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Palaeoclimates of Central Sahara during the early Holocene

J. Maley

Laboratoire de Palynologie, USTL, 34060 Montpellier, France.

In the Central Sahara lying approximately between 27°N and 18°N, rains were primarily due to tropical depressions in the early Holocene up to about 6500 BP. *Then the monsoon rains of Sahelian type dominated up to about 4400* BP.

POLLEN analysis was carried out on Holocene lacustrine deposits[1] sampled every 10–20 or 30 cm in a section of about 7.80 m at Tjéri (13°44′N–16°30′E) near the centre of the great Palaeochad[2,3] (Fig. 1). Chronology of the Tjéri section was established by two radiocarbon dates on organic material near the base (Fig. 2) and, for some other levels, by correlations with notable events radiocarbon dated elsewhere in the zone of the Palaeochad[1–3]. The chronology established in the Nile valley (see below) and elsewhere in the southern part of the Sahara gives some valuable correlations[1]. Approximate dating of the intermediate levels was established by rates of sedimentation. About 60 yr elapsed for each 10 cm from 9000 to around 7000 BP and about 220 yr from then till about 4000 BP. The change in rates of sedimentation at about 7000 BP could parallel the important change in conditions noted for the Blue Nile at about 7000 BP (ref. 4).

In the dry tropical zone where the Chad basin is situated, the rainfall and its distribution through the year are the most important climatic factors controlling the vegetation and its spatial distribution. Thus there is a direct relationship between vegetation and climatic pattern. In the Chad basin the regular succession of climatic and vegetation zones is a favourable factor for pollen analysis[5]. On the Tjéri section 46 samples were studied and for each about 1,000 to 6,000 pollen grains were counted. The Gramineae, Cyperaceae and *Typha* pollen grains represent about 80 to 90% of each total. Therefore those 3 taxa have been eliminated from the pollen sum and studied apart in order not to distort the percentages of all other pollen grains more typical. Those pollen grains were classified according to the present geographic distribution of the taxa to which they belong and the most typical were placed in four phytogeographical elements covering the four major vegetation zones of the Chad basin, that is, (from S to N) Sudano–guinean element (plants typically growing under 1,500 to 1,000 mm rain per annum), Sudanian element (1,000 to 500 mm), Sahelian element (500 to 100 mm), Montane (Tibesti) element (plants growing at the nearest on the upper Tibesti Plateaux) and also in a group of hygrophilous plants[5]. The relative percentages of the pollen grains for these four elements were used to construct curves which portray the climatic variations occurring in the four zones of the Chad basin[1].

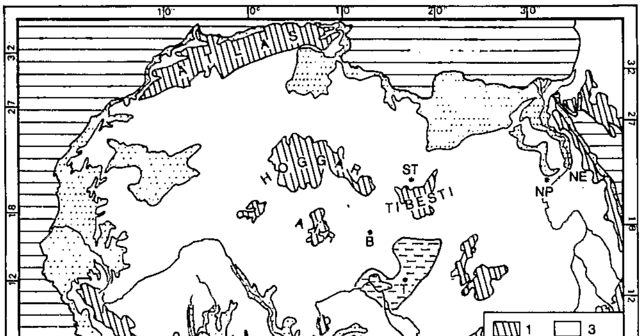

Fig. 1 North Africa. 1, Mountains over 1,000 m. 2, Regions under 200 m. 3, Regions between 1,000 m and 200 m. 4, Holocene Palaeochad, 320 m high. T, Tjéri. B, Bilma. ST, Sérir Tibesti. NP, Nabta Playa. NE, Egyptian Nubia.

