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# LATE GLACIAL $^{14}$C AGES FROM A FLOATING, 1382-RING PINE CHRONOLOGY

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**ABSTRACT.** We built a floating, 1382-ring pine chronology covering the radiocarbon age interval of 12,000 to 10,650 BP. Based on the strong rise of $\Delta^{14}$C at the onset of the Younger Dryas (YD) and wiggle-matching of the decadal-scale $\Delta^{14}$C fluctuations, we can anchor the floating chronology to the Cariaco varve chronology. We observe a marine reservoir correction higher than hitherto assumed for the Cariaco site, of up to 650 yr instead of 400 yr, for the full length of the comparison interval. The tree-ring $\Delta^{14}$C shows several strong fluctuations of short duration (a few decades) at 13,800, 13,600, and 13,350 cal BP. The amplitude of the strong $\Delta^{14}$C rise at the onset of the YD is about 40‰, whereas in the marine data set the signal appears stronger due to a re-adjustment of the marine mixed-layer $\Delta^{14}$C towards the atmospheric level.

## INTRODUCTION

Beyond 11,855 cal BP, the current calibration data set IntCal98 (Stuiver et al. 1998a) is based on marine radiocarbon data from corals and marine varves representing the local $^{14}$C level of the ocean mixed layer. Depending on the rate of gas exchange between the atmosphere and ocean and the exchange with underlying oceanic thermocline and deep waters, the mixed layer will attain an intermediate $^{14}$C level between the end-members of deep ocean and atmosphere. The resulting, apparent $^{14}$C age difference between coexistent samples of the terrestrial and marine biosphere is commonly referred to as the marine reservoir age, and in order to create a terrestrial calibration data set from marine data, the reservoir age must be subtracted. For IntCal98, a constant reservoir correction of 500 yr has been applied prior to 11 kyr BP (400 yr after 11 kyr BP).

It has been already noted (Stuiver et al. 1998a) that terrestrial data (Kitagawa and van der Plicht 1998, 2000) for the Glacial and Late Glacial show a systematic offset to the marine-based calibration data, but the issue remained unresolved due to uncertainties in the absolute time scale of the terrestrial data.

Over the past decades, we have collected several hundred pine tree-ring sections dated to the Late Glacial (LG) (Kromer et al. 1998; Friedrich et al. 1999; Friedrich et al. 2001). From these finds, floating chronologies have been built. Obviously, their full potential can be exploited only after the chronologies have been linked dendrochronologically to the absolutely dated chronologies, presently starting at 12,410 BP (Friedrich et al., this issue). However, if we can identify events that are common in marine sequences and in the tree-ring chronology, we can at least infer the terrestrial-marine $^{14}$C age difference by relying on the absolute time scale of the marine sequences. Here, we choose this approach based on (1) the rapid drop of $^{14}$C ages at the start of the Younger Dryas (YD) and (2) the decadal-scale $^{14}$C fluctuations in the Late Glacial.

## TREE-RING SERIES AND $^{14}$C DATA SET

The trees were found in gravel pits at the river Danube and tributaries in south Germany, at the bottom of a bog in the lignite area in east Germany, and in the Daettnau loam pit in a glacial drainage channel near Winterthur during tunnel work close to Zürich.

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We selected decadal tree-ring samples for $^{14}$C pre-dating some of the specimens in order to facilitate chronology building during the initial stages, when the replication was low. Hence, in those cases when, after successful tree-ring synchronization, the sections were found overlapping, "oversampling" of $^{14}$C and uneven spacing on the ring scale occurred.

The conifer samples were pretreated as follows: Soxhlet-extraction of resin by methanol-cyclohexane, alkali solution (80 °C) overnight, then acid-alkali-acid for about 30 min each. Of the initial 15 g of wood, about 50% is removed during pretreatment. The samples were combusted in a Parr-bomb, and the $CO_2$ gas was counted for 10 days in our multi-counter system. The typical precision of an analysis is 25 to 30 yr, including contributions from background and standard determinations (Kromer and Münnich 1992).

The $^{14}$C ages are shown in Figure 1 and listed in Table 1 (supplementary material, www.radiocarbon.org/IntCal04) based on the ring counting of the combined chronology. Individual tree sections are represented in Figure 1 by symbols demonstrating the multiple replication of $^{14}$C dates. We observe plateau-like intervals at 11,800, 11,550, and 11,000 $^{14}$C BP, but even more conspicuous are several strong $^{14}$C age inversions, the most prominent one centered around rings 1950–1900 of the chronology.

