I. The lacustrine environment and its evolution

1. Paleolimnology of an upper quaternary endorheic lake in Chad basin

M. Servant and S. Servant

A research program on the quaternary lakes of Chad basin, initially focused on stratigraphic, geomorphologic and sedimentological studies, (Servant 1973), but was completed by diatom (Servant-Vildary 1978) and pollen analysis (Maley 1980) from lacustrine deposits. The main purpose was to reconstruct the paleoenvironments of the quaternary lakes in order to determine climatic variations. The results are incorporated into a more comprehensive program on the paleogeography and paleolimnology of southern Sahara regions, from the Atlantic to the Red Sea.

From the end of the tertiary, the bottom of Chad basin was occupied by very large lakes which deposited diatomaceous clayey sediments up to several hundred meters in thickness. In the upper Pliocene or at the beginning of the Pleistocene, the first climatic change led to the drying up of the basin.

The whole late quaternary history of the basin is characterized by complex climatic fluctuations that resulted in wind modifications during dry periods and in the resurgence of lakes during rainy periods. This situation has been studied in detail for the last forty millennia and will be the object of our study (Fig. 1).

1.1 Variations in lacustrine levels

The first observations during the nineteenth century, suggest that the water level of Lake Chad undergoes significant variations of about 50% in its depth and extent (Tilho 1947) that are directly related to changes in the annual average rainfall in the whole drainage basin (Servant 1974) (Fig. 2). These variations were observed over ten years and reflect changes of greater magnitude which occurred over a century or a millennium scale. For instance, it is known that Lake Chad was as large as the Caspian during a recent geological time of about 6000 years BP (Tilho 1925; Schneider 1967). It is also known that this lake dried up temporarily during the quaternary, evidence for this being the existence of wind dunes which are almost completely submerged by the present lake. The lacustrine oscillations which have been obvious since the first observation are supported by

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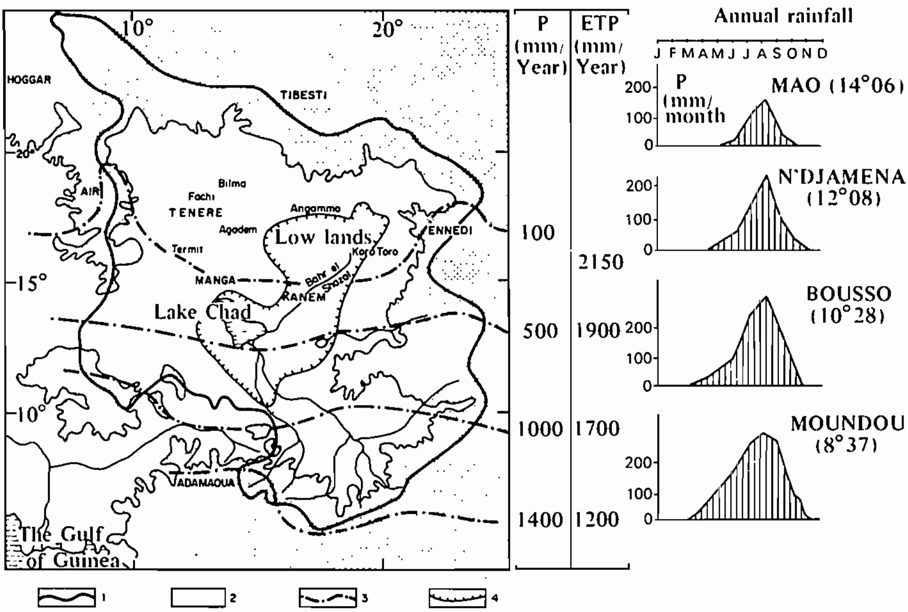

Fig. 1 The Chad basin and its main climatic features. 1: limits of the basin; 2: altitudes above 500 m; 3: isohyets; 4: limit of Lake Chad in about 6000 years BP (Schneider 1967); P: yearly average rainfall; ETP: potential yearly average evaporation.

numerous ^{14}C datings (Servant 1973), carried out for the last 40 000 years. From these three main geological periods can be singled out.

