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# $^{230}$Th-$^{234}$U AND $^{14}$C AGES OBTAINED BY MASS SPECTROMETRY ON CORALS

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## INTRODUCTION

In 1988, Fairbanks conducted a drilling expedition off the south coast of Barbados to recover submerged corals contemporaneous with the last deglaciation. Core recovery was excellent and >30 different samples were dated by conventional β-counting techniques (Fairbanks 1989). At about the same time, we developed, at Lamont, the thermal ionization mass spectrometry (TIMS) technique to obtain precise U-Th ages (Edwards 1988), and to compare them with the $^{14}$C estimates measured on the same samples. A surprising result was that the discrepancy between $^{14}$C and U-Th ages increased through time to *ca.* 3000–3500 yr at *ca.* 15,000 $^{14}$C BP (Bard *et al.* 1990a). Because the three youngest samples yielded U-Th ages in agreement with their calibrated $^{14}$C ages, we concluded initially that the TIMS U-Th determinations were not only precise, but also accurate, and that the $^{14}$C *vs.* U-Th data set could be used for a first-order $^{14}$C calibration.

We replicated $^{14}$C measurements through accelerator mass spectrometry (AMS) on very small samples, which enabled us to use strong acid leaching to eliminate surface contaminants (see Bard *et al.* 1990b for technical procedures and the report of initial measurements). To establish global uniformity of the observed phenomenon, we also measured ages in new samples from very different environments, Mururoa Atoll and Isabela Island in the tropical Pacific Ocean.

## RESULTS OBTAINED BY AMS AND TIMS ON BARBADOS CORALS

In five runs of the Gif-sur-Yvette Tandetron, we obtained *ca.* 80 new $^{14}$C determinations on *ca.* 20 samples previously dated by β-counting (Fairbanks 1989, 1990) and TIMS (Bard *et al.* 1990a). The large quantity of replicates enables us to calculate weighted-mean AMS $^{14}$C ages with an improved precision (better than ± 200 yr at 2 σ for the last 15,000 yr). The new AMS results agree to a first order with the β-counting estimates. However, we further confirm our previous observation (Bard *et al.* 1990b) that, for ages beyond the Holocene, the AMS determinations are often slightly older than the β-counting estimates (see Table 1A–C). The samples prepared for AMS were strongly leached with acid (loss of *ca.* 30–40% of the total weight), whereas the samples measured by β-counting were not (except samples RGF7-5-5, RGF7-16-2, RGF9-27-5 and RGF12-30-2). Consequently, a minor (<1pmC) contamination might cause this discrepancy. To illustrate how the calculation of $\Delta^{14}$C is sensitive to old ages, we cite the deepest *A. palmata* sample (RGF 9-27-5), which was AMS-dated 3 times at Gif (weighted mean = 16,360 ± 220 BP [2 σ]), once at Arizona (16,145 ± 240 BP [2 σ], Fairbanks 1990) and twice by TIMS at Lamont (weighted mean = 19,000 ± 70 BP [2 σ]). Thus, the $\Delta^{14}$C of this sample is *ca.* 300 ‰ instead of ca. 350 ‰ initially reported for that period, using β-counting ages obtained without leaching procedures.

Figure 1 shows results obtained by AMS and β-counting *vs.* the ages obtained by TIMS. Figure 2 shows enlarged detail of the intercomparison, which clearly illustrates the concordance between

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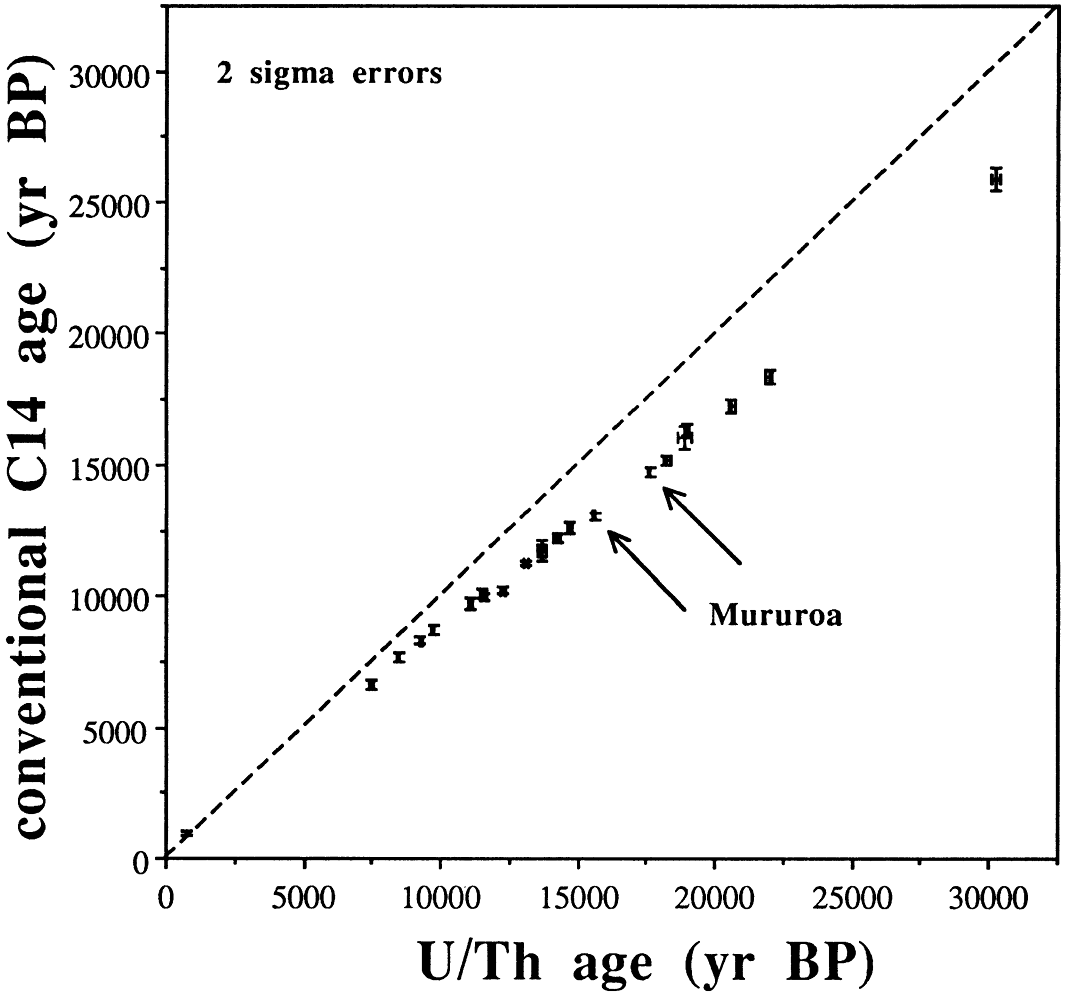