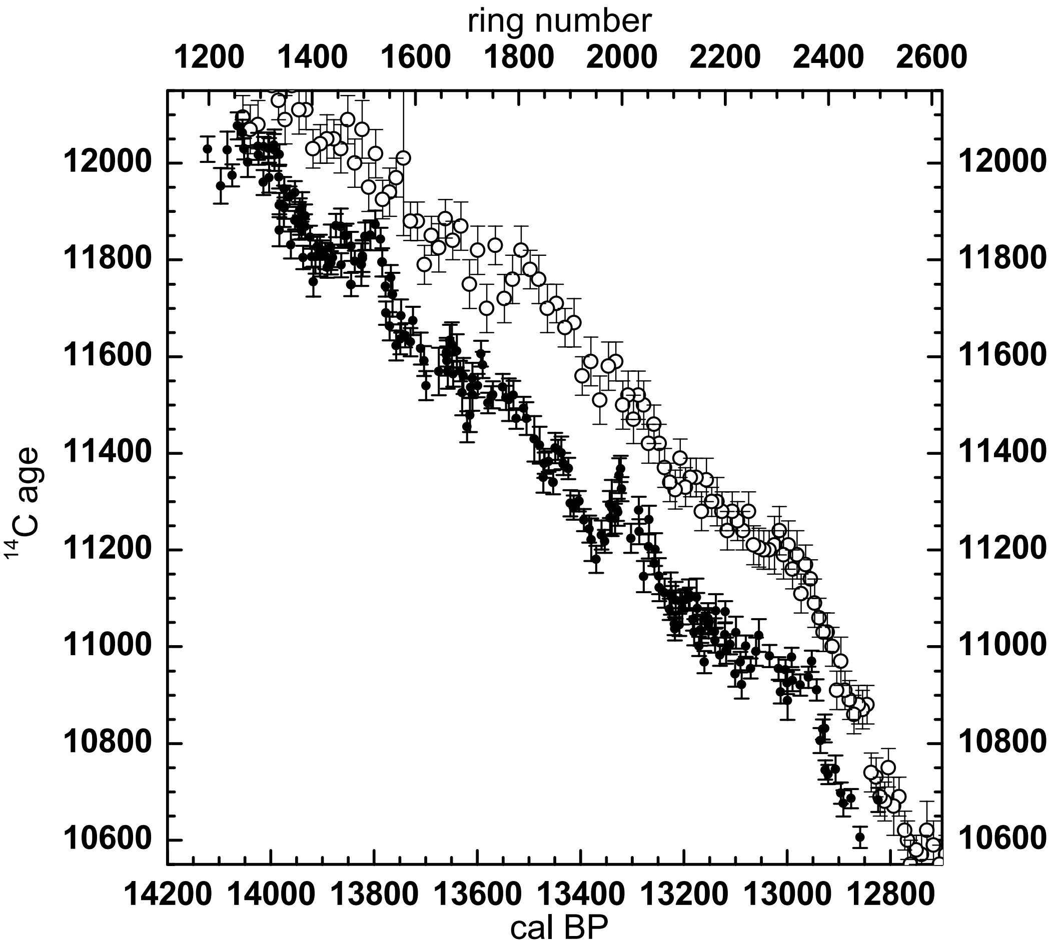

Figure 1 $^{14}$C ages of the Late Glacial pine chronology vs. ring number (top scale) compared to Cariaco mixed-layer $^{14}$C ages (open circles; Hughen et al. 2000). The tree-ring scale is anchored to the Cariaco varve scale as outlined in the text.

## $^{14}C$ AGE PATTERN PRIOR TO THE YOUNGER DRYAS

Regardless of the absolute age placement of the floating pine chronology, which will be attempted below, it is already evident from Figure 1 that terrestrial and marine $^{14}C$ ages cannot agree for an interval of at least 2 centuries prior to the YD. The $^{14}C$ ages obtained from the pine chronology show a two-step $^{14}C$ age plateau of 11,060 and 10,950 $^{14}C$ BP, respectively, for almost 300 true yr, followed by a drop of 300 $^{14}C$ yr in only 60 true yr to about 10,650 $^{14}C$ BP. However, in the Cariaco $^{14}C$ data, based on a reservoir age of 400 yr, the $^{14}C$ age plateau is at 11,300 to 11,200 $^{14}C$ BP, but the $^{14}C$ age drop levels off at about 10,650 $^{14}C$ BP, like in the terrestrial data. Therefore, it seems inevitable to postulate a reservoir age for the Cariaco site of about 600 yr for the final few centuries of the Allerød, and a value close to the Holocene level of 400 yr already early in the YD. We also note that the extension of the absolutely dated tree-ring-based $^{14}C$ data set of IntCal04, which now reaches back to 12,410 cal BP (Reimer et al., this issue; Friedrich et al., this issue—i.e. already including 820 yr of the YD—confirms a constant reservoir age of 400 yr for the major part of the YD.

