DIE ERDE **135** 2004 (3-4)	Beitrag zur Regionalen Geographie	S. 321-340

• *Ancient dunes – Desert margin – Paleosols – Holocene – Chad*

Peter Felix-Henningsen (Gießen) and **Barbara Mauz** (Liverpool)

Paleoenvironmental Significance of Soils on Ancient Dunes of the Northern Sahel and Southern Sahara of Chad

Paläoökologische Interpretation von Böden auf Altdünen in der nördlichen Sahelzone und der südlichen Sahara in Tschad

With 2 Figures, 4 Tables and 6 Photos

Ancient dunes are widespread in the southern Sahara and northern Sahel of Chad. Optical dating provides evidence that the dunes formed in arid phases during the mid-Holocene between ~ 5 ka and ~ 3 ka. Thus the humid period in which the paleosols developed and the lacustrine sediments were deposited commenced after ~5 ka but before ~2.5 ka. Cambic Arenosols were formed by precipitation-induced silicate weathering and leaching. In basin regions of the Sahara they are partly covered by lacustrine sediments. In the northern Sahel the upper parts of the Cambic Arenosols are indurated, due to accumulation of soluble salts, carbonates and amorphous silica during a drier climate following the period of soil formation.

1. Introduction

The Late Quaternary North African climate is characterised by changes between arid and humid periods, which caused shifts of the southern desert margin of the Sahara. During arid periods the Sahara extended southwards and caused the formation of dunes in the Sahel region. Sediments of paleolakes in the Sahara and fossil and relic paleosols, which developed on ancient dunes, provide evidence for humid climatic periods that followed the arid phases as a result of a northward shift of the African summer monsoon. From previous investigations, three humid periods during the late Quaternary must be considered in the southern Sahara: a) a late Pleistocene (Ghazalien) humid period between 40,000 and 20,000 BP (*Servant* 1983), b) a late Pleistocene to early Holocene (Tchadien) humid period between 14,000 and 7,500 BP with a maximum humid period between 10,000 and 7,500 BP (*Servant* 1983), and c) a middle Holocene (Nouakchottien) humid period (Young Neolithic) between 4,500 and 3,000 BP (*Michel* 1973). Therefore the Sahara dunes are indicated as “ancient” if they are covered by lacustrine sediments and/or if paleosols developed at the former land surface. In that case ancient dunes occur as more or less eroded remnants at the recent land surface in deflated areas or below younger dunes in sedimentation areas. The paleosols of interdunal valleys often show characteristics of gleyification under the influence of ground water, or the formation of a brown or red cambic B-horizon due to the weathering of silicates. A further characteristic is the mechanical stabilisation of the dune sand in the paleosol horizons, due to the accumulation of clay, pedogenic Fe-oxides and amorphous silica by weathering of silicates, followed by the infiltration of soluble salts and carbonates during the subsequent arid period. Under the recent semi-arid to semi-humid climatic conditions, the ancient dunes of the Sahel region have been stabilised by a vegetation cover. Especially in the northern Sahel, the thickness of the soils and the intensity of weathering does not coincide with recent semi-arid climatic conditions. Therefore they are considered to be relic soils or fossil soils, respectively, when covered by eolian sand. The occurrence and the stratigraphical and paleo-environmental information of ancient dunes and paleosols of the Sahara and Sahel were previously studied in countries adjacent to Chad: in Sudan by *Warren* (1970) and *Felix-Henningsen* (1983, 1984), in East Niger by *Grunert* (1988), *Völkel* (1988, 1989), *Pfeiffer* and *Grunert* (1989), *Pfeiffer* (1991), *Völkel* and *Grunert* (1990) and *Felix-Henningsen* (2000), and in Nigeria by *Thiemeyer* (1992, 1994, 1995).

Figure 1 summarises the main results of the paleosol stratigraphy carried out in East Niger.

For Chad, only *Mauz* and *Felix-Henningsen* (2005) present results of optical dating of ancient dunes and they discuss the stratigraphical and paleo-climatical evidence for a middle Holocene arid period. In contrast to the extensive occurrence of mid-Holocene ancient dunes in the Sahara and Sahel of Chad, they only occur in the Grand Erg de Bilma, adjacent to the west of the study area in Chad, in rather small and limited areas in the form of sand sheets and lee dunes. This is a rather new and astonishing aspect, especially considering that the mid-Holocene arid period was of relatively short duration in comparison to the Pleistocene arid periods. Furthermore, there are pronounced differences between the study areas in Niger and Chad in the degree of weathering and paleosol formation on the mid-Holocene dunes. Due to the stronger degree of soil development and/or better preservation of the paleosols in Chad, as compared to Niger, the paleosols provide a more eligible opportunity for paleo-environmental interpretations. Hence this paper focuses on the paleo-environmental evidence of paleosols on ancient dunes that were investigated in the southern Sahara and northern Sahel of the Republic of Chad.

2. Study Area

The area under investigation is situated in central Chad, south of the Tibesti Massif (*Fig. 1*), covering a part of the southern Sahara and the northern Sahel between 13°N 16°E and 18°N 19°E. The sites studied were aligned on a transect from northeast to southwest, starting in the basin of Faya Largeau, across the adjacent sandstone plateaus and the Erg du Djourab in the south, and roughly following the Bahr el Ghazal wadi system towards the basin of Lake Chad (*Fig. 2*). The climate of this region is hyperarid. The annual precipitation ranges between < 10 mm at Faya (18°N 19°E) and about 100 mm in the northern Sahel region (13°N 16°E).

Bedrocks, which are exposed at the foothills of the Tibesti north of Faya or at the surface of higher plateaus, consist of Cretaceous sand- and siltstones.

Ancient dunes of the Sahara (*Fig. 2*, Sites 1 and 2) are denudated barchans, longitudinal dune ridges and lee dunes at cuestas and inselbergs. In plains they are covered by modern mobile dunes and eolian sand sheets (*Fig. 2*, Sites 3 and 4). In basins and valleys, shallow ridges of ancient dunes can be found below layers of lacustrine silts, diatomite and carbonate crusts