— From about 40 000 to 20 000 or 18 000 years BP, the Chad basin was occupied by small lakes, much more numerous than at present, which generally deposited calcareous sediments with ostracods and diatoms. These deposits are often stratified with eolian sandy layers or desiccation cracks which indicate that the lakes went through temporary drying up periods.

— From 20 000 or 18 000 to 13 000 years BP, these lakes completely disappeared and the bottom of Chad basin was reworked by wind as now happens in the Sahara. Therefore the southern limit of the desert belt was displaced at least 500 km towards the Equator.

— From 13 000 years BP, numerous lakes again appeared in the basin. However, eolian sand layers, reworked layers, desiccation cracks or sometimes, evaporation deposits in lacustrine series, show that these lakes went through several drying up periods.

Figure 3 shows the methodology used to analyze the lacustrine oscillations of these three periods in various parts of Chad basin (Servant 1973; Servant-Vildary 1978; Maley 1981). It deals with lacustrine series deposited in the interdune depression of an erg currently fixed in the northeast of Lake Chad.

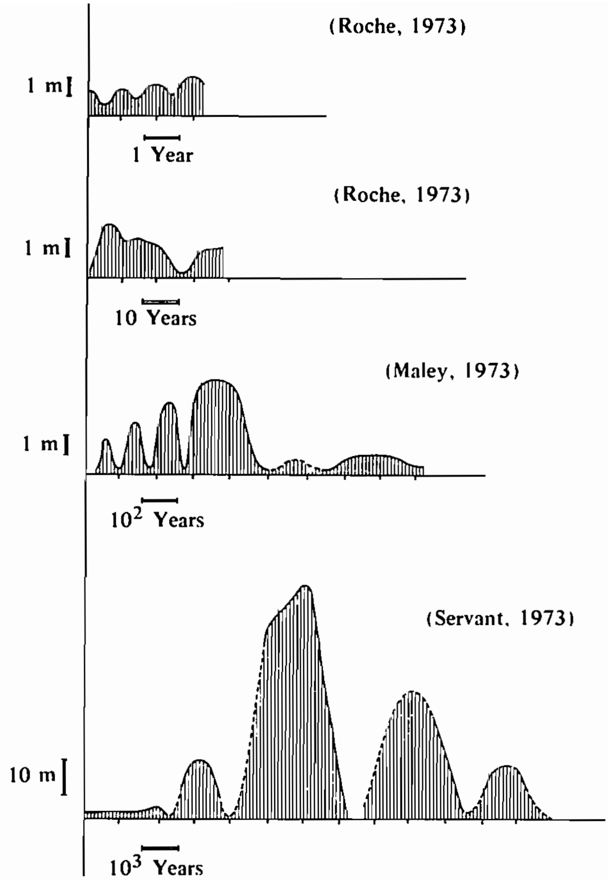

Fig. 2 Oscillations of the level of Lake Chad over different time scales (Servant and Servant-Vildary 1980).

The lithological development of this series makes it possible to specify the main periods of decreasing water levels or drying up periods, which were characterized by desiccation cracks (for instance at about 7.80 m depth). The altitude of the highest lacustrine deposits on the edges of the depression determines the water-level position (Martin, unpublished). The evolution of the diatom flora is another source of detailed information. Diatom assemblages have been divided into six different groups according to the extent and depth of the ancient lake:

Group I is mainly composed of periphytic and aerophilic species (*Hantzschia amphioxys*, *Pinnularia borealis*, *Navicula mutica* ...) Numerous phytolitaria are associated with these diatoms.

Group II is composed of benthic species typical of very shallow ponds

(*Navicula*, *Anomoeoneis*, *Campylodiscus*), or littoral species (*Fragilaria*, *Nitzschia*, *Coscinodiscus*...).

Group III is related to a lake whose level was probably rather unstable (*Gomphonema*, *Fragilaria* were present when the level was low, *Navicula* and *Cyclotella* when the rise in the water level led to an open water surface etc....).

Group IV is dominated by the genus *Cyclotella* with *Melosira* as subdominant or epiphytic species depending on the bottom topography.