Palaeoclimatic pattern of the Sahelian zone

Comparison of the Sudano–Guinean element and Sahelian element curves showed that the periods of climatic optima (relatively wetter phases) are in general out of phase with each other[1] (Fig. 2). It seems also that during the Holocene, the Sahelian climatic optima have always been synchronous with the warming periods, and the deteriorations with the coolings. Indeed the trends of the Sahelian curve at Tjéri—the amplitudes of variations being different—correlate well with the trends which appear on some curves portraying the evolution of the temperature on the Northern Hemisphere, such as that of Camp Century in Greenland[6,7]. For the most part of the Holocene, it seems that the Camp Century curve is quite well dated: first, the counting of annual layers was possible with some correction until 8300 BP (ref. 7); second, for the Holocene this curve has good cross-checkings with various eustatic curves[8–10], with the fluctuations in the atmospheric radiocarbon level[11,12], with glacier fluctuations in the Alps[13], and so on. Comparison of the Sahelian curve with that of Camp Century shows that the lowering periods of the Sahelian curve, which correspond to aridification periods in the Sahel zone, correspond also to cooling periods, and vice versa[1]. Study of diatoms[2,14] and pollen in the same samples provides a direct and important corroboration of this phenomenon. Indeed, from about 8000 up to about 4000 BP, the high percentages of a psychrophile ('cold') diatom *Cymatopleura elliptica* or of a diatom of temperate type *Cyclotella ocellata* occur during the phases of relative lowering or minima of the Sahelian element (Fig. 2). Considering these different correlations, one can also use the curve of Camp Century as a basis for an explanation of the Montane element.

M
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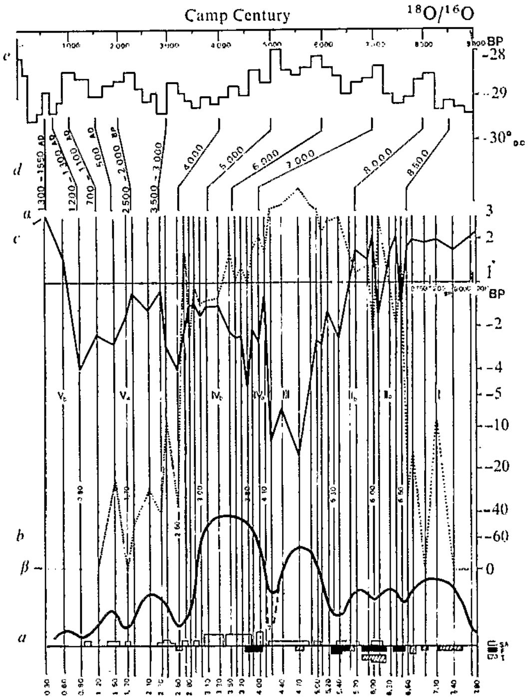

Fig. 2 Comparative evolution for the Tjéri station, from base to top, *a*, Relative lacustrine levels, after diatom studies[2,14]. The ? at 4.20 m is the author's interpretation[1] and a brief regression at 3.80 m (around 6600 BP) is also probable. Some diatoms of ecological importance: SA, *Stephanodiscus astrea var. minutula*; F, *Cymatopleura elliptica*; T, *Cyclotella ocellata* (relative scale). *b*, Dotted lines, pollen curve for the Sudano–Guinean element (relative %, mean: 20,2%). β, Present time % (two samples). *c*, Solid line, pollen curve for the Sahelian element (relative %, mean: 33,9%). α, Present time % (two samples). These two curves (*b*, *c*) were constructed using the ratio with the mean (value of 1) carried out on the whole of the levels studied (log scales). On this scale, the value of zero was arbitrarily fixed at −100. *d*, Chronology reconstituted after various regional correlations. Near the base, two radiocarbon dates: at 7.75 m, 9000±200 BP; at 7 m, 8750±200 BP. The dates are given in BP except for the last two milennia in AD (calendar years from ref. 12). *e*, Schematic curve of the $^{18}O/^{16}O$ ratio for the ice core at Camp Century (Greenland) adapted from M. Ters (ref. 10); from 9000 to 1700 BP after ref. 7 and from 1700 BP to the present after ref. 6. Figure reproduced from ref. 1 with kind permission.