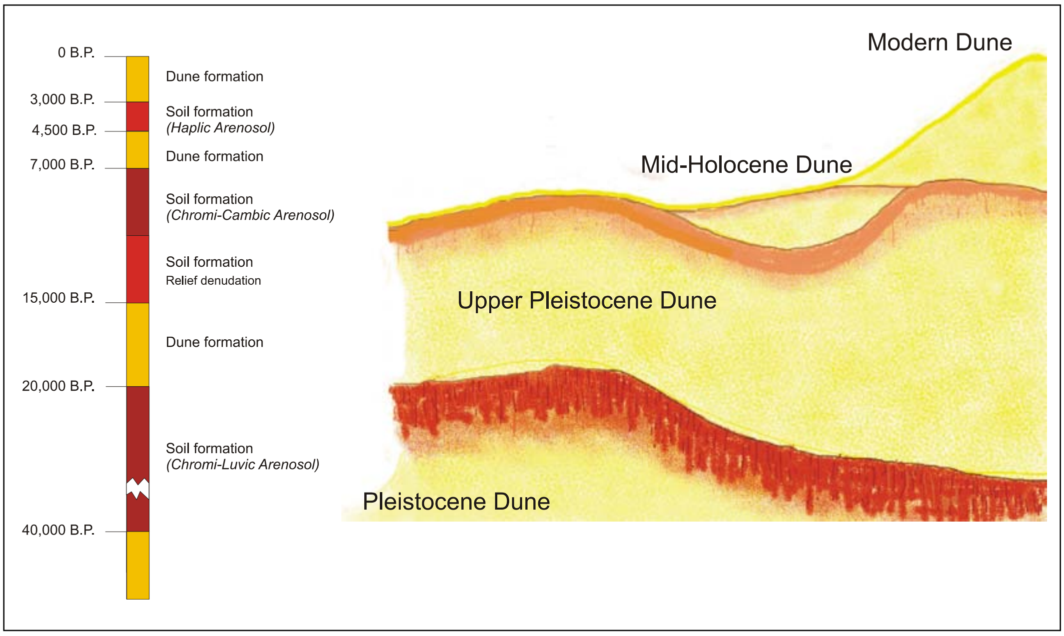

Fig. 1 Synthesis of the stratigraphy of ancient dunes and paleosols in the Sahara and Sahel of East Niger; ages according to *Michel* (1973), *Servant* (1973, 1983) and *Völkel* (1989): Pleistocene ancient dune: sporadic occurrences with a strongly weathered and indurated brown-red Chromi-Luvic Arenosol with clay accumulation (Btb horizon), Upper Pleistocene ancient dune: Greatest extension in the Ténéré and Grand Erg de Bilma, with a moderately weathered, up to 1 metre thick reddish-brown Chromi-Cambic Arenosol without clay migration, Mid-Holocene ancient dune: Sporadic occurrences in the Grand Erg de Bilma, with a weakly weathered and indurated brownish yellow Haplic Arenosol, Modern dunes: Unweathered and unconsolidated mobile dune sand of sand sheets, transversal and longitudinal dunes.
Zusammenfassung der Stratigraphie von Altdünen und Paläoböden in der Sahara und Sahelzone von Ostniger; Altersangaben nach Michel (1973), Servant (1973, 1983) und Völkel (1989): P1eistozäne Altdüne: Einzelvorkommen, mit einem stark verwitterten und verfestigten, braun-roten Chromi-Luvic Arenosol, der Tonanreicherungsbänder im Unterboden aufweist (Btb-Horizont). Jungpleistozäne Altdüne: Größte Verbreitung in der Ténéré und im Grand Erg de Bilma, mit einem mäßig verwitterten, bis zu einen Meter mächtigen rötlichbraunen Chromi-Cambic Arenosol ohne Tonverlagerung. Mittelholozäne Altdüne: Einzelvorkommen im Grand Erg de Bilma, mit einem schwach verwitterten und verfestigten bräunlichgelben Haplic Arenosol. Heutige Dünen: unverwitterte und mobile Dünensande der Flugsanddecken, Transversal- und Longitudinaldünen.

(*Fig. 2*, Sites 1 and 2), which were deposited in a humid period after formation of the dunes. In some places a terrestrial paleosol at the surface of the ancient dune is still preserved below the lacustrine sediments (*Fig. 2*, Site 1).

In the transition zone between the full arid Sahara and the semi-arid Sahel, a grass steppe developed. Here, ancient dunes form shallow ridges surrounded by paleo-lake basins (*Fig. 2*, Sites 3 and 4). Further south in the northern Sahel (*Fig. 2*, Sites 5

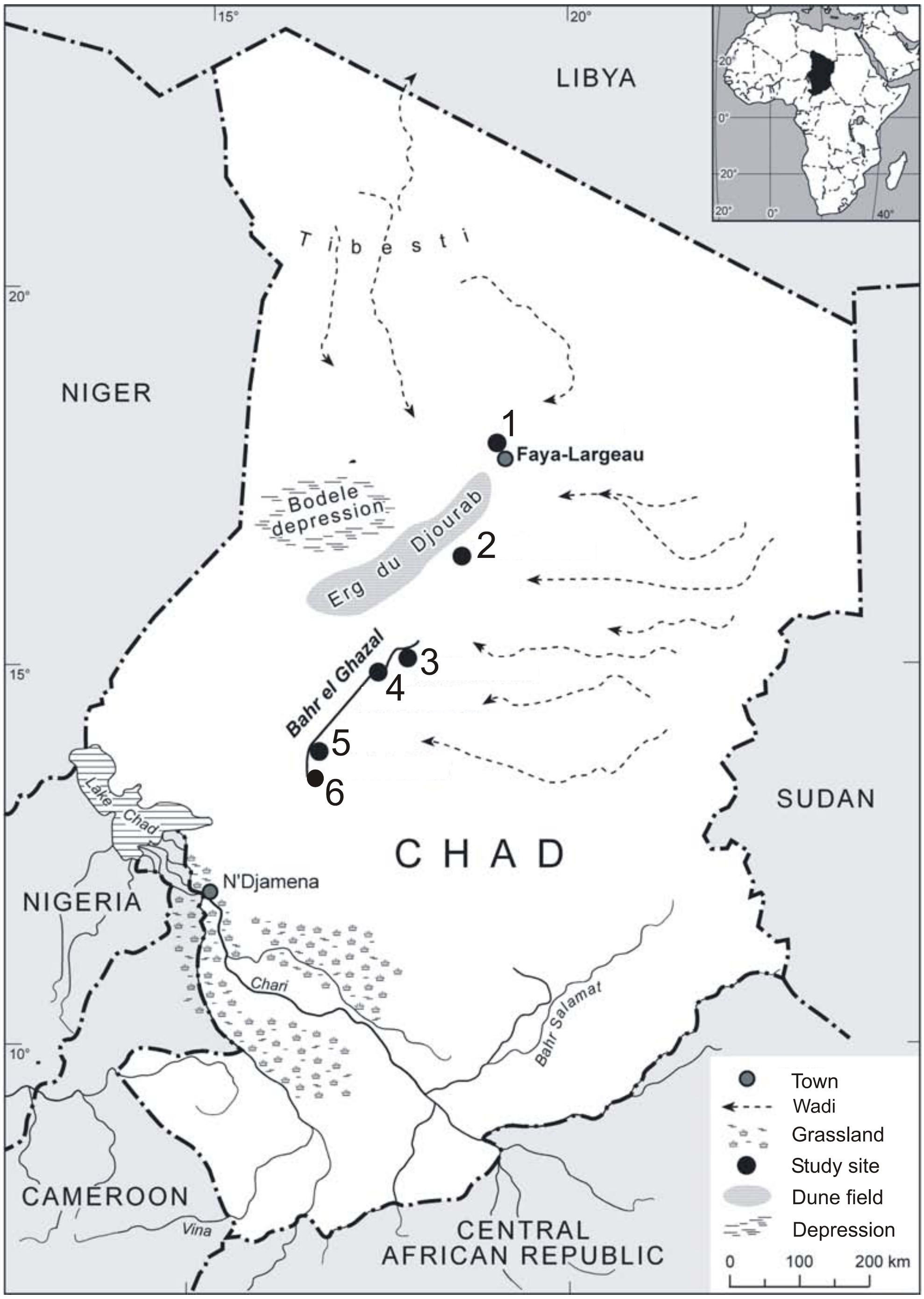

Fig. 2 Study area in the Republic of Chad and location of sampling sites
Untersuchungsgebiet in der Republik Tschad und Lage der Untersuchungspunkte

and 6), ancient dunes rise up to 40 metres high, with N-S striking ridges. These longitudinal dunes are fixed by an indurated paleosol which is covered by an eolian sand sheet with vegetation of grass, shrubs and single trees. In the interdunal valleys the ancient dunes are covered by lacustrine sediments.

3. Methods

3.1 Soil investigation

At selected sites (*Tab. 1*) along the transect (*Fig. 2*), ancient dunes and paleosols at or near the present land surface were exposed by digging. Soil horizons were described (Munsell colour, texture, structure and bioturbation, hardening and cementation, calcification and gleyification), and sampled for further pedochemical, physical, mineralogical and micromorphological investigations by the following methods, which are described in detail in *Schlichting* et al. 1995:

- Particle size analysis by sieving without sample pre-treatment, due to low contents of organic matter and carbonates,
- contents and types of clay minerals by X-ray diffraction (Cu K-alpha radiation) of orien-

Tab. 1 Locations of study sites, dune cover, soil type, soil characteristics and position of samples for luminescence dating and OSL ages / *Lage der Untersuchungsgebiete, geomorphologische Situation, Bodentyp, Bodeneigenschaften, Tiefenlage der Proben für die Lumineszenz-Datierung sowie die daran bestimmten OSL-Alter*

Site	Location	Geomorphology	Soil/ Dune Cover	Soil Characteristics	OSL Sampling Depth below Surface (cm)	Age (±1σ, ka)
1	17°54'22"N 19°05'23"E	Ancient dune below paleo-lake sediments	Gleyi-Cambic Arenosol below lacustrine sediment	Mottles of iron oxide	140	4.7 ± 0.2
2	16°23'25"N 18°36'59"E	Ancient dune below paleo-lake sediments	Ancient dune below lacustrine sediment	Indurated by silica and salts	40	4.7 ± 0.3
3	15°06'50"N 17°42'04"E	Plateau-like dune adjacent to paleo-lake depresssions	Gleyi-Cambic Arenosol	Weakly mottled	30	3.9 ± 0.4
4	14°50'41"N 17°15'28"E	Linear dune adjacent to paleo-lake depressions	Gleyi-Cambic Arenosol	Krotovinas	70	3.4 ± 0.2
5	13°50'31"N 16°28'43"E	Plateau-like dune	Cambic Arenosol	Krotovinas, fragments of pottery	40	3.1 ± 0.2
6	13°37'56"N 16°11'52"E	Plateau-like dune	Haplic Arenosol	Krotovinas, fragments of pottery and bones	120	1.3 ± 0.1

