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Environmental change and archaeology: lake evolution and human occupation in the Eastern Sahara during the Holocene

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Abstract

The West Nubian Palaeolake is the most large-scale hydrographic evidence in the Eastern Sahara of the early to mid-Holocene wet phase that affected northern Africa. It is the result of a significant increase in local rainfall due to the northward shift of the tropical rainfall belt. A series of fieldwork-based differential GPS (DGPS) measurements along several profiles across the West Nubian Palaeolake basin provides the first precise topographic data from this up to a 5330 km^2 large palaeolake feature. In combination with sedimentological, geochemical, and archaeological results, an almost complete picture of significant palaeoclimatic changes and human occupation during the early to mid-Holocene for this region is presented. Different stages of palaeolake evolution ranging from non-existence of the lake through stable freshwater conditions to its extinction were identified in the period from 9400 to 3800 ^{14}C yr BP. These lake stages coincide with phases of intensive human inhabitation between ca. 6300 and 3500 ^{14}C yr BP, and include at least four settlement phases distinguishable by style of pottery. These are known from adjacent areas of the palaeolake region, emphasizing strong prehistoric cultural connections in the Eastern Sahara. During the highstands of the palaeolake in the early to mid-Holocene, the Dotted Wavy-Line pottery relates to the Early Khartoum type culture with its supra-regional distribution from the Nile Valley to the Chad, and possibly with slightly different forms even to the Atlantic coast. Later in the Holocene, Western Nubia with its large palaeolakes and migration paths along palaeowadis, such as Wadi Howar, acted as an important natural and cultural link between the Nile Valley and the Chad Basin until the region was deserted during the fourth millennium BP.

Keywords: Environmental change; Palaeolimnology; Archaeology; Holocene; Sudan; Eastern Sahara

1. Introduction

At about 9 ^{14}C kyr BP the tilt of the earth's axis was stronger than today and the time of the perihelion was at the end of July (Berger, 1978). This led to stronger insolation during the Northern Hemisphere summer and an increase in the amplitude of the seasonal cycle which enhanced the land–ocean temperature contrast, which in turn amplified the African and Indian monsoon (Kutzbach and Otto-Bliesner, 1982; Kröpelin, 1994; Kröpelin and Petit-Maire, 2000). During the early and mid-Holocene period the Sahelian and Saharan regions were considerably wetter than today as indicated by faunal and botanical remains, lacustrine sediments and archaeological

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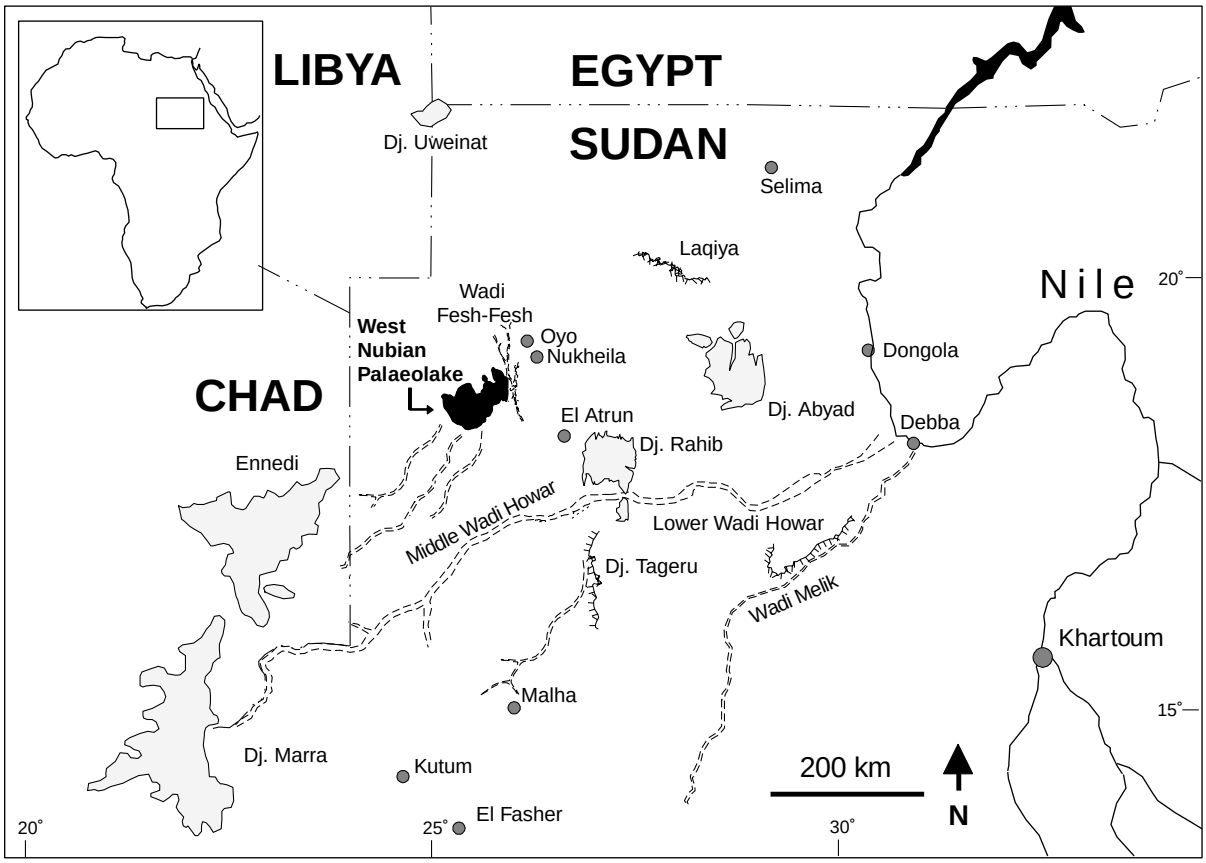

Fig. 1. Sketch map of Western Nubia and adjacent areas.

evidence (e.g. Wendorf and Schild, 1980; Williams and Faure, 1980; Petit-Maire and Riser, 1983; Close, 1987; Schandelmeier and Thorweihe, 1987; Pachur et al., 1987, 1990; Kuper, 1986, 1988; Klees and Kuper, 1992; Street-Perrott and Perrott, 1993; Hoelzmann et al., 1998). Due to its hypercontinental position, Western Nubia (Fig. 1) presently is one of the least-favoured regions of the Sahara in hydrological terms. However, it has proved to be a key area for information on palaeoclimate change (Pachur et al., 1990; Pachur and Hoelzmann, 2000) and human occupation (Kuper, 1995) during the early to mid-Holocene.

The West Nubian Palaeolake (Pachur and Hoelzmann, 1991; Hoelzmann, 1993; Pachur and Rottinger, 1997; Pachur, 1997; Hoelzmann et al., 2000) is the most large-scale hydrographic evidence of this period in the Eastern Sahara. Although several sites of lacustrine sediments of the lake were previously investigated in detail, showing that stable freshwater conditions persisted from 9400 to 3800 ^{14}C yr BP (Hoelzmann, 1993), the extent and water depth of the lake remained unclear due to the lack of precise topographic data (Pachur, 1997; Hoelzmann et al., 2000).

Here, we present the first series of fieldwork-checked differential GPS (DGPS) measurements along several transects across the West Nubian Palaeolake basin which include intensive archaeological surveys. The data comprise geomorphological, geochemical and archaeological findings and relate these to their geographical and topographic position, resulting in a better understanding of palaeoclimatic changes, the evolution of human occupation and the significance of this vast area for prehistoric societies.

2. Methods

2.1. Differential GPS

Between 18 and 19°N and 25 and 26°42′E, seven transects with a total of 368 localities were measured by DGPS. We used a SOKKIA-system with a base station reference recorder and a rover fixed on top of a car at a specific height. Measurements of 60 s were performed at all sites. The data was differentially processed and analyzed (Spectrum software, version 1.20a; projection WGS84, offset: $x = -130$; $y = 110$; $z = -13$; no rotation; ellipsoid constant 6,378,200 m; f: 1/298,300). Repeated measurements ($N = 70$; 19.0%) showed maximum horizontal differences of 1 m and maximum vertical differences of 1.9 m. The average absolute error for these repeatedly measured points is 0.37 m. Measurements during bad satellite-coverage exceeded these values (horizontal differences of up to 2.5 m and vertical differences of up to 4.5 m) but were not incorporated in our investigations ($n = 12$; 17%). The resulting accuracy of the presented measurements is therefore well below ± 1 m and hence adequate for the following investigations.

Due to the lack of precise topographic data to calibrate our measurements, a reference point was chosen in the centre of the DGPS-transects. This point (18°33′N/25°41′E) was cut by three DGPS-transects (Fig. 2a). According to Russian strategic topographic maps (scale 1:500,000) which are the best available maps of the region, this point was fixed to 540 m asl (above sea level) to which all present elevations in this study refer. The data range between the minimum elevation of 524.9 m asl in the sebkha of El Atrun, and 586.6 m asl as maximum elevation at the top of a sandstone ridge between the West Nubian Palaeolake basin and El Atrun (Fig. 2a–d).

The DGPS-data were analyzed and a contour image was interpolated (100 columns by 60 rows equal to 1.8 km by 1.8 km). As distance increases from the actual measuring points, the uncertainty of the interpolated elevations grows disproportionally. For this reason only those areas which are immediately adjacent to the measured profile are shown (Fig. 2a). Areas, differences in elevation, and lake volumes are calculated on the basis of this contour pattern.

In addition to the DGPS measurements, 301 archaeological sites were measured and mapped. The sites were integrated into the elevation model using the two-dimensional GPS-coordinates for the purpose of identifying the various settlement phases in correlation with the topographic elevations of the settlement locations.

2.2. Geomorphology

The spatial distribution of the DGPS-transects with the 298 localities included in this study is shown in Fig. 2a. Points of measurement were selected individually throughout the transects and 253 of these represent the most important geological surface units included in this study (Fig. 3):

(a) lake carbonates (Fig. 4): white, massive, and compact calcite and high Mg-calcite with low Mg-substitution rates (calcium carbonate contents of up to 94%) representing freshwater conditions;
(b) indurated carbonates: carbonate crusts, including microbialites representing decreased water depths, transition to strandlines, and/or seasonally flooded areas;
(c) carbonate crusts: massive calcareous crusts (thickness ≥10 cm) in higher positions; may reflect spring mounds and/or a higher (Pleistocene) lake level;
(d) iron crusts: goethite crusts (bog iron deposits) representing swamp-like environments;
(e) rhizoconcretions: moulds of calcified reed (*Phragmites* or *Typha*), marking the shoreline and/or shallow water areas;
(f) sebkha deposits: the sebkha-environments at El Atrun indicate the present near-surface groundwater table;
(g) dunes: dunes which formed islands in the palaeolake and which were often used for prehistoric settlement (mostly on the southeastern slopes);
(h) fluvial sediments: coarse sand to fine-grained gravel deposits mostly of aeolian origin and redeposited by local fluvial transport;
(i) bedrock: outcropping bedrock (Palaeozoic and Cretaceous sandstones).