The Montane (Tibesti) element

Pollen spectra of Tjéri also showed small percentages (average 3.1 %) of very characteristic taxa originating from more northern regions (*Artemisia* sp., *Pentzia monodiana*, *Erica arborea*, *Ephedra* sp., *Plantago* sp., *Silene* sp.). When many pollen grains are counted on successive samples of the same section, the variation of very low percentages can be used with some confidence—as, for instance, in a pollen study of the west part of the Sahara[15]. The pollen grains assigned to the Montane element must surely have been brought to Tjéri by the prevailing wind, that is, the harmattan, blowing from about NE or N. The water transport of pollen grains across the whole actual lake Chad is very limited[5] and probably was so for the Palaeochad, particularly for pollen grains coming from the Tibesti, because the nearest fluviatile source was about 450 km from the station studied. For these pollen grains, the nearest sources at present are some 700 km to the north on the High Plateaux of the Tibesti[16]. Further north, other important sources of *Artemisia*, for instance, are found only on the narrow Mediterranean zone of Libya, about 2,000 km from Tjéri. But the latter sources seem unlikely to be involved, because other pollen types present in the Mediterranean zone of Libya, such as Cupressaceae or *Quercus*—very easily carried in the atmosphere[17]—would have been found at Tjéri. In conclusion, the pollen grains of the Montane element originate most probably from the Tibesti.

Comparison of the early Holocene pollen curves for the Sahelian and Montane elements shows (Fig. 3) a rough synchroneity in terms of thousands of years and a good synchroneity for the main aridity maxima. This second point shows that the percentage variability of the Montane element is not governed by variations in intensity of the harmattan, as the aridity maxima coincide with maxima of eolian activity. On the other hand, thanks to the chronology established at Tjéri, it seems that the different pollen maxima of the Montane element show good correlations with the different geological and palaeoecological events radiocarbon dated in the Tibesti (Fig. 2, Table 1). These correlations also increase the reliability of the pollen curve.

The Middle Terrace

In the Tibesti, the early Holocene coincides with the end of the accumulation of the so-called 'Middle Terrace' (MT)[18–23] (Fig. 2). A radiocarbon dating in the lower part of the MT gave a date of 14055±135 BP (ref. 20). It is possible that the base of the MT in the Tibesti began about 17500 BP like the base of the equivalent formation in Nubia (Malki Member of Ineiba Formation)[24,25]. In general, throughout all the Tibesti, the stratigraphic and sedimentological evolution of the MT, especially the upper part, is constant[18]. Some sections with radiocarbon dates facilitate the precise dating of the occurrence of the principal events intervening during the accumulation of the upper part of the MT. For the phases A, B, C, in some craters or depressions throughout the massif, there are lacustrine deposits chronologically equivalent[18,19,26]. The accumulation of the MT occurred in several phases separated by calcareous crusts, the most recent of which were principally formed about 9200–9300 and 7600–7300 BP (D phase)[20–22]. By correla-

Table 1 Early Holocene events and correlations between Tibesti, Nabta Playa and Egyptian Nubia

Phases	Dates (approximate, in BP)	Tibesti	Nabta Playa (30°40′E–22°25′N) (from ref. 28)	Egyptian Nubia (from ref. 24)
H	4000–2000	Lower Gravel Terrace		
G	5500–4000	Erosion	Erosion (undated)	Erosion
F	6400–5500	Sahelian optimum		Shaturma Formation (Member I)
	~6400 Change of Climatic Régime			
E	7200–6500	Optimum: Palaeosol	Neolithic (II) 6450–7150 BP (6 dates)	Palaeosol (Omda Soil)
D	7700–7200	Erosion Aridity	Erosion	Erosion; (?) locally eolian activity, (Seiyala)
C	8100–7700	Optimum	Neolithic (I) 7850–8150 BP (10 dates)	
	8250–8100	Aridity	Erosion	Fluviatile Terrace, Sinqari Member (upper part Ineiba Formation) 10200–8000 BP
B	8400–8250	Optimum	(?)Terminal Palaeolithic (II)	
	8550–8400	Aridity	Erosion	
A	9000–8550	Optimum	Terminal Palaeolithic (I) (partly with A;2 dates:8580±80 and 9360±70 BP)	
	(?) 9300–9000	Aridity		

Note that in other places the Neolithic begins in 8065±100 (Tibesti), 8072±100 (Acacus), 8100±130 (Tassili), 8100±130 BP (Hoggar)[53].

tion with the Montane element curve, it seems that the last calcareous crust formation corresponds to an arid period (see below). At the end of the D phase, a small erosion occurred before sedimentation started again. This discontinuity is a very characteristic feature. The last phase of bedded deposits (E), sometimes with coarse material, exhibits in some places, before the beginning of phase F, a thin brown palaeosol rich in organic matter[23,26], which was dated 6600±140 BP at Mouskorbé (Gif n°3228). In Nubia, a palaeosol with kaolinite (Omda soil) was described and situated approximately at 7000 BP (ref. 24).

