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MARINE RESERVOIR CORRECTION FOR THE COCOS (KEELING) ISLANDS, INDIAN OCEAN

Quan Hua[1,2] • Colin D Woodroffe[3] • Mike Barbetti[4] • Scott G Smithers[5] • Ugo Zoppi[1] • David Fink[1]

ABSTRACT. Known-age corals from the Cocos (Keeling) Islands, Indian Ocean, have been analyzed by accelerator mass spectrometry (AMS) for radiocarbon to determine marine reservoir age corrections. The ΔR value for the Cocos (Keeling) Islands is 66 ± 12 yr based on the analyses undertaken for this study. When our AMS and previously published dates for Cocos are averaged, they yield a ΔR of 64 ± 15 yr. This is a significant revision of an earlier estimate of the ΔR value for the Cocos (Keeling) Islands of 186 ± 66 yr (Toggweiler et al. 1991). The (revised) lower ΔR for the Cocos (Keeling) Islands is consistent with GEOSECS ^{14}C data for the Indian Ocean, and previously published bomb ^{14}C data for the Red Sea, Gulf of Aden, and Cocos Islands. The revised ΔR is also close to values for the eastern Indian Ocean and adjacent seas. These suggest surface waters that reach the Cocos Islands might be partly derived from the far western Pacific, via the Indonesian throughflow, and might not be influenced by the southeast flow from the Arabian Sea.

INTRODUCTION

Exchanging with the atmosphere and the radiocarbon-depleted deep ocean, the surface ocean has a ^{14}C level intermediate between these 2 reservoirs. This causes an age offset between marine samples, which source their carbon at the surface ocean, and contemporaneous terrestrial samples. This age offset is known as the marine reservoir age (R) and can be several hundred years. To calibrate a ^{14}C age for a marine sample, one needs to know its marine reservoir age (Stuiver and Reimer 1986). Alternatively, the regional variation from the global marine model age for that sample, defined as ΔR, is required (Stuiver and Braziunas 1993; Stuiver et al. 1998). The ΔR value, which is also known as the regional marine correction, accounts for regional deviations in ^{14}C due to variations in ocean circulation and air-sea exchange of CO_2. The latter method is generally preferred for age calibration (Reimer and Reimer 2001) and ΔR values are typically determined by dating pre-bomb known-age marine carbonates (Southon et al. 2002).

The Cocos (Keeling) Islands (12°S, 97°E) are an isolated Australian atoll in the eastern Indian Ocean. An annual band chronology has recently been established for corals from this atoll, which covers most of the 20th century (Smithers and Woodroffe 2000, 2001). The corals were *Porites* microatolls and were collected alive in 1991 and 1992 from 2 reef-flat sites on the southern and eastern sides of Cocos that are freely connected to the open ocean. These Cocos corals offer the possibility of examining regional variability of ^{14}C in the surface waters of the eastern Indian Ocean during the past century. Here, we report ΔR measurements on 5 known-age coral bands and a known-age museum specimen of *Porites* coral. Our new data, in conjunction with previously published ^{14}C data for the atoll (Toggweiler et al. 1991; Woodroffe et al. 1994), can be used to determine a reliable mean ΔR marine correction for Cocos. This is important not only for reliably dating marine fossils of the Cocos Islands by ^{14}C, but also to improve our knowledge of ocean circulation around the Cocos Islands and the eastern Indian Ocean.

[1]Australian Nuclear Science and Technology Organisation (ANSTO), PMB 1, Menai, New South Wales 2234, Australia.
[2]Corresponding author. Email: qhx@ansto.gov.au.
[3]School of Geosciences, University of Wollongong, Wollongong, New South Wales 2522, Australia.
[4]NWG Macintosh Centre for Quaternary Dating, Madsen Building F09, University of Sydney, New South Wales 2006, Australia.
[5]School of Tropical Environment Studies and Geography, James Cook University, Townsville, Queensland 4811, Australia.

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MATERIALS AND METHODS

For this study, we used microatoll PP30, collected on the eastern side of the atoll from a reef-flat site that is freely connected to the open ocean (see Figure 1), for ^{14}C analysis. The coral was sampled alive in 1992 and no recrystallization has occurred. Five single annual bands, which grew in 1906, 1926, 1933, 1941, and 1950, were split for ^{14}C analysis using a dental drill. In addition, a museum specimen of *Porites* coral from Cocos, which was collected alive by Charles Darwin in 1836, was measured in this study to investigate possible changes in ΔR over the past 150 yr. This specimen (sample number 42.12.14.24) is deposited in the Department of Zoology, The Natural History Museum, London.