2.3. Sedimentology and geochemistry

Five stratigraphic sequences of Holocene age — ranging from 9400 ± 90 to 3805 ± 65 ^{14}C yr BP — from four different palaeolake sites representing

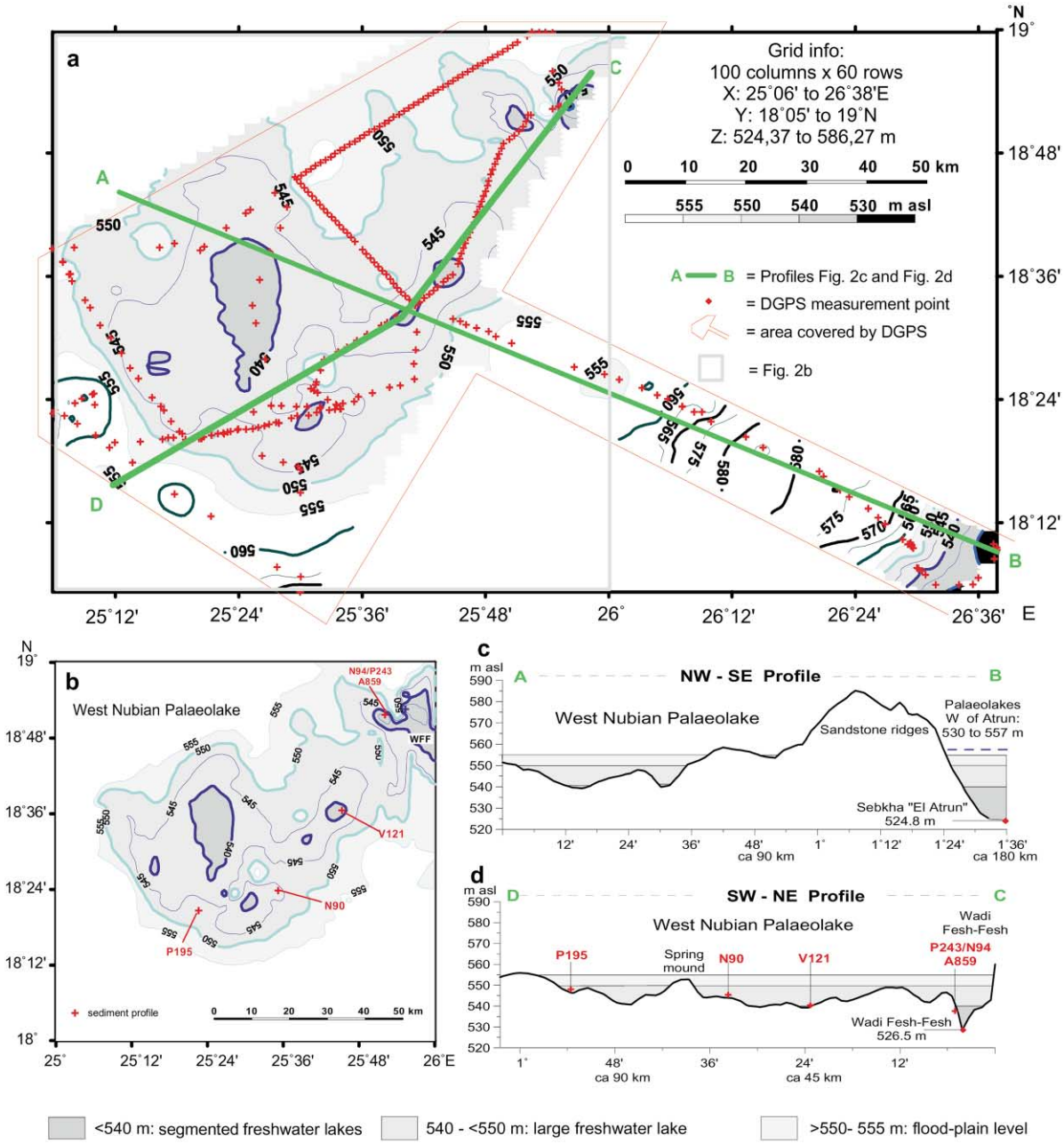

Fig. 2. Overview of the West Nubian Palaeolake showing (a) the spatial distribution of the DGPS measurements, the profiles crossing the palaeolake and the calculated elevations; (b) the contour line model for the West Nubian Palaeolake and the position of the investigated sections; (c) the NW–SE topographic profile through the palaeolake towards the sebkha of Atrun; (d) the SW–NE topographic profile through the palaeolake and its connection to the Wadi Fesh-Fesh.

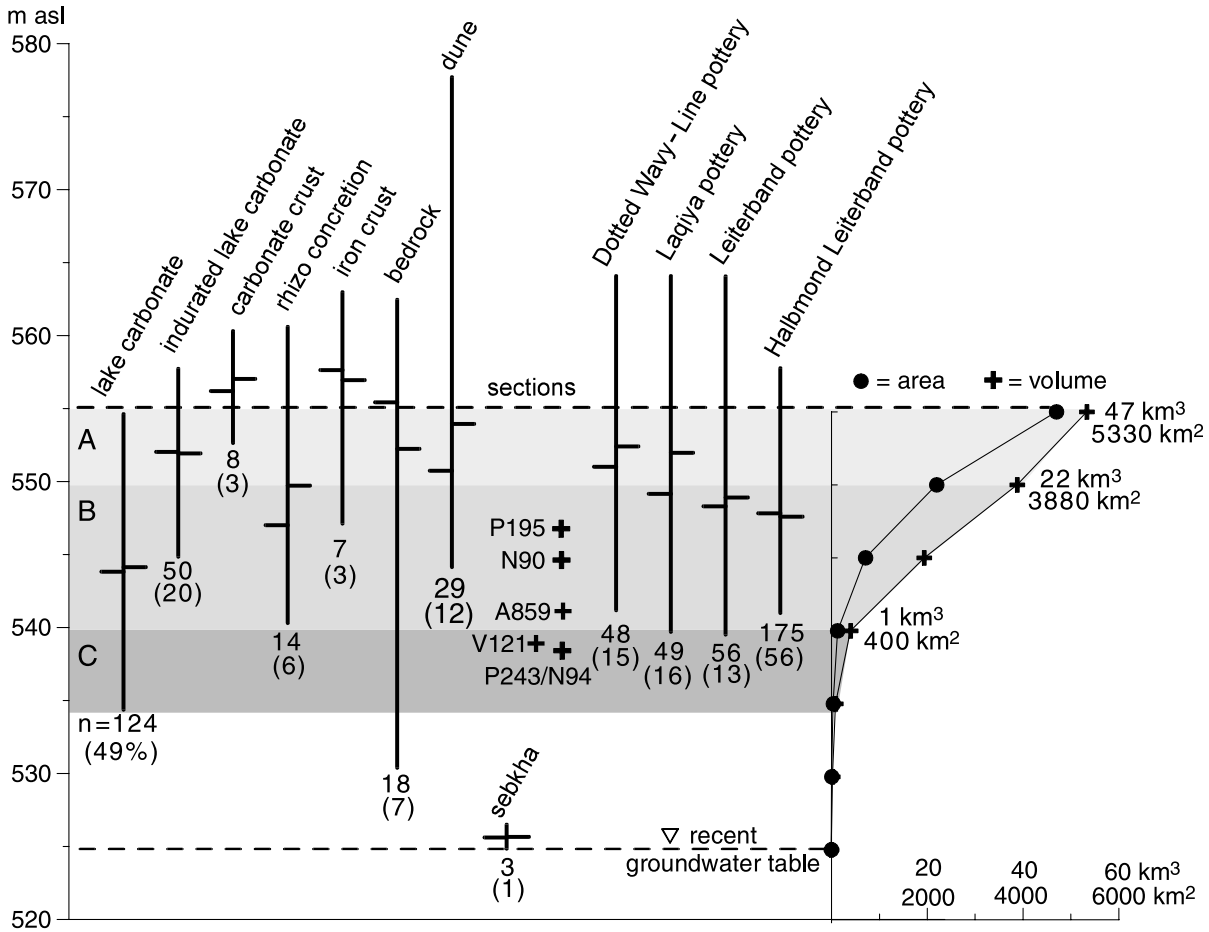

Fig. 3. The identified lake stages (floodplain level (A); large coherent freshwater lake (B); segmented freshwater lakes (C)) are related to the topographic position of the geologic surface units, the investigated sections and pottery phases. Range-plots of the topographic position indicate minimum, maximum, average (left), and median (right) for the geologic units and pottery phases. For the identified lake stages A–C resulting lake volumes and lake areas were calculated from the contour line model shown in Fig. 2b.

different lake stages, were examined in detail. Sections N90, P195 and V121 lie within the core region of the reconstructed palaeolake, whereas sections N94/P243 and A859 are situated to the north-west in the so-called Wadi Fesh-Fesh. The examined sections are up to 3.6 m thick lake carbonates (Figs. 4 and 5). Five centimetres thick samples representing approximately 30–50 years each were continuously extracted from the sections. A layer of 1 cm representing about 6–10 years from each of these samples was prepared for further analysis in the laboratory. The bulk carbonates were analyzed for Ca, Mg, Sr, organic (total organic carbon (TOC)) and inorganic carbon (total inorganic carbon (TIC)), oxygen and carbon isotopes; minerals were detected by X-ray diffraction (XRD). To determine only the metal contents within the carbonate fraction, a 3% HCl dilution was used and measurements of Ca, Mg, and Sr were performed with an ICP-OES (Perkin Elmer, Optima 3000). The minerogenic compositions of calcite and high Mg-calcite were determined by examination of the shift of the major diffraction peaks (Füchtbauer, 1988). Magnesium substitution in the calcite's crystal lattice has been interpreted as a palaeosalinity indicator

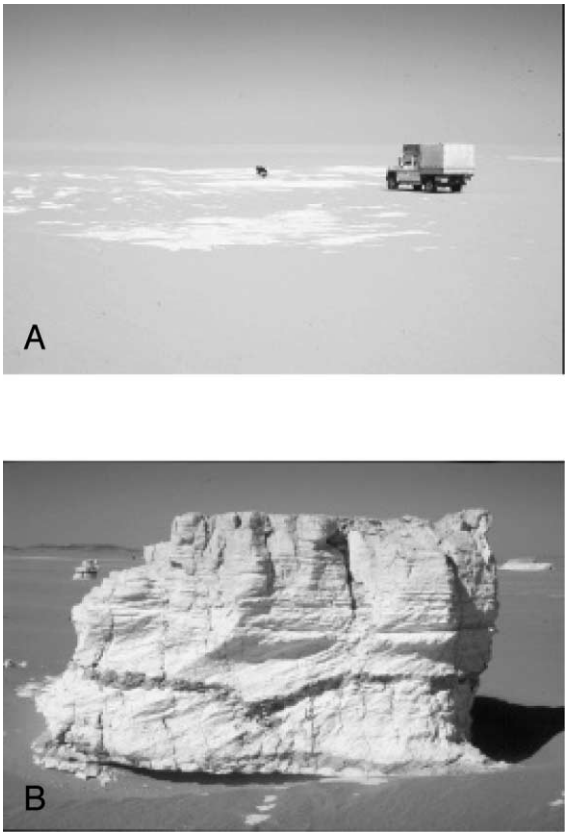

Fig. 4. (A) Wide-spread, deflated lake carbonates within the West Nubian Palaeolake. (B) 3.6 m thick lake carbonate yardang at section N94/P243.

(Eugster and Hardie, 1978; Chivas et al., 1986): high Mg/Ca ratios point to the existence of high Mg-calcites (>4–30 mole% $MgCO_3$) or even Ca-dolomite ($Ca_{0.5-0.7}Mg_{0.5-0.3}(CO_3)_2$). Therefore, the element mole ratios of Mg/Ca and Sr/Ca were used to determine the ion concentration of the palaeolake water; higher mole ratios represent higher ion concentrations (3–5‰ salinity; oligohaline lake), e.g. a Sr/Ca mole ratio of 3×10^{-3} is regarded as the transition from freshwater (<1‰ salinity) to brackish water conditions (Chivas et al., 1993; Gasse et al., 1987; Goschin, 1988; Hoelzmann, 1992).

In addition to the geochemical analyses, the molluscs, ostracods, diatoms and charophyte content of these sediments and bone remains of a diverse savanna fauna were examined.

