of their close correlation with sea level, clean mineralogy, readily observed diagenesis, generally good preservation, and wide geographic distribution, have been a favored dating material for many investigators using troth ^{14}C and U-series techniques. It is worth noting that the entire chronologic support for reading the deep sea and ice core oxygen isotope records in terms of Milankovitch cycles rests on :(1) interpolation from the age of the Brunhes-Matuyama paleomagnetic boundary, which has recently been revised from ea. 730,000 to 780,000 BP (Baksi et al., 1992), (2) ^{14}C dates on deep-sea carbonates back to only ca. 20,000 BP, and (3) U-series dates from last interglacial and Wisconsin interstadial coral reefs. While we have no reason to doubt the established chronology, neither can we assume that it is proven.

The coral reef record of the late Wisconsin-Holocene sea level rise is primarily submerged and accessible only by diving or drilling. Lighty et al. (1982) assembled 42 radiocarbon dates on in situ Acropora palmata specimens from 16 reefs in 6 regions of the western Atlantic into a minimum sea-level curve for the past 10,000 years (Fig. 1). For the first time, sea level researchers had a comprehensive coral reef record to compare with previously produced sea level curves based on salt marsh stratigraphy and molluscan shell banks, The radiocarbon ages by this time had counting errors of ±1 or 2 per cent, but were uncorrected for the several ills to which such dates are liable. No seawater age correction was made, based on analyses of living specimens. This sea level curve shows many general features of the final 10,000 years of sea level rise. As ice sheet volume diminished, the rate at which water returned to the sea also diminished. Of the total of about 120 m of sea level rise since about 18,000 BP, only some 30 m remained 10,000 years ago.





Figure]. **Minimum Holocene sea level curve based on ^{14}C ages and depths of 42 in situ** <u>Acropora palmata</u> framework samples from tropical western Atlantic. (Lighty et al., 1982). Vertical bars represent paleo water depths of O to 5 m.

Figure 2 (right). Barbados sea level curve based on ^{14}C-dated <u>A. palmata</u>. All ages corrected for seawater age by subtracting 400 years from measured ^{14}C ages. Open circles from Lighty et al. (1982) (Fairbanks, 1989).

Adding to the effect of meltwater returning to the sea was the isostatic response of the ocean floor, which produced a variety of flexural responses on islands and contintental margins. No two regions have exactly the same sea level history for the last 10,000 years; some regions were uplifted, some subsided. The isostatic response added or subtracted only a few meters of vertical displacement relative to changing sea level, however. In most regions of coral reef growth, the decelerating rise of sea level permitted reefs to establish and expand only during middle to late Holocene time. Most modem reefs are a veneer less than 10 m in thickness, built in the Holocene on a much older substrate. A similar record of Holocene fringing-reef growth in North Queensland was compiled from borehole samples by Hopley et al. (1978, 1983). Holocene reef growth was established by 9,500 years ago at a depth of about 20 m, although most of the fringing reefs in North Queensland are veneers less than 7 m in thickness and younger than 7,000 years.

Suddenly, within the last 5 years, the subject of late Wisconsin-Holocene sea level history from coral reefs has exploded. Fairbanks (1989) published the first radiocarbon-dated sea level curve that covered the entire deglacial hemicycle, based on offshore drilling in several drowned reefs off the west coast of Barbados (Fig. 2). The last 9000 years and 20 m of his submergence history merge into the data of Lighty et. al. (1982), when the latter are corrected for a seawater age of 400 years. The sigmoid curve covers 121 ± 5 m of submergence during the past 18,000 radiocarbon years, with two intervals of more rapid rise. The only bothersome feature of this scientific triumph is its lack of continuity among the several reefs that were drilled and dated.

A 52 m borehole in the emerged Holocene reef near Sialum, on the Huon Peninsula in Papua New Guinea, has also provided a sea level chronology for the late glacial interval from 11,000 to 7,000 years BP (Chappell and Polach, 1991). When corrected for tectonic uplift, the Sialum borehole ^{14}C dates from shallow water coral species impressively complement the discontinuous Barbados record (Fig. 3). Whereas the Barbados reefs could not keep up with the rapidly rising sea level, the Sialum reef kept pace from 11,000 years ago until tectonic uplift caused its emergence about 7,000 years ago. The average uplift rate of 1.9 m per 1000 years near Sialum is slow compared to the vertical reef growth rate of 12.7 m per 1000 years. The Barbados and Huon Peninsula radiometrically dated records of the deglacial sea level rise arc the foeus of the remainder of this case study.