Tab. 2 Analytical data of luminescence dating: n indicates the number of aliquots used for equivalent dose estimate; thermal transfer is the ratio (in %) of the corrected natural OSL (L_N/T_N) and the corrected zero OSL (L_0/T_0) measured at the end of the SAR cycles: it indicates a residual OSL produced by thermal treatment before OSL measurement; recycling ratio is the ratio of OSL from first regenerated dose and OSL from the repeated first regenerated dose at the end of the SAR protocol: it indicates the reliability of the dating procedure applied; IR sensitivity is given as ratio of IRSL/OSL after ~50 Gy laboratory dose: it indicates the purity of the quartz used for dating. A moisture factor of 1.08 ± 0.08 was assumed for all samples. Ages are indicated with ± 1σ total uncertainty; for location of the sites see *Fig. 2.* / *Analysedaten der Lumineszenz-Datierung: n bezeichnet die Anzahl der Aliquots, die zur Bestimmung der Äquivalenzdosis herangezogen wurden; thermal transfer bezeichnet das Verhältnis (in %) der korrigierten natürlichen OSL (L_N/T_N) und der korrigierten 0-OSL (L_0/T_0), gemessen am Ende der SAR-Zyklen: Sie kennzeichnet eine residuale OSL, die durch die thermale Behandlung vor der OSL-Messung entsteht. Recycling ratio ist das Verhältnis der OSL der ersten regenerierten Dosis und der OSL von der ersten regenerierten Dosis am Ende des SAR-Protokolls: Es kennzeichnet die Zuverlässigkeit des angewendeten Datierungsverfahrens; die IR sensitivity gibt das Verhältnis von IRSL/OSL nach ~50 Gy Labordosen an: Es kennzeichnet die Reinheit des für die Datierung verwendeten Quarzes. Ein Feuchtigkeitsfaktor von 1.08 ± 0.08 wurde für alle Proben angenommen. Die Alter sind mit 1σ-Fehlern angegeben; Lage der Profilstandorte siehe Fig. 2.*

Site and profile	Grain size (µm)	U (µg g^{-1})	Th (µg g^{-1})	K (wt %)	D_e (Gy)	n	Thermal transfer (%)	Recycling ratio	IR sensitivity	Effective dose rate (Gy ka^{-1})	Age (±1σ, ka)
1	90-200	1.16±0.03	3.46±0.08	0.08±0.01	3.36±0.13	10	0.46±0.17	1.00±0.02	0.48±0.40	0.72±0.01	4.7 ± 0.2
2	90-200	0.53±0.03	1.33±0.06	0.07±0.01	2.08±0.10	15	0.51±0.20	0.96±0.03	1.21±0.22	0.44±0.01	4.7 ± 0.3
3	90-200	1.80±0.07	6.37±0.22	0.66±0.05	6.85±0.62	13	0.36±0.16	2.81±0.50	1.87±2.10	1.77±0.09	3.9 ± 0.4
4	90-200	0.72±0.02	2.72±0.06	0.38±0.01	2.93±0.17	13	0.38±0.07	1.00±0.08	0.41±0.1	0.86±0.02	3.4 ± 0.2
5,1	90-200	0.52±0.02	1.84±0.05	0.16±0.00	1.75±0.09	13	0.13±0.07	0.99±0.03	0.13±0.19	0.56±0.01	3.1 ± 0.2
6,1	90-200	0.50±0.03	1.96±0.09	0.25±0.02	0.82±0.07	25	0.51±0.26	1.02±0.06	1.3±0.69	0.64±0.01	1.3 ± 0.1

tated Ca-saturated and glycolated specimen; 14Å-minerals were separated by saturating the sample with KCl (1 M) and subsequently heating it for one hour at 450°C and 550°C;

- the amount of clay minerals was estimated semi-quantitatively from the basal reflex intensities using the procedure of *Tributh* and *Lagaly* (1991);
- pH and electrical conductivity ($EC_{2.5}$) in a 1:2.5 soil-water extract, calculation of the normative total amount of dissolvable salts (TDS) from the $EC_{2.5}$ according to *Simon* et al. (1994);
- the content of carbonates was determined by the CO_2 gas volumetric method;
- pedogenic iron oxides (Fe-DCB) were extracted by dithionite-citrate-bicarbonate, while easily soluble (amorphous) Si and Al compounds were extracted with 0.5 M NaOH. The concentration of metal ions was analysed by Atom Absorption Spectrometry (AAS).

3.2 Optical dating

Under subdued laboratory light in the wavelength range > 630 nm, quartz grains 90–200 µm in size were extracted from the sediment and conventional procedures for sample preparation were conducted (*Mauz* et al. 2002).

The single aliquot regeneration protocol (SAR, *Murray* and *Wintle* 2000) was adopted on 10-15 aliquots of each sample. Feldspar contamination was checked using IR stimulation.

All measurements were conducted with an automated RisøTL/OSL DA-15 reader using blue diodes (470Ð20 mn) for stimulation and UV transmitting optical filter (7.5 mm Hoya U 340) for detection.

Low level b-counting and low-level g-spectrometry was used to calculate the external b- and g-dose rate. A representative water content was assumed, because samples arrived dry in the laboratory (for all data see *Tab. 2*).

4. Results

The locations of the investigated ancient dunes and paleosols are presented in *Figure 2* and *Table 1*. *Table 2* depicts the results of the optical dating, and *Tables 3* and *4* show the morphological and analytical characteristics of the paleosols.

4.1 Sahara

Profiles at sites 1 and 2 provide an example of the occurrence of ancient dunes and paleosols in the Sahara of Chad.

Site 1 is situated in the basin of the Faya Largeau oasis, boardering the southern sandstone plateaus of the Tibesti massif. In the basin, extensive plains of paleo-lakes with lacustrine sediments, consisting of gray silt and layers of diatomite, are covered by modern longitudinal dunes and barchans. In small deflation valleys an ancient dune with reddish brown Bw horizons of a paleosol (*Tab. 1*) is exposed below the deflated lacustrine sediments (*Photo 1*). An optical age of the lower Bwb horizon in the ancient dune displays a mid-Holocene age of dune formation (*Tab. 2*). The 110 cm thick lacustrine sediment layer consists mainly of silt and diatomite (*Photo 2*). The increasing amount of fine sand in the upper layer indicates increasing eolian activity and hence increasing aridity. Furthermore, the lacustrine sediments are enriched in soluble salts, carbonates and amorphous silica, as compared to the underlying paleosol from dune sand (*Tab. 4*). The maximum amount of soluble salts and amorphous silica is found in the uppermost layer, thus indicating high rates of evaporation of lake water and hence increasing aridi-