Fig. 1. U-Th ages obtained by TIMS plotted *vs.* AMS $^{14}$C ages obtained on corals from Barbados and Mururoa. $^{14}$C ages are conventional ages in yr BP with statistical errors given at 2 $\sigma$, which does not include the error in the reservoir correction. For the interval between 8500 and 20,000 $^{14}$C yr BP, a simple linear calibration is: cal age BP = 1.24($^{14}$C age BP) – 840.

our reconstruction and the dendrochronological determinations of Kromer & Becker (1992).

We also studied the 400-yr reservoir age correction by dating a very recent Barbados coral drilled on the flat part of the reef at *ca.* 7 m below the present sea level (RGF B56). The U-Th age is 773 ± 10 BP [2 $\sigma$] (weighted mean on 2 replicates); the $^{14}$C age is 956 ± 90 BP [2 $\sigma$] (weighted mean on 4 measurements), which leads to a calibrated age of 775–957 cal BP, using the "atmospheric" calibration program of the Quaternary Isotope Laboratory, University of Washington. This cal age is in statistical agreement with the U-Th estimate. However, we can also apply the marine $^{14}$C calibration of the same program (with $\Delta R = 0 \pm 0$) on the raw $^{14}$C age (1356 ± 90 BP [2 $\sigma$]). In that case, the calibrated age is 787-967 cal yr BP which is close but slightly older than the U-Th estimate.