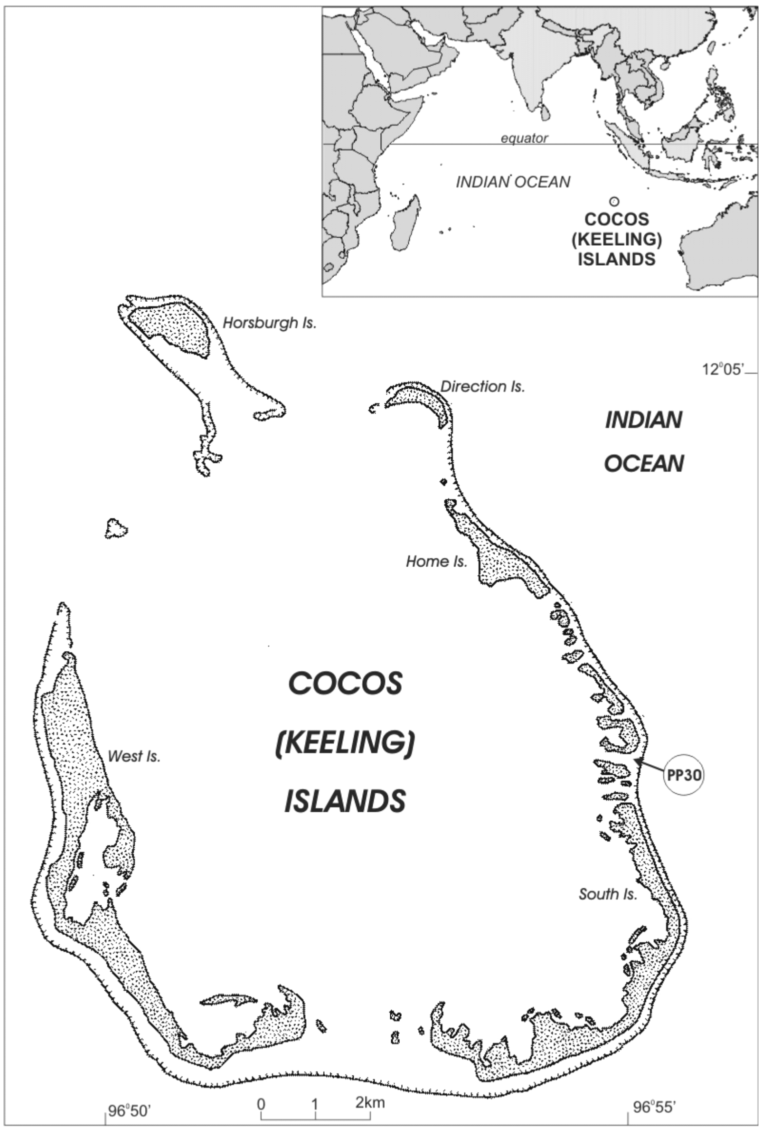

Figure 1 The Cocos (Keeling) Islands, showing location of open reef-flat microatoll PP30

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The samples were cleaned with deionized water in an ultrasonic bath 3 times for 20 min each to remove any surface contamination. They were then dried in an oven at 60 °C for 2 days before hydrolysis. The cleaned samples were hydrolyzed to CO_2 using 85% phosphoric acid. The CO_2 samples were then converted to graphite using the Zn/Fe method. The technical aspects of these methods have been described in Hua et al. (2001). The mass of graphite was typically 4 mg. A small portion of graphite from each sample was employed for the determination of $\delta^{13}C$ using the Micromass IsoPrime Elemental Analyser/Isotope Ratio Mass Spectrometer (EA/IRMS) at ANSTO. AMS ^{14}C measurements were performed using the ANTARES facility at ANSTO (Lawson et al. 2000; Fink et al. 2004) with a precision of 0.3–0.4%.

RESULTS

The results of AMS ^{14}C measurements of the coral samples for this study are shown in Table 1. The regional marine correction ΔR (Stuiver and Braziunas 1993) is determined as the difference between the conventional ^{14}C age for each sample after correction for $\delta^{13}C$ (Stuiver and Polach 1977) and the global marine model age for the year of collection or growth. To be compatible with the online marine reservoir correction database (Reimer and Reimer 2001), we used the 1998 marine calibration data set, Marine98 from Stuiver et al. (1998), as the model age of global ocean for the calculation of ΔR.