Horizon	Depth (cm)	Indura-tion relative	Munsell		Sand > 63 µm (mass%)	Fines < 63 µm (mass%)	Smec-tite (mass%)	Illite (mass%)	Kaoli-nite (mass%)
			dry	moist					
Site 1: Fossil Cambic Arenosol – Paleo-Lake Basin									
Cg1	50	4	5Y 8/2	5Y 7/3	38.65	61.35	2	63	35
Cg2	110	4	7.5Y 8/1	5Y 7/2	13.61	86.39	19	52	29
2 Bwgb	130	2	10YR 7/4	10YR 5/4	90.61	9.39	24	41	35
Bwb	160	2	7.5YR 6/6	7.5YR 5/6	98.29	1.71	n.d.	n.d.	n.d.
Site 5_1: Cambic Arenosol – Upper Slope									
C	4	0	10YR 6/2	10YR 3/1	81.89	18.11	46	36	18
2 Ahb1	6	3 - 4	10YR 6/3	10YR 3/3	87.90	12.10	43	25	32
Ahb2	20	3	7.5YR 6/6	7.5YR 4/4	92.05	7.95	31	30	39
Bwb1	60	1 - 2	10YR 6/6	7.5YR 5/6	97.31	2.69	36	23	41
Bwb2	80	1 - 2	10YR 7/8	10YR 4/6	98.11	1.89	n.d.	n.d.	n.d.
C	> 100	1	10 YR 7/6	10YR 5/6	99.54	0.46	n.d.	n.d.	n.d.
Site 5_2: Cambic Arenosol – Lower Slope									
C	2	0	10YR 6/1	10YR 3/1	77.02	22.98	55	23	22
2 Ahb	10	3	10YR 5/2	10YR 4/2	88.93	11.07	48	26	26
Mb1	40	2	10YR 5/2	10YR 3/2	91.63	8.37	43	33	24
Mb2	80	2	10YR 6/2	10YR 3/2	90.62	9.38	44	34	22
3 BwbC	> 120	2	7.5YR 5/2	10YR 3/2	94.60	5.40	45	31	24
Site 5_3: Eutric Fluvisol – Interdunal Valley									
C	10	0	10YR 4/1	10YR 1.7/1	44.17	55.83	38	44	19
2AhMb	> 40	3	10YR 4/1	10YR 1.7/1	36.54	63.46	47	34	18
Site 6_1: Cambic Arenosol – Upper Slope									
C	3	0	10YR 7/3	10YR 4/2	91.94	8.06	48	22	29
2 Ahb1	8	4	10YR 6/3	10YR 3/3	89.30	10.70	40	34	26
Ahb2	20	3 - 4	10YR 5/2	10YR 3/3	95.74	4.26	30	36	34
AhBwb	60	2 - 3	10YR 5/3	7.5YR 3/2	96.52	3.48	29	35	36
3 Bwb1	80	1	7.5YR 5/3	7.5YR 3/3	96.10	3.90	20	36	44
Bwb2	100	1	7.5YR 5/4	7.5YR 3/3	97.87	2.13	20	47	33
C	120	1	10YR 6/4	7.5YR 5/4	97.94	2.06	26	37	37
Site 6_2: Cambic Arenosol – Lower Slope									
C	2	0	10YR 6/2	10YR 4/2	90.91	9.09	34	38	28
2 Ahb	10	4	10YR 5/2	10YR 3/2	88.72	11.28	36	35	29
MAhb	20	4	10YR 5/2	10YR 2/1	87.59	12.41	12	64	24
Mb	50	3	10YR 4/2	10YR 2/1	83.83	16.17	17	51	32
MBwb	70	2	10YR 4/3	10YR 2/1	88.98	11.02	26	39	34

Tab. 3 Morphological, physical and mineralogical characteristics of fossil soils, developed on mid-Holocene ancient dunes at Sites 1, 5 and 6 (see *Fig. 2*); Induration: 0= loose, 5 = very hard; n.d. = not determined
Morphologische, physikalische und mineralogische Eigenschaften fossiler Böden auf mittel-holozänen Altdünen an den Standorten 1, 5 und 6 (siehe Abb. 2); Verfestigungsgrad: 0 = lose, 5 = sehr hart; n.d. = nicht bestimmt

Explanation of the soil horizons:

Cg = Yellow, unweathered dune sand with some mottles of iron oxide due to gleyification;

Ahb = buried dark gray humic topsoil, frequently with secondary induration by salts and amorphous silica;

AhMb = buried dark gray humic topsoil, frequently with secondary induration by salts and amorphous silica, developed in a gray humic colluvium which results from the accumulation of eroded topsoil material;

Mb = buried gray humic colluvium resulting from the accumulation of eroded topsoil material;

Bwb = buried weathered B horizon of yellow brown, brown or reddish brown colour, slightly indurated, frequently with traces of animal burrowing;

Bwgb = Bwb with some mottles of iron oxide due to influence of inundation or ground water

Photo 1 Study site 1 (*Fig. 2*) in the oasis of Faya, an extensive basin with paleo-lake sediments up to 1 metre thick, covering a weathered ancient dune exposed in the deflation valley / *Untersuchungsstandort 1 (Fig. 2) in der Oase von Faya: Ein ausgedehntes Becken mit bis 1 m mächtigen Sedimenten eines Paläosees, die eine verwitterte Altdüne überlagern, welche im Deflationstal aufgeschlossen ist*

Tab. 4 Chemical characteristics of fossil soils, developed on mid-Holocene ancient dunes at Sites 1, 5 and 6 (see *Fig. 2*). $EC_{2,5}$: electrical conductivity in extract from a soil:water ratio of 1:2,5; TDS = total dissolvable salts, Fe_{DCB} = pedogenic iron oxides, Si_{NaOH} = amorphous silica, Al_{NaOH}= amorphous aluminium oxides / *Chemische Eigenschaften fossiler Böden auf mittelholozänen Altdünen an den Standorten 1,5 und 6 (siehe Fig. 2).* $EC_{2,5}$*: Elektrische Leitfähigkeit in Extrakten mit einem Boden:Wasser-Verhältnis von 1:2,5; TDS = Gesamtgehalt an löslichen Salzen,* Fe_{DCB}*= Gehalt an pedogenen Eisenoxiden,* Si_{NaOH} *= Gehalt an amorpher Kieselsäure;* Al_{NaOH} *= Gehalt an amorphen Aluminiumoxiden*

Photo 2 Study site 1 (*Fig. 2*) in the oasis of Faya. Profile of the lacustrine sediment from diatomites covering the reddish brown Bwb horizon of the fossil Chromi-Cambic Arenosol developed in an ancient dune of mid-Holocene age (4.7 ± 0.2 ka)
Untersuchungsstandort 1 (Fig. 2) in der Oase von Faya. Profil des Diatomiten-Seesediments, das den rötlich-braunen fossilen Bwb-Horizont der Braunerde überlagert, die auf der Altdüne im Mittelholozän (4,7 ± 0.2 ka) gebildet wurde

Horizon	Depth (cm)	pH (H_2O)	$EC_{2,5}$ (µS cm^{-1})	TDS (mg kg^{-1})	Org. matter (mass %)	$CaCO_3$ (mass %)	Fe_{DCB} (g kg^{-1})	Si_{NaOH} (g kg^{-1})	Al_{NaOH} (g kg^{-1})	$SiO_{2(NaOH)}$/ $Al_2O_{3(NaOH)}$ (molar ratio)
Site 1: Fossil Cambic Arenosol – Paleo-lake basin										
Cg1	50	7.36	5470	6860.00	0.00	12.37	4.83	137.75	0.49	552.5
Cg2	110	8.70	1710	2303.00	0.00	57.40	2.51	53.00	0.25	409.2
2 Bwgb	130	9.02	64	100.45	0.00	0.00	1.57	4.37	1.17	7.3
Bwb	160	9.51	111	176.40	0.00	1.79	0.83	4.75	1.51	6.1
Site 5_1: Cambic Arenosol – Upper slope										
C	4	8.22	291	418.95	0.00	0.00	1.14	12.04	2.82	8.3
2 Ahb1	6	8.45	104	161.70	0.16	0.00	1.23	5.13	1.70	5.9
Ahb2	20	8.16	28	41.65	0.08	0.00	0.93	3.13	1.29	4.7
Bwb1	60	8.46	16	24.50	0.00	0.00	0.43	2.15	0.94	4.5
Bwb2	80	8.25	16	24.50	0.00	0.00	0.56	1.80	0.79	4.5
C	> 100	8.02	13	19.60	0.00	0.00	0.37	0.89	0.47	3.7
Site 5_2: Cambic Arenosol – Lower slope										
C	2	9.09	333	502.25	0.00	2.04	1.09	27.02	5.80	9.1
2 Ahb	10	9.24	57	90.65	0.22	0.00	0.56	12.04	2.90	8.1
Mb1	40	8.76	69	95.55	0.12	0.00	0.45	13.71	2.75	9.7
Mb2	80	7.96	220	276.85	0.10	0.00	0.37	6.01	1.08	10.9
3 BwbC	> 120	8.66	70	93.10	0.00	0.00	0.24	4.37	0.93	9.2
Site 5_3: Eutric Fluvisol – Interdunal valley										
C	10	8.77	2650	5022.50	0.15	0.61	0.19	27.67	2.95	18.3
2 AhMb	> 40	8.16	3360	4400.20	0.45	0.00	0.83	19.92	2.72	14.3
Site 6_1: Cambic Arenosol – Upper slope										
C	3	8.56	157	269.50	0.00	0.00	0.55	7.42	1.82	8.0
2 Ahb1	8	8.36	54	95.55	0.33	0.00	0.58	6.40	1.38	9.0
Ahb2	20	8.16	37	63.70	0.20	0.00	0.77	5.38	1.22	8.6
AhBwb	60	7.97	51	83.30	0.16	0.00	0.60	3.62	1.48	4.8
3 Bwb1	80	8.02	23	36.75	0.13	0.00	0.60	3.87	1.37	5.5
Bwb2	100	8.30	13	19.60	0.00	0.00	0.49	3.87	1.51	5.0
C	120	8.01	12	19.60	0.00	0.00	0.45	2.64	0.91	5.6
Site 6_2: Cambic Arenosol – Lower slope										
C	2	8.12	231	362.60	0.00	0.31	0.24	5.51	1.42	7.6
2 Ahb	10	8.18	85	139.65	0.25	0.00	0.48	5.00	1.16	8.4
MAhb	20	8.15	35	56.35	0.42	0.00	0.49	11.39	1.50	14.8
Mb	50	8.12	42	66.15	0.37	0.00	0.66	4.11	1.61	5.0
MBwb	70	8.26	36	56.35	0.24	0.00	0.63	7.21	2.01	7.0

