Cupressus dupreziana: a dendroclimatic record for the middle–late Holocene in the central Sahara

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Abstract: Dendroclimatology of *Cupressus dupreziana*, the Tassili cypress, has been attempted on samples obtained from the door beams of the old cities of Ghat and Barkat located at the foot of the Tassili, where the cypress still lives. The tree rings of 20 samples were measured and dated by 24 AMS ^{14}C dates. A mean ring-width chronology has thus been obtained, spanning, though discontinuously, 5220 to 100 ^{14}C BP (5990–65 cal. BP). As the tree-ring width in dry lands depends mainly on water availability, the mean ring-width chronology represents a detailed record of changes in rainfall on a decade scale for the middle and late Holocene of the central Sahara. It indicates main drought spells at 5200–5000 ^{14}C BP (5900–5760 cal. BP) and at 4350 BP (5120 cal. BP), followed by phases of enhanced precipitation and by the onset of extreme arid conditions at 1550 ^{14}C BP (1500 cal. BP).

Key words: Climatic change, dendroclimatology, drought, Tassili cypress, *Cupressus dupreziana*, central Sahara, desert onset, Holocene.

Introduction

Dendroclimatological research on trees in semi-arid and arid regions (Zahner, 1968; Glerum, 1970; Fritts, 1976) often gave questionable results as the unfavourable ecological conditions characteristic of these environments at times induce modifications in the growth rate of the wood, with the appearance of rings not connected to the annual growth increment (rain rings, false, discontinuous and missing rings) (Liphschitz *et al.*, 1979; Meko *et al.*, 1995; Diaz *et al.*, 2002).

The suitability of Cupressaceae in general, and among them the *Cupressus dupreziana*, for dendrochronological study, is generally reputed to be low (Liphschitz, 1986; Grissino-Mayer, 1993; Schweingruber, 1993). Recent studies are still more pessimistic (Abdoun, 2002), as they have demonstrated that during the years 1967–1997, the growth of *Cupressus dupreziana* has been far from regular. On the other hand, a radiocarbon date on a dead trunk of *Cupressus* (Messerli and Kienholz, 1981; Hachid, 1998) gave the age of 1640 ± 80 ^{14}C BP and demonstrated that *Cupressus dupreziana* may be very old and its rings may have recorded environmental change over a long period.

In the framework of the geoarchaeological research aimed at the reconstruction of the Holocene climatic changes in the valley of wadi Tanezzuft (Cremaschi, 2001, 2002; Cremaschi and di Lernia, 2001) the proxies for the last millennia have proven to be so rare that the reliability of *Cupressus dupreziana* as a source of dendroclimatic and palaeoclimatic data needed to be checked.

Wood and samples

Cupressus dupreziana (the Saharan cypress, *tarut* in the Tuareg language) was first described by the French captain Maurice Duprez in 1924 (Maire, 1933; Dubief, 1999) and classified by Camus, in 1926 (*Cupressus dupreziana* Camus 1926; synonymous: *C. lereddii* Gaussen 1950).

A total of 233 living trees have been recently recorded (Abdoun and Beddiaf, 2002) on the northeast sloping surface of the Tassili N'Ajjer plateau (Central Sahara), at 1430–1800 m elevation, very close to Janet and some 60 km west of Ghat (Figure 1) (Abdoun and Beddiaf, 2002). As dead trunks surround living specimens, a much larger occurrence should be hypothesized for the past (Simoneau and Debazac, 1961; Dobry, 1988).

Cupressus dupreziana has adapted to severe conditions: in the area where it occurs, the summer temperatures are

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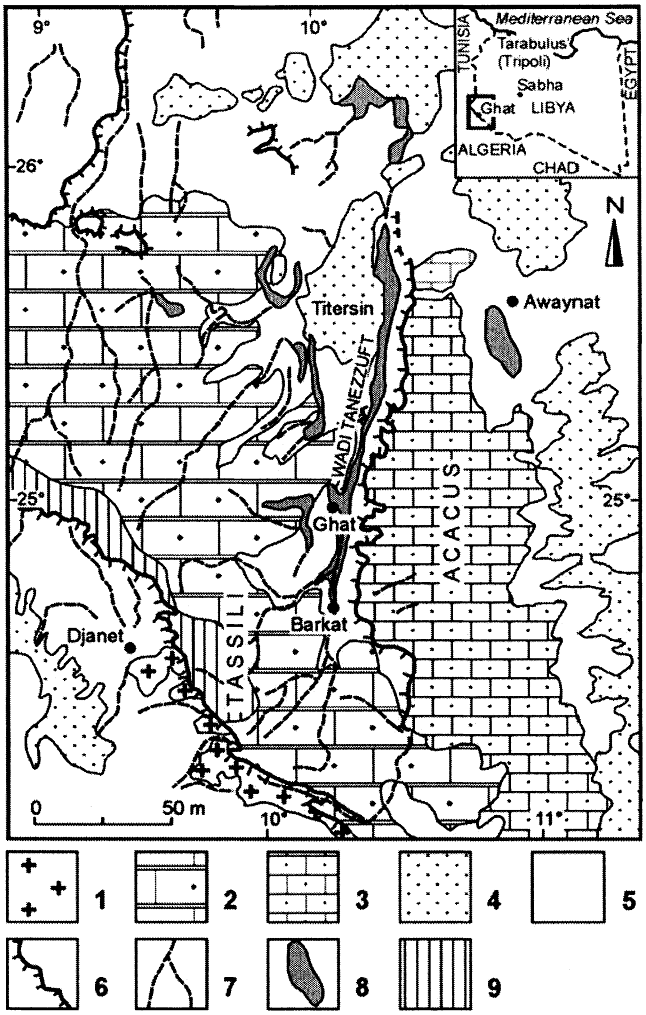

Figure 1 The *Cupressus dupreziana* area and in its physiographic context. The desert towns in which the door samples were collected are indicated (Ghat and Barkat). 1, Pre-Ordovician granite; 2, Tassili sandstone (Silurian); 3, Acacus sandstone (Upper Silurian–lower Devonian); 4, 5, pediment; 6, main escarpments; 7, main drainage directions; 8, Holocene alluvial deposits; 9, location of the *Cupressus dupreziana* area

estimated to be *c.* 20–30°C, in winter *c.* 1–13°C. There is scarce information regarding the local rainfall and its distribution through the year. The pluviometric stations of Janet and Ghat, which are both located at the base of the plateau, gave, respectively, a mean annual rainfall of 25 and 12 mm (1926–1960) (Fantoli, 1937; Dubief, 1999), but precipitation is likely to be higher on the top of the plateau (Dubief, 1999). The rainy season occurs mainly during late spring, brought on by the southern winds that coincide with the maximum rise to the north of the western monsoon (Fantoli, 1937). The growth period of the *Cupressus* is from October to May, coinciding with the late winter–spring rain, and not apparently affected by summer rain (Abdoun, 2002).