## ABSOLUTE PLACEMENT OF THE PINE CHRONOLOGY WITH RESPECT TO THE CARIACO VARVE TIME SCALE

To anchor the floating tree-ring chronology to the absolute time scale, we assume that the strong $^{14}C$ age drop is caused by a strongly rising atmospheric $^{14}C$ level, e.g., following a reduction of ocean ventilation. Because of the rapid turnover time of atmosphere/mixed-layer reservoirs with respect to $^{14}C$ of less than a decade, the $^{14}C$ spike will be seen similarly in both reservoirs, and we can align the $^{14}C$ age drop in the pine chronology to the Cariaco data as shown in Figure 1. We note that this setting leads to a consistent picture with respect to the timing of the eruption of the Laacher See volcano (LSE) relative to the onset of the YD. We obtained a 95-ring section of a poplar which grew about 10 km SE of the LSE site, and which was buried in situ by the eruption, i.e., the outermost ring represents the time of the eruption (Baales et al. 1999). The poplar could be dendro-synchronized to the pine sections, and we also measured decadal $^{14}C$ samples (tree "Krufft" in Table 1 and Figure 1). From varved lake sediments in south Germany and Switzerland, the time difference between the date of the eruption and the biostratigraphic boundary indicating the YD is known to be about 190 to 200 yr (Brauer et al. 1999; Merkt and Müller 1999; Litt et al. 2002). Hence, in Figure 2 we can relate the $^{14}C$ ages from our Late Glacial pine chronology to the high-resolution marine data of the Cariaco Basin (Hughen et al. 2000), where the onset of the YD is clearly indicated by a change in varve thickness (Hughen et al. 1996). The setting of the pine chronology, as based on the $^{14}C$ age drop, is compatible with the constraints imposed by the time interval between the LSE and the onset of the YD.

## $\Delta^{14}C$ LINK TO CARIACO $\Delta^{14}C$

We can constrain the absolute position of the LG chronology even tighter by wiggle-matching the high-frequency $\Delta^{14}C$ fluctuations in the terrestrial and marine record. This approach is based on the idea that due to the above-mentioned fast turnover time of $^{14}C$ between the atmosphere and the marine mixed layer of about 8 yr, $\Delta^{14}C$ fluctuations on a time scale of a few decades will be seen as high-frequency signals in both archives [with allowance for attenuation and phase shift (Siegenthaler et al. 1980; Stuiver et al. 1998b)], superimposed on a potentially long-term, time-varying offset (marine reservoir age) caused by changes in the ocean/atmosphere dynamics. We note that this approach requires high precision in $\Delta^{14}C$ and high temporal resolution, which fortunately has been achieved in the 2 data sets.