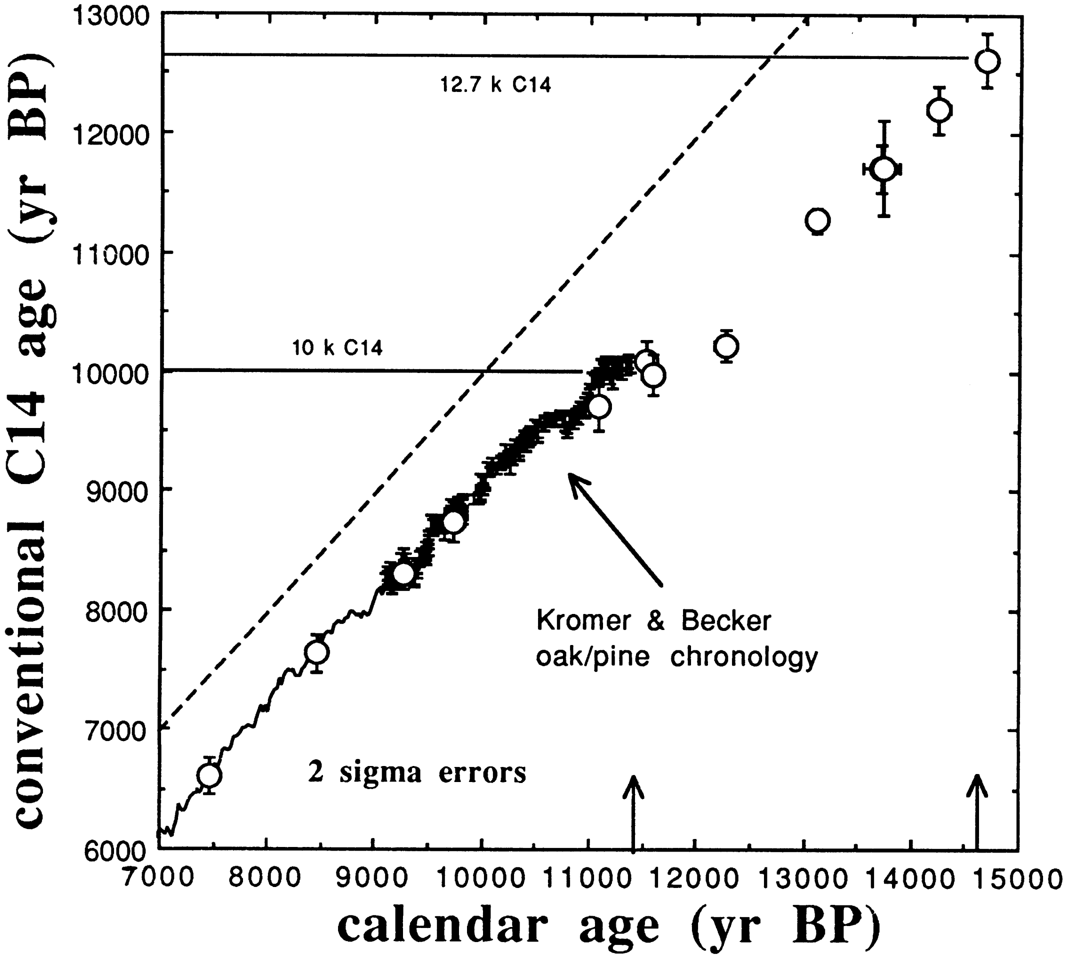

Fig. 2. Enlargement of Figure 1, also showing the tree-ring data base. Until 9100 cal BP, the solid curve is the 20-yr running average of the dendrochronology. Between 9100 and 11,400 cal BP, it comprises German oak and pine data (Kromer & Becker 1992). All errors are given at 2 σ (for $^{14}C$ ages of corals they do not include the error in the reservoir correction).

Thus, the reservoir age offshore Barbados is not very different from our adopted value of 400 yr (DIC $\Delta^{14}C \approx$ -50 ‰), which is a mean for low- and mid-latitude open ocean waters (Bard 1988). However, if we take the results obtained on sample RGF B56 at face value, we could also adopt a different reservoir correction. Indeed, there are still some uncertainties about the pre-anthropogenic $\Delta^{14}C$ of the West Atlantic/Caribbean zone; Druffel & Suess (1983) reported $\Delta^{14}C$ values of -50 ‰ for Belize and Florida corals while Nozaki *et al.* (1978) obtained $\Delta^{14}C$ values of *ca.* -30 ‰ (≈250 yr) for 19th-century annual bands collected from a Bermuda coral head. Perfect agreement should not be expected, and the reservoir age probably exhibits small temporal variations in response to changes of tradewind, temperature and mixed-layer depth (Bard 1988).

## RESULTS OBTAINED BY AMS AND TIMS ON MURUROA CORALS

We measured ages of two coral specimens collected with a land-based deviated drill (≈30°) at *ca.* 170 m below present sea level, offshore Mururoa atoll, French Polynesia. For sample 313, the U-Th age is 17,595 ± 70 BP [2 σ] (weighted mean on 3 replicates), whereas the $^{14}C$ age is 14,735 ±

TABLE 1A. Comparison of ages obtained by classical $^{14}C$ β counting, $^{14}C$-AMS and U-Th-TIMS. All ages are expressed as yr BP (before 1950). The $^{14}C$ ages are conventional ages with a reservoir correction of 400 yr. Statistical errors are given at 2 σ, which does not include the error in reservoir correction.

| Sample | U/Th (yr BP) | ± 2s | C14 (yr BP) L-DGO | ± 2s | C14 (yr BP) Geochron | ± 2s | Leaching * | Replication ** | C14 (yr BP) Gif-sur-Yvette | ± 2s |
|---|---|---|---|---|---|---|---|---|---|---|
| Galapagos 2#1 | 283 | 13 | | | | | | | | |
| Galapagos 2#2 | 265 | 6 | | | | | | | | |
| Galapagos 1#1 | 295 | 20 | | | | | | | | |
| Galapagos 1#2 | 269 | 12 | | | | | | | | |
| RGF B56#1 | 773 | 11 | | | | | + | | 825 | 180 |
| RGF B56#2 | 773 | 28 | | | | | + | du | 1050 | 180 |
| RGF B56#3 | | | | | | | + | | 995 | 160 |
| RGF B56#4 | | | | | | | + | du | 975 | 180 |
| RGF7-4-2#1 | 7460 | 80 | 6400 | 200 | | | + | | 6640 | 200 |
| RGF7-4-2#2 | | | | | | | + | du | 6560 | 220 |
| RGF7-5-5#1 | 8450 | 50 | | | 7780 | 220 | + | | 7640 | 240 |
| RGF7-5-5#2 | | | | | | | + | du | 7640 | 220 |
| RGF7-12-2#1 | 9285 | 95 | 8200 | 200 | | | + | | 8160 | 220 |
| RGF7-12-2#2 | 9250 | 80 | | | | | + | du | 8080 | 360 |
| RGF7-12-2#3 | | | | | | | + | | 8410 | 220 |
| RGF7-12-2#4 | | | | | | | + | du | 8410 | 220 |
| RGF7-16-2#1 | 9730 | 50 | | | 9050 | 250 | + | | 8750 | 240 |
| RGF7-16-2#2 | | | | | | | + | du | 8750 | 240 |
| RGF7-27-4#1 | 11090 | 70 | 9400 | 200 | | | + | | 9690 | 320 |
| RGF7-27-4#2 | | | | | | | + | du | 9720 | 280 |
| RGF12-5-2#1 | 11590 | 60 | 10100 | 200 | | | + | | 9760 | 380 |
| RGF12-5-2#2 | | | | | | | + | | 10070 | 340 |
| RGF12-5-2#3 | | | | | | | + | du | 10020 | 240 |
| RGF12-6-7#1 | 11530 | 70 | 9800 | 200 | | | + | | 9730 | 400 |
| RGF12-6-7#2 | | | | | | | + | | 10080 | 240 |
| RGF12-6-7#3 | | | | | | | + | du | 10250 | 260 |
| RGF12-9-5#1 | 12260 | 90 | 10300 | 200 | | | + | | 10320 | 320 |
| RGF12-9-5#2 | | | | | | | + | du | 10280 | 280 |
| RGF12-9-5#3 | | | | | | | + | | 10280 | 260 |
| RGF12-9-5#4 | | | | | | | + | du | 10090 | 220 |