At the top of the MT, phase F represents a very clear sedimentological change, that is, a dramatic increasing amount of pebbles and cobbles. This phenomenon, which had started after 6600 BP, is general across the Tibesti and the Central Sahara at the top of formations equivalent to the MT. This sudden influx of pebbles is surely related to a change in climatic regime. Then the erosion of the MT (phase G) to below the actual level of the rivers could occur between about 5500 and 4000 BP. In the Tibesti, during the following H phase approximately dated 4000–2000 BP, a Lower Gravel Terrace was deposited[18,19].

The upper part of the MT with its main characteristics or some equivalent lacustrine deposits, can be found in many regions of the Central Sahara—for the MT, in the Hoggar[18,27], in Central Aïr[3] and in Egyptian Nubia (Sinqari Member, upper part of Ineiba Formation and Shaturma Formation, Member I)[24] (Table 1). For the lacustrine deposits, the depression of Nabta Playa[28] (altitude about 300 m) about 100 km west of Abu Simbel, exhibits a stratigraphic succession and lacustrine phases with prehistoric occupation sites closely correlated with the events of the Tibesti (Table 1). The Terminal Palaeolithic II (or Epipalaeolithic), though without radiocarbon date, corresponds most probably to the climatic optimum B of the Tibesti (about 8400–8250 BP). On the other hand, near Bilma in the Ténéré (18°40′N–13°E; altitude about 360 m) the early Holocene lacustrine deposits[3] can be correlated with phases A, B, C of the Tibesti (Fig. 3). In Adrar Bous (20°18′N–9°E; altitude about 700 m) early Holocene lacustrine deposits are radiocarbon dated before 7310±120 BP (refs 29, 30). In the middle of Serir Tibesti (23°30′N–17°20′E; altitude about 500 m) lacustrine deposits about 10 m thick are dated of the early Holocene[31]. Thus all these correlations suggest that during the early Holocene the climatic conditions were similar and apparently synchronous throughout all the Central Sahara. Therefore, the local factors seem to have had but a limited action.

One typical section of the MT for the early Holocene was chosen in order to show the correlations with the evolution of the Montane element of Tjéri (Fig. 3). This section was taken by J. Grunert[23] near Yebbi-Bou (20°53′N–18°4′E; altitude about 1,440 m) on the north side of the Tibesti. A radiocarbon-dating on shells at about 2.5 m (8180±70 BP) locates this section in the chronological framework of the Tibesti and the Central Sahara.

Palaeoclimatic interpretation

To try to understand the palaeoclimates of the Tibesti in the early Holocene we can compare the pollen curves for the Montane and Sahelian elements (Fig. 3*c*, *d*). The system of representation (the ratio with the mean) facilitates direct comparison for the two curves (see other examples in refs 5, 17). Thus, from one sample to the next we can see completely opposite trends, or similar trends but of very different amplitude. Although in the scale of thousands of years there is a rough synchroneity between the curves for these two elements, the opposite trends shown up by detailed analysis imply that the rains were of different origins in the Sahel zone and the Tibesti.

For palaeoclimatological interpretations it is necessary to use as climatic models meteorological situations and climatic patterns of the present time. For instance, in Aegean regions, the climatic pattern of one winter was used to explain that of the period around 1200 BC (ref. 32); or seasonal change through the year was used to explain some aspects of the past climatic changes[33]. Here the present evolution of the Saharian climate through the year is used in an attempt to establish the climatic pattern of this region in the early Holocene.