ty. The wide molar ratio (*Tab. 4*) of amorphous silica versus aluminium oxides shows a selective concentration of silica, which indicates that eolian dust was not the source of the amorphous silica. Therefore the silica concentration of the lake water, which enabled the formation of diatomite, obviously resulted from the weathering of the hard rocks and ancient dunes in the course of soil formation, followed by the leaching of soluble silica by subsurface flow and surface runoff.

The unconformity between the paleo-lake sediments and the ancient dune below is sharp. The upper 10 cm of the paleosol consist of reworked sand of the topsoil with some remnants of grey layers with some organic matter (Ahb horizon). This is followed by a 60 cm thick homogenous reddish brown (7.5 YR) Bwb horizon, merging gradually into the yellow C horizon. The Bwb horizon shows some mottles of iron oxide only in the upper 15 cm. This is a result of gleyification and induration due to the accumulation of amorphous silica. The deeper horizons show no characteristics of strong gleyification, such as mottling or as bleaching, although the ancient dune is situated in a basin and was covered by lacustrine sediments of a paleolake. The clay minerals are dominated by illite. A neo-formation of smectite in the lacustrine sediment was not identified.

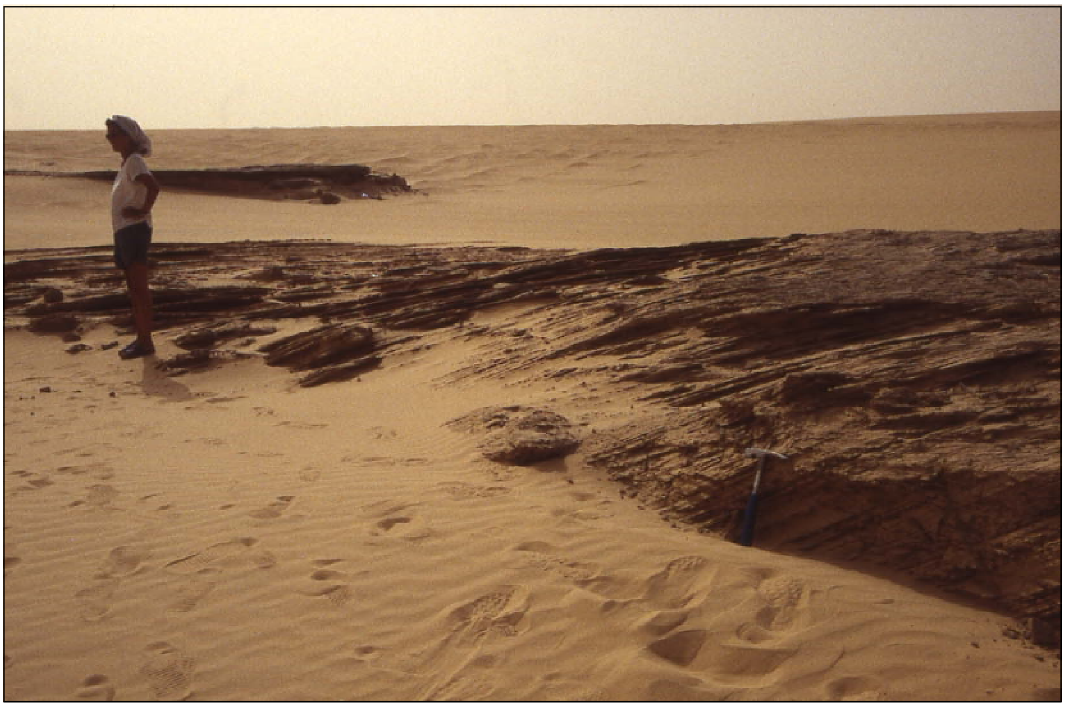

Photo 3 Study site 2 (*Fig. 2*) at the Erg du Djourab. Outcrops of indurated ancient dunes of mid-Holocene age (4.7 ± 0.3 ka), covered by a layer of lacustrine sediments and a thin crust of calcium carbonate, occur below modern mobile dunes. / *Untersuchungsstandort 2 (Fig. 2) im Erg du Djourab. Ausbisse verhärteter mittelholozäner Altdünen (4,7 ± 0.3 ka), überdeckt von einer Schicht von Seesedimenten und einer dünnen Kruste aus Calziumkarbonat, treten zwischen rezenten Wanderdünen auf.*

Site 2 was situated at the southern edge of the Erg du Djourab. It consists of mobile longitudinal dunes and barchans, migrating over extended paleo-lake floors with layers of diatomite and gray silts, carbonate crusts and banks of rhizocretions from carbonate (*Photo 3*). In small deflation basins a mid-Holocene (*Tab. 2*) ancient dune is exposed below the lacustrine sediments. The yellow dune sand is indurated due to accumulation of carbonate and soluble salts. Apart from single diffuse mottles in the uppermost part of the ancient dune, characteristics of strong gleyification as bleaching are not developed. Because the upper horizons of a paleosol were removed by strong deflation prior to the deposition of lacustrine sediments, only one sample for optical dating was taken from the BwbC horizon.

4.2 Northern Sahel

Sites 3 and 4 are situated near the southern desert margin of the Sahara. In this area a grass steppe vegetation without trees or bushes grows on flat ancient dune shields, covered by single mobile dune ridges. Wide interdunal depressions with lacustrine sediments and diatomites indicate the existence of paleo-lakes adjacent to the Bahr el Ghazal wadi system. 50 km south of this desert margin, the height of the paleo-dunes increases.

Photo 4 Northern Sahel of Chad, study site 5 (*Fig. 2*). View from an interdunal valley towards a longitudinal dune of mid-Holocene age, covered by scattered shrub vegetation. The valley is filled with humic clayey sand of colluvium and high water sediments of a wadi. / *Nördlicher Sahel im Tschad: Untersuchungsstandort 5 (Fig. 2). Blick aus einem Dünen-Tal auf eine Längsdüne aus dem Mittelholozän, die von vereinzelter Strauchvegetation bedeckt ist. Humose lehmige Kolluvialsande und Hochwassersedimente eines Wadi bilden die Talfüllung.*

Photo 5 Northern Sahel of Chad, study site 5 (*Fig. 2*). View aspect from the plateau of the mid-Holocene ancient dune towards the interdunal valley, filled with humic clayey sand of colluvium and high water sediments of a wadi; opposing dune in background / *Nördlicher Sahel im Tschad: Untersuchungsstandort 5 (Fig. 2). Blick vom Plateau der mittelholozänen Altdüne in das Tal zwischen den Dünen, das humose lehmige Kolluvialsande und Hochwassersedimente eines Wadi füllen; im Hintergrund die gegenüberliegende Düne*

At Sites 5 and 6, situated a further 150 km southwards, they form an ancient erg of longitudinal dunes. Here the N-S trending dune ridges are up to several km long and 40 m high. The vegetation changes in the same direction from a grass steppe to a thorn bush savannah due to the increase in annual precipitation.

