(Reprinted from Nature, Vol. 269, No. 5629, pp. 573–577, October 13, 1977)

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].

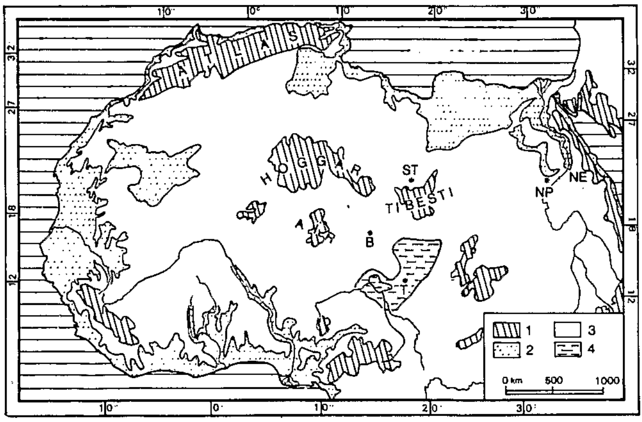

Fig. 1 North Africa. 1, Mountains over 1,000 m. 2, Regions under 200 m. 3, Regions between 1,000 m and 200 m. 4, Holocene Palaeochad, 320 m high. T, Tjéri. B, Bilma. ST, Sérir Tibesti. NP, Nabta Playa. NE, Egyptian Nubia.

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.

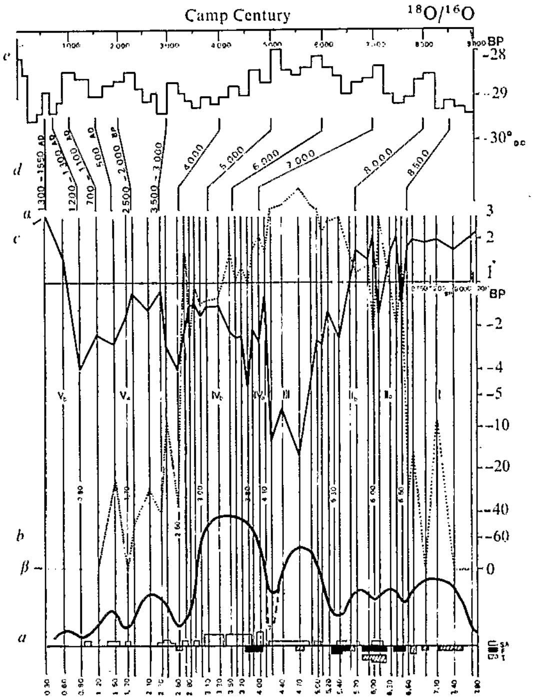

Fig. 2 Comparative evolution for the Tjéri station, from base to top, *a*, Relative lacustrine levels, after diatom studies[2,14]. The ? at 4.20 m is the author's interpretation[1] and a brief regression at 3.80 m (around 6600 BP) is also probable. Some diatoms of

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

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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]

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

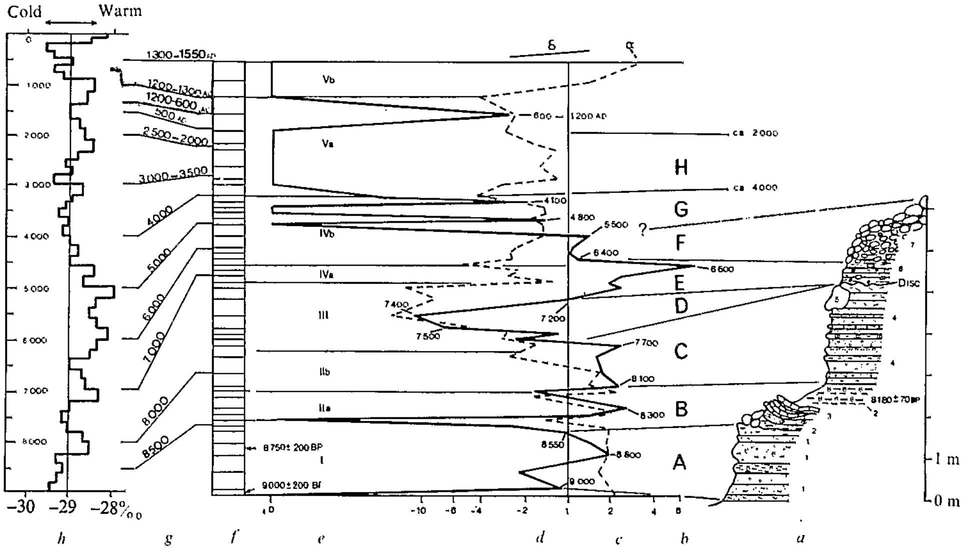

Fig. 3 Comparative evolution of the MT in the Tibesti, of the pollen curves for the Montane and Sahelian elements and of the $^{18}O/^{16}O$ ratio at Camp Century. *a*, 'Middle Terrace' (MT), section near Yebbi-Bou, after J. Grunert (23,pr.20). 1, Indurated layers with coarse sands, bedded towards the 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.

I thank M. Van Campo, H. H. Lamb, J. Dubief, K. W. Butzer, B. Messerli and P. Guinet for comments, F. Wendorf [illegible]

Received 10 January; accepted 29 June 1977.

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