*+ = strong leaching (>30% weight loss of the sample; for AMS samples only)

**Results obtained by duplicating (du) or triplicating (tri) the AMS runs on 2 or 3 aliquots of the same Fe+C powder.

150 BP [2 σ] (weighted mean on 5 age determinations). For sample 315, the U-Th age is 15,585 ± 50 yr BP [2 σ] (weighted mean on 3 replicates), whereas the $^{14}C$ age is 13,060 ± 140 yr BP [2 σ] (weighted mean on 5 age determinations). These new results show again a significant difference between the two geochronometers, corresponding to $\Delta^{14}C$ values of 330 ± 30 ‰ and 290 ± 25 ‰ at *ca.* 18,000 and 16,000 Th yr BP, respectively. These values are in excellent concordance with AMS redeterminations of the Barbados $^{14}C$ ages (*cf.* Fig. 1). This new comparative data set of U-series and $^{14}C$ ages demonstrates that the large discrepancies first evidenced in Barbados are not caused by local alteration processes.

TABLE 1B. Comparison of ages obtained by classical $^{14}$C β counting, $^{14}$C-AMS and U-Th-TIMS. All ages are expressed as yr BP (before 1950). The $^{14}$C ages are conventional ages with a reservoir correction of 400 yr. Statistical errors are given at 2 σ, which does not include the error in reservoir correction.

| Sample | U/Th (yr BP) | ± 2s | C14 (yr BP) L-DGO | ± 2s | C14 (yr BP) Geochron | ± 2s | Leaching * | Replication ** | C14 (yr BP) Gif-sur-Yvette | ± 2s | C14 (yr BP) other AMS labs | ± 2s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RGF12-16-5#1 | 13220 | 110 | 10900 | 200 | | | + | | 11640 | 280 | | |
| RGF12-16-5#2 | 12970 | 120 | | | | | + | | 10940 | 260 | | |
| RGF12-16-5#3 | | | | | | | + | | 11020 | 240 | | |
| RGF12-16-5#4 | | | | | | | + | | 11200 | 260 | | |
| RGF12-16-5#5 | | | | | | | + | du | 11490 | 280 | | |
| RGF12-16-5#6 | | | | | | | + | | 11570 | 340 | | |
| RGF12-16-5#7 | | | | | | | + | du | 11190 | 260 | | |
| RGF12-21-6#1 | 13700 | 170 | 11850 | 200 | | | + | | 11630 | 260 | | |
| RGF12-21-6#2 | | | | | | | + | du | 11820 | 300 | | |
| RGF12-21-10#1 | 13800 | 140 | 11800 | 200 | | | + | | 11720 | 400 | | |
| RGF12-21-10#2 | 13660 | 140 | | | | | | | | | | |
| RGF9-8-2#1 | 14235 | 100 | 11800 | 400 | | | + | | 12240 | 260 | | |
| RGF9-8-2#2 | | | | | | | + | du | 12130 | 320 | | |
| RGF9-13-3#1 | 14660 | 160 | 12500 | 200 | | | + | | 12000 | 420 | | |
| RGF9-13-3#2 | 14700 | 100 | | | | | + | | 12910 | 340 | | |
| RGF9-13-3#3 | | | | | | | + | du | 12710 | 380 | | |
| RGF9-21-11#1 | 18240 | 140 | 14700 | 400 | | | | | 14930 | 400 | | |
| RGF9-21-11#2 | | | | | | | | | 15390 | 400 | | |
| RGF9-21-11#3 | | | | | | | + | | 15110 | 320 | | |
| RGF9-21-11#4 | | | | | | | + | du | 15230 | 340 | | |
| RGF9-24-04 | 18890 | 250 | 15400 | 400 | | | + | | 16020 | 420 | | |
| RGF9-27-5#1 | 18980 | 90 | | | 17085 | 520 | + | | 16260 | 420 | 16145 | 240 |
| RGF9-27-5#2 | 19030 | 100 | | | | | + | | 16240 | 360 | AMS Arizona | |
| RGF9-27-5#3 | | | | | | | + | du | 16550 | 360 | | |
| RGF9-27-4 | | | 15200 | 520 | | | | | | | 15850<br>AMS Arizona | 240 |
| RGF9-32-4#1 | 20610 | 120 | 16700 | 600 | | | + | | 16920 | 420 | | |
| RGF9-32-4#2 | | | | | | | + | du | 17470 | 380 | | |
| RGF9-34-8#1 | 21930 | 150 | 18200 | 400 | | | + | | 18820 | 520 | | |
| RGF9-34-8#2 | 22130 | 260 | | | | | + | | 18260 | 420 | | |
| RGF9-34-8#3 | | | | | | | + | du | 18300 | 400 | | |

*+ = strong leaching (>30% weight loss of the sample; for AMS samples only).

