The Younger Dryas: absolute and radiocarbon chronology

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One of the main purpose of calibrating ^{14}C is to provide a common absolute chronological framework for the numerous researchers studying the last forty millennia and in particular the Younger Dryas climatic event which took place approximately 11 000–10 000 ^{14}C yr BP (Mangerud et al., 1974). For this time-period there are basically two different ways to obtain an absolute chronology independent of ^{14}C: counting annual layers and radiochronology. So far, four different types of archives have been used: trees, varved sediments, ice cores and corals.

From these archives it is possible to count annual layers and obtain climatic informations based on geochemical measurements such as: δD and $\delta^{13}C$ in the cellulose of trees (Becker et al., 1990), $\delta^{18}O$ in the carbonate fraction of the lake sediment (Rozanski et al., 1992), δD and $\delta^{18}O$ in polar ice (Johnsen et al., 1992) and δ18O and Sr/Ca ratios in corals (Beck et al., 1991; Guilderson et al., 1994). From lake sediments, it is also feasible to study pollen which can be compared to the $\delta^{18}O$ variability (Lotter 1991; Ralska-Jasiewiczowa et al., 1992). By using the technique of thermal ionization mass spectrometry (TIMS) it is possible to obtain accurate and precise ^{230}Th-^{234}U ages in corals (Bard et al., 1990).

Each type of archive has its advantages and drawbacks. The ultimate chronology of the Younger Dryas (YD) period will probably emerge from a consensus between the different types of information.

The trees have provided a chronology which is highly precise and can be tied accurately to the ^{14}C chronology by direct ^{14}C dating of the wood cellulose (Kromer and Becker 1993). Unfortunately, it is not yet possible to cover continuously the whole YD chronozone by means of tree rings since no pines are found north of the Alps covering the YD event (they disappeared after 11 000 ^{14}C yr BP Kaiser 1993). Another drawback of the tree ring data base is that the carbon and hydrogen isotopic ratios in the cellulose can be affected by physiological processes and it is sometimes difficult to extract the isotopic signal reflecting the large scale climatic variations (Lipp et al., 1991).

The varved lakes have the advantage that it is possible to study at least two types of climatic records which can be related to the YD boundaries: $\delta^{18}O$ in the carbonate fraction and pollen relative abundances. It is also feasible to date the varves by ^{14}C provided that enough plant macrofossils can be found in the sediments. However, by contrast with trees and corals, the link between the age of the varves and the ^{14}C dates remains indirect since only 'allochtonous' terrestrial plants should be dated to avoid the hardwater effect. Another disadvantage of the chronologies based on varves is that there are often numerous missing varves which remain undetected in the sediment sequences. During the last decade several well known sequences of varves have been redated and hundreds to thousands of missing varves were added to the initial counts. Such revisions have been used in the particular cases of the Swedish glacial varves (Wohlfarth et al., 1993, 1994) and the lacustrine varves from Soppensee (Hajdas et al., 1993) and Holzmaar lakes (Hajdas et al., 1995). Since the varved sequences are rarely continuous throughout the Holocene, the technique of ^{14}C wiggle matching has also been used to test the validity of the chronologies and to quantify the number of missing varves.

The long Greenland ice cores (GRIP and GISPII projects) have the advantage of exhibiting continuous annual banding throughout the Holocene and the last deglaciation (Johnsen et al., 1992; Alley et al.; 1993, Taylor et al., 1993). However, the main drawback of the ice cores is that the annual layers disappear progressively with depth through thinning of the ice sheet deeper layers. Moreover, it is not always easy to relate the δD-$\delta^{18}O$ profiles with other ^{14}C dated climatic records. Indeed, it is necessary to assume that the YD boundaries are synchronous in order to obtain information useful for the ^{14}C calibration. In order to circumvent this problem volcanic ash layers can be used as instantaneous time markers for correlating accurately Greenland ice cores with ^{14}C dated terrestrial sequences.

The corals have the advantage that they can be dated directly by at least two radiochronological methods: ^{14}C and ^{230}Th-^{234}U by mass spectrometric techniques (Bard et al., 1990). In addition it is sometimes possible to sample larges colonies showing a few centuries to a thousand of seasonal bands (X-radiograph sclerochronology). These long annual time series have enabled to test the U-Th technique (Edwards et al., 1988; Bard et al., 1993) and may bring valuable information during specific time periods such as the YD (Burr et al. 1994).

Nevertheless, the coral sclerochronology is still in infancy when compared to the dendrochronology. At the moment it is not feasible to reconstruct a continuous sequence of seasonal bands during the Holocene or the Late Glacial period. Another drawback of the corals is that they do not record directly the atmospheric ^{14}C changes but rather the variations at the sea surface. A reservoir age correction is thus needed which is on the order of 400 yr for low latitudes but this could be slightly variable though time. The other effect of this reservoir phenomenon is to smooth the short term ^{14}C excursions which are typically due to solar fluctuations. The overall precision of an isolated ^{14}C/Th-U comparison is thus probably limited to 100 to 200 yr.

In the particular case of the YD period the climatic signals extracted from tropical corals ($\delta^{18}O$, Sr/Ca and depth of recovery for sea level reconstructions) are difficult to compare and correlate to the well recognized climatic records observed for mid and high latitudes. This problem further complicates the use of the coral data base to study the European deglaciation chronology (Guilderson et al., 1994).

During the last five yr numerous data sets have been produced to calibrate radiocarbon during the last deglaciation and in particular during the YD climatic event. For the moment the different records are not always in agreement with each other. This problem can be summarized by the calibration of two ^{14}C benchmarks (table 1):

1/ the end of YD at about 10 000 14C yr BP which corresponds to a range of absolute ages caused by a large ^{14}C age plateau of at least 500 cal yr.