An indurated, 0.8-1 m thick Cambic Arenosol, which developed on top of the ancient dunes, displays similar morphological characteristics at all places along the transect between Sites 3 and 6 (*Fig. 2*).

The paleosol is covered by a layer of loose sand with a variable thickness ranging from several cm to decimetres. Where this layer is thicker, such as at Sites 3 and 4, it shows a distinct stratification. At Sites 5 and 6 the sand cover is only between a few cm to 10 cm thick. From the similar morphological, physical and chemical characteristics of this layer, as compared to the humic topsoil (*Tables 3* and *4*), we conclude that the sand cover developed by breaking up the topsoil horizon due to burrowing soil animals and trampling of grazing animals, rather than by eolian sedimentation of sand. However, the higher concentrations of amorphous silica and soluble salts could be a consequence of eolian dust deposition.

A 20 cm thick indurated Ahb horizon of dark gray colour appears below the sand cover. The

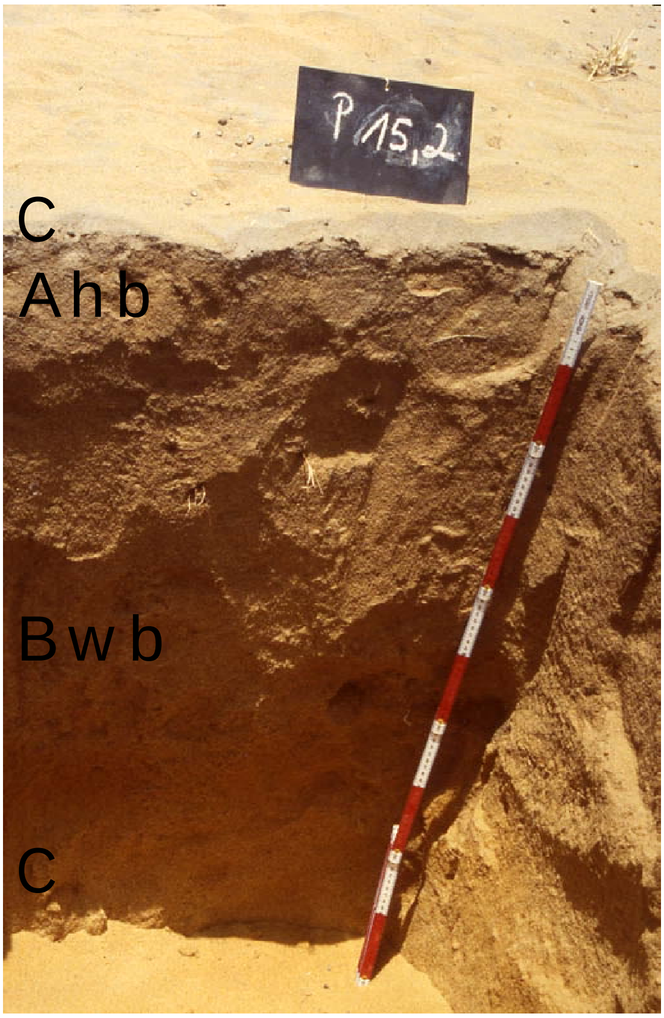

Photo 6 Northern Sahel of Chad, study site 5 (*Fig. 2*). Profile of a fossil Cambic Arenosol below a layer of loose eolian cover sand (C), with a strongly indurated humic A horizon (Ahb) above a slightly indurated, weathered brown-coloured subsoil (Bwb), followed by yellow unconsolidated dune sand as parent material (C)

Nördlicher Sahel im Tschad: Untersuchungsstandort 5 (Fig. 2). Profil einer fossilen Braunerde unter einer Schicht losen äolischen Decksandes (C), mit einem stark ausgehärteten humosen A-Horizont (Ahb) über einem leicht ausgehärteten,verwitterten, braungefärbten Unterboden (Bwb), dem gelber, unkonsolidierter Dünensand als Ausgangssubstrat (C) folgt

existing very sparse grass vegetation cover, the formation of sand cover and the strong induration indicates the fossil nature of this Ahb horizon, which is followed by an approximately 60 cm thick brown Bwb horizon. The degree of induration in the latter horizon is less pronounced and decreases with depth down to the unweathered C horizon, which consists of unconsolidated eolian sand. Krotovinas, filled with humic topsoil material, occur within the Bwb horizon and indicate animal burrowing.

The horizonation and morphological characteristics of the Cambic Arenosols varies systematically with relief position. On shallow dune ridges near the shore of a paleo-lake at Sites 3 and 4, gleyification of the B horizon (Gleyi-Cambic Arenosol) caused the formation of mottles from iron oxide. The steeper slopes of the longitudinal dunes at Sites 5 and 6 favoured the formation of a humic colluvium (Mb horizon in *Tab. 3* and *4*) which consists of material from the humic toposoil that accumulated following erosion and transport along the slope. It formed when creeping soil erosion, possibly induced by grazing animals and climatic change to more arid conditions, started at the end of the humid period. As the thickness of the humic topsoil horizon does not change in the higher relief positions as a consequence of erosion, we assume that the colluvium was formed through continuous surface runoff during the period of soil formation. Scattered stone artifacts and fragments of pottery on the soil surface and within the humic topsoil indicate that the dunes were settled by man during the period of soil formation. Destruction of the grass cover by grazing therefore may have favoured the formation of the colluvium.

The amount of fines (*Tab. 3*) in the paleosol shows a maximum in the superficial sand layer, in the humic topsoil and in the colluvium. Due to the redistribution of topsoil material slope downwards, the concentration of fines generally increases in the same direction. Calcium carbonate is only present in the superficial sand layer due to recent deposition of dust. All paleosol horizons show pH values between 8 and 9. In most layers the clay mineralogy is dominated by smectite. The amounts of smectite display clear gradients and generally increase from the C horizon of the ancient dune towards the superficial eolian sand layer at the land surface. Furthermore the smectite content increases from the plateau and upper slope profiles towards the soils in lower slope and basin positions and corresponds with the increase of the SiO_2:A_2O_3-molar ratio of the amorphous Si- and Al-oxides (*Tab. 4*). This shows that a high concentration of silica and bases in the soil solution must have prevailed, which favoured the neoformation of smectite.

At Site 6 (*Tab. 1*), a prehistoric soil pit was excavated. It had been refilled at about 1.3 ka with layers of organic topsoil material and fragments of pottery. The topsoil horizon, which developed in the infilled dune sand of the pit, displays the same degree of induration as the adjacent undisturbed soil.

5. Discussion

The northern Sahara and the Sahel of Chad is today characterised by a hyperarid climate with average annual precipitation less than 100 mm per year. In this area ancient dunes and sand sheets as well as paleo-limnic sediments, calcarous and saline crusts and paleosols, are present. These deposits represent evidence of previous climatic phases with arid and humid conditions. Proxy data from the eastern Sahara reveal a humid period from ~9.5 ka to ~4.5 ka (e.g. *Ritchie* and *Haynes* 1987), leading to perennial lakes (*Petit-Maire* and *Riser* 1981; *Kröpelin* and *Soulié-Märsche* 1991) and changes in vegetation and soil properties between 8° and 20°N (*Street-Perrot* and *Perrot* 1993, *Kutzbach* et al. 1996). From the Sahara and the Sahel, *Gasse* et al. (1990) report an abrupt transition from arid to humid conditions at > 12 ka and at ~9.3 ka with a reversal (from humid to arid) at ~10.50-10 ka. The climate changes took place within a few centuries or even decades.

The ages of the optically dated paleo-dunes of Chad along the transect assembly indicate that the uppermost sand layers were deposited in the mid-Holocene between ~5 ka and ~3 ka. The southernmost ancient dunes at Site 5 (*Fig. 2*) show the youngest age of 3.1 ka BP. Although the mean values of the OSL ages (*Tab. 2*) appear to show a trend of decreasing age from the Sahara to the Sahel, which would be logical according to the regression of the desert margin and the shift in aridity from N to S, no time shift is obvious between the central Sahara and the Sahel within 1σ-uncertainty. Due to changes in the level of Lake Chad, *Michel* (1973) assumed the existence of an arid period prior to the mid-Holocene humid period before 4.5 ka BP.