Groups V and VI are characterized by the prevalence of euplanktonic species (*Melosira*, *Stephanodiscus*) mixed with small quantities of periphytic diatoms (V) or not (VI).

The distribution of these different groups along the sedimentary columns and comparative results from the different methods make it possible to estimate the relative variations in water level.

For the lacustrine period from about 40 000 to 20 000 years BP, it was not possible to date accurately the water-level fluctuations which clearly appeared in the sedimentary series. It must be noted that the ^{14}C datings for this period involve considerable margins of error (from ± 1000 to ± 2000 years), with other possible causes for error, related to the type of deposits analyzed. Datings were performed on lacustrine limestones whose isotopic composition may have been modified by recrystallization of calcite. Therefore it would be futile to try to date with high accuracy the main stages in the changes in water level in spite of all the precautions taken in the analysis and interpretations of ^{14}C datings (Servant 1973).

For more recent periods, datings are much more accurate (from ± 100 to ± 300 years) and have been made on various materials (plant waste, shells, lacustrine limestones). Therefore, it is possible to make a detailed study of the lacustrine oscillations over the millennium. The comparative study, based on numerous lacustrine depressions (the majority of which are now dried up) is represented in diagrams of the absolute or relative variations in ancient water level.

The topographical, hydrological and hydrogeological context of each lake must be taken into account in order to interpret these diagrams. The bottom of Chad basin was never occupied by a single lake but by numerous lakes which could be completely isolated from one another. These lakes can be divided into three groups:

— Interdune lakes were situated in the depressions of a fossil erg which appeared during the arid period from 20 000 to 13 000 years BP. Completely isolated from the hydrographic system, they were fed by rainfall and especially by underground water. Numerous examples of this group now exist in the north of Lake Chad.

— Piedmont lakes were located at the foot of low mountains that gave a broken appearance to the bottom of the Chad basin. Water originated from these mountains but their small drainage basins excluded a remote water origin.

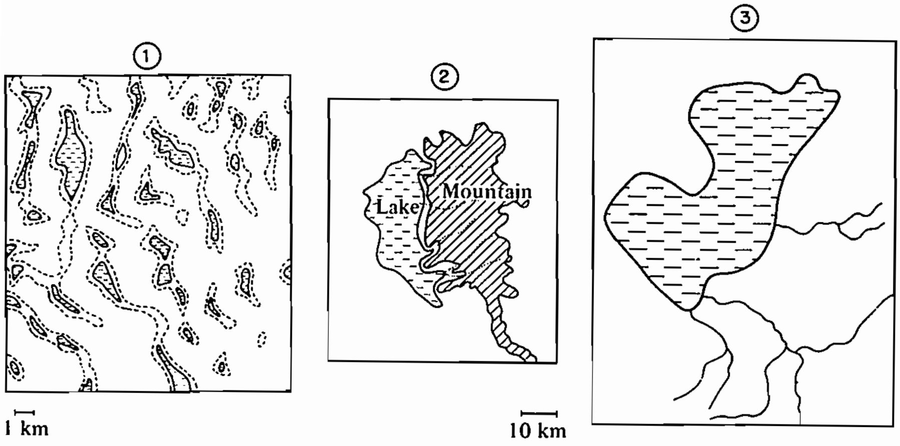

Fig. 4 Classification of the lacustrine depressions (Servant 1978). 1: interdune lakes related to the outcrop of the groundwater level; 2: piedmont lake fed by a small drainage basin; 3: lake fed by a very large drainage basin (here, the Holocene lake in about 6000 years BP, Schneider 1967).

— Hydrographic lakes were fed by a large river system and were thus similar to the present Lake Chad (Fig. 4).

During the last 13 000 years BP, the evolution of these different lakes was parallel and synchronous. It may be noted for instance, that from 8000–6000 years BP floods were observed in all the depressions, even where drainage basins occupied small areas, as the lacustrine floods were independent of local topography. Therefore, the remote supplies were not the main reason for the rise in water levels. Local climatic factors, such as an increase in rainfall and/or a decrease in evaporation must have played a decisive role. On the contrary, at about 3000 years BP, a very different paleogeographical situation is observed. A substantial rise in lacustrine levels only occurred in depressions (such as the 'Pays-Bas') which were fed by river systems, while the endorheic basins of the Niger were occupied by very shallow lakes.