Table 1 ΔR values for the Cocos (Keeling) Islands, derived from corals. Note: [W-J] - Museum specimen collected by F Wood-Jones; [G-H] - Museum specimen collected by C A Gibson-Hill; [D] - Museum specimen collected alive by C Darwin. This specimen (sample number 42.12.14.24) is kept in the Department of Zoology, The Natural History Museum, London; and [S-W]- Annual coral band from open reef-flat microatoll PP30 (Smithers and Woodroffe 2000, 2001).

Laboratory code	Coral species	Year of growth or collection	$\delta^{13}C$ (‰)	Conventional ^{14}C age (yr BP)	Model age[a] (yr BP)	ΔR (^{14}C yr)
Previous studies						
L-DGO-1657	—	1941	—	652 ± 66[b]	466 ± 8	186 ± 66
ANU-6151	*Acropora scherzeriana* [W-J]	1906	—	370 ± 60[c]	452 ± 5	–82 ± 60
ANU-6152	*Montipora foliosa* [W-J]	1906	—	670 ± 60[c]	452 ± 5	218 ± 60
ANU-6153	*Porites nigrescens (=P. cylindrica)* [W-J]	1906	—	410 ± 60[c]	452 ± 5	–42 ± 60
ANU-7638	*Montipora ramosa* [G-H]	1941	—	510 ± 70[c]	466 ± 8	44 ± 70
ANU-7639	*Montipora lobulata* [G-H]	1941	—	480 ± 60[c]	466 ± 8	14 ± 61
This study						
OZG553	*Porites arenaceae* [D]	1836	–2.8	586 ± 29	494 ± 5	92 ± 29
OZG956	*Porites* [S-W]	1906 ± 2[d]	–2.8	485 ± 21	452 ± 6[e]	33 ± 22
OZF535	*Porites* [S-W]	1926	–2.0	530 ± 25	456 ± 4	74 ± 25
OZF536	*Porites* [S-W]	1933	–3.5	565 ± 25	460 ± 5	105 ± 25
OZF537	*Porites* [S-W]	1941	–3.0	510 ± 25	466 ± 8	44 ± 26
OZF538	*Porites* [S-W]	1950	–4.1	540 ± 25	472 ± 13	68 ± 28

[a]Estimated value from decadal Marine98 data (Stuiver et al. 1998) by linear interpolation.
[b]Calculated from $\Delta^{14}C$ data from Toggweiler et al. (1991).
[c]Data reported in Woodroffe et al. (1994).
[d]Estimated uncertainty in age of growth band reflects the occurrence of zones of ambiguous growth band definition within the coral skeleton (Smithers and Woodroffe 2001).
[e]Estimated model age for AD 1906 ± 2.

In addition, ^{14}C data for the Cocos (Keeling) Islands from previous studies (Toggweiler et al. 1991; Woodroffe et al. 1994) are presented in Table 1. A summary of the ΔR marine correction values for Cocos from previous studies and this investigation are plotted in Figure 2.

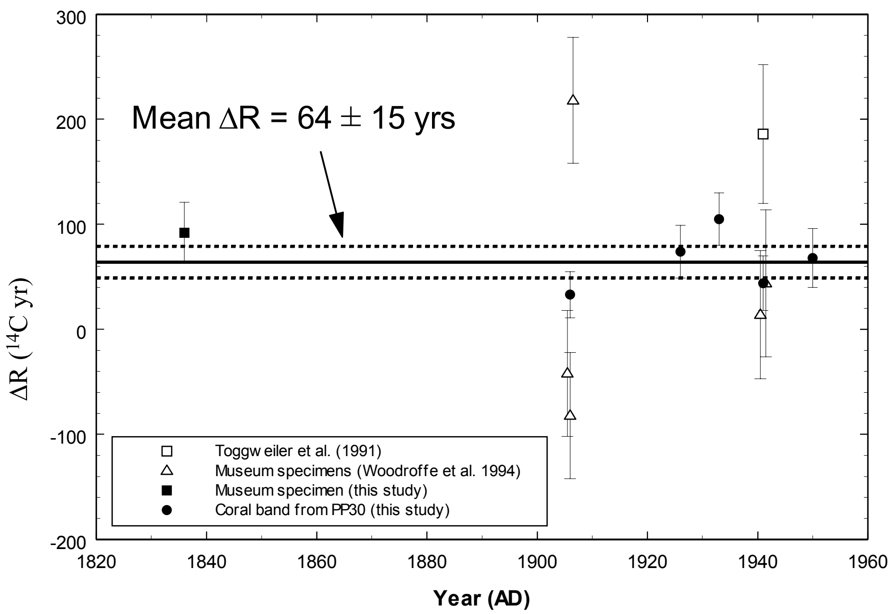

Figure 2 ΔR marine corrections for the Cocos (Keeling) Islands from previous studies and this investigation. The error-weighted mean value of ΔR for Cocos is 64 ± 15 yr.