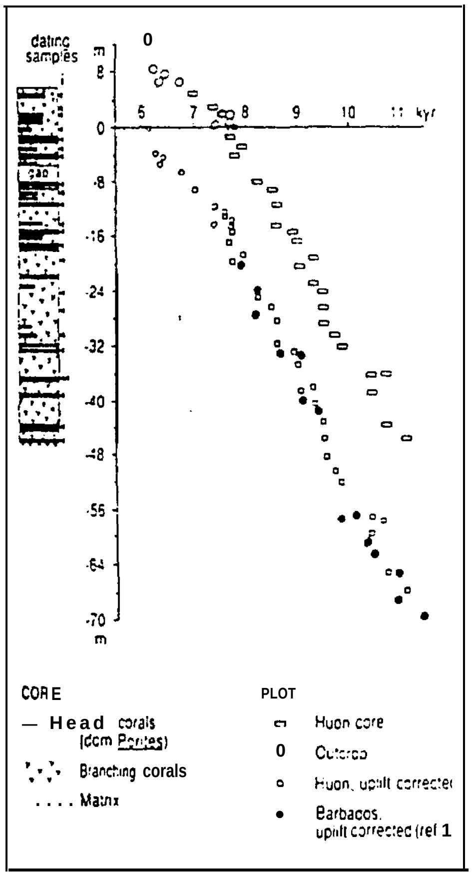


Figure 3. Core log and age-depth plot of Sialum borehole, Papua New Guinea. ^{14}C ages corrected by subtracting 400 years for seawater age. Upper rectangles are uncorrected for tectonic uplift of ca 2 mm/yr. Lower rectangles are corrected for uplift and compared-with Barbados curve (Fairbanks, 1989) (Chappell and Polach, 1991).

IMPACT OF HIGH PRECISION CORAL DATING

Both ^{14}C and Uranium-series dating methods have been radically improved by mass spectrometry, better calibration, and better instruments and techniques. Counting errors are now routinely smaller than 1 percent of the age of the sample. Radiocarbon dates are now precisely calibrated by dendrochronology to at least 9,200 BP (Stuiver et al., 1986). U-series dates by thermal emission mass spectrometry now routinely carry counting errors (2σ) of approximate y 0.5 per cent, good enough to extend the calibration of the ^{14}C time scale to at least 30,000 BP (Bard et al., 1990 a and b). The U-series dates from corals in Barbados and Papua New Guinea not only consistently record a "French two step" model of late glacial sea level rise, but they promise to link a whole series of events: reef growth, sea level, the late-glacial Younger Dryas climate oscillation, ^{14}C in the atmosphere, and the $\delta^{18}O$ record in pelagic foraminifera and Greenland ice cores.

Consider late glacial sea level history from the viewpoint of a coral reef in Barbados (Fig. 4). Acropora palmata and other species of the impoverished Atlantic coral province were building a fringing reef 120 m below present sea level on the exposed island shelf of Barbados, 18,000-20,000 BP. As sea level rise accelerated to a maximum of 45-50 mm/yr during Fairbank's meltwater pulse 1A, about 14,100 BP (U-series; equivalent to 12,000 ^{14}C BP) the fringing reef was drowned. A second, shallower fringing reef was established during the Younger Dryas time, when sea level rise markedly slowed to between 6-10 mm/yr (Fig. 4), but it too was subsequently drowned by rapid sea level rise during meltwater pulse 1 B, when sea level rose at a maximum rate of 35 to 40 mm/yr at about 11,300 BP (U-series; equivalent to 9500 BP 14C years). Near the end of meltwater pulse lB, a third, even shallower, fringing reef began, from which Fairbanks established the Holocene part of his curve with additional dates from other western Atlantic reefs by Lighty et at. (1968).

The testable hypotheses offered to students of Atlantic coral reefs by Fairbanks (1989, 1990) and Bard et al. (1990a, 1990b) is clear: were other fringing reefs of the region overtopped during the late-glacial meltwater pulses? With the varied rates of sea level rise and the history of surface water temperature reasonably inferred for the region, the late-glacial paleoecology of reef-building corals has been largely circumscribed, although additional variables such as substrate composition, shelf gradient, and turbidity need to be considered. How did the reefs of the region respond? How many other islands have triple drowned reefs at depths of less than 120 m? Someone should take a submersible ride down to look at them.