**Results which have been obtained by duplicating (du) or triplicating (tri) the AMS runs on 2 or 3 aliquots of the same Fe+C powder.

## RESULTS OBTAINED BY TIMS ON GALAPAGOS CORALS

To further study the reliability of TIMS age estimates on very young samples, we dated samples from a *Pavona clavus* colony collected on Isabela Island (Galapagos). This recent coral head was killed in 1954 due to tectonic uplift from the shelf of Urvina Bay. A high-resolution chronology was previously obtained for this colony through counting of growth bands imaged by x-rays (Shen *et al.* 1991 and references therein). We dated two samples by TIMS: Gal. 2, which has a sclerochronological age of 283–285 cal BP, and yielded a U-Th age of 269 ± 6 BP [2 σ] (weighted mean on 2 replicates), and Gal. 1, dated at 296–298 cal BP with a U-Th age of 277 ± 10 BP [2 σ] (weighted mean on 2 replicates). Thus, the results obtained by TIMS are very close to the true ages, but not in complete agreement if the statistical errors are taken into account.

We made these first attempts to date very young corals on a rather old solid-source mass spectrometer (VG-MM30) equipped with an analog Daly detector. For these analyses, the $^{230}$Th+ ion currents were very close to background, and it would have been preferable to make additional

TABLE 1C. Comparison of ages obtained by classical $^{14}C$ $\beta$ counting, $^{14}C$-AMS and U-Th-TIMS. All ages are expressed as yr BP (before 1950). The $^{14}C$ ages are conventional ages with a reservoir correction of 400 yr. Statistical errors are given at 2 $\sigma$, which does not include the error in reservoir correction.

| Sample | U/Th (yr BP) | ± 2s | C14 (yr BP) Geochron | ± 2s | Leaching * | Replication ** | C14 (yr BP) Gif-sur-Yvette | ± 2s | C14 (yr BP) other AMS labs | ± 2s |
|---|---|---|---|---|---|---|---|---|---|---|
| RGF12-30-2#1 | 30470 | 240 | 27120 | 1520 | + | | 26290 | 860 | 26480<br>AMS Zürich | 1000 |
| RGF12-30-2#2 | 30040 | 210 | | | | | 24600 | 820 | | |
| RGF12-30-2#3 | | | | | | | 25290 | 840 | | |
| RGF12-30-2#4 | | | | | + | | 25790 | 840 | | |
| RGF12-30-2#5 | | | | | + | du | 25370 | 660 | | |
| RGF1-17-4#1 | 70820 | 600 | 30080 | 3520 | + | | >48000 | | | |
| RGF1-17-4#2 | | | | | | | >48000 | | | |
| RGF8-27-1#1 | 79400 | 700 | 36240 | 7980 | | | | | | |
| RGF8-27-1#2 | 77800 | 800 | | | | | | | | |
| Mururoa 315#1 | 15550 | 100 | | | | | 13160 | 280 | | |
| Mururoa 315#2 | 15660 | 90 | | | | | 13160 | 300 | | |
| Mururoa 315#3 | 15550 | 80 | | | + | | 13030 | 360 | | |
| Mururoa 315#4 | | | | | + | | 12840 | 360 | | |
| Mururoa 315#5 | | | | | + | du | 12990 | 300 | | |
| Mururoa 313#1 | 17500 | 120 | | | | | 14690 | 320 | | |
| Mururoa 313#2 | 17630 | 100 | | | | | 14770 | 340 | | |
| Mururoa 313#3 | 17650 | 130 | | | + | | 14630 | 360 | | |
| Mururoa 313#4 | | | | | + | | 14620 | 360 | | |
| Mururoa 313#5 | | | | | + | du | 14910 | 320 | | |
| Mururoa Irène 30#1 | 259000 | 6000 | | | + | | >48700 | | | |
| Mururoa Irène 30#2 | | | | | + | du | >48600 | | | |
| Mururoa Irène 30#3 | | | | | + | tri | >48400 | | | |
| Mururoa Irène 30#4 | | | | | + | | >48500 | | | |
| Ir30 0.25 mg | | | | | + | | >46700 | | | |
| Ir30 0.22 mg | | | | | + | | >47200 | | | |
| Ir30 0.19 mg | | | | | + | | >47900 | | | |
| Ir30 0.13 mg | | | | | + | | >39700 | | | |
| stalagmite | | | | | + | | >48300 | | | |
| IAEA-C1 marble | | | | | + | | >48300 | | | |

*+ = strong leaching (>30% weight loss of the sample; for AMS samples only).