Since time immemorial, because of the large size of mature specimens and because of the resilience of the wood and its resinous scent, the cypress was systematically used by local people for carpentry, especially to make the main doors of the traditional houses of desert villages (Figure 2). Some doors are still in use in the cities of Ghat and Barkat, but after the hinges break, many have been recently replaced with iron doors and thereafter discarded. As the living trees and dead trunks of the Tassili were inaccessible to us, the discarded doors were used as samples for the present work.

Methods

The doors are composed of two to five beams, ranging in size from 120 to 150 cm in length, from 10 to 25 cm in width, and from 2 to 4 cm in thickness, obtained by cutting the trunk, or large branches, longitudinally through superposed tangential sections. Therefore, cutting individual beams perpendicular to their length gave the best exposures for tree rings. The sample surfaces were polished with abrasive paper and prepared according to standard procedures (Schweingruber, 1988).

The width of all visible rings was measured with a precision of 0.01 mm with a LINTAB device and plotted using the TSAP software (Rinn, 1996). Standardization of the raw data was carried out using the ARSTAN program (Cook and Holmes, 1986). Specifically, considering the wide range of the sample lengths (see below), the raw data were detrended by taking residuals from a cubic smoothing spline function with a spline stiffness of two-thirds of the series length (Cook and Kairiukstis, 1990). Each individual sample was dated by at least one AMS radiocarbon date. A total of 24 radiocarbon dates were acquired at the GEOCHRON laboratory. Samples for radiocarbon dating were mechanically separated in order to include from three to five single rings. The date obtained was considered to represent the mid-point of the sampled interval.

Individual samples

When polished sections of the cypress beams are observed under the microscope, tree-rings and their annual components (early- and latewood) can be distinguished and measured in most cases (Figure 2). However, while sets of clear rings are dominant, there are also several discontinuous and indistinct rings. They probably correspond to intra-annual bands and diffuse annual rings common in the family of Cupressaceae (Dobry and Kyncl, 1992). Twenty single samples were studied, ranging in length from 65 to 809 rings, but many had at least 300–400 rings or more (Figure 3). The shape of the rings in each sample corresponds to the part of the trunk from which the beams have been obtained. The samples with bowed rings, as they were cut near the core of the trunk, display a characteristic growth trend: the curves have a negative exponential shape, implying a progressive reduction of the ring width (Schweingruber, 1988). Other sets of rings have a quite flat tendency, and appear to have been extracted from large trunks and probably old trees, far from their cores. In order to reduce the effects of the growth trend, and to render the different types of samples homogeneous, all the curves were standardized (detrended) as indicated above.

Age and synchronization

No synchronization being self-evident, the samples have been put in a chronological framework on the basis of radiocarbon dating. Each single set of rings measured in an individual sample was dated by radiocarbon dating. Twenty-four radiocarbon dates were obtained, spanning the period from 5160 to 220 ^{14}C BP (Table 1). In the case of long samples, with many rings, two or three datings were performed at broad intervals, in order to check the annual rate in ring growth.

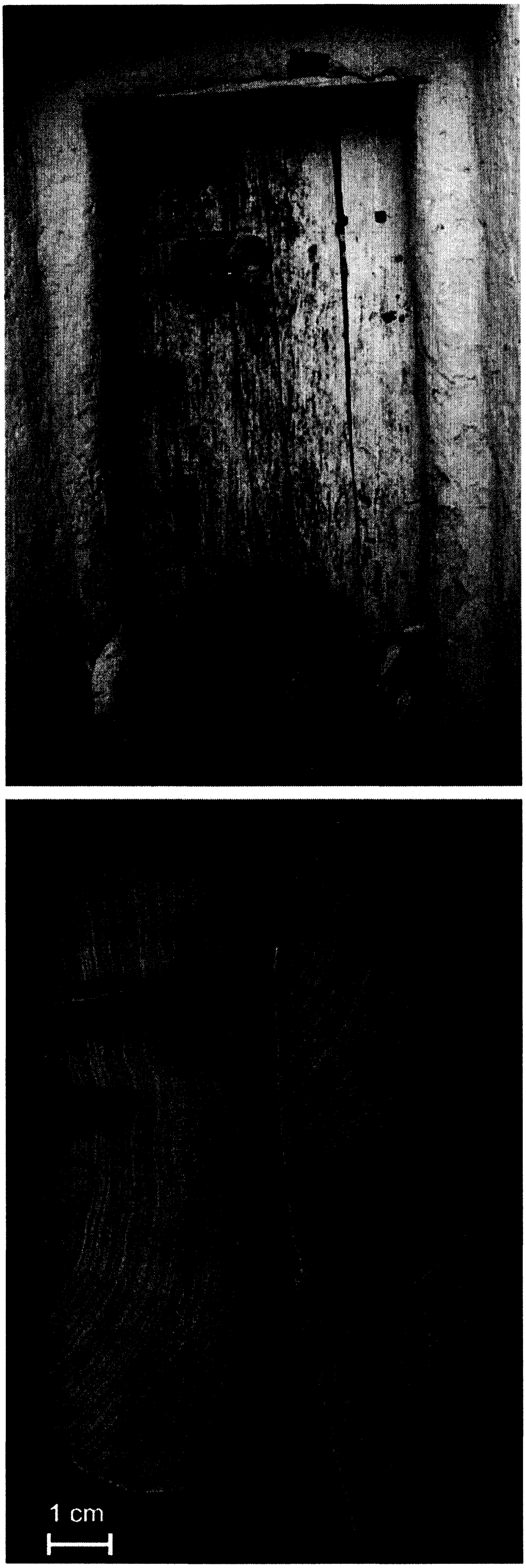

Figure 2

In sample GhC203, the radiocarbon dates of 990±40 ^{14}C BP at the tenth ring and 640±50 ^{14}C BP at the 304th were obtained. Therefore, 295 rings correspond to 350 radiocarbon years. Considering the radiocarbon uncertainty (1 sigma ±40–50 yr), the radiocarbon age appears consistent with the number of counted rings.

In sample Gh701, the radiocarbon date at the 150th ring was 1920±30 ^{14}C BP, and at the 385th was 1720±60 ^{14}C BP: 236 rings correspond to 200 radiocarbon years. In this sample, an additional dating of 1030±40 ^{14}C BP obtained at the 615th ring was rejected (it suggests 690 radiocarbon years for 231 rings) since the resin impregnated the wood after the formation of the rings, rejuvenating the date.