2.4. Archaeology

The first intensive archaeological survey of this region sought to record all sites along a NE–SW transect crossing the West Nubian Palaeolake basin in its full length, to locate levels of former settlements and correlate these with the different lake stages. In addition to the selected DGPS-transects which total in length almost 150 km, all sites visible from the cars were studied in more detail. In areas without site recognition, a foot survey was undertaken every 10 km to check the archaeological situation. This survey was completed by data from 43 sites recorded in the southwestern basin during another field season in autumn 1999.

The following features have been recorded to characterize the archaeological sites: geographical position, altitude, topographic location, size and degree of disturbance. Structures such as stone-circles, pits, hearths and graves were also described. The finds were mainly composed of stone artefacts grinding stones, pottery, ostrich-eggshell beads, bones and botanical remains. All these data provide basic information on the archaeological heritage and on the various human activities carried out on the sites. They also give information about economic activities, former environments and inter- and supra-regional cultural contacts of the prehistoric population.

2.5. Chronology

The chronology for the archaelogical finds is based on stylistic comparisons with find inventories from the Wadi Howar region, with stratigraphic sequences for relative dating, as well as with inventories with absolute dates. At the same time, clear evidence for the cultural classification of the West Nubian Palaeolake basin pottery is obtained by regional and supra-regional comparative analyses of vessel forms as well as of techniques and combinations of decoration patterns. Since the criteria for the relative chronology are provided by the stratigraphy of the Conical Hill 84/24 site in the Lower Wadi Howar (Gabriel et al., 1985) (see also Section 3.3.1.) the absolute dating of the different phases according to specific pottery types is still approximate. Unfortunately, charcoal is very rare and the bones usually do not contain enough

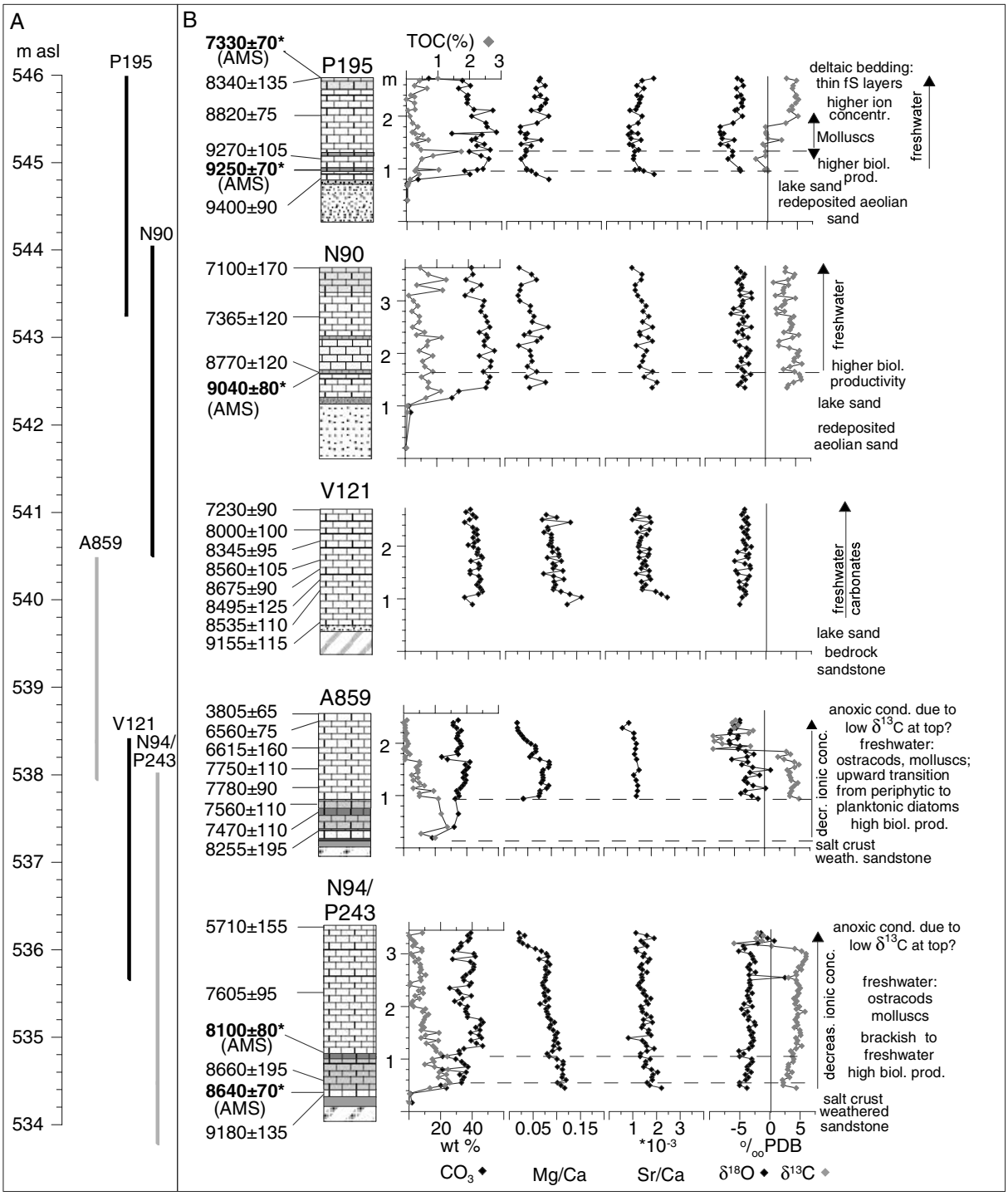

Fig. 5. Topographic position (A), geochemistry and sedimentology (B) of the sections within the West Nubian Palaeolake (black) and Wadi Fesh-Fesh (grey). Radiocarbon dates in bold represent AMS datings of organic matter. Section V121 modified from Pachur (1997).

collagen for radiocarbon dating. Furthermore, many sites are eroded and were occupied several times, thus making a proved connection between dated material and pottery sometimes impossible. All available radiocarbon dates from the Wadi Howar region have been used to establish the chronological framework (Fig. 11). In total 36 radiocarbon dates from 18 sites comprise datings of bones ($n = 18$), charcoal ($n = 3$), snail-shells ($n = 2$), ostrich-egg shell ($n = 1$), sediment ($n = 1$), and pottery ($n = 11$). These datings originate from the West Nubian Palaeolake basin ($n = 5$), the Middle Wadi Howar ($n = 25$), the Lower Wadi Howar ($n = 4$), and from the Djebel Tageru ($n = 2$). Despite all dating problems connected with the different materials of the samples, even the resulting blurred picture gives a general trend of the chronological position of the analyzed sites when combined with the relative chronology and supra-regional comparisons.

In addition to the archaeological finds a total of 38 samples of lacustrine sediments have been radiocarbon dated in the catchment of the West Nubian Palaeolake: 32 originate from the five lake carbonate sections that have been investigated in detail (Fig. 6). These include 27 conventional radiocarbon dates on the TIC and five AMS dates on the TOC. The other dates originate from near-surface lake carbonates ($n = 6$; TIC dated), charcoal ($n = 1$), carbonate-encrusted roots ($n = 1$; TIC dated) or faunal remains ($n = 17$; collagen dated). Comparisons of organic (including AMS dating) and inorganic radiocarbon ages of lacustrine sediments from Western Nubia revealed discrepancies of 600–1000 years and resemble values obtained elsewhere from the Eastern Sahara (Haynes et al., 1989; Hoelzmann, 1993; Pachur and Hoelzmann, 2000). Therefore, the datings within this paper represent uncorrected radiocarbon years.

3. Results

3.1. Differential GPS

Figs. 2 and 3 show the data of the DGPS-transects. The lowest measured points are the sebkha of El Atrun (524.9 m asl) and the talweg of Wadi Fesh-Fesh (526.5 m asl). These mark the recent near-surface groundwater level, as both localities show moist sediments associated with recent efflorescences (trona and gypsum). In the main lake basin the lowest point (538.2 m asl; 18°33′N/25°27′E) exhibits lake carbonates but these lie well above the actual groundwater level and therefore cannot be associated with moist sediments nor recent efflorescences. From the difference of the highest measured lake carbonates within the palaeolake basin (554.6 m asl) and the actual groundwater level (526.5 m asl), the maximum rise of the groundwater during the Holocene amounts to 28.1 m. This correlates in magnitude with earlier estimates (21.8 m) drawn from investigated sections in Wadi Fesh-Fesh (Hoelzmann, 1993). Based on the DGPS measurements, several lake levels were defined that represent different stages of the lake's evolution.

3.1.1. A floodplain level at 550– < 555 m asl

Altitudes above 550 m asl are marked by indurated lake carbonates, but these do not reach beyond the 555 m contour line. This marks a maximum lake level between 550–555 m asl. During temporary transgressions, sandy lacustrine carbonates with a maximum thickness of 20–30 cm or microbialites were formed. These algal mats have a concentric structure and developed on aeolian sand or outcropping sandstone (Pachur, 1997). Thick lake carbonate layers do not occur at this lake level. Therefore, these areas represent a plain which was only episodically or seasonally flooded.

The northeastern part of the West Nubian Palaeolake is close to Wadi Fesh-Fesh which is draining southward into a depression in the foreland of El Atrun. Even at the maximum lake level (555 m asl), a hydrological link between the main basin of the West Nubian Palaeolake and the lower areas of the foreland west of El Atrun only existed via the talweg of the Wadi Fesh-Fesh. A direct connection must be excluded because several sandstone ridges with altitudes of up to 586.6 m asl at the eastern rim of the lake basin separate the West Nubian Palaeolake from the palaeolakes west of El Atrun. The eastern limit (land terrace) of the Wadi Fesh-Fesh has an altitude of 560.3 m asl and therefore lies well above the maximum flood level of 555 m asl. For this reason, a direct connection with the areas between Wadi Fesh-Fesh and Nukheila/Oyo can also be excluded. This is supported by additional field observations that lake