**Results obtained by duplicating (du) or triplicating (tri) the AMS runs on 2 or 3 aliquots of the same Fe+C powder.

†Quantification of the blank was conducted on three samples: 1) a stalagmite from Orgnac cave (>300 ka by $\alpha$-counting U-Th dating); 2) the IAEA-C1 marble; and 3) sample Irène-30 dated by TIMS at 259 ± 6 ka. The $^{14}C$ contamination was also tested on very small aliquots of Irène-30 (0.25 mg C–0.13 mg C). Note that the normal size of the coral samples is always between 1 and 2 mg C. A more comprehensive study of the blank levels on carbonate and organic samples is under preparation and will be published elsewhere (Bard & Arnold, ms. in preparation).

baseline corrections at mass 229.5 and 230.5, instead of using the simpler procedure of measuring a common baseline at mass 227.5. However, this would have caused significant loss in $^{230}Th$ measurement time, which would have reduced measurement precision. Consequently, we believe that these preliminary results constitute a trade-off between accuracy and precision. Ideally, we will replicate the analyses using the VG Sector-54-30 mass spectrometer recently installed at LGE-Marseille; this instrument is equipped with an ion-counting Daly detector that can decrease significantly the detection limit (by about 100 times) for small ion currents. Another explanation for the 10–20 yr discrepancy could also come from the sclerochronological estimates. It could be caused by problems in correlating different coral sections which had to be corrected for small gaps (Shen *et al.* 1991), or to additional stress bands in response to exceptionally cold years (see, *e.g.*, Druffel & Linick 1978, who showed evidence for three stress bands in a 30-yr section of *Montastera annularis* from the Florida Keys).

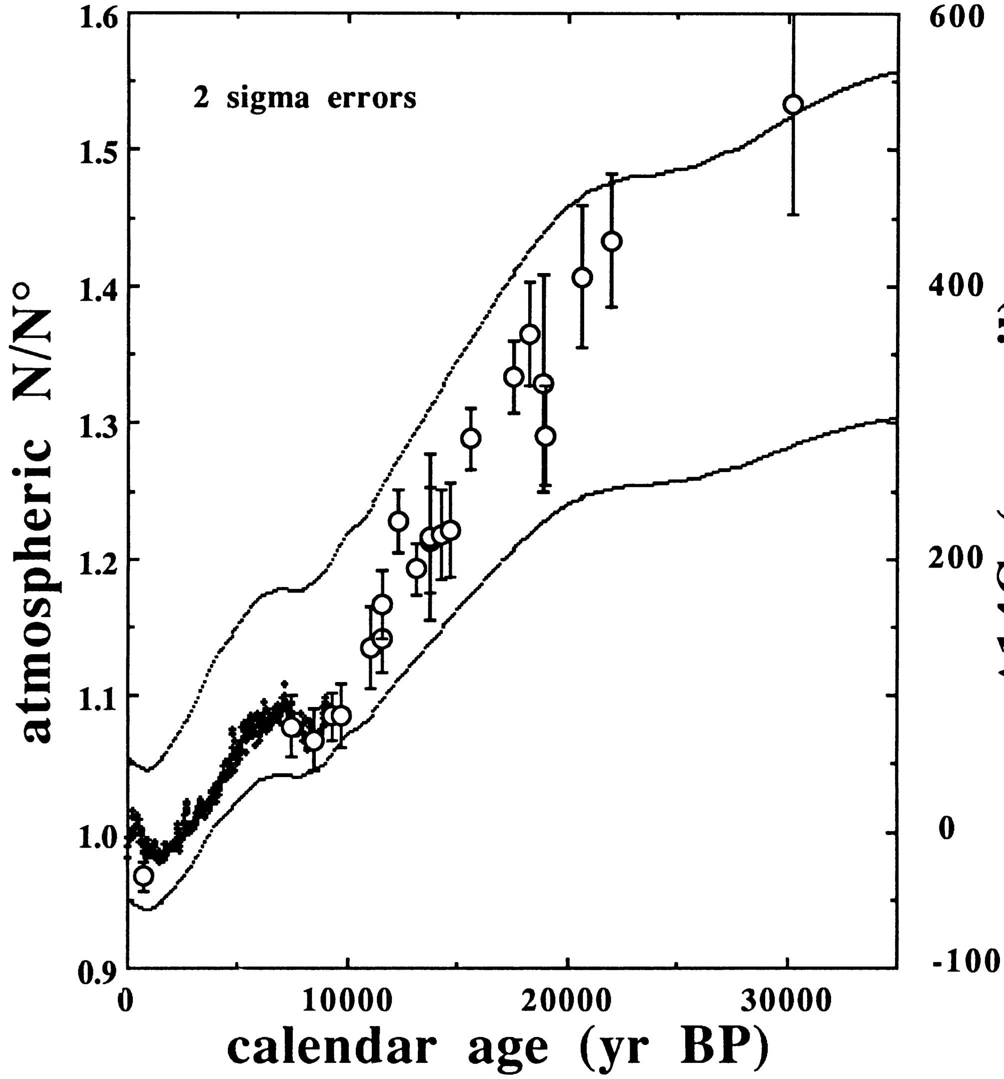

Fig. 3. $\Delta^{14}C$ *vs.* time as calculated by using the AMS-$^{14}C$ *vs.* U-Th comparison. + = dendrochronological calibration. All statistical errors are quoted at 2 σ. For sample RGF12-30-2, we used the $^{14}C$ replicates obtained by AMS after very strong acid-leaching procedures. The two sets of solid lines correspond to the envelopes of $\Delta^{14}C$ expected as a response to geomagnetic field variations as reconstructed by McElhinny & Senanayake (1982). For those calculations, we used a two-box model and assumed constant errors of ± 10% of the present-day dipole (Bard *et al.* 1990a).