The comparison of two different types of lakes, at the same time, and at the same latitude, suggests that at 3000 years BP, there was no significant increase in the rainfall to evaporation ratio (R/E), contrary to what had happened in about 6000–8000 years BP. These examples provide the major principles upon which the interpretation of lake oscillations was based (Servant 1973). Only a comparative analysis allows us to determine the relative variations in the rainfall and evaporation ratio over time (Fig. 5).

Many other data likely to be meaningful from the paleoclimatic point of view can be added profitably to the paleohydrological interpretation. For example, the palynological analysis shows that with time, the relative ratios of pollens

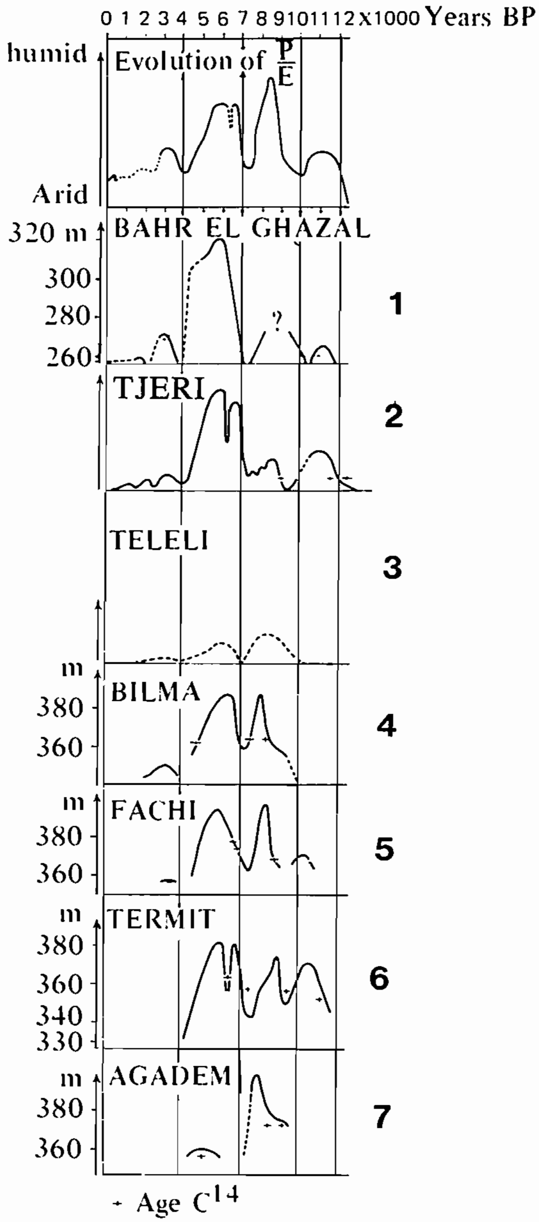

Fig. 5 Variations in the level of some lakes in the Chad basin and paleoclimatic interpretation (Servant 1973, 1974; Servant and Servant-Vildary 1980). 1: oscillations of a lake fed by the river system; 2: oscillations of a lake fed by the groundwater level with river supplies during some periods (above all in about 6000 years BP); 3: oscillation of an interdune lake always isolated from the river system; 4, 5, 6 and 7: oscillations of piedmont lakes in Eastern Niger fed by small-sized drainage basins (see Fig. 4, classification of the lacustrine depressions).

from Soudano-Guinean, Sudanese or Sahelian plants have varied considerably. These variations are related to changes in the vegetation cover near the ancient lakes or in the drainage basins as a whole (Maley 1977). Prehistoric sites, near the ancient lakes, help to determine the paleoenvironments of prehistoric man (Maley et al. 1971).