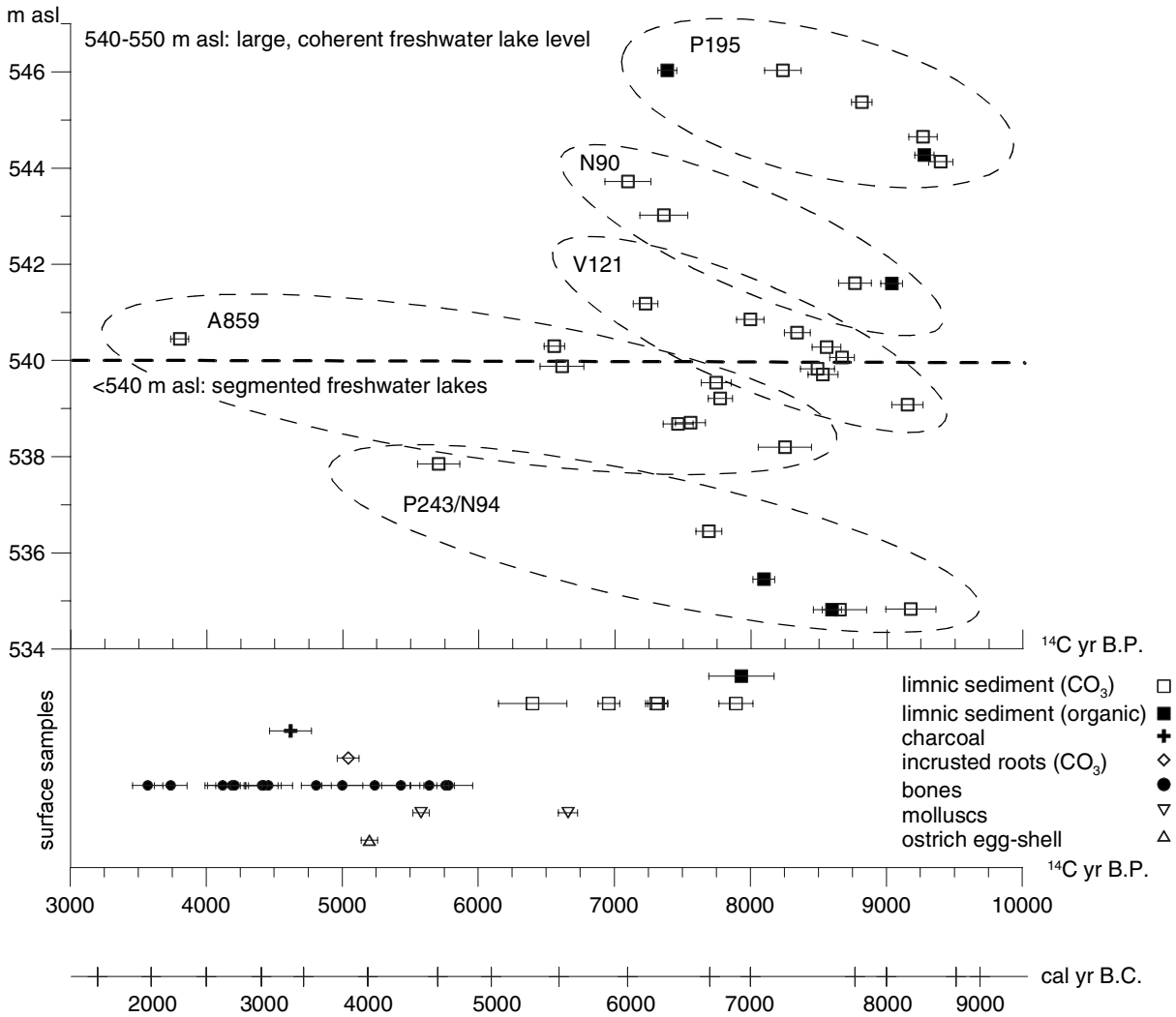

Fig. 6. Age distribution of radiocarbon dates within the West Nubian Palaeolake and age–depth correlation for radiocarbon dates obtained from sections.

carbonates are exclusively outcropping in the lower parts of the depressions of Nukheila and Oyo.

A nearly perfect circular shaped feature with solid indurated carbonates and sand with carbonate nodules has been located in the southern part of the West Nubian Palaeolake at 18°27′N/25°33′E (Fig. 2a,b and d; 555.6 m asl). This might have been a diffuse groundwater outlet or spring mound that led to the formation of carbonate crusts during temporary maximum lake levels, presumably in the early Holocene. However, since there are no chronological dates available, we cannot exclude their formation under Artesian groundwater conditions at high lake levels and permanent water cover during the Pleistocene.

Wadi Fesh-Fesh lies north almost immediately adjacent to the palaeolake. It is separated from the main basin only by a sandstone ridge at 551 m asl. Several yardangs consisting of lake carbonate with maximum thicknesses of 3.6 m are exposed in a tributary to Wadi Fesh-Fesh at 18°52′N/25°52′E at an altitude of 534.4 m asl, approximately 8 m above the valley floor (the onset of lake carbonate formation

in section N94/P243 was dated to 9180 ± 135 ^{14}C yr BP and the top of the lake carbonate at 538.0 m asl was dated to 5710 ± 155 ^{14}C yr BP; Figs. 5 and 6). The lake carbonates were deposited immediately on the sandstone. By comparison of differences in height between the wadi floor (526.5 m asl) and the highest lake carbonate (at 554.6 m asl), a maximum water depth of 28.1 m can be inferred.

For the areas west of Wadi Fesh-Fesh, the DGPS measurements result in a West Nubian Palaeolake area of 5330 km^2 at the maximum lake level of 555 m asl with a lake volume of 47 km^3 (calculated average lake depth 8.8 m; Fig. 3). This calculation does not account for lake areas which existed within the Wadi Fesh-Fesh and its connection to El Atrun as these areas were not fully covered by our DGPS measurements.

3.1.2. A large, coherent freshwater lake at 540–550 m asl

The land surface between 540–550 m asl is characterized by largely exposed lake carbonates which are almost void of quartz sand. Large lake-carbonate yardangs occur particularly in the southeast. The surface of the lake carbonates has been subjected to severe deflation and southward movement of recent dunes (barchans) due to the prevailing northeasterly trade winds.

The southwestern bank of the West Nubian Palaeolake is marked by palaeowadis which run into the lake and originate in the eastern flanks of the Ennedi Mountains. In the field these wadis are less recognizable than on satellite imagery because of merging with more recent sand shields at ground level. Southwest of the palaeolake basin these sand shields reach altitudes of more than 570 m asl and form the border of the palaeolake.

The palaeowadis are marked by sandy mud (indicating swampy environments), sandy lake carbonates (indicating shallow lakes) as well as bleached dune sand (littoral areas) with calcified reed stems and goethite crusts (Pachur et al., 1990). The lake carbonate section P195 (18°20′N/25°23′E; 546.0 m asl; dated to 7390 ± 70 ^{14}C yr BP at the top and to 9400 ± 90 ^{14}C yr BP at the base at 544.2 m asl; Figs. 5 and 6) is located at the edge of the palaeolake in the extension of the mouth of the northernmost of the three wadis coming from the Ennedi. The contour lines clearly show the delta and delta bedding of the wadi. The section is characterized by an alternation of lake carbonates and thin layers of fine sand at the top with an overall thickness of the lake carbonate of >180 cm. Section N90 (18°24′N/25°35′E; Fig. 5) is located in the southeast within the deeper part of the palaeolake where the lake carbonates reach thicknesses of 260 cm (base of lake carbonates at 541.4 m asl; top at 544 m asl and dated to 7100 ± 70 ^{14}C yr BP).

The surface of the coherent freshwater lake was oscillating between 400 km^2 (at a lake level 540 m asl) and 3880 km^2 (at 550 m asl; Fig. 3). During this stage the lake volume reached up to 22 km^3 and the average lake depth was between 3.6 m (at 545 m asl) and 5.7 m at a lake level of 550 m asl.

3.1.3. Segmented freshwater lakes below <540 m

Below a lake level of 540 m asl the resulting lake area (<400 km^2) was subdivided into several smaller basins with a total volume of 1.3 km^3 and an average water depth of 3.2 m. This lake phase is reflected in section V121 (18°37′N/25°46′E). It shows a lake carbonate sequence with a thickness of 240 cm in the northeastern part of the basin (base of the lake carbonate at 536.1 m asl and dated to 9155 ± 115 ^{14}C yr BP; top of lake carbonate layer at 538.5 m asl and dated to 7230 ± 90 ^{14}C yr BP). A larger non-segmented water body existed only below 540 m asl in the central part of the lake between 18°24′ and 18°36′N and 25°21′ and 25°27′E (Fig. 2a and b).

3.2. Sedimentology and geochemistry

The carbonates overlie unstratified, bleached aeolian sand. The transition from aeolian to limnic sedimentation is restricted to a layer of only a few centimetres, and changes from aeolian sand to lake sand (sporadically fine gravel), and finally to lake carbonates. The lake sand is grey due to the presence of up to 0.5% of organic carbon, and contains burrows. It probably represents an aeolian sand that was redeposited by local fluvial transport prior to the lake transgression.

The lacustrine sediments consist of white massive and compact carbonates. Broad desiccation cracks refilled with fragments of lake carbonates indicate

fluctuating water levels toward the end of the Holocene wet phase in all sections. The terminal lake phase is not recorded in all sections. Taking into account calculated sedimentation rates of 0.8–1.4 mm/a (Figs. 5 and 6) and a wet phase duration of 5700 years until 3800 ^{14}C yr BP, a deflation of ca. 2.6–4.6 m of sediment has to be assumed.

3.2.1. Composition and carbonate mineralogy

The calcium carbonate content of the lake carbonates ranges from 30.3 to 94.3%. The standard mean average of calcium carbonate for these sections lies between 59.8 ± 10% (P243/N94: $n = 59$) to 79.5 ± 12% (N90: $n = 27$). Treatment with a 10% HCl solution resulted in an insoluble residue consisting mainly of diatoms, clay and quartz grains that varied between 6.7 and 55.4%. The grain size distribution of this detrital matter peaks in the middle to fine silt fraction (20–2 μm: 42–89%), has an extremely low sand content >63 μm (maximum 6.7%) and a variable content of <2 μm (3–58%). The lacustrine deposits are therefore almost sand-free pelites (mudstones), composed primarily of carbonate and diatom frustules with low values of clay, indicating a rather dense vegetation cover.

The lake carbonates primarily comprise calcite and high Mg-calcite with varying amounts of magnesium substitution in the calcite lattice between 0 and 10.5 mole% Mg (Fig. 5). In addition to the high Mg calcite, low Mg-calcite (<4 mole% $MgCO_3$) and calcite also occur in all of the profiles. The element mole ratios Mg/Ca and Sr/Ca closely follow the rate of Mg substitution in the calcite lattice (Fig. 5). The fluctuations of the element mole ratios of the lake carbonates and the amount of Mg uptake in the calcite's crystal structure indicate only slight differences in the salinity of the palaeolake water between each profile and throughout the palaeolake. The average Sr/Ca mole ratios well below 3×10^{-3} confirm that all of the observed palaeolake stages were freshwater lakes. However, minor fluctuations of the lake's palaeosalinity occur in different levels of the sections and may reflect their topographic position. The more littoral section P195 shows lower ion concentrations at the beginning (between 9400 and ca. 9000 ^{14}C yr BP) and slightly brackish conditions towards the top of the section (between 9000 and 7400 ^{14}C yr BP). The topographically low-lying sections N94/P243 and A859 show higher ion concentrations at the beginning of the lacustrine sedimentation (from 9200 to 7500 ^{14}C yr BP) and freshwater conditions towards the top of the sections (Fig. 5). This may point to the existence of a chemocline for the deepest basins within the Wadi Fesh-Fesh during highest water levels. A chemocline did not exist for the topographically higher positions (sections N90 and P195) where only minor differences in the carbonate geochemistry occur. N90 reveals higher portions of detrital input due to the relatively small distance to the palaeowadis which entered the palaeolake from the south. The Mg/Ca and Sr/Ca ratios of section V121 show very narrow ranges and indicate stable freshwater conditions. The abundance of planktonic diatoms (*Aulacoseira granulata*) and the dominance of the ostracods *Darwinula* spp. and *Limnocythere* spp. (Hoelzmann, 1992, 1993) corroborate the stability of these lakes, and the salinity ranges inferred from geochemical analyses indicate freshwater to oligohaline lakes with a <3–5‰ salinity.

3.2.2. Stable oxygen isotopes

The measured oxygen isotope ratios of the lake carbonates (Fig. 5) can be compared with the isotopic ratios expected for carbonates formed at these latitudes and altitudes. According to Abell and Hoelzmann (2000), isotope ratios of the bulk carbonates for the West Nubian Palaeolake at 18°20′N and about 500 m asl elevation are near −5.8‰ δ^{18}O. The most negative $\delta^{18}O_{PDB}$ value (−7.8‰ at site P195) of the lake carbonates in the West Nubian Palaeolake catchment indicates precipitation from lake waters highly depleted in ^{18}O, especially when taking into account the effects of evaporation that may have changed the δ^{18}O value of the calcite towards isotopically heavier values. Bulk carbonates from other sites in NW Sudan and southern Egypt exhibit even more depleted $\delta^{18}O_{PDB}$ values between −13.5 and −5.1‰ (Hoelzmann, 1993; McKenzie, 1993; Abell and Hoelzmann, 2000), originating from extremely depleted lake waters. In the deep wells and oases of NW Sudan, fossil waters show $\delta^{18}O_{SMOW}$ values from −11.2 to −6.4‰ (Thorweihe, 1986, 1990; Thorweihe et al., 1990). In southern Egypt a $\delta^{18}O_{SMOW}$ value of −8.4‰ (McKenzie, 1993), indicates that large quantities of isotopically depleted (light) precipitation fell in the form of intense tropical rainfall of

convective origin during the pluvial phases in the Eastern Sahara.