## DISCUSSION

The new AMS and TIMS results presented here confirm the precision and accuracy of the U-Th geochronometer applied to scleratinian corals. We show again that the $^{14}C$ ages are systematically younger than true ages during most of the $^{14}C$ application range (except for the brief period between 500 and 2500 cal BP). For the 10,000–30,000 $^{14}C$ yr BP period, other authors found similar discrepancies between $^{14}C$ and K-Ar dating (Gillot & Cornette 1986), between $^{14}C$ and thermoluminescence (TL) dating (Valladas & Valladas 1987; Bell 1991) and between $^{14}C$ ages and U-Th ages obtained in samples from speleothems (Vogel 1983) or corals (Veeh & Veevers 1970; Moore, Normak & Szabo 1990).

On the basis of available data, it is clear that the calendar duration of the Holocene chronozone (0–10,000 $^{14}$C yr BP) ranges from 11,200 to 11,500 cal yr, and that the Younger Dryas chronozone (10,000–10,800 $^{14}$C yr BP or 10,000–11,000 $^{14}$C yr BP) corresponds to *ca.* 1000–1600 cal yr. These results agree with the study of varved sediments from Lake Gosciaz (Rozanski *et al.* 1992; Goslar *et al.* 1992).

If we assume that the $^{2}$H and $^{13}$C records measured by Becker, Kromer and Trimborn (1991) on German pine sections represents the whole European climate, we estimate an age of *ca.* 9700 $^{14}$C yr BP for the midpoint of the Younger Dryas/Preboreal $^{2}$H–$^{13}$C transition. Consequently, the U-Th age of the midpoint can be dated at about 11,100 yr by means of the U-Th *vs.* $^{14}$C age comparison (close to sample RGF 7-27-4).

The AMS-$^{14}$C age of the early Bølling $\delta^{18}$O shift varies between 12,700 BP (Ammann & Lotter 1989) and 12,500 BP (Bard *et al.* 1987), which corresponds to U-Th ages between 14,700 and 14,500 BP. As proposed by Broecker (1992), this benchmark could be used to correlate records obtained from ice cores, tree rings, corals, oceanic and continental sediments, but we should also expect a correlation problem since 12,700 $^{14}$C yr BP corresponds to another $^{14}$C age plateau (Ammann & Lotter 1989).

Bard *et al.* (1990a) and Stuiver *et al.* (1991) discuss in detail the geophysical interpretation of the difference observed between $^{14}$C and U-Th ages obtained in corals. As Figure 3 shows, the results can be explained mainly by changes in cosmogenic nuclide production linked to the gradual decrease of the geomagnetic field, which has been documented by paleomagnetism studies (Barbetti & Flude 1979; McElhinny & Senanayake 1982; Mazaud *et al.* 1991; Salis & Bonhommet 1992). Changes in the carbon cycle also can account for *ca.* 10–20% of the age discrepancy observed between the two geochronometers; these may involve fluctuations in deep-ocean ventilation (Shackleton *et al.* 1988; Broecker *et al.* 1990) and variations in the carbon content of the atmosphere (Berner, Oeschger & Stauffer 1980; Delmas, Ascencio & Legrand 1980) and biosphere (Adams *et al.* 1990).

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## REFERENCES

Adams, J. M., Faure, H., Faure-Denard, L., McGlade, J. M. and Woodward, F. I. 1990 Increases in terrestrial carbon storage from the last glacial maximum to the present. *Nature* 348: 711–714.

Ammann, B. and Lotter, A. F. 1989 Late-Glacial radiocarbon and palynostratigraphy on the Swiss Plateau. *Boreas* 18: 109–126.

Barbetti, M. and Flude, K. 1979 Geomagnetic variation during the late Pleistocene period andchanges in the radiocarbon timescale. *Nature* 279: 202–205.

Bard, E., 1988 Correction of accelerator mass spectrometry $^{14}$C ages measured in planktonic foraminifera: Paleoceanographic implications. *Paleoceanography* 3: 635–645.

Bard, E., Arnold, M., Maurice, P., Duprat, J., Moyes, J. and Duplessy, J.-C. 1987 Retreat velocity of the North Atlantic polar front during the last deglaciation determined by $^{14}$C accelerator mass spectrometry. *Nature* 328: 791–794.

Bard, E., Hamelin, B., Fairbanks, R. G. and Zindler, A. 1990a Calibration of $^{14}$C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature* 345: 405–410.

Bard, E., Hamelin, B., Fairbanks, R. G., Zindler, A., Arnold, M. and Mathieu, G. 1990b U/Th and $^{14}$C ages of corals from Barbados and their use for calibrating the $^{14}C$ time scale beyond 9000 years BP. *In* Yiou, F. and Raisbeck, G., eds., Proceedings of the 5th International Conference on AMS. *Nuclear Instruments and Methods* B52 461–468.

Becker, B., Kromer, B. and Trimborn, P. 1991 A stable isotope tree-ring time scale of the Late Glacial/Holocene boundary. *Nature* 353: 647–649.

Bell, W. T. 1991 Thermoluminescence dates for the Lake Mungo aboriginal fireplaces and the implication for the radiocarbon time scale. *Archaeometry* 33: 43–50.

Berner, W., Oeschger, H. and Stauffer, B. 1980 Information on the $CO_2$ cycle from ice core studies. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 10th International $^{14}C$ Conference. *Radiocarbon* 22(2): 227–235.