1.2 Lacustrine paleoenvironments — paleosalinity

1.2.1 *Regions related to the change from a dry to a wet period*

At about 12 000 years, after a very dry period, numerous small lakes appeared in the bottom of the Chad basin, especially in the interdune depression located in the north and northeast of the present Lake Chad. The benthic and epithytic flora, characteristic of shallow water ponds, shows great geographical variability in the chemical composition of the water. (They were derived from the outcrop of groundwater in topographic hollows.)

—high pH value, sodium carbonate-rich water with *Anomoeoneis costata, Rhopalodia gibberula, R. musculus.*

— sodium chlorosulphate-rich water with *Campylodiscus clypeus,* particularly numerous in the eastern Niger.

— calcium carbonate-rich water with *Navicula oblonga, Nitzschia denticula, Cymbella microcephala.*

In fact at about 12 000 years BP, lake regions were very similar to those observed now near Lake Chad (Maglione 1974; Iltis 1974). Under similar climatic conditions, we observe the juxtaposition of environments with different hydrochemical features, which can be explained through the local hydrological and hydrogeological conditions. The lakes could be completely closed and under those circumstances, evaporation led to a rapid increase in salinity. The differences in hydrochemistry result mainly from the initial composition of water with regard to drainage basins (chlorides are not very abundant in Chad and more abundant in Niger). Some of these ponds could have had underground outlets which drove some of the dissolved salts out of the lacustrine environment, thus lessening the increase in salinity through evaporation.

1.2.2 *Regions related to the maximum of a wet period*

We shall take the example of a lacustrine extension which occurred in about 6000 years BP, when a large lake occupied a large part of the bottom of Chad basin. Towards the northwest there were isolated oligotrophic lakes in endorheic depressions of eastern Niger. In the west, the large lake was bordered by regions very similar to those located on the northern edge of present Lake

Chad: they corresponded to an ancient dune system, more or less completely submerged, where the diatom flora was characterized by the prevalence of the genus *Fragilaria.* The existence of fully grown herbs is shown by the great number of Phytolitaria in lacustrine sediments. The center of the basin was occupied by a large deep lake where planktonic diatoms developed well (*Stephanodiscus astrea, Melosira granulata,* etc.). The main characteristics of this lacustrine period were generally low paleosalinity in the basin, sedimentation of smectites and diatomites and the absence of carbonate precipitation.

1.2.3 *Regions related to the change from a wet to a dry period*

It is difficult to study the evolution of lacustrine environments under climatic conditions which moved towards increasing drought, because their deposits often disappeared through erosion after the total dryness which may have occurred at the end of this development.

The best preserved sedimentary series were observed in the bottom of interdune depressions in the northeast of Lake Chad (Bahr El Ghazal). The lowering of lake levels resulted in a decreased percentage of diatoms, an increase in detrital sandy fractions from reworked neighbouring dunes and frequent carbonated accumulations in diffuse form or in slabs and limestone nodules. Phytolitaria are numerous and associated with aerophilic diatoms such as *Navicula mutica, Hantzschia amphioxys, Pinnularia borealis.* A slight increase in paleosalinity (*Cyclotella meneghiniana, Coscinodiscus* sp.) was followed by a greater increase which did not appear in the diatom flora. Evaporites were deposited when lake levels were very near the soil surface and sodium layers were preserved at the top of recent Holocene lacustrine deposits in eastern Niger (Bilma) and Chad (Largeau).

Diatom study shows that the paleosalinity was low (less than $1 g l^{-1}$ throughout the basin, and dissolved salts reached a high value only during short periods of time and in localized areas.

It is surprising to find low paleosalinities in an endorheic basin where salts, brought into solution by surface water, should accumulate in lacustrine basins with time. But for the Quaternary, it should be emphasized that those basins which are endorheic from the hydrological point of view are not so from the sedimentological point of view. During drying up periods, lacustrine sediments and in particular evaporites derived from this drying up are affected by wind erosion. Thus a considerable part of the deposits is driven out of the basin by the wind as is shown by the presence of continental diatoms in the quaternary deposits of the western Atlantic.