DISCUSSION

The marine corrections for the Cocos (Keeling) Islands from this study show a small variation ranging from 33 to 105 yr (Table 1 and Figure 2). This variation in our data may indicate the temporal variability in ^{14}C of surface ocean waters around the Cocos Islands for the past 150 yr. The average ΔR marine correction value for the Cocos Islands is 66 ± 12 yr based on the analyses undertaken for this study. To be compatible with the online marine reservoir correction database (Reimer and Reimer 2001), the uncertainty associated with an error-weighted mean ΔR was chosen as the larger of the error of the mean and the standard error. When compared with the previously published ^{14}C data for Cocos, our ΔR value for 1941 (44 ± 26 yr) is in good agreement with those (44 ± 70 yr and 14 ± 61 yr) of Woodroffe et al. (1994), but all these 3 ΔR values are significantly lower than that of Toggweiler et al. (1991) (186 ± 66 yr). For the 1906 data from Woodroffe et al. (1994), the first (*Acropora scherzeriana*) and third (*Porites nigrescens*) ΔR values overlap within 1 σ uncertainty, but they are significantly lower than the second ΔR (*Montipora foliosa*; see Table 1, Figure 2). Our ΔR value for 1906 (33 ± 22 yr) overlaps with their third ΔR value (–42 ± 60 yr) within 1 σ uncertainty, but is significantly different from their first (–82 ± 60 yr) and second (218 ± 60 yr) ΔR values.

The large spreads in ΔR values (300 yr for 1906 and 170 yr for 1941) of the previously published data may be due to the spatial variability within the Cocos lagoon. However, the location of the museum specimens collected by Wood-Jones [W-J] and Gibson-Hill [G-H] (see Table 1), which were presumably collected alive, is largely unknown. Several of the specimens are likely to have been collected from the lagoon, such as *Montipora foliosa*, *Porites nigrescens*, and *Montipora lob-*

ulata (Wells 1950). In addition, no details of sample species and location for Toggweiler et al.'s sample of 1941 were reported. On the other hand, the lagoon of the Cocos (Keeling) Islands, which is enclosed by 26 islands and covers a surface area of 190 km^2, is well connected with the open ocean through tidal currents, indicated by a short flushing time of the lagoon between 5.4 and 2.3 days for neap and spring tidal conditions, respectively (Kench 1994). One may argue that the large spreads in the previously published data are simply due to experimental scatter. However, a scatter of this magnitude (170 to 300 yr) is too large to be accounted for in normal ^{14}C analyses, leaving the excessive ΔR spreads for 1906 and 1941 samples unexplained. When our AMS and previously published dates for Cocos are averaged, they yield a ΔR marine correction of 64 ± 15 yr. This is a significant revision of an earlier estimate of the ΔR value for Cocos of 186 ± 66 yr (Toggweiler et al. 1991), which has recently been restated in the literature (Southon et al. 2002).

The ^{14}C data for the Indian Ocean from the Geochemical Ocean Section Study (GEOSECS) program during 1977–1978 showed that bomb ^{14}C appears less abundantly in the west Indian Ocean than in the east Indian Ocean (Stuiver and Östlund 1983). In other words, ^{14}C levels in surface waters of the western Indian Ocean are generally lower than those of the eastern Indian Ocean, resulting in ΔR values that are higher in the western Indian Ocean than those for the eastern Indian Ocean. This is due to the intense monsoon-driven upwelling which takes place off the Somali and southern Arabian coasts and to a lesser extent off Pakistan and India (Southon et al. 2002 and references therein). Our revised ΔR value of 64 ± 15 yr for the Cocos (Keeling) Island is consistent with the above GEOSECS ^{14}C data as it is lower than the ΔR values of the tropical southwest Indian Ocean (135 ± 24 yr), western Arabian Sea (207 ± 30 yr), and eastern Arabian Sea (187 ± 25 yr) (see Table 2 and Figure 3).