Climatic model for the present time

At present nearly all the rains falling in the Sahel zone are monsoonal in origin. In summer (July–August) these rains reach the Hoggar and Tibesti mountains[34–36]. But, over the Central Sahara the heaviest rains fall chiefly during the intermediate seasons of spring (March–June) and autumn (September–December)[35,37,38]. The study of the cloud formations over the Sahara also confirms the importance of the intermediate seasons[39]. The rains of interseasons are linked with the tropical depressions[34,40–43] also called Sudano–Saharian depressions[35] or 'Khamsin' depressions in Eastern Sahara[44,45]. Rains of this type are often fine and continuous[46], whereas the monsoon rains are stormy. At present these depressions occur rarely in winter except in Western Sahara (Senegal, Mauritania: 'Heug' rains[34,35]). On the other hand, these depressions are absent in the height of summer when the ITCZ reaches the Sahara. Schematically the synoptic situations are as follows[41–46]: (1) influx of polar air in the middle or upper troposphere above the Sahara along shallow troughs in the upper westerlies and (2), frequently, ahead of these cold troughs, undulations occur in the ITCZ with brief invasions of humid equatorial air. The undulations of the ITCZ could be due to the action of boreal cold troughs or to surges of monsoon caused by perturbations travelling in the Southern Hemisphere[36]. The depressions created by the cold air aloft favour the advection of the equatorial humid air. In this part of the year the movements of these depressions are northeastwards or eastwards[35]. The advection of humid equatorial air is essential for the formation of rain from these depressions. At present in winter, the scarcity of these depressions over the Sahara, except the western part with 'Heug' rains, can be explained by the fact that at this time of the year the ITCZ is situated at very low latitudes. But when there is interaction between cold troughs and the ITCZ, the trajectory of depressions remains chiefly over the Sudan and Sahel zones[34–36].

A study of all rainfall data available since the beginning of the century for Africa north of the equator was carried out[47]. It showed, by the method of spatial correlation of annual rainfalls, that in some years there is a clear opposition between the Sahel and Central Saharian zones. Either the Central Sahara gets heavy rains and the Sahel low or average rainfall, or vice versa. The phenomenon is less clear for Eastern Sahara, due to the lack of sufficient data and to the probability that the trend for the whole Central Sahara is only apparent for longer periods. Thus, for instance, only anomalies over 30 yr have a similar trend through the Mediterranean area[48]. Nevertheless, this climatic opposition is genuine because it had an effect on the distribution, and perhaps the evolution, of some taxa. To give an example, two Gramineae, with close taxonomic affinities, *Aristida meccana* and *A. mutabilis*, have geographic distributions which exhibit the same pattern. The first one has an area restricted to the Central Sahara, the second a Sahelian area with some stations in the Central Sahara in zones exposed to the monsoon[49]. I consider that this opposition Sahel–Central Sahara, can only be explained by the hypothesis of different origins for the rains, that is, the direct monsoon and the tropical depressions. Thus this opposition must no doubt be comparable with that which existed over longer periods in the early Holocene.

Application of the present model in the early Holocene

The dominance of tropical depressions over the Tibesti seems to be proved, especially between around 8000 and 6500 BP,