The $\delta^{18}O_{carb\ PDB}$ values of the West Nubian Palaeolake sequences generally follow the pattern of the element mole ratios (Fig. 5), ranging from −7.82‰ (P195) to +2.49‰ (P243/N94) with an average of 3.98‰ for all of the sections (N90 ∅ = −3.8; A858 ∅ = −3.4; N94/P243 ∅ = −3.2; V121 ∅ = −3.4). Immediately after the onset of limnic sedimentation, the $\delta^{18}O_{carb}$ values were relatively negative and varied between −4.5 and −3.4‰. The uniform course without major shifts of the $\delta^{18}O_{carb}$ curves indicates that the lakes were stable and that a state of equilibrium existed between an uninterrupted (continual) water supply and evaporation. This stability is corroborated by the parallelism of the $\delta^{18}O_{carb}$ curves with the $\delta^{13}C_{carb}$ curves throughout all sediment profiles for the period from the onset of the limnic sedimentation until ca. 6500 ^{14}C yr BP. This covariant trend in the isotopic analyses of the lacustrine sediments as well as the consistency with the other geochemical analyses (Mg/Ca and Sr/Ca ratios) reflect hydrological changes to a closed lake system from which the lacustrine carbonates precipitated (Talbot, 1990). This covariance is only disturbed in the sections within the Wadi Fesh Fesh (N94/P243 and A859) where a major shift in $\delta^{13}C_{carb}$ occurred towards more negative values after ca. 6500 ^{14}C yr BP — a period that is not reflected in the other sediment sections probably due to the severe deflation. Without additional analyses (especially $\delta^{13}C_{org}$) the reasons for such a large shift over >10‰ must remain speculative. However, such negative $\delta^{13}C_{carb}$ values may result from anoxic conditions at the sediment water interface with (diagenetic) methanogenesis followed by oxidation of methane to CO_2 with highly depleted $\delta^{13}C$ as traced in the precipitated lake carbonates. Anoxic conditions are supported from dark coloured ostracode valves within this part of the section (personal communication Günther, 1987). The anoxic conditions may have resulted from higher water levels accompanied with weaker mixing of the water column. Short-lived episodes with higher water levels within the wadi system do not necessarily reflect more humid conditions after 6500 ^{14}C yr BP, as they could result from local changes within the catchment (i.e. temporary formation of dune barriers).

3.2.3. Radiocarbon chronology

Dating inconsistencies and age reversals occur throughout the sections for the carbonate dates as demonstrated by age–depth correlation (Fig. 6). This shows that the carbonates are influenced by reservoir effects (Olsson, 1986). Apparent changes in sedimentation rates — which were not confirmed by the sedimentary record — suggest that the reservoir effects have changed through time.

The average sedimentation rate for the sequences varies between 0.8 and 1.4 mm/a. Thus, the carbonate date 3805 ± 65 ^{14}C yr BP at section A859 seems to be too young as the sediment accumulation rate would increase to >1.9 mm/a. However, a duration of the wet phase until as late as ca. 3800 ^{14}C yr BP is supported by dates of faunal remains (Fig. 6) within the West Nubian Palaeolake basin and other localities of the Eastern Sahara (Pachur and Hoelzmann, 1991; Hoelzmann, 1993; Kröpelin, 1993), as well as from geologic evidence from palaeolakes at El Atrun where the sebkha stage was reached at ca. 3700 ^{14}C yr BP when trona formation began (Goschin, 1988).

The radiocarbon dates that correspond to the sedimentary record reflect Holocene ages and carbonate sedimentation in the West Nubian Palaeolake ranging from ca. 9500 to at least 5600 ^{14}C yr BP and probably as late as 3800 ^{14}C yr BP. The onset of lacustrine sedimentation in the core region of the lake was dated between 9400 ± 90 (P195), 9155 ± 115 (V121) and before 9040 ± 80 ^{14}C yr BP (AMS date; N90). Wadi Fesh-Fesh shows a similar onset at 9180 ± 135 ^{14}C yr BP (8600 ± 80 ^{14}C yr BP; AMS date; P243/N94). This is consistent with dates from other investigated sites in the Eastern Sahara (Gabriel and Kröpelin, 1983; Ritchie et al., 1985; Ritchie and Haynes, 1987; Haynes et al., 1989; Pachur et al., 1987, 1990; Pachur and Kröpelin, 1987; Pachur and Hoelzmann, 1991, 2000; Kröpelin, 1993, 1999) which indicate a rapid shift to more humid conditions at approximately 9500 ^{14}C yr BP.

Due to deflation, the end of the early to mid-Holocene wet phase cannot be dated by lake carbonates. The youngest dated lake carbonates within the West Nubian Palaeolake show an age of 7100 ± 100 ^{14}C yr BP (section N90) at a height of 543.5 m asl. Within the topographically low-lying Wadi Fesh-Fesh, lake carbonates occur as late as 5710 ± 155 ^{14}C yr BP (section P243/N94 at a height of 538 m asl) or as

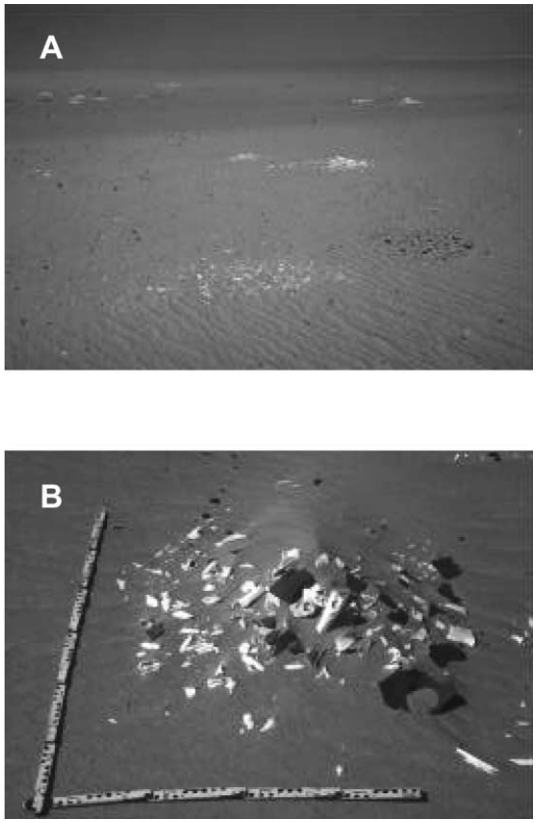

Fig. 7. Typical, open-air archaeological site at 18°13′N/25°14′E in the littoral zone southwest of the West Nubian Palaeolake. (A) Overview. In the flat landscape the dense scatter of archaeological finds is fairly discernible. The pottery and bone concentrations — here identifiable as dark and white spots — are evidence of settling activities. (B) Detail. The photo exhibits pottery and bone concentrations at the surface. This is the eroded rest of a former pit, which was filled with Leiterband pottery fragments and bone remains.

late as 3805 ± 65 ^{14}C yr BP (section A859 at 540.5 m asl). The sediments and their geochemistry still indicate freshwater conditions at that time in the Wadi Fesh-Fesh. However, according to continuous sedimentary records from the oases Selima, Oyo and Atrun (Ritchie et al., 1985; Ritchie and Haynes, 1987; Haynes et al., 1989; Pachur et al., 1990) the termination of the wet phase can be tentatively placed at around 4000 ^{14}C yr BP.

3.3. Archaeology

The archaeological investigations focus on the following points: had this area been occupied by humans, and if so, how do the occupation phases correlate with the lake evolution? How did humans use the changing environments and its resources during the different stages of the lake evolution? Were there obvious cultural contacts with human groups in adjacent regions?

A total of 301 open-air sites (Fig. 7) have been recorded. They indicate an intensive prehistoric occupation of the littoral zones of the West Nubian Palaeolake during the early and mid-Holocene. The distribution of the archaeological sites turned out to be very diverse (Fig. 8a–d). In the northeastern part of the palaeolake, archaeological remains are very scarce and mainly consist of some single finds of stone artefacts. The majority of the sites (98%) are situated in the southwestern palaeolake area, stretching from more elevated dune areas into the main basin of the lake.

3.3.1. Chronology

Judging from the archaeological inventories, the prehistoric occupation of the West Nubian Palaeolake basin lasted from 6300 to 3500 ^{14}C yr BP (Figs. 9 and 11). Since pottery fragments are the most characteristic finds on nearly 90% of the discovered sites, they were used first for chronological and cultural classification of the archaeological material (Fig. 9). Pottery has been found on 263 sites, and at least four pottery types with different chronological phases can be distinguished. They comprise — in chronological order — Dotted Wavy-Line, Laqiya, Leiterband and Halbmond-Leiterband pottery (Fig. 10).

All four pottery types are represented in the stratigraphy of the settlement dune Conical Hill 84/24 (Gabriel et al., 1985) where a test excavation yielded a pottery sequence 1.25 m deep and provided a first rough chronological framework. Dotted Wavy-Line pottery, mainly in the lowest layers, is followed by Laqiya pottery and the Leiterband pottery. The whole sequence is topped by Halbmond-Leiterband pottery. Corresponding sequences are found on the settlement dunes S95/2 and S97/1 in the Lower Wadi Howar.

Studies of the material from the West Nubian Palaeolake basin itself, as well as that from the Wadi Howar to the south (Keding, 1998, 2001a,b, 1997a,b; Jesse, 1998, 2001a,b; Kuper, 1995), show that the four pottery phases cover at least a period