Table 2 ΔR values for the Indian Ocean and adjacent seas from previous studies. All ΔR values were calculated using the 1998 marine calibration data set (Marine98; Stuiver et al. 1998) as the model age of global ocean. The first 9 ΔRs are regional marine corrections. The last 4 ΔRs are marine corrections for a site or a small region. The first 8 regional ΔRs were reported in Reimer and Reimer (2001).

Region or Location	Latitude	Longitude	References	ΔR (^{14}C yr)
Western Arabian Sea (N=8)	11–24°N	43–58°E	—	207 ± 30
Eastern Arabian Sea (N=16)	7–25°N	66–80°E	—	187 ± 25
Bay of Bengal (N=6)	9–13°N	78–94°E	—	64 ± 55
Northwest Australia - Java (N=9)	7–18°S	106–132°E	—	64 ± 24
Northeast Australia (N=5)	10–12°S	141–143°E	—	50 ± 31
Tropical southwest Indian Ocean (N=12)	6–21°S	39–56°E	—	135 ± 24
South Africa (N=2)	30–34°S	18–31°E	—	218 ± 38
South China Sea (N=10)	1–17°N	99–121°E	—	–17 ± 17
Southwest Australia (N=4)	32–35°S	115–117°E	Gillespie (1977) Gillespie and Polach (1979) Bowman and Harvey (1983) Bowman (1985)	66 ± 46
Raffles Bay, N. Australia (N=1)	11°S	132°E	Southon et al. (2002)	58 ± 40
Pelebuhanratu, S. Java (N=1)	7°S	107°E	Southon et al. (2002)	40 ± 70
Port Sudan, Red Sea (N=3)	20°N	37–38°E	Cember (1989) Southon et al. (2002)	120 ± 28
Djibouti, Gulf of Aden (N=5)	11–13°N	43–45°E	Toggweiler et al. (1991) Southon et al. (2002)	193 ± 36

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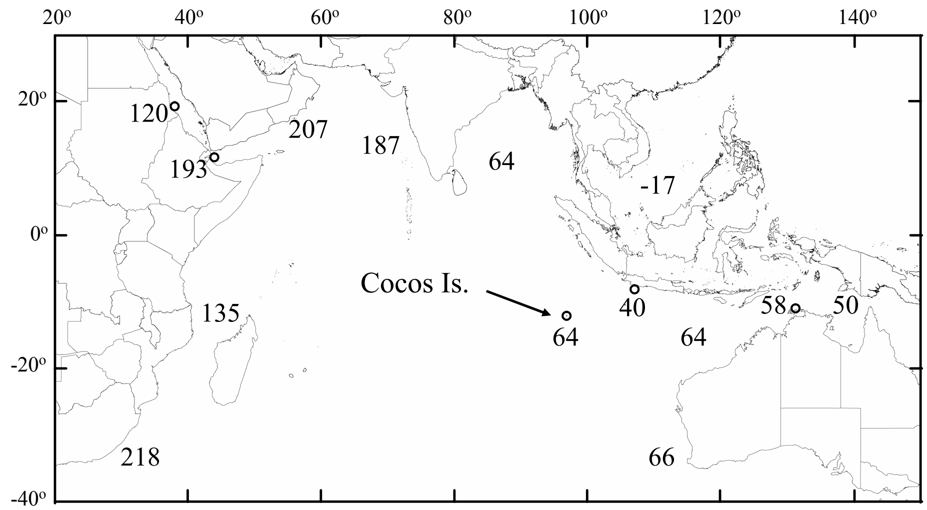

Figure 3 ΔR marine corrections for the Indian Ocean and adjacent seas with our revised ΔR value for the Cocos (Keeling) Islands. ΔR for a region is shown by its value in the middle of the region. ΔR for a site or a small region is shown by its value with an open circle indicating the location of the site or small region. The details of these ΔR marine corrections are given in Table 2.