2/ the ^{14}C age of 11 000 yr BP which often corresponds to the inception of YD in terrestrial and oceanic records. This value is also close to the ^{14}C age of the Laacher See volcanic eruption (note that Lotter (1991), Zolitschka et al. (1992) and Hajdas et al. (1993) use 11 000 ^{14}C yr BP whereas Hajdas et al (1995) use 11 200 ^{14}C yr BP for the mean age of the Laacher sea tephra).

In the case of the ice cores it is assumed that these benchmarks correspond to the inception and end of the YD. Because of the presence of a major ^{14}C age plateau, the YD/PB boundary is not equivalent to the calibration of the 10 000 ^{14}C yr BP but should fall within the time range of the ^{14}C age plateau.

For the varved sediments records we have used the most recent version of the chronologies: Hajdas et al. (1993) for Soppensee, Hajdas et al. (1995) for Holzmaar, Goslar et al. (1995) for Gosciaz lake and Wohlfarth et al. (1994) for the Swedish glacial varves.

From table 1 it is clear that several mismatchs exists. Nevertheless an agreement within 100 to 200 yr can be found between four independent and complementary pieces of information:

Table 1. Calibration of 10 000 and 11 000 ^{14}C yr BP.

Radiocarbon:	**~10 000 ^{14}C yr BP**	**~11 000 ^{14}C yr BP**
German pines and oaks	11 600–11 100 Cal yr BP	
Soppensee (^{14}C matched)	11 400–11 200 Cal yr BP	12 500 Cal yr BP
Holzmaar (^{14}C matched)	~11 300 Cal yr BP	12 000 Cal yr BP
Gosciaz (^{14}C matched)	11 800–11 200 Cal yr BP	12 700 Cal yr BP
Swedish varves	11 400–11 000 Cal yr BP	12 200 Cal yr BP
U-Th in corals	11 600–11 100 Cal yr BP	12 900 Cal yr BP
GRIP ice core	11 550 Cal yr BP	12 700 Cal yr BP
GISP ice core	11 660 Cal yr BP	12 900 Cal yr BP

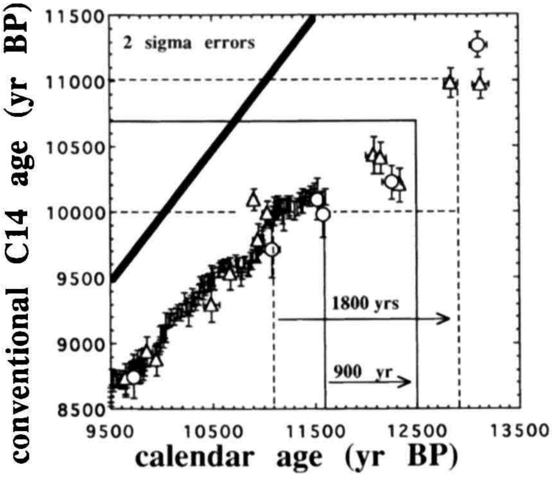

Fig. 1. Radiocarbon ages versus calendar ages based on tree rings (vertical bars: Kromer and Becker 1993) and corals dated by U-Th (open dots: Bard et al., 1990, 1993, Barbados); open triangles: Edwards et al., 1993, New-Guinea). All errors are given at 2 sigma level (for ^{14}C ages of corals they do not include the uncertainty in the reservoir correction). The thick line is the 1 to 1 line. The thin dashed lines indicate the maximum value (1800 yr) of the calendar interval corresponding to 11 000 to 10 000 ^{14}C yr BP. The thin lines indicate the minimum value (900 yr) of the calendar interval corresponding to 10 700 to 10 000 ^{14}C yr BP.

1/ Tree rings: the German pine-oak chronology which is continuous for the last 11 650 Cal yr (Kromer and Becker,1993).

2/ Lake varves: the long sequence from lake Gosciaz in Poland (Goslar et al. 1994, 1995) which shows that the YD started at about 12 600 Cal yr BP (~10 700 ^{14}C yr BP) and ended at about 11 450 Cal yr BP (~10 000 ^{14}C yr BP).

3/ Ice cores: the two most recent Greenland cores which indicate that the YD event started at about 12 800 Cal yr BP and ended at about 11 500–11 600 Cal yr BP (Johnsen et al., 1992, Alley et al., 1993, Taylor et al., 1993)

4/ Corals: the ^{14}C/U-Th comparisons in samples from the islands of Barbados (Bard et al., 1990,1993), Mururoa (Bard et al., 1993), New-Guinea (Edwards et al., 1993), Vanuatu (Gray et al., 1992) and Tahiti (Bard et al., 1995) which show that the YD chronozone (assumed to be 11 000 to 10 000 ^{14}C yr BP) started at about 12 900 Cal yr BP and ended between 11 600 and 11 100 Cal yr BP. By using the YD start observed for Lake Gosciaz (about 10 700 ^{14}C yr BP) the beginning of YD could be as young as 12 500 Cal yr BP by applying the coral calibration.

In order to reach an optimal agreement within a few decades, the accuracies and precisions of these different chronologies should, and probably will, be improved in the near future. Two problems are particularly important: the relative position of the Younger Dryas/PreBoreal boundary with respect to the ^{14}C age plateau at 10 000 ^{14}C yr BP and the ages (Cal and ^{14}C) of the beginning of the YD event.

Nevertheless it is probable that the broad agreement described above is not fortuitous and it may thus be possible to propose a temporary best solution for the YD absolute chronology (cf fig. 1):

- beginning of YD between 12 900 and 12 500 Cal yr BP
- end of YD between 11 600 and 11 000 Cal yr BP.
- best estimate for the YD duration in the order of 1000 to 1300 Cal yr.

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