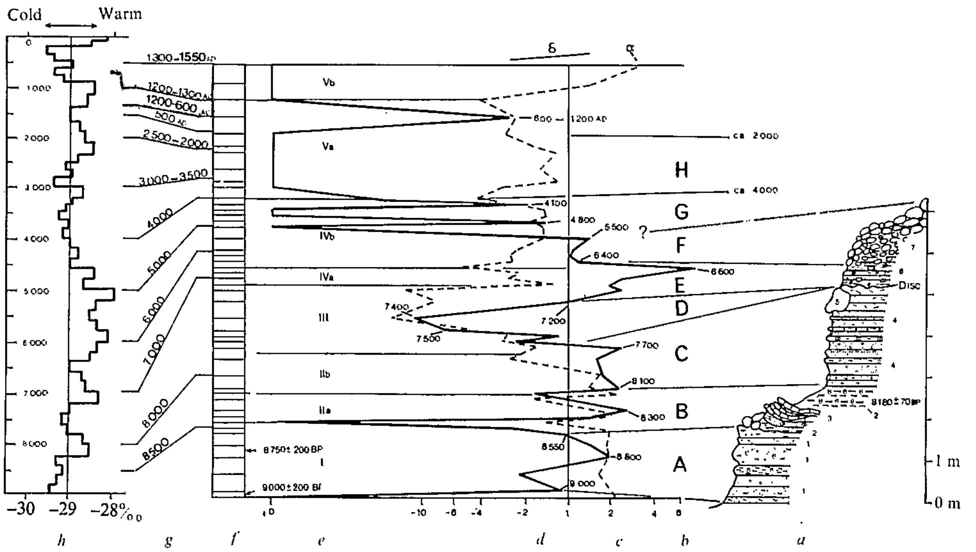

Fig. 3 Comparative evolution of the MT in the Tibesti, of the pollen curves for the Montane and Sahelian elements and of the $^{18}O/^{16}O$ ratio at Camp Century. *a*, 'Middle Terrace' (MT), section near Yebbi-Bou, after J. Grunert (23,pr.20). 1, Indurated layers with coarse sands, bedded towards the base and becoming silty towards the top. 2, Compact silts with shells. Radiocarbon date of 8180±70 BP near 2.50 m. 3, Compact indurated silt layer. 4, Alternating layers of indurated coarse sands and looser silts. 5, Boulder of calcareous tufa. Discontinuity. 6, Finely bedded layers of sand, gravels and some pebbles. 7, Conglomerate of pebbles and cobbles. *b*, Subdivisions of the MT and of the pollen curve for the Montane element of the Tibesti. *c*, Solid line, Tjéri section, pollen curve for the Montane element of the Tibesti (relative %, mean: 3.1 %). δ, Present time % at Tjéri (two samples). *d*, Dotted line, Tjéri section, pollen curve for the Sahelian element (relative %, mean: 33,9%. α, Present time % at Tjéri (two samples). For the construction of curves *c*, *d* see Fig. 2. *e*, Subdivisions of the pollen curve for the Sahelian element (ref. 1 and Fig. 2). *f*, Positions of the samples and two radiocarbon-dates near the base (see Fig. 2). *g*, Chronological correlations between the $^{18}O/^{16}O$ curve and Tjéri samples (see Fig. 2, *d*). *h*, See Fig. 2*e*.

by the fact that the fluctuations of the curve for the Montane element approximately follow those of the present tropical depressions over the Sahara through the period of 1 yr (refs 37, 38, 45), when in the Northern Hemisphere temperatures are rising (spring) or falling (autumn). When temperatures are at their lowest (winter) these depressions are infrequent and when at their highest (summer) they do not occur. Between 8000 and 6600 BP the following correlations appear between the trends of temperatures on the Northern Hemisphere ($^{18}O/^{16}O$ curve at Camp Century[6,7], see above) and those of the curve for the Montane element (Fig. 3 *h*, *c*).

At around 8000–7700 BP—temperature is falling (autumn climatic model)—the Montane curve is at a maximum. At 7500–7400 BP—temperature and Montane curve are at a minimum (winter climatic model). At 7400–7100 BP—temperature is rising (spring climatic model)—there is a strong positive trend in the Montane curve. At 7100–7000 BP—temperature reaches a maximum (summer climatic model)—there is a slight drop in the Montane curve. At the same time a brief optimum occurs for the Sahelian element[1]. At 7000–6600 BP—temperature is falling (autumn climatic model)—there is a strong positive trend in the Montane element curve.