Warren (1970) attributed the “High Goz” in North Kordofan, Sudan, *Völkel* (1989) the “Manga dune field” in northern Sahelian of East Niger, and *Thiemeyer* (1995) the “Gudumbali dune field” in NE-Nigeria, to belong to the mid-

Holocene arid period. In the northern Sahel of Chad and adjacent countries, these dunes show a rather weak development of Cambic Arenosols, which makes them sensitive to re-mobilisation in the course of desertification. In contrast, thick Chromi-Cambic Arenosols developed during the late Pleistocene-early Holocene humid period before 7 ka BP on Pleistocene dunes (*Warren* 1970, *Thiemeyer* 1994, *Felix-Henningsen* 2000). Therefore the relatively weak degree of soil development on the ancient dunes in the northern Sahel of Chad is in accordance with stratigraphical results from adjacent countries.

The sediments of paleo-lakes as well as fossil and relict paleosols, which developed on the ancient dunes of the Sahara and Sahel in Chad, reveal the occurrence of one or two distinct short-lived humid climate intervals after ~5 ka and ~3 ka and also the formation of local lakes after ~5 ka. The soils are Cambic Arenosols, formed by precipitation-induced leaching and silicate weathering under vegetation cover. The pedogenic Fe- and Al- oxides display a clear gradient with increasing concentrations from the C horizon to the topsoil due to the increasing intensity of weathering of silicates, which must have occurred under acid conditions.

The formation of a fossil Cambisol below lacustrine sediments at Faya and other study sites in the Sahara of Chad indicates different paleoclimatic stages of the humid period. During a first stage, with a rather low humidity, the Cambisol development occurred on the ancient dunes. Then in a second stage, with an increase in humidity, paleolakes were formed. As indicated by the missing gleyification of the ancient dunes and the fossil Cambisols, the paleolakes were not fed by a rising ground water table, but by floods of wadis from the mountainous regions of the Tibesti foreland and the Bahr el Ghazal. Possibly the basins were rapidly filled with lake water and the lake bottom was sealed by the depositions of fines which prevented the underlying paleosol from gleyification. In contrast, in interdunal basins of the Grand Erg de Bilma in East Niger paleo-limnic sediments cover white ancient dune sand which was bleached by gleyification due to a rise of the regional ground water table (*Felix-Henningsen* 2003).

The third stage of climatic development after ~2.5 ka is characterised by increasing aridity up to the present, indicated by several pedo-chemical characteristics of Cambic Arenosols on the ancient dunes of the northern Sahelian. The upper parts of the Cambic Arenosols are indurated due to accumulation of soluble salts, carbonates and amorphous silica, which derive from dust deposition as a consequence of deflation of lacustrine sediments from the interdunal basins. The pH values between 8 and 9 exceed the buffer range of calcium carbonate and indicate eolian deposition, infiltration and superficial accumulation of sodic salts ($NaHCO_3$ or Na_2CO_3). Therefore the soils on ancient dunes of the northern Sahel of Chad must be classified as relic and fossil soils, respectively, which originally developed under more humid conditions during the mid-Holocene. Due to a rather low soil stability and the present severe aridity, the remobilisation of the ancient dunes due to desertification is widespread.

The stone artefacts and fragments of pottery reveal that the ancient dunes of the northern Sahelian were settled in many places during periods with a more favourable climate than today. The optical date from a soil pit with remnants of pottery (Site 6, *Tab. 2*) shows that settlements prevailed at least until 1 ka. Thus, the processes of fossilisation by the deposition of sand cover and dust as well as the cementation of the upper soil horizons by amorphous silica and soluble salts occurred quickly and can be attributed to the recent arid climate within the last 1,000 years. However, the relatively high amounts of amorphous silica and soluble salts in the refilled soil sediment (AhBwb horizon, *Tab. 4*) indicate that an accumulation of these elements in the topsoil horizons may have existed previously. This shows that the underlying brown 3 bBw horizon must have developed, as in the profile of Site 5, over a long period with a climate of more humid conditions than today, when salts and carbonates were completely leached and pH was below 7.

Acknowledgements

Fieldwork in the Sahara was only made possible by the professional organisation and preparation of the expedition by *R. Baumhauer* (University of Trier), *H. Hagedorn* and *B. Sponholz* (University of Würzburg) and the help of *D. Schmidt* (University of Gießen). Their active support in the field and by many fruitful interdisciplinary discussions as well as the generous funding of the project by *Deutsche Forschungsgemeinschaft (DFG)* is gratefully acknowledged. Part of the dating work was conducted at the *Forschungsstelle Archaeometrie*, Heidelberg, with support from the DFG project Sm 17-24.

6. References

Felix-Henningsen, P. 1983: Zur Genese und Vergesellschaftung von Böden auf den Altdünen der nördlichen Goz-Region im Sudan. – Mitteilungen der Deutschen Bodenkundlichen Gesellschaft **38**: 485-490

Felix-Henningsen, P. 1984: Zur Relief- und Bodenentwicklung der Goz-Zone Nordkordofans im Sudan. – Zeitschrift für Geomorphologie, NF **28**: 285-303

Felix-Henningsen, P. 2000: Paleosols on Pleistocene Dunes as Indicators of Paleo-Monsoon Events in the Sahara of East Niger. – Catena **41**: 43-60

Felix-Henningsen, P. 2003: Genesis and Paleo-Ecological Interpretation of Swamp Ore Deposits at Sahara Paleo-Lakes of East Niger. – In: *Smykatz-Kloss, W.* and *P. Felix-Henningsen* (eds.): Palaeoecology of Quarternary Drylands. Lecture Notes in Earth Sciences **102**. – Berlin: 47-72

Gasse, F., R. Téhet, A. Durand, E. Gibert and *J.C. Fontes* 1990: The Arid-Humid Transition in the Sahara and Sahel during the Last Deglaciation. – Nature **346**: 141-146

Grunert, J. 1988: Verwitterung und Bodenbildung in der Süd-Sahara, im Sahel und im Nord-Sudan. Mit Beispielen aus Niger, Burkina Faso und Nord-Togo. – In: *Hagedorn, J.* und *H.G. Mensching* (Hrsg.): Aktuelle Morphodynamik und Morphogenese in den semiariden Randtropen und Subtropen. – Abhandlungen der Akademie der Wissenschaften in Göttingen, Mathematisch-Physikalische Klasse **41**: 22-43

Kröpelin, S. and *I. Soulié-Märsche* 1991: Charophyte Remains from Wadi Howar as Evidence for Deep Mid-Holocene Freshwater Lakes in the Eastern Sahara of Northwest Sudan. – Quaternary Research **36**: 210-223

Kutzbach, J.E., G.B. Bonan, J.A. Foley and *S.P. Harrison* 1996: Feedbacks between Climate and Grassland/Soils in Northern Africa during the Middle Holocene. – Nature **384**: 623-626

Mauz, B., T. Bode, E. Mainz, H. Blanchard, W. Hilger, R. Dikau and *L. Zöller* 2002: The Luminescence Dating Laboratory at the University of Bonn: Equipment and Procedures. – Ancient TL **20** (2): 53-61

Mauz, B. and *P. Felix-Henningsen* 2005: Palaeosols in Saharan and Sahelian Dunes of Chad: Archives of Holocene North African Climate Changes. – The Holocene **15**: 453-458

Michel, P. 1973: Les bassins des fleuves Sénégal et Gambie. Étude géomorphologique. – Mémoires de l'ORSTOM **63**. – Paris

Murray, A.S. and *A.G. Wintle* 2000: Luminescence Dating of Quartz using an Improved Single-Aliquot Regenerative-Dose Protocol. – Radiation Measurements **32**: 57-73

Petit-Maire, N. and *J. Riser* 1981: Holocene Lake Deposits and Palaeoenvironment in Central Sahara, Northeastern Mali. – Palaeogeography, Palaeoclimatology, Palaeoecology **35**: 45-61

Pfeiffer, L. 1991: Schwermineralanalysen an Dünensanden aus Trockengebieten mit Beispielen aus Südsahara, Sahel und Sudan sowie Namib und der Taklamakan. – Bonner Geographische Abhandlungen **83**

Pfeiffer, L. and *J. Grunert* 1989: Heavy Mineral Associations in Dune Sands and Soils of the Sahel and the Sudan (Niger, Burkina Faso, Togo). – Paleoecology of Africa **20**: 55-68

Ritchie, J.C. and *C.V. Haynes* 1987: Holocene Vegetation Zonation in the Eastern Sahara. – Nature **330**: 645-647

Schlichting, E., H.-P. Blume und *K. Stahr* 1995: Bodenkundliches Praktikum: Eine Einführung in pedologisches Arbeiten für Ökologen, insbesondere Land- und Forstwirte und für Geowissenschaftler. – 2. Aufl. – Pareys Studientexte **81**. – Berlin et al.