Furthermore, in sample GhA2S, the 130th ring is dated at 4870±40 ^{14}C BP, and the 640th ring at 4110±40 ^{14}C BP, indicating 760 radiocarbon years for 510 rings. This discrepancy cannot be explained by the imprecision of the radiocarbon dating. It is more accurately to be considered contextual to the *Cupressus* growth, meaning that several missing rings occur in the most recent part of the sample.

The radiocarbon scale obtained by dating, considering the uncertainty implicit in the method, was used to arrange the single samples in a general chronological framework. When comparing the single curves, although chronological superposition exists for several samples (Figure 4), the standard cross-dating procedure on an annual basis was not possible, even among the curves, derived from the same sample.

Better results were obtained by basing the synchronization on a decade-scale trend derived from a 21-year running mean. Thus, good overlapping was achieved from different curves measured on the same sample (eg, sample GhA2S in Figure 5A); the trend being clearly the same and the slight differences between the curves attributable to the sporadic occurrence in the sequence of discontinuous missing and/or false rings. A similar result was obtained from samples of different beams of the same period (eg, sample Gh6B and Gh6D in Figure 5B).

Tree ring chronology and wiggle matching

Single indexed curves were superposed on the best fit, according to their chronological relationships, and six discontinuous segments were obtained, covering the last six millennia. Because of the floating nature of the radiocarbon chronology, each segment was wiggle-matched (Figure 6), with the wiggle-matching option of the OXCAL program, in order to check the degree of confidence of the synchronization based on the best fit, and to obtain a calendar chronology.

The uncalibrated tree-ring chronology (Figure 7) we obtained is discontinuous, consisting of the following segments:

(1) The oldest portion of the curve ranges between 5220 and 4260 ^{14}C BP. It was obtained by the overlapping of seven samples whose synchronization is fairly good, except for the period around 4800 ^{14}C BP. Eight dates are available for this segment. They fit the master calibration curve almost exactly (Figure 6), except the date 4110±40 ^{14}C BP (sample GhA2S), which indicates that in the more recent

Figure 2 A door made of *Cupressus dupreziana* still in use in the old town of Ghat (top: the door is about 1.2 m wide). Two samples (bottom: GhG4 left; GhE2S right) obtained from beams of Cypress, ready for dendroclimatic measurement (below). Notice the narrowness of individual rings, but their sharp and clear-cut shape

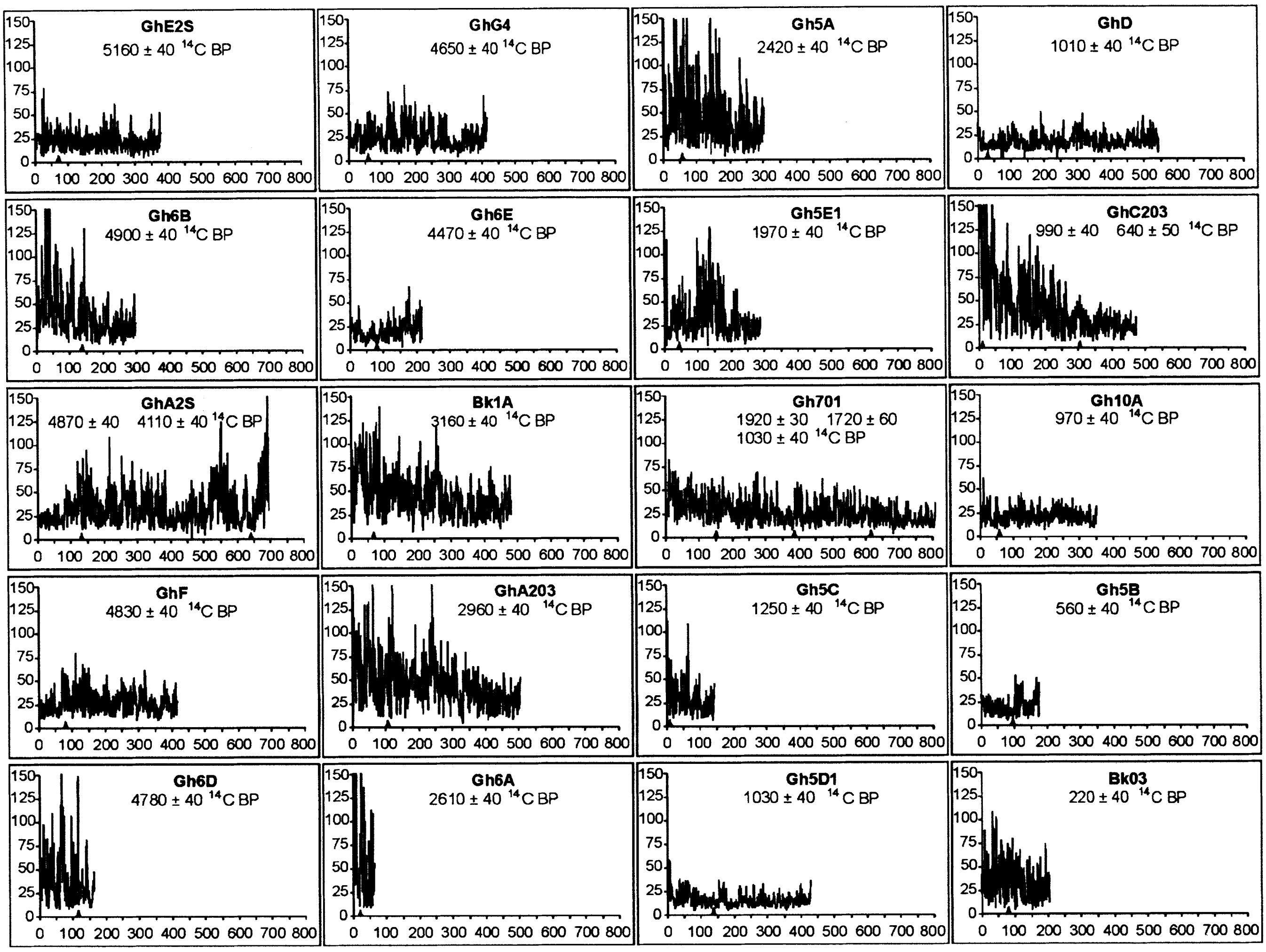

Figure 3 Growth curves of individual samples. Solid triangles on abscissa show the position of the radiocarbon dates. Ring width (microns, × 10) is indicated in ordinate, number of rings is indicated in abscissa

Table 1 Radiocarbon dating of the *Cupressus dupreziana* samples.