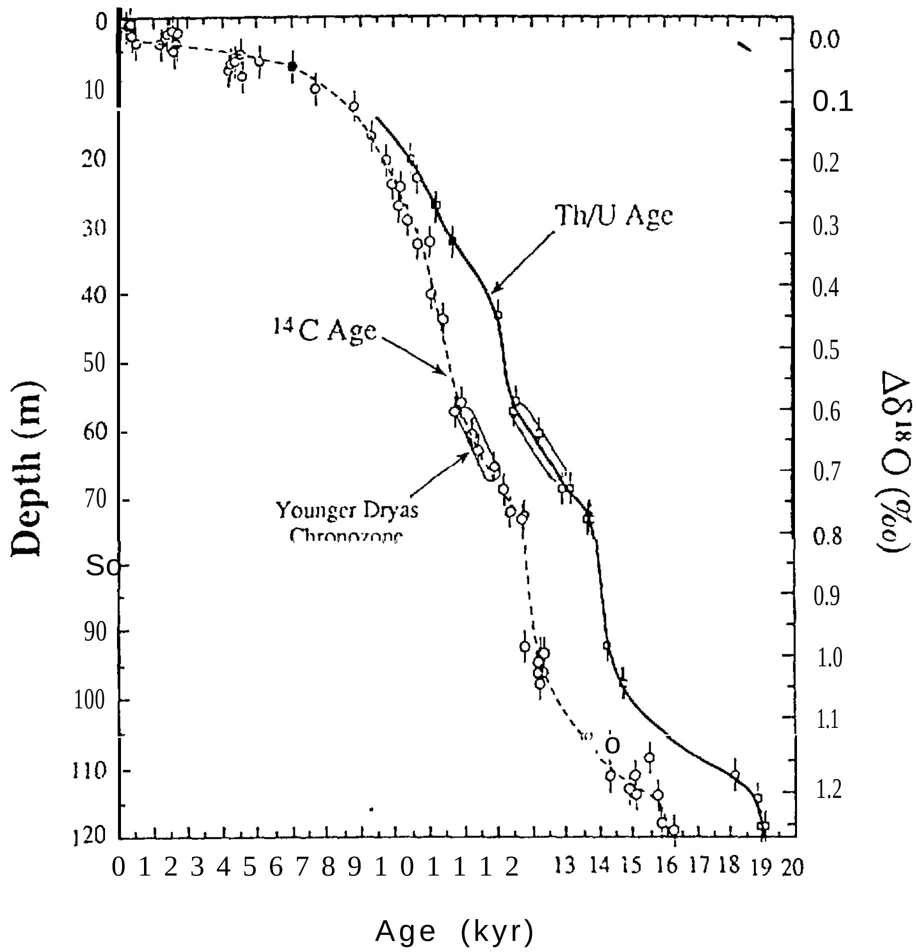


Figure 4. Barbados ^{14}C- and U-series ages compared. The differencc bctwcen thc two curves is a measure of thc ^{14}C calibration correction (Fairbanks, 1990).

The Holoccnc reef crest near Sialum in Papua Ncw Guinea is now about 6 m above sea level. The depth-corrected radiocarbon sea level curve from Fig. 3 is supported by a new series of high precision ^{14}C and U-series ages (Fig. 5). The tectonic uplift rate of nearly 2 m/1000 yr at this part of the Huon Peninsula at least partially negated the rapid pulses of late glacial sea level rise recorded in the Sialum borehole, but even without tectonic uplift, the more abundant and prolific corals of the Indo-Pacific reef province would have been more likely to keep up with the rapid rises than the less vigorous Caribbean reefs. Back to at least 13,100 BP (u-series; equivalent to 10,970 ^{14}C BP), the Sialum reef did so; 48.3 m of vertical accretion occurred in the interval from 13,129 to 8363 BP (U-series) at an average rate of slightly more than 10 mm/yr. Incremental rates of sea level rise varied from 16 mm/yr prior to 12,325 BP to only 2 mm/yr in the Younger Dryas period of reduced recking from 12,325 to 11,045 BP, then increased rapidly to a maximum of 28 mm/yr thereafter (ail U-series) (Edwards et al., in press).