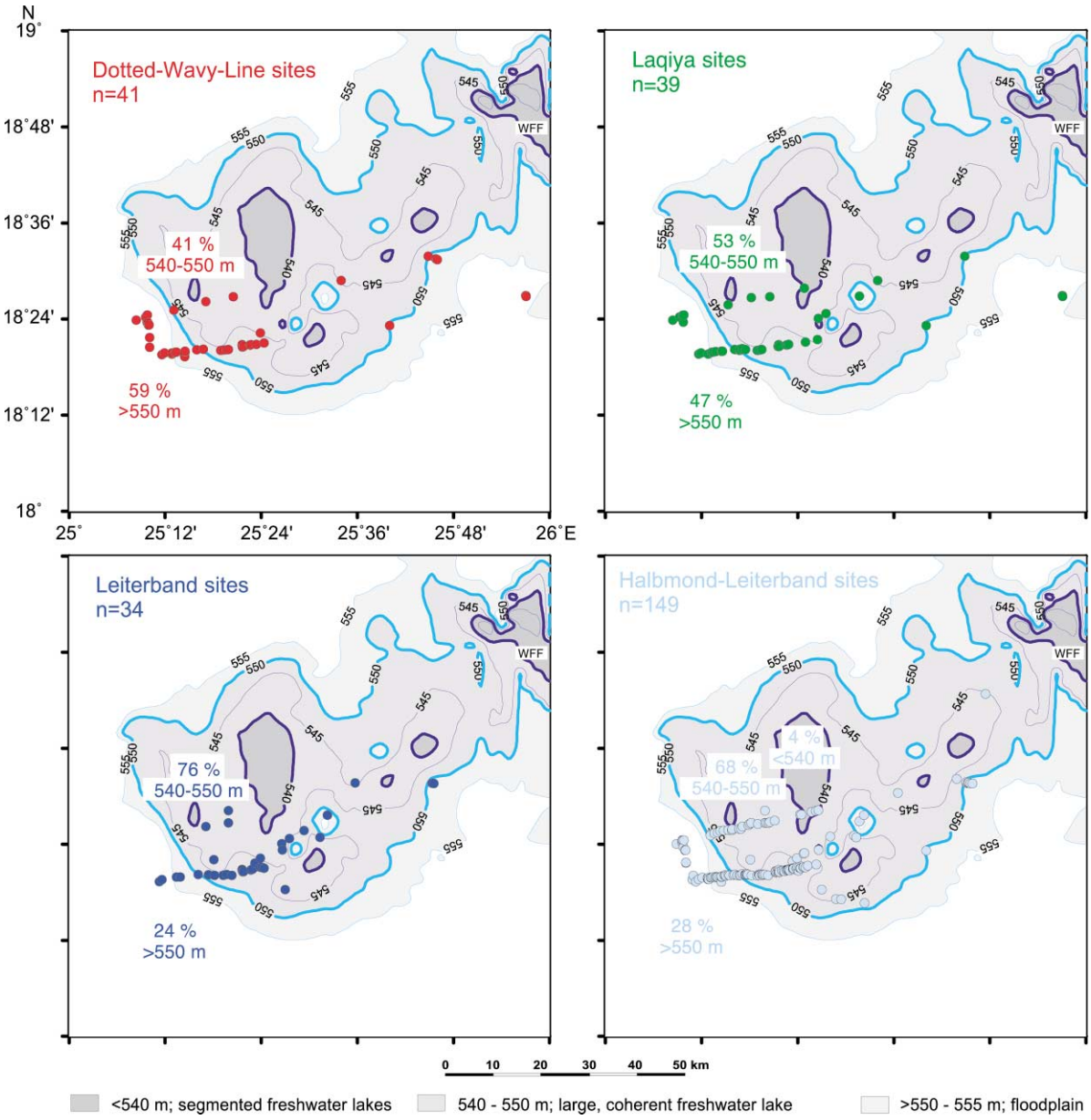

Fig. 8. Spatial distribution and percentages for archaeological sites of the different pottery phases related to identified lake stages within the West Nubian Palaeolake.

from 6300 to 3500 ^{14}C yr BP (Fig. 11). A total of 11 radicarbon dates from five sites in the Wadi Howar region and the West Nubian Palaeolake basin containing Dotted Wavy-Line and Laqiya pottery ranged mainly between 6000 and 5300 ^{14}C yr BP. Since a clear chronological order for these two pottery types is not proved by these dates, further reference to supra-regional comparisons and the above mentioned stratigraphic evidence from the settlement dunes in the Lower Wadi Howar indicates a general earlier

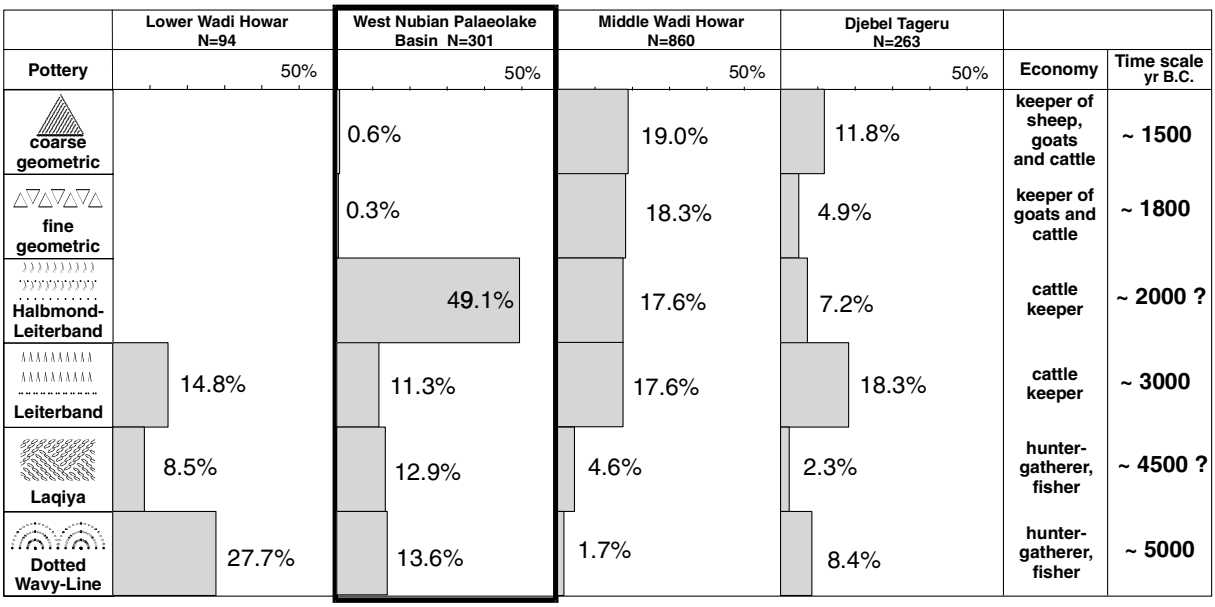

Fig. 9. Archaeological sequences of the West Nubian Palaeolake basin and adjacent research areas. '*N*' indicates the total number of sites in each area. Percentages indicate the share of sites with pottery of the different phases. Since sites where no pottery was found as well as sites which had been reoccupied during different phases are included, the sum is never 100%.

appearance of the widespread Dotted Wavy-Line pottery than the regional distributed Laqiya pottery.

On the basis of 15 radiocarbon samples, the Leiterband complex dates chiefly between 5200 and 4000 ^{14}C yr BP. A chronological subdivision into two phases — Leiterband and Halbmond-Leiterband — is still mainly based on the stratigraphy of the Conical Hill 84/24 site (Gabriel et al., 1985).

Two different subsistence patterns are associated with the different pottery styles. In the early phases — which are characterized by Dotted Wavy-Line and Laqiya pottery — the people were mainly hunter–gatherers. In the later phases — characterized by Leiterband and Halbmond-Leiterband pottery — they had changed to a cattle-herding way of life (Fig. 9). Hand in hand with the changing economy, a change in the settlement pattern can be observed; in the use of land and resources as well as in the structure, spatial and temporal distributions and the density of sites (Keding, 2001b).

3.3.2. Correlation between occupation phases and stages of the lake evolution

The archaeological data indicate that the Holocene occupation of the West Nubian Palaeolake basin mainly took place during the existence of the stable freshwater lake. However, settlement of the West Nubian Palaeolake basin area apparently did not start synchronously with the formation of the lake. Although a significant increase of local rainfall in this region occurred around 9400 ^{14}C yr BP, the earliest indications of human settlement date from about 6300 ^{14}C yr BP, a lag of ca. 3300 calendar years (Fig. 11). In contrast, the end of the occupation of the West Nubian Palaeolake basin seems to coincide roughly with the end of the wet phase around 3500 ^{14}C yr BP, which finally led to a complete desiccation of the lake.

Since the archaeological sequence reveals constant settlement activity in the area between the seventh and the fourth millennium BP, it is assumed that site mappings and settlement patterns as well as the various economic activities would reflect particular stages of the palaeolake in each period.

3.3.2.1. Dotted Wavy-Line and Laqiya pottery phases. Fourteen percent of the 301 known sites in the research area are attributed to the Dotted Wavy-Line

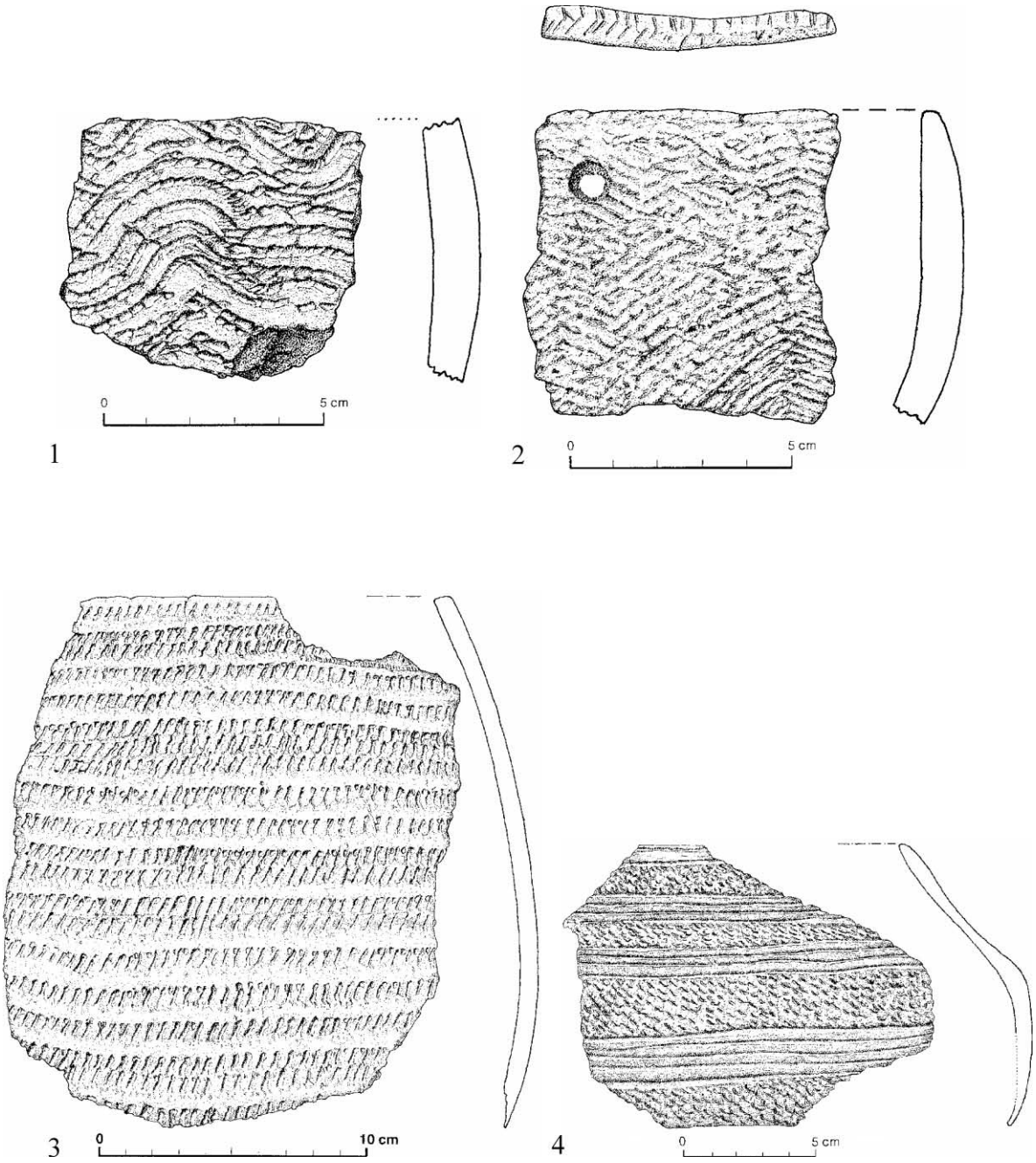

Fig. 10. Pottery samples showing different pottery types: 1 — Dotted Wavy-Line, S98/20 site; 2 — Laqiya, S98/21 site; 3 — Leiterband, S99/1 site; 4 — Halbmond-Leiterband, S98/24 site.