Sample	Location	Sample type	Geochron laboratory code	Conventional age ^{14}C yr BP (^{13}C corrected)	δ^{13}C‰ PDB	Ring number
GhE2S	Ghat	Tarut wood	GX-27377-AMS	5160±40	−20.0	70
Gh6B	Ghat	Tarut wood	GX-27932-AMS	4900±40	−21.0	137
GhA2S	Ghat	Tarut wood	GX-27032-AMS	4870±40	−20.8	130
F2SUP	Ghat	Tarut wood	GX-29656-AMS	4830±50	−20.7	80
Gh6D	Ghat	Tarut wood	GX-29661-AMS	4780±60	−19.6	115
GhG4	Ghat	Tarut wood	GX-27376-AMS	4650±40	−21.8	60
Gh6E	Ghat	Tarut wood	GX-29660-AMS	4470±50	−18.5	80
GhA2S	Ghat	Tarut wood	GX-27033-AMS	4110±40	−20.5	640
Bk1A	Barkat	Tarut wood	GX-27935-AMS	3160±40	−21.3	67
GhA203	Ghat	Tarut wood	GX-29553-AMS	2960±30	−20.5	106
Gh6A	Ghat	Tarut wood	GX-29659-AMS	2610±40	−22.3	20
Gh5A	Ghat	Tarut wood	GX-27933-AMS	2420±30	−21.5	55
Gh5E1	Ghat	Tarut wood	GX-28979-AMS	1970±40	−22.2	43
Gh701	Ghat	Tarut wood	GX-27934-AMS	1920±30	−19.5	150
Gh701	Ghat	Tarut wood	GX-30600-AMS	1720±60	−19.1	385
Gh5C	Ghat	Tarut wood	GX-29658-AMS	1250±40	−20.9	9
Gh5D1	Ghat	Tarut wood	GX-28980-AMS	1030±40	−21.4	138
Gh701	Ghat	Tarut wood	GX-29578-AMS	1030±40	−19.0	615
GhD	Ghat	Tarut wood	GX-27034-AMS	1010±40	−20.4	30
GhC203	Ghat	Tarut wood	GX-29552-AMS	990±40	−19.5	10
Gh10A	Ghat	Tarut wood	GX-27936-AMS	970±40	−20.9	58
GhC203	Ghat	Tarut wood	GX-29579-AMS	640±50	−18.0	304
Gh5B	Ghat	Tarut wood	GX-29662-AMS	560±50	−18.8	95
BkO3	Barkat	Tarut wood	GX-29657-AMS	220±40	−19.2	81

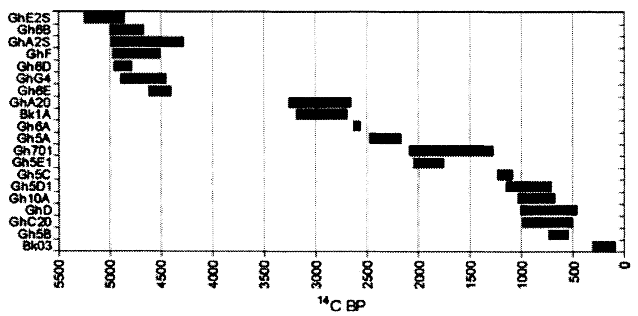

Figure 4 Chronological intervals covered by the studied samples. The length of the black bar gives an account of the extension of the one-sigma error term

part of the segment, the ring number is much lower than the number of years (see above).

(2) The second segment ranges between 3250 and 2660 ^{14}C BP. It is represented by only two samples, which are well synchronized.

(3) The third segment consists of two isolated samples (Gh6A, 2630–2570 ^{14}C BP; and Gh5A, 2470–2180 ^{14}C BP), which do not overlap and are chronologically positioned on the basis of the radiocarbon dating available for each.

(4) The fourth segment is based on the sample Gh701, which covers a rather long interval (2100–1290 ^{14}C BP). Synchronization with the only other sample available for this period (Gh5E1) is fairly good. Wiggle matching gives consistent results (Figure 6), all the dates falling precisely on the calibration curve, except for the date 1030±40

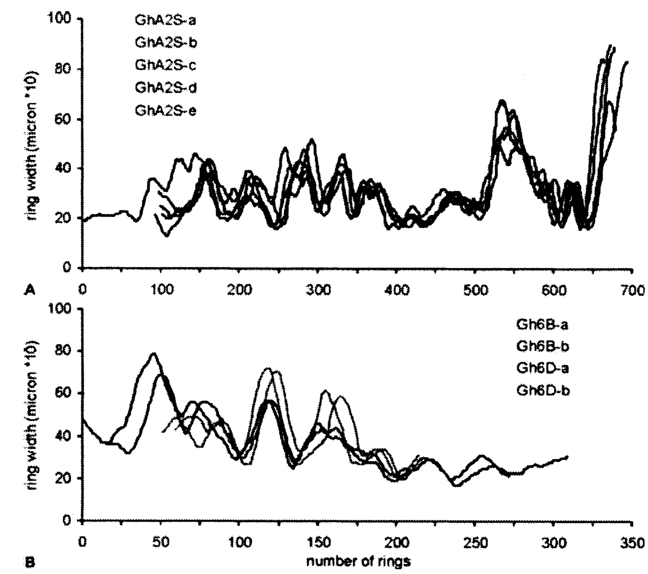

Figure 5 Example of synchronization on a decade base (21-yr moving average) between different measures on the sample, GhA2S (A), and between different samples, Gh6B and Gh6D (B)

^{14}C BP, which must be rejected owing to late impregnation of resin (see above).

(5) The portion of the curve ranging from 1230 to 460 ^{14}C BP is composed of six overlapping samples, dated with seven radiocarbon dates. The wiggle matching is quite successful (Figure 6), as all the seven dates fall on the calibration