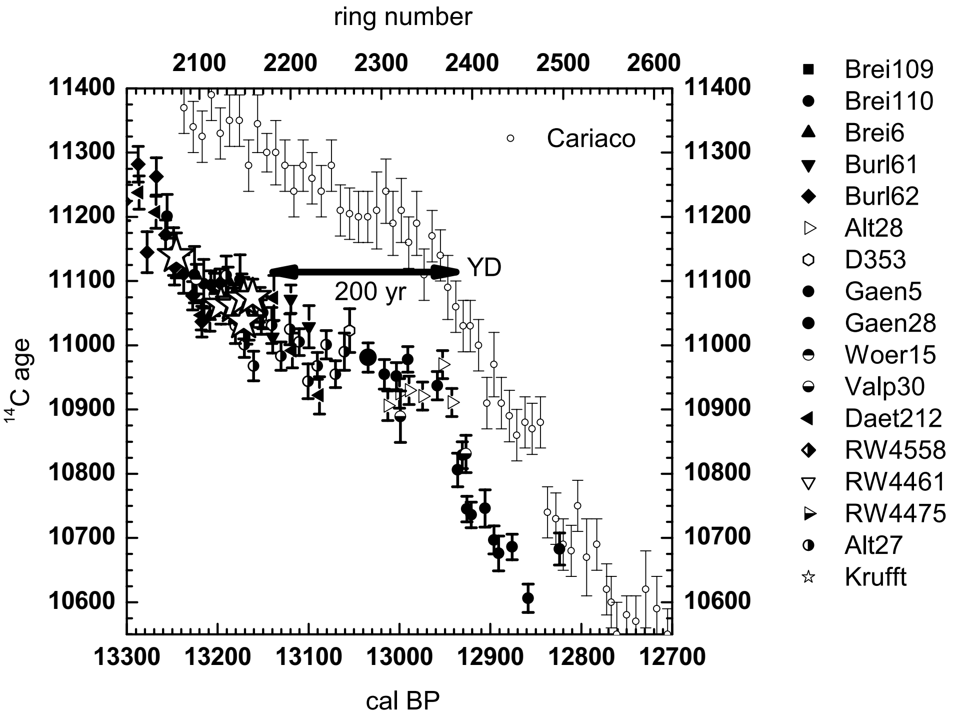

Figure 2 $^{14}$C ages of decadal samples of the final 600 rings of the pre-Younger Dryas Late Glacial pine chronology compared to the Cariaco $^{14}$C data set (open circles; Hughen et al. 2000). The tree sections are indicated by various symbols. Tree "Krufft" (star symbol) was buried by the Laacher See eruption. Hence, its outermost rings (bark preserved) mark the time of the eruption, which occurred about 200 yr prior to the beginning of the Younger Dryas (YD). The strong $^{14}$C age decline, coincident with a drop in grayscale (see Figure 3) at the onset of the YD (strong rise of $\Delta^{14}$C), is used to anchor the floating pine section to the Cariaco time scale.

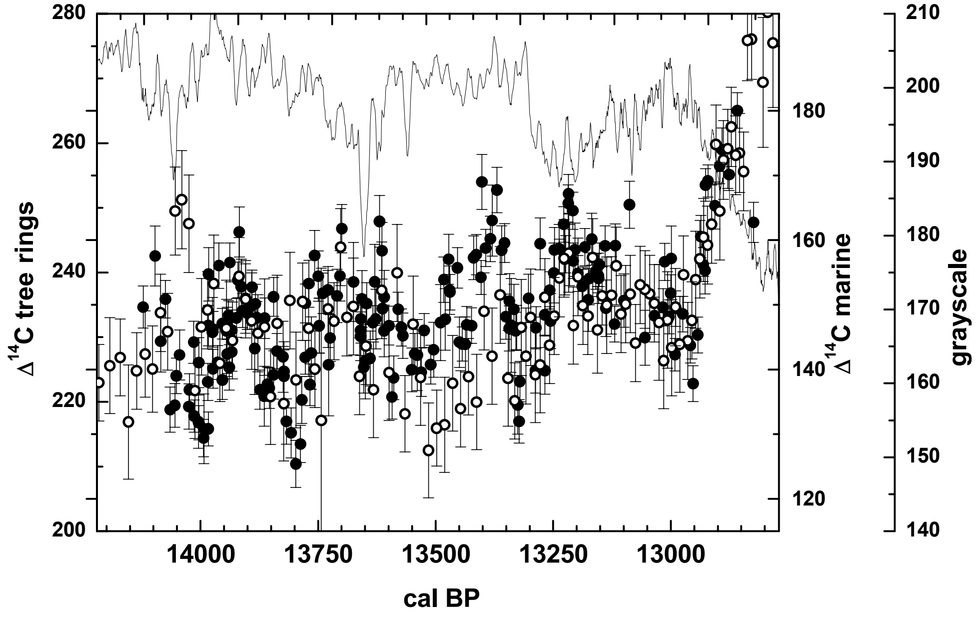

Figure 3 $\Delta^{14}$C obtained from the Late Glacial pine (full dots) with its absolute age set according to Figure 2 (ring 1000 corresponds to 14,320 cal BP) compared to marine mixed-layer (Cariaco) $\Delta^{14}$C (open circles) and the grayscale signal at Cariaco (thin line), a proxy of upwelling/trade wind strength. For comparison, the marine $\Delta^{14}$C scale is shifted by 85‰.