Possibly this type of correlation existed before 8000 BP, but the data available are not sufficient to allow us to demonstrate it. A consequence of this climatic pattern is that the climatic optima in the Tibesti lasted longer than those in the Sahelian zone, as is clearly evident between 8000 and 7000 BP (Fig. 3*c*,*d*). For the optima of the Tibesti, the climate consisted probably of rains fairly well distributed throughout the year, with two principal rainy seasons, one in spring, the other in autumn and with a strong reduction of the evaporation (see the lacustrine deposits). It should also be noted that the disappearance of the 'cold' diatom *Cymatopleura elliptica* in the Palaeochad (2, 14), dated after about 6600 BP at Tjéri (fig. 2) occurs just before the appearance of a warmer climate of Sahelian type (see below). Moreover during some years or periods with large seasonal contrasts (very cold winters and very hot summers), there could have been a combination of rains from tropical depressions and from the monsoon, as can sometimes be observed in present years[37,42]. This could account for the alternation of finer and coarser layers in phase C of the MT. Finally for the climate of the Tibesti during the arid phases, of which phase D is a good example, we could perhaps imagine tropical depressions in winter and, possibly, with snow[35], the rest of the year being almost without rain, which would cause intense evaporation favouring the formation of calcareous crusts. Cyclonic rains from the Polar front in surface are also possible in winter without the intervention of equatorial air. But since the cold air carries little humidity, these rains would in general be relatively light[34,50].

Interpretation of the upper part of the MT

From around 6500 to 5500 BP, the relationship with temperature seems to be different (phase F). The trends of the curves for the Montane and Sahelian elements become similar. One may thus suppose that during this time the Tibesti underwent the same regime as the Sahelian zone, which means that almost all rains would be provided by the summer monsoon.

First, the sudden massive appearance of the pebbles and cobbles near the top of the MT is subsequent to 6600 BP, as the palaeosol radiocarbon dated about 6600 BP is itself covered by 40 cm of coarse alluvium[26]. On the other hand, the spreading of the pebbles requires a very heavy fluviatile regime for which rains of Sahelian type can easily be accountable. However one must note that this spreading occurred over the MT without apparent erosion. The erosion period of the MT is not yet well placed in time: perhaps after 5500 BP and before 4000 BP (Fig. 3). In Central Aïr, the presence of vertisols with calcareous nodules of dates 5680±110 and 5010±110 BP (ref. 3) indicate a wetter climate of Sahelian type. In Adrar Bous a vertisol has been situated between 7300 and 4500 BP (ref. 30). In Egyptian Nubia Member I of the Shaturma Formation[24] has a chronology and sedimentology corresponding to the phase F of the Tibesti. The alluviation of Member I ceased before the initiation of a renewed period of Nile dissection which occurred after 5000 BP (ref. 24). The end of Member I and the beginning of the erosion can thus be dated between around 5500 and 5000 BP. Butzer and Hansen[24] conclude that these deposits "imply rather effective sheet-flooding with 50 to 100 mm of rainfall at most".

A climate of Sahelian type over the Tibesti and probably also over the Central Sahara is all the more probable as other pollen data at Tjéri indicate a northwards movement of the Sahel zone at that time. The removal of the Sahelian vegetation northwards would explain the flat of the curve for the Sahelian element between around 5500 and 4400 BP (Fig. 2*c*). This interpretation is corroborated by the curve for the Sudanian element which reached its maximum between around 5900 and 4400 BP (ref. 1), corresponding no doubt also to a slight northwards movement of the Sudanian zone.

Conclusion

First, it seems that for the Central Sahara there are two kinds of wetter periods (optima)—one, more frequent in the Quaternary period, with tropical depressions and temperature relatively low, and the other with direct monsoon rains and higher temperatures. Second, the annual climatic mechanisms of the present time enable the palaeoclimates of the early Holocene to be coherently explained. The opposition, both seasonal in the present time, and for longer periods during the early Holocene, between the tropical depressions and the monsoon rains can be interpreted by variations in trends of temperature over the Northern Hemisphere and also by variations in general atmospheric circulation. Indeed, the penetrations of the polar troughs aloft, necessary for the formation of tropical depressions, are related to the occurrence of large amplitude waves in the upper westerlies. On the other hand, during hotter years or periods, the polar troughs towards lower latitudes are much less frequent and the circulation of the upper westerlies becomes more zonal. This situation leads to a dimunition of tropical depressions, favouring, in contrast, the extension of monsoon rains over the Sahara[51,52]. But the opposition between these two kinds of rain remains only partial since both are also linked to the activity of the ITCZ. Better knowledge of present events as well as the study of other old periods should allow greater precision in this field.

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