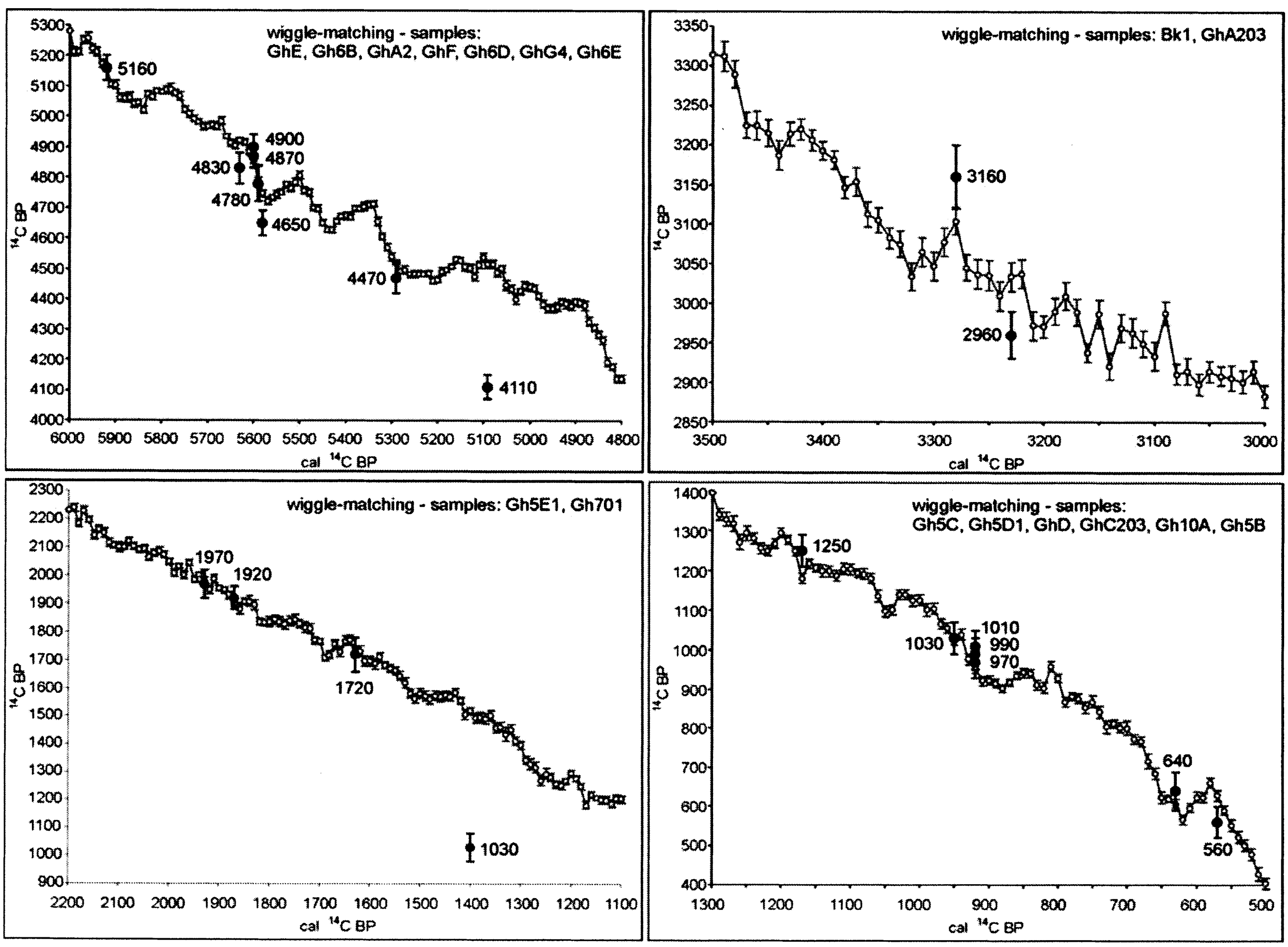

Figure 6 Wiggle matching of the studied samples, based upon the wiggle-matching option OXCAL, figures indicate the ^{14}C dates

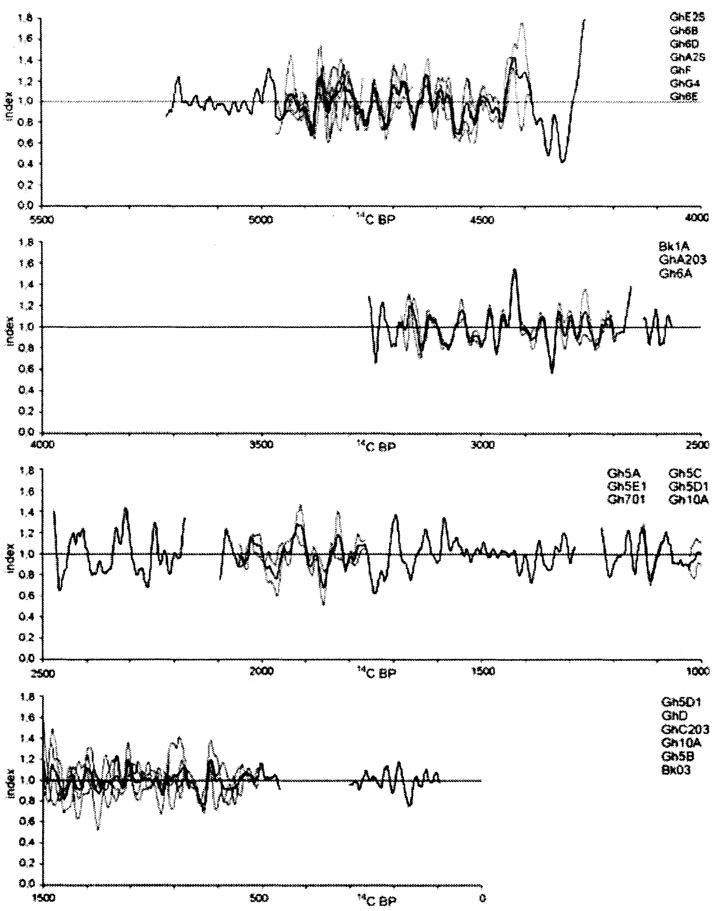

Figure 7 Uncalibrated tree ring chronology of *Cupressus dupreziana*. Solid line indicates the mean curve, dashed lines indicate individual samples

curve, indicating a consistency between the number of rings, the radiocarbon years and the chronological position of each curve. The synchronization of the curves is less effective than in the other segments. This fact may be attributed to difficulties in the physiological growth over the period.

(6) The last segment consisting of the sample BK03, the most recent, is dated by only one radiocarbon date, covering the period 300–100 ^{14}C BP.

On the basis of the radiocarbon dates and of the wiggle matching, a calibrated mean ring-width chronology has subsequently been achieved (Figure 8), based on the INTCAL98 calibration curve (Stuiver *et al.*, 1998).

The palaeoclimatic interpretation of the *Cupressus dupreziana* tree ring series

Cupressus dupreziana lives in a very harsh environment, and increasing aridity challenges its survival. It might be regarded as a sensitive tree (Fritts, 1976), living at the limit of its climatic tolerance. Its growth, as that of many trees of the arid and semi-arid area, is primarily determined by the availability of water. Therefore, the growth of rings mainly reflects this variable (Bradley, 1999), giving large regular rings in periods of a fair supply of water, narrow rings or discontinuous or missing rings in periods of drought.

The cypress trees have a flat-root system without tap-root, and therefore may exploit the water available in shallow layers of the substrate (Abdoun and Beddiaf, 2002), without reaching deep water-tables. Owing to the geological characteristics of the area, the upper limit of hydrologic reservoirs is expected to be much deeper than the reach of most trees. But the cypresses, as all conifers, also absorb water and nutrients through their foliage. Therefore, the only possible water supply for *Cupressus* is rainfall, of which the growth rings are to be regarded as a record. Wide rings indicate a greater supply of rain, and narrow rings scarce precipitation.