Broecker, W. S. 1992 Defining the boundaries of the late glacial isotope episodes. *Quaternary Research* 38: 135–138.

Broecker, W. S., Peng, T. H., Trumbore, S., Bonani, G. and Wölfli, W. 1990 The distribution of radiocarbon in the glacial ocean. *Global Biogeochemical Cycles* 4: 103–117.

Delmas, R. J., Ascencio, J. M. and Legrand, M. 1980 Polar ice evidence that atmospheric $CO_2$ 20,000yr BP was 50% of present. *Nature* 284: 155–157.

Druffel, E. and Linick, T. 1978 Radiocarbon in annual coral rings of Florida. *Geophysical Research Letters* 5: 913–916.

Druffel, E. and Suess, H. 1983 On the radiocarbon record in banded corals: Exchange parameters and net transport of $^{14}CO_2$ between atmosphere and surface ocean. *Journal of Geophysical Research* 88: 1271-1-280.

Edwards, R. L. (ms.) 1988 High precision thorium-230 ages of corals and the timing of sea level fluctuations in the late Quaternary. Ph.D. Thesis. California Institute of Technology.

Fairbanks, R. G. 1989 A 17,000-year glacio-eustatic sea level record influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature* 342: 637–647.

_____ 1990 The age and origin of the "Younger Dryas climate event" in Greenland ice cores. *Paleoceanography* 5: 937–948.

Gillot, P. Y. and Cornette, Y. 1986 The Cassignol technique for potassium-argon dating, precision and accuracy examples from the late Pleistocene to recent volcanics from southern Italy. *Chemical Geology* 59: 205–222.

Goslar, T., Kuc, T. and Pazdur, M. F., Ralska-Jasiewiczowa, M., Rozanski, K., Szeroczynska, K., Walanus, A., Wicik, B., Wieckowski, K., Arnold, M., Bard, E. 1992 Possibilities of reconstruction of radiocarbon level changes during the late glacial by laminated sequence of the Gosciaz Lake. *In* Long, A. and Kra, R. S., eds., Proceedings of the 14th International $^{14}C$ Conference. *Radiocarbon* 34(3): 826–832.

Kromer, B. and Becker, B. 1992 German oak and pine $^{14}C$ calibration, 7200 BC to 9400BC. *Radiocarbon*, this issue.

Mazaud, A., Laj, C., Bard, E., Arnold, M. and Tric, E. 1991 Geomagnetic field control of $^{14}C$ production over the last 80 ky: Implications for the radiocarbon time-scale. *Geophysical Research Letters* 18: 1885-1888.

McElhinny, M. W. and Senanayake, W. E. 1982 Variations in the geomagnetic dipole I the past 50,000 years. *Journal of Geomagnetism and Geoelectricity* 34: 39–51.

Moore, J., Normak, W. R. and Szabo, B. 1990 Reef growth and volcanism on the submarine southwest rift zone of Mauna Loa, Hawaii. *Bulletin of Volcanology* 52: 375–380.

Nozaki, Y., Rye, D. M., Turekian, K. K. and Dodge, R. E. 1978 A 200 year record of carbon-13 and carbon-14 variations in a Bermuda corals. *Geophysical Research Letters* 5: 825–828.

Rozanski, K., Goslar, T., Dulinski, M., Kuc, T., Pazdur, M. F. and Walanus, A. 1992 The Late Glacial-Holocene transition in laminated sediments of Lake Gosciaz (central Poland). *In* Bard, E. and Broecker, W. S., eds., *The Last Deglaciation: Absolute and Radiocarbon Chronologies.* NATO ASI Series I-2. Heidelberg, Springer-Verlag: 69–80.

Salis, B. and Bonhommet, N. 1992 Variation of geomagnetic intensity from 8-60 Ky BP, Massif Central France. *In* Bard, E. and Broecker, W. S., eds., *The Last Deglaciation: Absolute and Radiocarbon Chronologies.* NATO ASI Series I-2. Heidelberg, Springer-Verlag: 155–162.

Shackleton, N. J., Duplessy, J. C., Arnold, M., Maurice, P., Hall, M. A. and Cartlidge, J. 1988 Radiocarbon age of the last glacial deep water. *Nature* 335: 708–711.

Shen, G. T., Campbell, T. M., Dunbar, R. B., Wellington, G. M., Colgan, M. W. and Glynn, P. W. 1991 Paleochemistry of manganese in corals from the Galapagos Islands. *Coral Reefs* 10: 91–100.

Stuiver, M., Brazunias, T. F., Becker, B. and Kromer, B. 1991 Climatic, solar, oceanic and geomagnetic influences on Late-Glacial and Holocene $^{14}C/^{12}C$ changes. *Quaternary Research* 35: 1–24.

Valladas, H. and Valladas, G. 1987 Thermoluminescence dating of burnt flint and quartz: Comparative results. *Archaeometry* 29: 214–220.

Veeh, H. H. and Veevers, J. J. 1970 Sea level at -175 m off the Great Barrier Reef 13,600 to 17,000 years ago. *Nature* 226: 536–537.

Vogel, J. C. 1983 $^{14}C$ variations during the Upper Pleistocene. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 10th International $^{14}C$ Conference. *Radiocarbon* 25(2): 213–218.