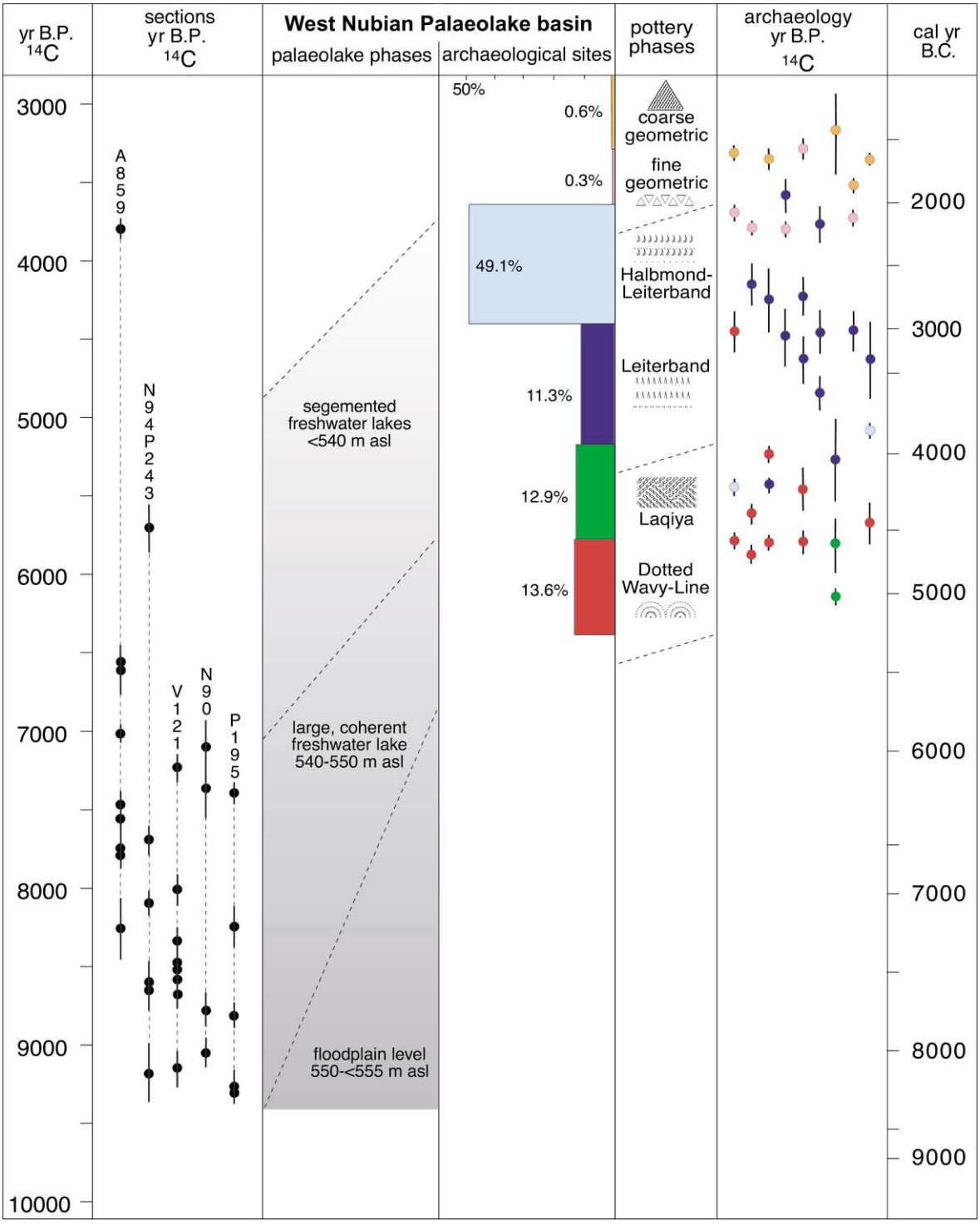

Fig. 11. Synthesis diagram relating archaeological to geological radiocarbon dates and pottery phases to lake stages. All dates are plotted as ^{14}C yr BP. The Archaeological dates include all available radiocarbon dates from the entire Wadi Hawar Region (see also page 8).

period, mainly dated to the sixth millennium BP (Figs. 9 and 11). They are scattered along the southwestern shore of the palaeolake during the early Holocene with its probably seasonal floodplain (Fig. 8). One centre of distribution lies above the 550 m contour line (59%) and a second one between the 540 and 550 m contour line (41%). This distribution pattern is consistent with the radiocarbon dates and confirms the assumption of a diachronous start of lake evolution and human occupation in this area (Fig. 11). It indicates that during this period the lake only seasonally rose higher than 540–550 m asl. On the other hand, there are no Dotted Wavy-Line sites below a level of 540 m asl. Therefore, a lake level near 545 m asl with seasonal flooding occurred most likely as late as 6000 ^{14}C yr BP.

Nearly the same picture emerges for the succeeding period which is characterized by Laqiya pottery (Fig. 8). The density and location of the sites did not change. Thirteen percent of all known settlements belong to this period. The majority of the settlements are still located above 550 m asl (47%) and between 540 and 550 m asl (53%). However, the distribution of the sites reveals a slight move to lower grounds.

The favourable environment providing man with manifold permanent resources seems to have been characteristic of this way of life during these early occupation phases. For the users of Dotted Wavy-Line and Laqiya pottery, the archaeological evidence indicates a sedentary or semi-sedentary, non-specialized foraging waterfront life-style. Most sites of both periods are located on large dunes. Although no clear evidence of habitation structures has been discovered so far, the usually very large size of the settlements as well as the dense scatter of occupational refuse point to long-term stays or repeated stays. This (semi-) sedentation must have been triggered by a favourable environment. The artefacts as well as the faunal remains indicate a wide range of economic activities. The large number of lower and upper grinding stones, present in different raw materials and in a wide variety of forms, point to an intensive exploitation of wild plant food. The spectrum of stone artefacts which is dominated by flakes and lunates, suggests hunting activities with microliths used as hunting projectiles.

The faunal remains indicate hunting as well as fishing (Berke, 2001). Bones with clear butchering traces demonstrate big game hunting of a wide range of animals such as hippopotamus, giant buffalo, elephant and giraffe. Also smaller animals such as warthog and oryx-gazelle were hunted. Large vertebrae of Nile perch (*Lates niloticus*) with lengths of more than 1 m underline the importance of lake resources. Unambiguous evidence of the keeping of domesticated animals has not yet been found in either archaeological contexts.

The large amount, composition and evidence of some special items of the material culture support long-term stays on the sites. Among the preserved finds — mainly composed of pottery, stone artefacts, grinding stones, ostrich-egg shell fragments and beads — the large number of high quality pottery fragments is especially remarkable. They include sherds of well made, large, heavy and at times extremely thick-walled, round or knobbed bottomed pots. These were made using the coiling technique and tempered with a large range of different inorganic as well as organic material. Whereas in the earlier phase the pottery was mostly decorated from rim to base in various kinds of Dotted Wavy-Line patterns, in the later phase Laqiya decoration seems to have become more popular (for Dotted Wavy-Line and Laqiya pottery in the Wadi Howar region see Jesse, 1998, 2001a,b). These vessels were probably used for cooking, but the very large and heavy pots were more likely used for storage.

Some typical but less numerous finds provide additional hints pointing to long-term inhabitation. Small stone balls, often made of colourful raw materials, as well as ostrich-egg shell beads are a possible indication of leisure time activities on the dunes.

3.3.2.2. Leiterband and Halbmond-Leiterband pottery phases. Whereas both early occupation phases coincide with early Holocene large freshwater lake with water levels between 540–550 m asl, the succeeding occupation phases, characterized by two styles of Leiterband-decorated pottery, are more clearly marked by an increasing aridity of the environment. These occupation phases coincide with segmented freshwater lakes below 540 m asl.

During the Leiterband phase, which represents 11% of the total of 301 sites (Fig. 9) and which mainly dates from 5200 to 4000 ^{14}C yr BP, the distribution of settlements indicates an increasing use of lower ground at the southwestern shores of the lake. At

this time, the majority of sites are located between the 540 and 550 m contour lines (76%; Fig. 8). This site distribution points to a continuing drop in lake level. However, since no sites are situated below the 540 m contour line, freshwater lakes still existed at a level of ca. 540 m asl during this phase.

In the succeeding Halbmond-Leiterband phase which marks the end of the occupation of this region, two points are striking: firstly, the distribution of Halbmond-Leiterband sites does not differ markedly from the distribution of the Leiterband sites (Fig. 8). It is therefore assumed that stable freshwater lakes still existed during the last occupation phase. However, nearly 30% of the sites are situated below 545 m asl, and five sites are even below 540 m asl. This confirms the relative chronological sequence of the pottery phases and indicates a fragmentation of the large freshwater lake into several smaller ponds near the end of the human settlement (Fig. 11). Secondly, a significant increase in the number of sites is observed. Almost 50% of all recorded settlements ($N = 149$) belong to the Halbmond-Leiterband pottery phase probably dated to the fourth millennium BP (Fig. 8). However, this remarkable increase in the number of sites does not mean an intensified use of the area in comparison to the Dotted Wavy-Line and Laqiya horizons but rather a different economic use of the region.

Considerable cultural and economical changes become obvious. The Leiterband and the later Halbmond-Leiterband phases are connected to people who have adopted a fully developed food-producing economy (for Leiterband in the Wadi Howar region see Keding, 1997a). Cattle-rearing groups now occupied the lake region (Berke, 2001). However, so far neither the exact origin of the adoption of a pastoral economy nor the process of transition from hunter–gatherer to cattle-herders in the Wadi Howar and the West Nubian basin region can be traced in detail. Diffusion of the new way of life through — perhaps seasonal — contacts between hunter–gatherers from the lake region with pastoralists from the Nile Valley is conceivable. According to the faunal remains, the people using Leiterband and Halbmond-Leiterband pottery were basically cattle-herders, probably well provided with milk and blood by their animals. Judging from fish remains they also exploited aquatic resources. Hunting seems to have been of less importance. However, butchering traces on some hippopotamus bones indicate large game hunting and the existence of a permanent lake. Plant use certainly played an important role, but cannot be detected in more detail. Lower and upper grinding stones are recorded on nearly all the sites.

As a result of the economic transition and the increasing aridity, the settlement patterns also changed: the size of the sites became smaller, and the location of most sites moved from the top of the dunes towards the lake shore (Keding, 2001a,b). Judging from the structure of the sites and the finds, many settlements in the West Nubian Palaeolake basin were used as temporary grazing camps within the seasonal migration cycles of the pastoralists. The Middle Wadi Howar which is characterized by larger sites, probably was the focal point within these transhumance cycles. Moreover, in both areas, some large sites with special features, such as dozens or even hundreds of pits filled with cattle bones and almost complete vessels, indicate special activities at these places (Keding, 1997a). Archaeological and ethnographical comparisons point to rituals, signifying the social significance of these features, which are peculiar to the research area in this particular form. They point to a social intensification in this period of increasing aridity, and a possible development of a specialized pastoralism, where cattle played an important role in the economic as well as in the ritual sphere.

In contrast to the profound changes in different sectors of life, the assemblages from the Leiterband and Halbmond-Leiterband sites did not change very much. They are mainly characterized by certain forms of stone artefacts, axes and pottery (Keding, 1993). Among the stone artefacts, various transverse arrowheads, 'mega'segments as well as scrapers, especially small forms, are typical. Because of the lack of remains of hunted animals, the microliths are not interpreted as hunting projectiles but rather as tools for bleeding cattle — a custom still practised by cattle-rearing groups in the Sudan. The numerous scrapers in different forms may point to an intensive finishing of skins. Necked axes in different sizes, classified as axes of the Darfur type, demonstrate wood working and corresponding vegetation.

The most prominent finds are the numerous pottery fragments, consisting mostly of medium-sized, neckless pots with round bottoms. Their whole surfaces are often decorated overall with banded patterns which

run parallel to the rim. They are mainly produced in a rockerstamp return technique with a special kind of implement. The results are banded ladder-like decorations which in the earlier Leiterband phase are characterized by straight impressions, in the later Halbmond-Leiterband phase by rounded impressions (Keding, 1997a, 1998).