A similar phenomenon occurred on the shores of Lake Chad (Roche 1970) on another time scale. Saline alluviums appeared on the edge of this lake when there was a lowering of the water level and they may have been reworked by

clayey neo-formations (smectites) lead to immobilization of some dissolved elements as shown geologically by Dupont (1970) and geochemically by Carmouze (1976). Organisms fix numerous substances, mainly calcium and silica which are at least partly incorporated into sediments. Higher aquatic plants can also play a decisive role during recession periods. Very numerous on the edge of the lake, they are left on the surface when the water level drops. So a considerable amount of matter can be removed from the aquatic environment, even when some of the plants appear again through a new extension of the lake (Carmouze et al., 1978).

The limited paleosalinities can be accounted for by the composition of the water in Chad basin which always has a very low chloride content (Roche 1973; Carmouze 1976). Moreover, chlorides which are not fixed by sedimentation can reach high concentrations only in endorheic environments with high evaporation.

Finally, it should be noted that the mechanisms which limit paleosalinities are compounded by water-level fluctuations. Decreasing water levels deposit surface saline alluviums and a large amount of organic matter which leads to an elimination of dissolved substances. The transgression of a lake onto permeable sandy land leads to leakages by infiltrations etc. Therefore, the main reason for the low percentage of dissolved salts is probably the constant variation in lake levels. In other tropical regions, it is possible that the quaternary water coverage in endorheic basins did not suffer such sudden and distinct variations.

1.3 Trophic conditions

At 7000 years BP, interesting changes in the diatom flora were observed in ten 'interdune' lakes, located near the Bahr el Ghazal river. *Stephanodiscus astrea, Melosira granulata* var. *tubulosa, Fragilaria construens* replaced *Cyclotella ocellata, Melosira granulata* var. *muzzanensis, Fragilaria brevistriata* (Fig. 6). This modification of diatom assemblages was connected with a change in the trophic conditions. The evolution from oligotrophic to eutrophic conditions can be explained by an internal change but is better related to a major paleogeographical event. Interdune depressions were fed before 7000 years BP by subterranean waters and rainfall, but after 7000 years BP, they were fed by the flooding of river water. The comparison between many topographically and hydrologically different lakes supports this hypothesis.

At 8000–9000 years BP, interdune lakes were oligotrophic but at the same time, hydrographic lakes (such as the lakes of the 'Pays-Bas du Tchad', the lower part of the basin) were characterized by the presence of 94% of the eutrophic species, *Stephanodiscus astrea.* Yet these lakes were fed by southern and northern rivers. In the Nigerian part of the basin, the lakes were fed only by runoff, never by rivers, and the complete absence of *Stephanodiscus astrea* was

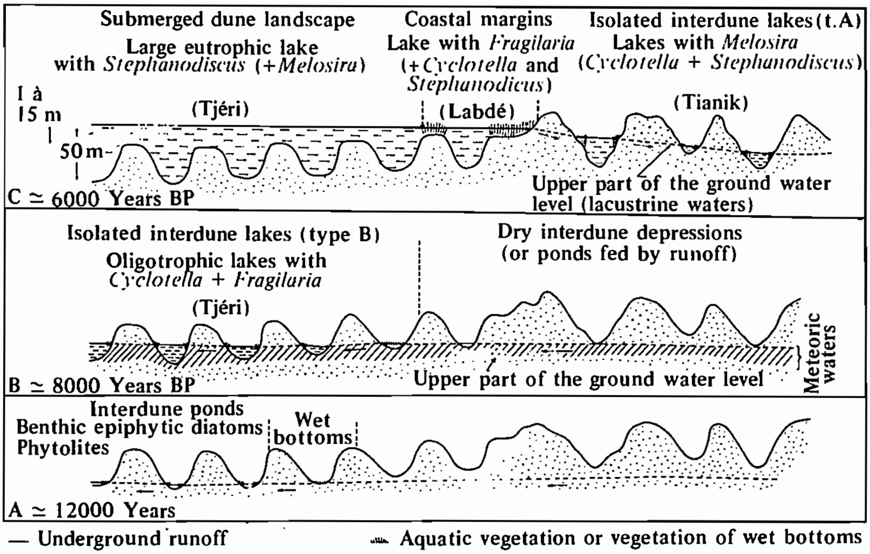

Fig. 7 Cross section of some quaternary lacustrine landscapes in the northeast of Lake Chad. Here lakes develop in a dune landscape resulting from the previous periods (Servant-Vildary 1978).

observed, even at the maximum of the wet period. An example of the development of the regions is given in Fig. 7.