Because of the spacing of dated samples, the maximum rates of sea level rise inferred for Barbados and the Huon Peninsula cannot be directly compared. Nevertheless, there arc no indications of interupted growth in the Sialum borehole, and coral growth seems to have kept up. The Sialum borehole passed though many thick Porites sections, probably large single heads. We have no idea how much deeper wc might have been able to drill in the Holocene reef at Sialum; one could hope for another, deeper borehole at the site. It would be exciting to find a reef anywhere that "kept up" with sea level for the entire deglacial hemicycle.

For coral reefs struggling to avoid drowning in Barbados, Papua Ncw Guineas, and elsewhere, the 1 000 year cold interval of reduced glacier melting and slower sea level rise known as the Younger Dryas may have provided a "breathing spell". Polyps could settle on newly submerged suitable substrates and perhaps build small fringing reefs, before the renewed rapid sea level rise defeated them. This may be what is recorded by Fairbank's middle drowned reef. On many coasts, this brief event may not be recorded, or if it is, it will be found only under the reef talus of the younger and much larger Holocene reel' that succeeded it.

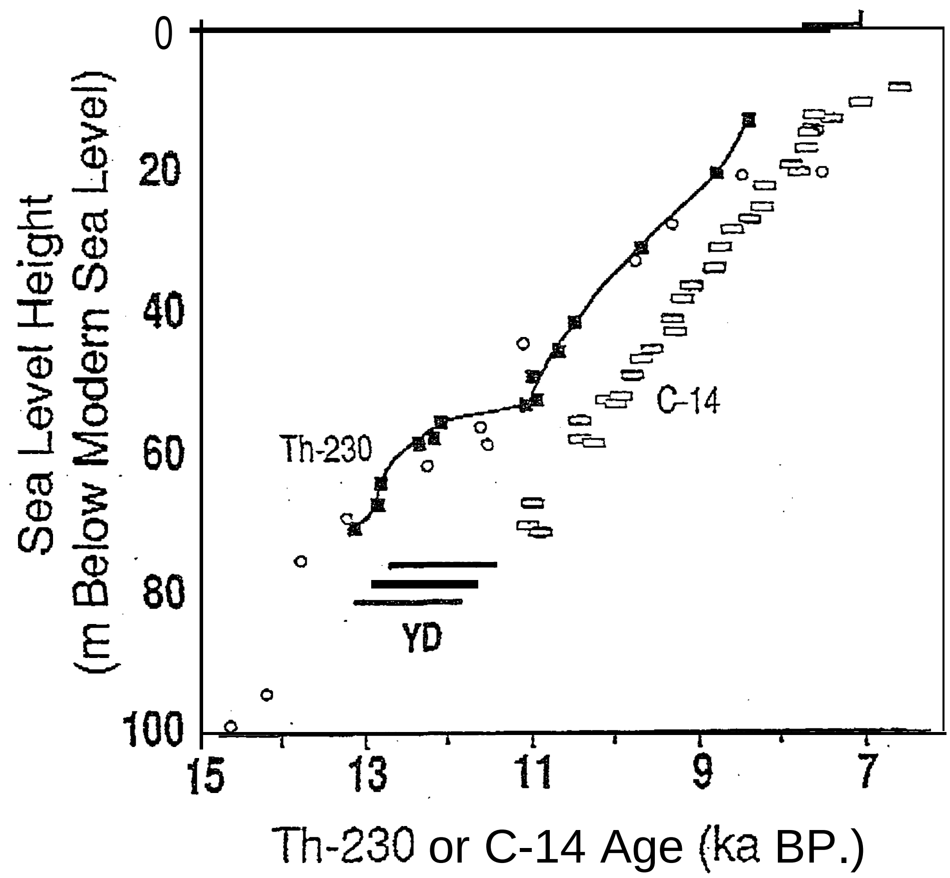


Figure 5. Sialum borehole, Papua New Guinea ^{14}C and U-series ages compared. During part of the Younger Dryas interval, the ^{14}C ages changed by only 210 years while the U-series ages record 1280 years. The Younger Dryas rate of sea level rise is much less than the rate inferred from the Barbados U-series ages (Edwards, et al., in press).

CONCLUSIONS

The real significance of the new high precision paired ^{14}C and U-series dates on corals lies in their ability to calibrate the ^{14}C content of the atmosphere, oceans, and ice sheets, and identify abrupt, step-like climate changes in the late Pleistocene. Coral samples are commonly large enough for a variety of analyses to be done on the same material--even on single, probably annual, layers. With the new analytical tools now available, and coralline aragonite as a proven and in many ways ideal analytical material, we can look forward to additional exciting developments.

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