Published bomb ^{14}C data derived from corals from the northwestern Indian Ocean—Port Sudan (20°N, 37°E, the Red Sea; Cember 1989) and Djibouti (11°N, 43°E, Gulf of Aden; Toggweiler et al. 1991)—compared to those from the Cocos (Keeling) Islands (Toggweiler et al. 1991) are shown in Figure 4. We have also measured ^{14}C in annual bands of corals from the Cocos (Keeling) Islands for 1955–1985 (the bomb pulse period). There is a good agreement between our preliminary results and the data from Toggweiler et al. (1991) for 1970–1976. However, reporting and discussing our bomb ^{14}C results for Cocos are beyond the scope of this paper. Bomb ^{14}C for the Cocos Islands is higher than that for Port Sudan, which, in turn, is higher than bomb ^{14}C for Djibouti. These bomb ^{14}C data also support the revised ΔR value for the Cocos Islands as it (64 ± 15 yr) is lower than the ΔR of Port Sudan of 120 ± 28 yr, which, in turn, is lower than that of Djibouti of 193 ± 36 yr (see Table 2 and Figure 3). Like other parts of the northwest Indian Ocean, the Gulf of Aden is a region of monsoon-driven seasonal upwelling (Cember 1989). This explains why there are high ΔR and low $\Delta^{14}C$ values for Djibouti (Gulf of Aden) and, consequently, medium-high ΔR and medium-low $\Delta^{14}C$ values for Port Sudan as surface waters of the Red Sea are partly derived from those of the Gulf of Aden through the Straits of Bab-el-Mandeb (Cember 1989).

When compared with the marine corrections for the east Indian Ocean (Table 2 and Figure 3), the revised ΔR of 64 ± 15 yr for the Cocos (Keeling) Islands is close to values for the eastern Indian Ocean, e.g., 40 ± 70 yr for Pelebuhanratu (South Java; Southon et al. 2002) and 64 ± 24 yr for northwest Australia and Java (Reimer and Reimer 2001). The Cocos ΔR value is also similar to those for Raffles Bay, northern Australia (58 ± 40 yr; Southon et al. 2002) and Torres Strait and northeastern Australia (50 ± 31 yr; Reimer and Reimer 2001), but significantly higher than that for the South China Sea (–17 ± 17 yr; Reimer and Reimer 2001). In addition, the Cocos ΔR value is significantly lower than those for the western Indian Ocean as discussed above. These suggest surface waters that reach the Cocos Islands might be partly derived from the far western Pacific, flowing through the Indonesian seas (Fieux et al. 1994; Moore et al. 1997), and might not be influenced by the southeast flow from the Arabian Sea as suggested by Southon et al. (2002).

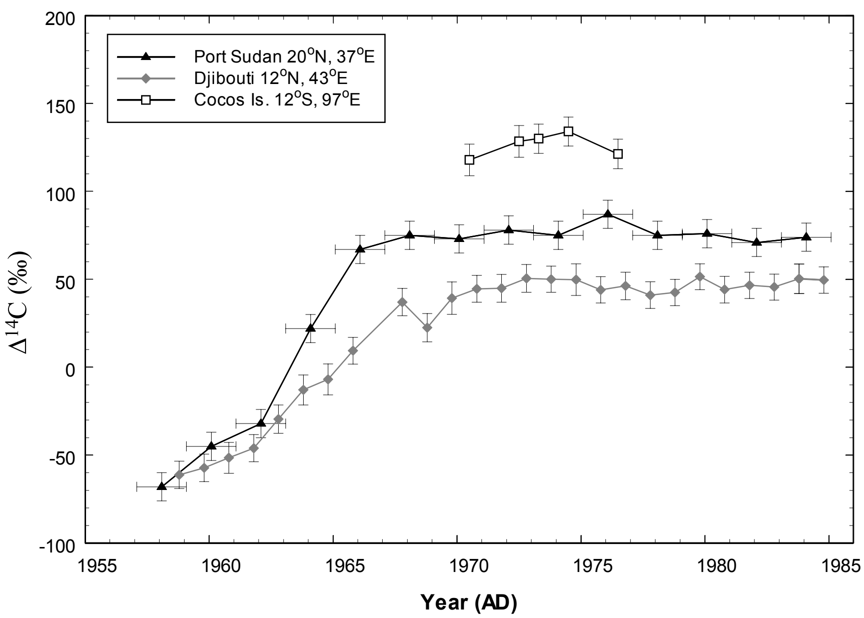

Figure 4 Published bomb ^{14}C data from corals from Port Sudan (the Red Sea; Cember 1989), Djibouti (Gulf of Aden; Toggweiler et al. 1991), and the Cocos (Keeling) Islands (Toggweiler et al. 1991). Djibouti and Cocos records consisted of annual data, meanwhile Port Sudan data were biannual data.

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