The changes in ring-width as recorded in the calibrated mean ring-width chronology (Figure 8) are as follows.

- The first segment from 5220 to 4260 ^{14}C BP (5990–5020 cal. BP) begins with a period of narrow rings (5200–5000 ^{14}C BP, 5900–5760 cal. BP), followed by high frequencies of alternating intervals of narrow/wide rings, with an important positive peak at 4425 ^{14}C BP (5200 cal. BP). This is followed by two periods of very narrow rings, at 4350 BP (5120 cal. BP) and 4310 BP (5090 cal. BP). However, the radiocarbon dating of the second period is 4110±40 ^{14}C BP (4650–4530 cal. BP, 46.2% probability) (sample GHA2S ring 640), which is 200 radiocarbon years younger than the date inferred from the relative position of the period in the ring-width curve, indicating a loss of at least 200 rings. The missing rings can be related to a very dry period during which the absence of water hindered tree development.

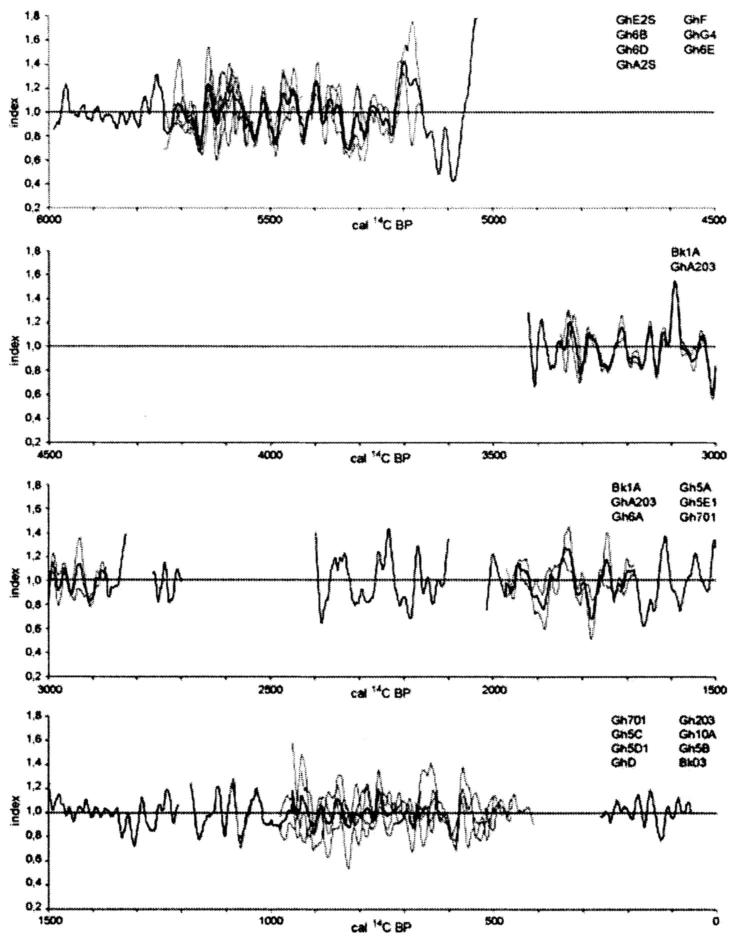

Figure 8 Calibrated tree ring chronology of *Cupressus dupreziana*. Solid line indicates the mean curve; dashed lines indicate individual samples

- The second and third segments range from 3250 to 2180 ^{14}C BP (3420–2100 cal. BP). They consist of moderately wide rings (with peaks at 2920, 2400 and 2300 ^{14}C BP; 3100, 2350, 2220 cal. ^{14}C BP), alternating with moderately narrow rings, with a frequency of about 50 years.
- The first part of the fourth segment, from 2100 to 1550 ^{14}C BP (2040–1500 cal. BP) is quite similar in periodicity and amplitude to the previous section. There are peaks of wide rings at 1910, 1810 (maxima) and 1680 ^{14}C BP (1850, 1760 and 1620 cal. BP). After 1550 ^{14}C BP (1500 cal. BP), to the end of the segment at 1290 ^{14}C BP (1200 cal. ^{14}C BP), there is a general reduction in ring width, an increase of frequencies and a greater development of narrow-ring peaks.
- The fifth segment ranges from 1230 to 460 ^{14}C BP (1190–415 cal. BP) and is followed by the most recent isolated sample; the sixth segment, ranging from 300 to 100-^{14}C BP (270–65 cal. BP). From the beginning of this segment up to 460 ^{14}C BP (410 cal. BP), there is an alternation between moderately-wide and narrow rings, after which the tree rings are, in general, narrower, with minima at 620 and 170 ^{14}C BP (595 and 130 cal. ^{14}C BP).

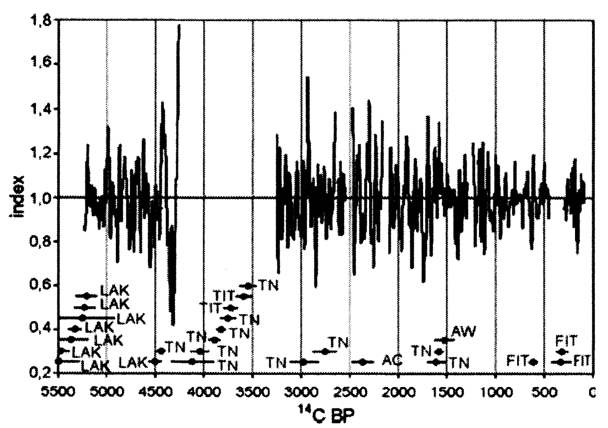

Figure 9 Uncalibrated tree ring chronology of *Cupressus dupreziana* compared with radiocarbon dates available for the late Holocene of the Wadi Tanezzuft and connected ergs (see Table 2)

If we move to the interpretation of the ring size as a measure of water availability, we can envisage a fairly dry period from 5220 to 5000 ^{14}C BP (5990–5770 cal. BP), followed a short wet period, interrupted by a very dry spell beginning at 4350 ^{14}C BP (5120 cal. BP) and probably lasting till 4110 ^{14}C BP (4650–4530 cal. BP 46.2% probability). From 3250 on up to 1550 ^{14}C BP (3520–1500 cal. BP), briefly alternating periods of wide and narrow rings may indicate recurrent rainy periods. At 1550 ^{14}C BP (1500 cal. BP), the pattern of the curve changes: prevailing narrow rings may indicate the onset of dry conditions. The difficulty in the synchronization of the curves in the interval 1050 and 500 ^{14}C BP (1000–460 cal. BP) may be explained by irregular growth consistent with unfavourable dry climate.