Trophic conditions were different from one lake to another at the same time in the Chad basin.

1.4 Paleotemperatures

It is difficult to find methods for estimating changes in temperature in lacustrine deposits; however, some information can be provided by diatoms. In Chad sediments, we found some psychrophilic diatoms (diatoms which preferably live in high- and mid-latitude regions, or in high tropical mountains). The only explanation for their presence in the ancient lakes is that they had found suitable conditions for life. At 11 500 years BP, they developed in oligotrophic conditions and then disappeared although the oligotrophic conditions remained, as a result of temperature variations.

As far back as the ancient Quaternary, associations of psychrophilic diatoms appeared in Chad, whose climatic significance is particularly interesting:

— The species which developed between 25 000 and 20 000 years are: *Cyclotella ocellata* (20–80%), *Cyclotella comta* var. *radiosa* (5–20%), *Diploneis domblittensis* (1–5%), *Fragilaria lapponica* (0–1%), *Melosira italica* var. *subarc-*

tica (5–20%). They completely disappeared at 18 000 years BP, when cosmopolitan and tropical species developed.

— Some rather thin layers inserted in lacustrine sediments (one dated back 11 500 years) gave rise to another psychrophilic flora: *Melosira italica subarctica* (0–1%), *Cymbella augustata* (1–5%), *Cymbella hybrida* (0–1%), *Cymbella naviculoïdes* (1–5%), *Cyclotella ocellata* (20–40%).

— At about 9000 years (9610 ± 155 years BP Kamala): *Cyclotella ocellata* (5–20%), *Cymatopleura elliptica* and var. *hibernica* (0–1%). *Navicula scutelloïdes* (1–20%), *Cymbella augustata* (0–1%) almost completely disappeared after 7000 years BP in favour of tropical diatoms such as *Nitzschia lancettula* (5–20%), *Melosira granulata* var. *valida* (1–5%), var. *tubulosa* (1–5%), *Navicula confervacea* (5–40% Tjeri), etc....

1.5 Discussion: paleoclimatic interpretations of paleolimnological data

The most conspicuous characteristics of the history of the lake in this region are the instability of lacustrine levels and water volume over all time scales (10, 10^2, 10^3 years).

This phenomenon is inevitably related to climatic changes on the southern edges of the Sahara. These changes which were analyzed over the last decade resulted mainly from a decrease or an increase in tropical rainfall and a greater or lesser movement of the Intertropical Convergence Zone inside the African continent during the recent Quaternary; for instance, at about 6000 years BP, when large areas were submerged, paleogeographical studies show that at that time, hydrographic lakes were fed as today by southern rivers. Moreover, diatoms and pollen emphasize the tropicality of the lacustrine environments and paleoenvironments. Therefore, a northern movement of the isohyets may have occurred in relation to their current position.

But some paleohydrological and paleolimnological data suggest that other phenomena may have occurred. For instance, it is known that from the beginning of the Holocene (8000–9000 years BP) lakes received river supplies simultaneously from the north (Tibesti) and the south, and the latitudinal climatic zonation which is now very distinct was not clear. At that time, streams in central Saharian mountains deposited fine alluvial and stratified sediments whose presence cannot be explained under tropical climatic conditions which are characterized by seasonal and stormy rainfall. It is also known that the diatom flora of ancient lakes, at least temporarily, included species which are now unknown in tropical plains.

This biogeographic information appears still more clearly for some more ancient periods: for example, from about 25 000 to 20 000 years BP, tropical diatoms disappeared as a whole in favour of cosmopolitan or paleoarctic species.

This instability and these modifications are part of global atmospheric circulation. Therefore, the paleolimnology of the tropical waters extends far beyond the regional framework where it is applied (Fig. 8).

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