Servant, M. 1983: Séquences continentales et variations climatiques: Évolution du Bassin du Tchad au Cénozoïque supérieur. – Travaux et Documents de l'ORSTOM **159**. – Paris

Simon, M., O. Cabezas, I. Garcia and *P. Martinez* 1994: A New Method for the Estimation of Total Dissolved Salts in Saturation Extract of Soils from Electrical Conductivity. – European Journal of Soil Science **45**: 153-157

Street-Perrott, F.A. and *R.A. Perrott* 1990: Abrupt Climate Fluctuations in the Tropics: The Influence of Atlantic Ocean Circulation. – Nature **343**: 607-611

Thiemeyer, H. 1992: Desertification in the Ancient Erg of NE-Nigeria. – Zeitschrift für Geomorphologie NF, Supplement-Band **91**: 197-208

Thiemeyer, H. 1994: Bodengesellschaften im Longitudinaldünengebiet NE-Nigerias. – In: *Heinrich, J.* und *H. Thiemeyer* (Hrsg.): Geomorphologisch-bodengeographische Arbeiten in Nord- und Westafrika: Arno Semmel zum 65. Geburtstag. – Frankfurter Geowissenschaftliche Arbeiten D **17**: 37-53

Thiemeyer, H. 1995: Dating of Palaeodunes from NE-Nigeria with Thermoluminescence. – Zeitschrift für Geomorphologie NF, Supplement-Band **99**: 97-106

Tributh, H. und *G. Lagaly* (Hrsg.) 1991: Identifizierung und Charakterisierung von Tonmineralen. Tagung der Deutschen Ton- und Tonmineralgruppe, Gießen und Schloss Rauischholzhausen, 10.-12. Mai 1989. – Gießen

Völkel, J. 1988: Zum jungquartären Klimawechsel im saharischen und sahelischen Ost-Niger aus bodenkundlicher Sicht. – In: *Hagedorn, H.* und *R. Baumhauer* (Hrsg.): Geowissenschaftliche Untersuchungen in Afrika. – Würzburger Geographische Arbeiten **69**: 255-276

Völkel, J. 1989: Geomorphologische und pedologische Untersuchungen zum jungquartären Klimawechsel in den Dünengebieten Ost-Nigers (Südsahara und Sahel). – Bonner Geographische Abhandlungen **79**

Völkel, J. and *J. Grunert* 1990: The Problem of Dune Formation and Dune Weathering during the Late Pleistocene and Holocene in the Southern Sahara and Sahel. – Zeitschrift für Geomorphologie, NF **34**: 1-17

Warren, A. 1970: Dune Trends and their Implications in the Central Sudan. – Zeitschrift für Geomorphologie, NF **10**: 154-180

Summary: Paleoenvironmental Significance of Soils on Ancient Dunes of the Northern Sahel and Southern Sahara of Chad

Ancient dunes are widespread in the southern Sahara and Sahel of Chad. Optical dating provides evidence that the dunes were sedimented in arid phases during the mid-Holocene between ~5 ka and ~3 ka. During a following phase with a humid climate, a Cambic Arenosol developed by precipitation-induced silicate weathering and leaching which caused the formation of a reddish brown Bw horizon below a humic topsoil and colluvium. In basins of the Sahara, the ancient dunes with the already existing paleosol were covered by paleo-limnic sediments, diatomites and carbonate crusts. Due to an increase in humid conditions, the paleo-lakes extended. Missing characteristics of gleyification in the ancient dunes beneath the lacustrine sediments give evidence that the paleo-lakes were not formed by a gradual rise of a ground water table but mainly fed by run-off from wadis. In the northern Sahel of Chad, mid-Holocene longitudinal dunes form an ancient erg. Fossil and relic Cambisols at the recent land surface show an intensive cementation of the topsoil horizons due to eolian deposition and accumulation of amorphous silica, soluble salts and carbonates. They derive from deflation of the lacustrine sediments from the paleo-lakes and indicate an arid to semi-arid climate following the period of soil formation.

Zusammenfassung: Paläoökologische Bedeutung von Böden auf Altdünen der nördlichen Sahelzone und südlichen Sahara in Tschad

In der Sahara und nördlichen Sahelzone der Republik Tschad wurden Paläoböden auf OSL-datierten Altdünen untersucht und paläoklimatisch interpretiert. Die Altdünen wurden in einer ariden Klimaphase oder in mehreren ariden Intervallen zwischen ~5 und ~3 ka BP im Mittelholozän gebildet. In einer anschließenden humiden Klimaphase entstand eine Braunerde (Cambic Arenosol), die unter einem humosen Oberboden und Kolluvien einen rötlichbraunem Bv-Horizont aufweist. In Beckenlagen der Sahara wurde die Altdüne mit dem bereits entstandenen Paläoboden mit der Zunahme der Humidität von paläolimnischen Sedimenten, Diatomit und Kalkkrusten bedeckt, nachdem ausgedehnte Paläoseen durch Zufluss aus Wadis entstanden waren. Fehlende Gley-Merkmale in den Altdünen deuten darauf hin, dass die Paläoseen nicht durch langsamen Grundwasseranstieg gebildet wurden. In der nördlichen Sahelzone weisen die fossilen und reliktischen Braunerden auf mittelholozänen Längsdünen eines alten Ergs eine intensive Verfestigung des Oberbodens durch äolische Deposition und Anreicherung von amorpher Kieselsäure, löslichen Salzen und Carbonaten auf. Sie wurden aus den angrenzenden Paläoseebecken ausgeweht und kennzeichnen die gegenwärtig vorherrschenden ariden bis semiariden Klimabedingungen, die eine Auswaschung der relativ leicht mobilisierbaren Minerale nicht zulassen.

Résumé: Signification paléoenvironnementale des sols développés sur les paléodunes sahariennes et sahéliennes au Tchad septentrional

Au Sahara et au Sahel dans le Nord de la République du Tchad des paléosols sur dunes anciennes, datées par OSL, sont étudiés et interprétés sous des aspects paléoenvironnementaux. Les paléodunes se sont formées pendant une ou plusieurs phases arides entre 5 et 3 ka BP, à l'Holocène moyen. Pendant une phase climatique postérieure plus humide, un arenosol cambique s'est développé, présentant un horizon rougeâtre/brun surmonté d'un horizon humifère et de colluvions. Dans les dépressions sahariennes cette génération de dunes avec son paléosol a été recouverte par des dépôts paléolimniques, des diatomites et des calcrètes liés à une augmentation de l'humidité. Ces paléolacs ont été formés par des apports d'oueds. L'absence d'une gleyification dans les paléodunes indique que les lacs ne se sont pas formés par une lente remontée de la nappe. Dans le Nord du Sahel les arenosols cambic fossiles et reliques sur les dunes longitudinales (mi-Holocènes) d'un erg ancien montrent une fixation importante de l'horizon supérieur par apport éolien et concentration de la silice amorphe, des sels solubles et des carbonates. Ceux-ci étaient transportés par le vent à partir des dépressions paléolacustres voisines et représentent les conditions climatiques actuelles arides à semiarides qui ne permettent même plus le lessivage des minéraux fortement solubles.

Prof. Dr. Peter Felix-Henningsen, Institut für Bodenkunde und Bodenerhaltung der Justus-Liebig-Universität Gießen, Heinrich-Buff-Ring 26, 35392 Gießen, Germany, Peter.Felix-H@agrar.uni-giessen.de

Dr. Barbara Mauz, Department of Geography, University of Liverpool, Liverpool L69 7ZT, UK, mauz@liv.ac.uk

Manuskripteingang: 27.10.2004
Annahme zum Druck: 08.12.2004