Table 2 Radiocarbon dating available for the late Holocene of the Wadi Tanezzuft and connected ergs (see Figure 9).

Site Number	Geochron laboratory code	Conventional age ^{14}C yr BP (^{13}C corrected)	$\delta^{13}C‰_{PDB}$	Sample type
Duna2-1	GX-27686	320±60	−23.4	FIT
96/267(3)	GX-24057	330±100	−24.3	FIT
96/267(6)	GX-24058-LS	615±45	−23.8	FIT
TZ36	GX-27930	1530±100	−24.4	AW
ANFo	GX-27920-AMS	1580±40	−24.5	TN
ANC	GX-27029	1610±90	−25.5	TN
94/106(c)	GX-20710	2375±110	−22.5	AC
96/271 (2)	GX-24056	2755±125	−23.6	TN
96−149	GX-24060	2970±150	−24.9	TN
96/149	GX-25003	3545±85	−24.9	TN
96/164	GX-24061	3590±80	−22.2	TIT
96/164	GX-25001-LS	3720±80	−22.8	TIT
96/111	GX-24059	3750±80	−23.8	TN
TZ 01/159	GX-27926-AMS	3820±40	−24.8	TN
TA2	GX-20011-AMS	3890±60	−25.3	TN
96/428/4	GX-24998	4040±100	−24.6	TN
96/268	GX-24062	4120±220	−25.8	TN
TDS-Tahala	GX-27030-AMS	4440±40	−21.7	TN
GAFP147	GX-27922	4500±70	−21.4	LAK
96/427 B	GX-24996	5200±110	−23.5	LAK
97/181(2)	GX-25008	5230±110	−12.9	LAK
99/191−2	GX-26262-HA	5250±330	−20.6	LAK
TH103	GX-19116-AMS	5323±70	−12.4	LAK
96/107	GX-24055	5370±180	−25.7	LAK
99/177−2	GX-26258-HA	5470±90	−17.3	LAK
96/107	GX-25000	5490±210	−25.9	LAK

Matching with local geological proxies

In order to check the significance of *Cupressus dupreziana* for climate, the tree-ring chronology is compared with the radiocarbon dates of geological proxies indicative of water availability, or the lack thereof, from the basin of Wadi Tanezzuft and from the ergs of Tanezzuft, Uan Kasa and Murzuq (Figure 9).

The radiocarbon dates listed in Table 2 are coded as follows:

- LAK. These dates were obtained from deposits of water bodies in the sand seas of Murzuq, Uan Kasa, Titersine and Tanezzuft. In the interdune corridors, lakes were formed by the rising water-table, fed by heavy rain input, during the wet Holocene since 8500 ^{14}C BP (Cremaschi, 1998, 2002). There is no evidence of sedimentation in most interdune lakes later than 5000 ^{14}C BP, with the exception of a few cases in the Murzuq area. The date AC refers to an Acacia root breaking the gypsum crust at the top of lacustrine deposits, and therefore to a phase of rising water-table (Cremaschi, 2003).
- TN. Fluvial activity in the wadi Tanezzuft is recorded also after the drying of interdune lakes occurring at about 5000 ^{14}C BP (Cremaschi, 2002). The radiocarbon dates were obtained from charcoal collected in archaeological sites, where they were buried in alluvial sequences. The dates indicate sustained run-off inside the valley of the Tanezzuft, and therefore the availability of water in its catchment basin where the cypress grows.
- TIT. These dates refer to the organic lenses in a gypsum crust at the fringe of wadi Tanezzuft. They indicate the late availability of water from a spring at the base of the adjoining erg. AW is a radiocarbon date on a buried hydromorphic soil. It indicates a greater availability of water and wider extent of the Awaynat oasis (Figure 1), at the north of the Acacus massive, close to the Tanezzuft valley (Cremaschi, 2003).
- FIT. These radiocarbon dates were obtained from two phytogenic dunes of *Tamarix*, developed on top of the late Holocene channel deposits of the wadi Tanezzuft in its distal part. As *Tamarix* is typical of desert conditions, the dates obtained from it are to be regarded as a minimum age of the onset of full desert conditions on the alluvial plain of the wadi Tanezzuft.

Comparing these dates with the uncalibrated tree-ring chronology of *Cupressus*, we observe (Figure 9) that the oldest samples of *Cupressus dupreziana* wood date back to the time when most of the lakes of the ergs were drying, and the lakes appear to dry out in correspondence with the dry period located at the beginning of the curve (5220–5000 ^{14}C BP; 5990–5770 cal. BP).

Many dates related to fluvial activity in the wadi Tanezzuft, and thus indicative of wet conditions, fall in the chronological interval 4260–3250 ^{14}C BP (5990–3520 cal. BP), which is coincident with the long gap of the *Cupressus* chronology. Further dates indicating water availability in the wadi Tanezzuft valley and surroundings fit fairly well with the intervals of wide rings of 4380–4450 ^{14}C BP (5150–5210 cal. BP) and 3000–1500 ^{14}C BP (3260–1440 cal. BP) and further suggest such rings correspond to wet periods. On the other hand, the two dates of the *Tamarix* in phytogenic dunes, indicating desert conditions in wadi Tanezzuft, fall within a period of narrow rings.

Concluding remarks

Cupressus dupreziana represents a prime source of palaeoclimatic information, still to be fully explored, for the middle and