In conclusion, the archaeological record of the Leiterband and Halbmond-Leiterband pottery phases, mainly dated between 5200 and 4000 ^{14}C yr BP, indicates an intensive use of the region by cattle-rearing groups. After this occupation phase the area was abondoned. Later archaeological remains are very rare, which proves the dramatic deterioration of the environmental conditions in the fourth millennium BP.

3.3.3. Supra-regional and regional context

Since the occupation of the West Nubian Palaeolake basin is embedded in the climatic and occupation history of the Eastern Sahara, it has to be interpreted in a supra-regional and regional context.

Supra-regional comparison of the different pottery styles demonstrates far reaching connections with the Southern Sahara as well as an increasing regionalization. The Dotted Wavy-Line pottery which characterizes the earliest Holocene occupation of this area, fits into the known 'Khartoum Horizon Style' (Hays, 1971). Its distribution includes the whole Southern Sahara from the Sudanese Nile Valley (Arkell, 1949), to Chad (Bailloud, 1969), Libya (Cremaschi and Di Lernia, 1998), Algeria (Camps, 1969), Mali (Raimbault, 1994), Niger (Roset, 1987) and the Atlantic coast and covers a period between the 10th and the 6th millennium BP. Besides the use of comparable vessels, many of these early pottery manufacturing groups led a broadly similar life as hunter–fisher–gatherers in the vicinity to lacustrine environments (Garcea, 1993). The decoration of the pottery from the research area belongs to the eastern variant of Dotted Wavy-Line pottery which is distributed between the Ennedi Mountains in the west and the Nile Valley in the east (Jesse, 2001a,b). However, both the origin of the earliest Holocene settlers of the West Nubian Palaeolake basin after the end of the arid post-aterien phase (Jesse, 2001a,b) and the cause of their comparably late appearance in the region are still unclear. Possible areas of retreat prior to the repopulation of the Eastern Sahara could be the Sahel or the Nile Valley (Close, 1995), which are not far away. Long distances as the cause for a delay of 3300 calendar years in the recolonization of the Wadi Howar region can therefore be excluded. Another reason for the delay could have been the apparently favourable but rather humid environmental conditions. During the most humid phase with its extensive floodplains, the West Nubian Palaeolake basin was probably too swampy for colonization. Only with the development of the large stable lake with a confined areal extent, did the region become favourable for human life.

The succeeding, to a certain extent contemporaneous, Laqiya pottery type is already a regional development of the Wadi Howar and Laqiya area. Its main distribution between the Middle Wadi Howar, the Wadi Shaw and the Laqiya area 400 km to the northeast (Kuper, 1986, 1995; Schuck, 1989) indicates north–south rather than east–west connections.

Clear influences from the cultures of the Nile Valley become apparent during the Leiterband phase of the cattle pastoralists. In the early periods of the Leiterband pottery, connections with the 500–1000 years older Khartoum Shaheinab culture (Arkell, 1953; Caneva, 1988) of the Sudanese Nile Valley are obvious in the material as well as in some traits of the economic system. During the fifth millennium BP in the Wadi Howar region, different pottery variants within the Leiterband style developed (Keding, 1997a,b). At first these were mainly distributed in the Middle Wadi Howar, but later — during the Halbmond-Leiterband phase — also in the West Nubian Palaeolake basin and the Ennedi Mountains.

On a regional level, analysis of the archaeological inventories gives insight into the connections between the prehistoric populations of the West Nubian Palaeolake basin and its neighbouring areas as well as an understanding of their economic and cultural systems. The West Nubian Palaeolake basin was bordered by ecologically favoured areas during the early and mid-Holocene. These were the Ennedi Mountains to the west and the Wadi Howar and the Djebel Tageru to the south. The Ennedi Mountains, with a maximum height of 1100 m, are cut by deep valleys which are, still today, characterized by bush and tree vegetation and small seasonal and permanent lakes. The Wadi Howar, today a dry water course, was the largest tributary of the Nile from the Sahara

(Kröpelin, 1993, 1999). Its cultural and economic importance as a connection between Eastern and Central Africa must have been considerable. To the south, south–north trending palaeowadis along the foreland of the sandstone plateau of Djebel Tageru connected the Wadi Howar with the recent Sahel.

A cultural linking of the West Nubian Palaeolake basin to these areas with different ecological settings in the Holocene is reflected in the pottery sequence described above. The pottery types of the West Nubian Palaeolake basin are also distributed in the adjacent areas and emphasize strong cultural connections within the southeastern Sahara (Fig. 9). A comparative study of the prehistoric occupation sequences of the West Nubian Palaeolake basin, the Lower Wadi Howar, the Middle Wadi Howar and the Djebel Tageru reveal different durations as well as different centres of occupation for each pottery or settlement phase (Fig. 9). Distinct north–south and east–west gradients of settlement shifting from older to younger periods are obvious. These also reflect changes in the economic systems through time.

Considering the distribution and structure of Dotted Wavy-Line and Laqiya sites, as well as the indications of economic activities on the sites, the evidence is very similar in all areas. Except in the Middle Wadi Howar which seems to have been too swampy for long-term stays during this period, the data of all areas point to hunting–fishing–gathering populations with a comparable broad-spectrum utilization of resources.

During the Leiterband and Halbmond-Leiterband phases, profound changes become obvious. The various structures and sizes of sites as well as the indications of economic activities of the cattle-herders in each area now point to a seasonal exploitation of the different environments in the Wadi Howar region.

The distribution of Leiterband sites and the seasonal migration cycles in the early cattle-herding phase still included all four areas with their probable focal point in the Middle Wadi Howar. In the succeeding Halbmond-Leiterband phase, the trend towards increasing aridity continued and the Lower Wadi Howar became too arid for permanent occupation while the ecological situation was still favourable in the West Nubian Palaeolake basin. Consequently, the transhumance cycles changed to more north–south orientated seasonal migrations, with a new centre in the West Nubian Palaeolake basin for grazing, fishing and gathering. However, there are also signs of supra-regional transhumance or even population displacements extending to the adjacent Ennedi Mountains more than 160 km to the southwest.

While the occupation sequence in the West Nubian Palaeolake basin ended during the fourth millennium BP, the settlement of the Middle Wadi Howar and the Djebel Tageru continued for at least another millennium (Fig. 9). During this period, characterized by sites with the geometric pottery of the cattle and small stock keepers, botanical and faunal evidence points to an increasingly arid, Sahelian climate. At this stage the transhumance cycles seem to become smaller and limited to the Wadi Howar and the Djebel Tageru until permanent occupation was finally abandoned.

4. Conclusions

By means of integrating DGPS measurements with geomorphological field mapping, geochemistry and archaeology it is now possible, for the first time, to make precise statements on the environmental and cultural evolution of the remote region of the West Nubian Palaeolake during the Holocene. The West Nubian Palaeolake was the largest coherent lake in the Eastern Sahara of Northern Sudan during the early to mid-Holocene wet phase. Earlier estimates of the lake area were solely based on the interpretation of Russian topographic maps (Soviet Ordnance Survey Map 1: 500,000, sheet 'Oasis El Atrun'), with their rather unreliable and incomplete altitudes, and postulated lake areas of 17.864 km^2 at a lake level of 550 m asl (Pachur, 1997) including areas east of the Wadi Fesh-Fesh.

With the new measurements presented here, these estimates can be disproved: the maximum size of the lake in the centre of the vast catchment area of the West Nubian basin and Wadi Fesh-Fesh did not exceed 5330 km^2. We can also show that during the Holocene wet phase, a direct connection of the West Nubian Palaeolake with the areas east of the Wadi Fesh-Fesh and southeast towards El Atrun can be excluded because of sandstone ridges which significantly exceed the detectable maximum lake level. However, during seasonal floods which did not

produce thick layers of lake carbonate sequence, a connection of the palaeolake with the Wadi Fesh-Fesh seems reasonable (floodplain level at >550–555 m asl). The widespread palaeolakes within the western foreland of El Atrun were connected only via the talweg of Wadi Fesh-Fesh to the West Nubian Palaeolake during this lake stage. Beyond that we must exclude the existence of an overflow into the basins of Nukheila and Oyo because these basins are also topographically separated from the West Nubian Palaeolake.

Closed lake systems are regarded as good indicators for palaeoclimate, as the lake area/catchment area ratio (z-value) reflects the relation of precipitation to evaporation and is near zero for arid regions (Street-Perrott and Harrison, 1985; Mason et al., 1994). Our results show for the West Nubian Palaeolake, with a catchment area of ca. 78,000 km^2, z-ratios between 0.07 (at a lake level of 555 m asl) and 0.005 (lake level of 540 m asl), compared to a significantly higher z-ratio of 0.3 calculated from Pachur's (1997) estimates at a lake level of 550 m asl.

Palaeohydrologic modelling for different scenarios also supports the results presented here. A palaeolake with an assumed area of 7000 km^2 and an estimated maximum evaporation of 2000 or 3000 mm/a would have required rainfall of 760 or 920 mm/a, respectively (Hoelzmann et al., 2000). For still larger lake areas such as those postulated by Pachur (1997), even higher figures of palaeo-rainfall would be required. Such high rates of precipitation, however, are not in line with any of the former rainfall estimates that are based on various and independent indicators and point to approximately 550 mm/a for the southeastern Sahara between 16 and 20°N during the Holocene humid optimum (Kröpelin, 1993).

During a stable, long lasting early to mid-Holocene freshwater phase with a coherent palaeolake surface (approximately 9400 to at least 7500 ^{14}C yr BP), thick lake carbonate sequences developed within the West Nubian Palaeolake. During this period the lake level reached 540–550 m asl with a maximum water depth of ca. 15 m. Based upon the DGPS measurements, this large, coherent freshwater lake covered an area of 1940–3880 km^2 with a respective water volume of 7–22 km^3. From these calculations it is inferred that palaeo-rainfall reached values between 460 and 600 mm/a during the Holocene wet optimum within the West Nubian Palaeolake basin.

Such environmental conditions coincide very well with the distribution of sites of the earliest occupation phase, characterized by Dotted Wavy-Line pottery (mainly dated between 6300 and 5300 ^{14}C yr BP) exclusively above the 545 m contour line (Fig. 11). Archaeological evidence for this period suggests a sedentary or semi-sedentary, non-specialized foraging waterfront life-style which corroborates the stable freshwater phase. Faunal remains prove fishing and hunting activities, rounding-up the picture of a favourable, stable environment during this early to mid-Holocene phase. From the discrepancy between the onset of the lake phase at about 9400 ^{14}C yr BP and the first known Holocene occupation around 6300 ^{14}C yr BP a lag-time of ca. 3300 calendar years can be estimated before the region became inhabited. It is assumed that the reason for this was the excessively swampy environment which made it unsuitable for human occupation. Thereafter the lake level fell and archaeological sites with Laqiya pottery can be found below 545 m asl. This indicates that Holocene settlements followed the decreasing lake level into topographic lower positions.

Below a level of <540 m asl, only fragmented freshwater lakes with a substantially smaller lake area (<400 km^2) and water volume (1.3 km^3) existed. Since the lake sequences in the palaeolake basin itself are affected by intense deflation, this lake phase could only be sampled and dated by the topographically low-lying section V121 and the sections within Wadi Fesh-Fesh (P243/N94; A859; Fig. 11). In the archaeological context this period is characterized by two different styles of the Leiterband-decorated pottery. During the Leiterband and Halbmond-Leiterband phases an increase in lower positions corroborates decreasing lake levels.

This is backed up by more near-shore sites at the foot of dunes and a decrease in their size, pointing to seasonal migration cycles of cattle-pastoralists and only seasonal occupation. The climatic transition to arid conditions around 4000 ^{14}C yr BP is reflected by the waning palaeolake, as well as in the increasing cultural regionalization. For the later times there is no archaeological evidence in the West Nubian Palaeolake basin due to the increasing aridity and the lack of open water.

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