Within the constraints provided by the link of the previous paragraph, we find a clear match of $\Delta^{14}$C fluctuations as shown in Figure 3. For the best match, the difference in $\Delta^{14}$C between the atmosphere and the Cariaco mixed layer is 85‰, equivalent to an apparent age difference of about 650 yr—i.e., according to this absolute age placement of the Late Glacial pine, the marine reservoir age at the Cariaco site between 14 and 13 kyr BP has a value of about 650 yr.

## DISCUSSION

Using 2 independent arguments about the absolute position of the floating LG pine chronology, we can demonstrate that for several centuries prior to the YD, the marine reservoir age at the Cariaco Basin was higher than the hitherto assumed value. Before turning to an interpretation of possible causes, it appears justified, given the difficult and ongoing task of building Late Glacial tree-ring chronologies, to discuss how dendrochronological errors could be responsible for the observed increase in the offset between the terrestrial and marine $^{14}$C data sets. We already noted that the long $^{14}$C age plateaus [at 11,000 (terrestrial) and 11,250 (marine) $^{14}$C BP, respectively] in the 2 centuries prior to the YD cannot be reconciled without invoking an increased marine $^{14}$C age at the Cariaco site at this time.

Prior to that $^{14}$C age plateau, we observe a strong $^{14}$C age inversion centered around rings 1950–1900; hence, we see no room for a shift to younger ages for the earlier part (and there is no indication of a tree-ring synchronization for any younger placement, but rather the finding of statistically valid links leading to the placement of Figure 1). Similarly, the multiple replication of $^{14}$C dates in many overlapping tree sections lends additional credit to the tree-ring synchronization.

What could cause a long-lasting (at least 8 centuries) increase of the difference in $\Delta^{14}$C between the atmosphere and the tropical Atlantic? Following the box model results presented by Siani et al. (2000, 2001), we consider changes in the water masses at low latitudes in the Atlantic as the most likely candidate, most probably a northward movement of South Atlantic intermediate water. Recently, nutrient tracer data from the Brazilian margin at 27°S (Came et al. 2003) support this concept. The tracer data document a fully-developed Holocene oceanic configuration only after the end of the YD, whereas the youngest $^{14}$C date of our LG pine chronology supports an early retreat of the southern source at Cariaco already 150 yr after the beginning of the YD. The difference may be due to the difference in latitude—i.e., the Holocene-type configuration of $\Delta^{14}$C in the atmosphere and mixed layer may have been achieved earlier at equatorial latitudes than at the Brazilian margin.

This sequence of events (i.e. a rise of atmospheric $\Delta^{14}$C at the beginning of the YD), and at the same time a restoring of the marine $\Delta^{14}$C closer to the atmospheric value due to the retreat of intermediate water, helps to explain the difficulty in attributing $\Delta^{14}$C dynamics quantitatively to changes in ocean ventilation or solar activity (Stocker and Wright 1996; Goslar et al. 2000; Hughen et al. 2000; Muscheler et al. 2000). With an atmospheric $\Delta^{14}$C signal of only 60% of the full marine amplitude, the processes may be modeled more easily once high-resolution $^{10}$Be data for the late Allerød/early YD become available.

## CONCLUSION

From 517 tree-ring sections, we constructed a floating Late Glacial pine chronology. $^{14}$C analyses on decadal samples show strong, rapid atmospheric $^{14}$C fluctuations in the Late Glacial, with $^{14}$C age inversions of up to 200 $^{14}$C yr in less than 60 true yr. Based on the $^{14}$C age pattern at the onset of the Younger Dryas, we can demonstrate an increased value, compared to the Holocene one, of the marine reservoir age at the Cariaco Basin of about 650 yr for several centuries prior to the YD.

$^{14}$C fluctuations in the atmosphere during the Late Glacial, documented in several overlapping pine sections, appear considerably more pronounced than their counterpart in the marine mixed layer, pointing to a production change scenario rather than an ocean ventilation cause for these short time fluctuations. The strongest age inversion occurs roughly coincident with the well-documented Gerzensee oscillation, and it is followed, with a lag of about 30 yr, by a strong drop in the grayscale signal at Cariaco.

At the onset of the YD, $\Delta^{14}$C appears highly synchronous in both reservoirs; hence, here the amplitude and phase relation of the atmosphere/mixed-layer difference in $\Delta^{14}$C supports a dominating ocean ventilation signal causing the observed $\Delta^{14}$C spike.

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