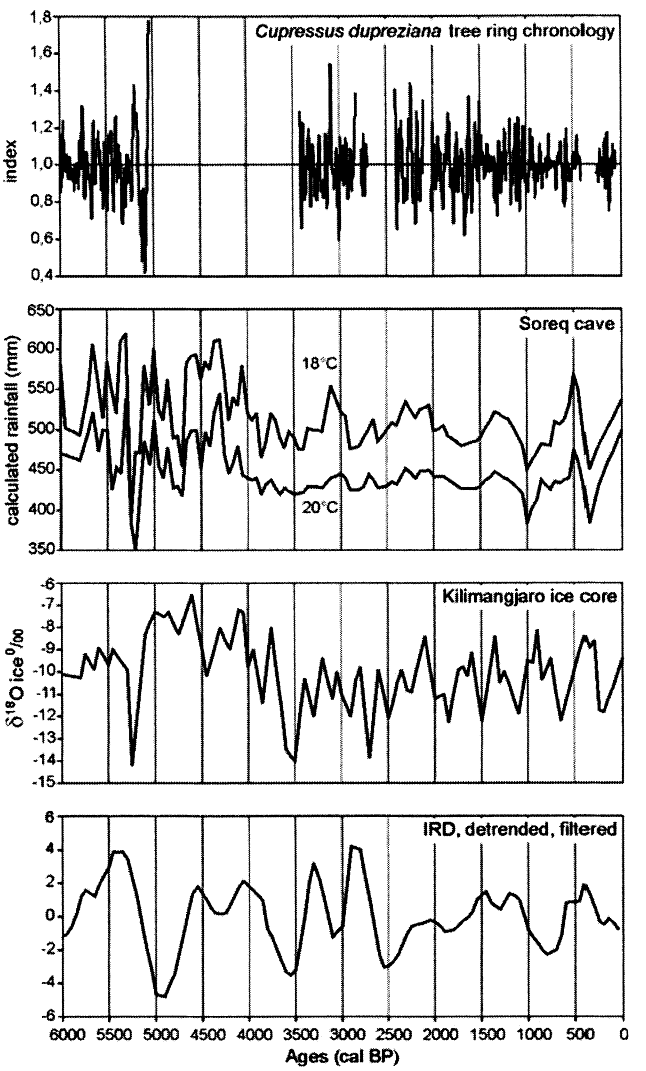

Figure 10 Calibrated tree ring chronology of *Cupressus dupreziana* compared with the isotopic records of the Kilimanjaro ice cores and of the record from the speleothems from the Soreq Cave and from the IRD of the north Atlantic. Notice the good superposition of the event at about 5000 cal. BP

late Holocene of the central Sahara. At the present state of research, however, it provides reliable data to understand the climatic and environmental changes of the last six millennia, and fills an almost complete gap of geologic proxies for the palaeoclimatic reconstruction of the last four millennia.

Pollen of Cupressaceae is recorded in the area neighbouring the Tassili throughout the wet Holocene at 8000 ^{14}C BP in Uan Afuda and Uan Tabu rockshelters, in the Acacus (Mercuri, 1999; Mercuri and Trevisan Grandi, 2001), and at 6800 ^{14}C BP in the Mathendush cave in the Messak Sattafet (Cremaschi, 1998). As no other Cupressaceae is known in the area, it is quite probable that this pollen be attributable to *Cupressus dupreziana* (Mercuri and Trevisan Grandi, 2001). This means that the cypress may have existed throughout the wet Holocene, but its wood, lost for that period, has been preserved only since the beginning of the dry Holocene.

Wood samples are also absent in the interval from 4260 to 3250 ^{14}C BP (5020-3520 cal. ^{14}C BP). This interval, being contemporary with relevant water availability in the wadi Tanezzuft, could coincide at least in part to a wet period. The preservation of *Cupressus* wood therefore appears to have required dry conditions. The wood of wet periods (wide rings, large cells, less resinous) may have been less durable, while the wood formed during dry periods, (resinous, more compact, hard) is almost imperishable. Radiocarbon dates suggest that in several periods of the last 5000 years, *Cupressus dupreziana* enjoyed almost regular growth and annual tree rings.

Synchronization of the single samples (on an annual basis) was not possible for the interval of almost regular growth, because of the occurrence of false and missing rings. This problem depends on the type of samples used–narrow sections of the trunks, conceptually similar to cores–and may be solved when whole sections of the trunk are studied. However, periods of accentuated growth irregularities (discontinuous, false and missing rings) are of the utmost interest as they correspond to stress periods, mainly determined by very arid climate.

The mean ring-width chronology plotted on a small scale (Figure 10) quite clearly summarizes the climatic changes in the middle–late Holocene for the central Sahara as recorded by *Cupressus dupreziana*. A dry period at the beginning of the dendroclimatic sequence (5220–5000 ^{14}C BP; 5990–5770 cal. BP) is followed by a very dry spell beginning at 4350 ^{14}C BP (5120 cal. BP) and probably lasting until 4110 ^{14}C BP (4650–4530 cal. BP, 46.2% probability). Notwithstanding the slight uncertainty in dating, owing to the fact the *Cupressus* radiocarbon-based chronology is still fluctuating, this episode may reasonably be correlated with the abrupt termination of the African humid period, as recorded in the lakes of the monsoon-dominated areas of Africa (Gasse, 2002), in the core extracted off Cap Blanc, Mauritania (de Monecal *et al.*, 2000), and in the ice cores from the Kilimanjaro glaciers (Gasse, 2002; Thompson *et al.*, 2002). This episode is recorded widely in the Northern Hemisphere, as seen in the speleothems of the Soreq cave in Israel in the southeast Mediterranean area (Bar-Matthews *et al.*, 1998), coinciding with a major warm interval in the North Atlantic, as seen in the minimum ice rafted debris (IRD) of deep-sea sediment cores (Bond *et al.* 2001) (Figure 10). This evidence further supports the idea that the African monsoon climate system is linked to the high-latitude climate driven by the deep ocean thermohaline circulation (de Monecal *et al.*, 2000).

The lack of information from 4260 to 3250 ^{14}C BP (5020–3520 cal. BP) is interpreted as coinciding, at least in part, with a wet phase that is also recorded, for instance, in lake Bosumtwi in central Africa (Maley, 1994). The coincidence between periods of water availability (indicated by geological proxies) and wide rings reinforces the idea that wide rings indicate periods of greater availability of water. After 3250 ^{14}C BP (3520 cal. BP) accentuated wet periods alternated with short dry phases. The former end at 1550 ^{14}C BP (1500 cal. BP) when narrow rings mostly dominate, indicating the onset of very dry conditions, that have lasted to the present. The latter part of the *Cupressus* mean chronology has little relation to other records. While a general similarity exists (most of the main oscillations are in phase), the drop in precipitation indicated by the *Cupressus* rings for the last 1500 years does not appear in the Kilimanjaro and Soreq records.

Observed as a whole, the *Cupressus dupreziana* record, mainly after 5100 cal. BP, shows a progressive decrease in ring width, indicating that environmental conditions were gradually trending toward a dry climate. However, this change is not linear, being modulated in quasi-centennial scale fluctuations, and it fits with a simulation model recently proposed for the Holocene climate evolution in North Africa (Renssen *et al.*, 2006).

A most relevant piece of information provided by the *Cupressus dupreziana* record is that after the dramatic event of 5000 years ago, the development of the oasis was accompanied by wet periods that supplied the local water-tables, deferring, for some time, incoming desertification. Dry conditions accelerated at 1550 ^{14}C BP (1500 cal. BP) and, as a consequence, the oases of the wadi Tanezzuft contracted to their present state (Cremaschi, 2003). It is worth remembering that the climatic trend, as inferred from the cypress record, is linked to societal dynamics, as it accompanied the concentration of the late pastoral communities into spreading oases (Cremaschi and di Lernia, 2001), the rise of the Garamantian state (Liverani, 2003), and its collapse coinciding with the final drying of the area.

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