PALAEOECOLOGY OF AFRICA

International Yearbook of Landscape Evolution and Palaeoenvironments

29

Holocene Palaeoenvironmental History of the Central Sahara

Roland Baumhauer & Jürgen Runge

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HOLOCENE PALAEOENVIRONMENTAL HISTORY
OF THE CENTRAL SAHARA

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and Palaeoenvironments

Volume 29

Holocene Palaeoenvironmental History of the Central Sahara

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Foreword

Volume 29 of the series ‘Palaeoecology of Africa’ on the ‘Holocene Palaeoenvironmental History of the Central Sahara’ continues the publishing of interdisciplinary scientific papers on landscape evolution and on former environments of the African continent, e.g. changes in climate and in vegetation cover interconnected to all kinds of environmental dynamics from the Cainozoic up to the present, including since the Late Quaternary the growing influence of humans in many of the study areas.

Since its re-edition in 2007/2008 with a modified editorial board—attended by the ‘Frankfurt Centre for Interdisciplinary research on Africa’ (CIRA/ZIAF, www.ziaf.de)—and a completely new and up-to-date layout, assisted by the publishers group Taylor & Francis, the series has already begun to be again recognized by the scientific community.

However, Palaeoecology of Africa is not as yet been accredited by international citation indices, what is regarded as a certain drawback for the series. As it is essential to change this in the future, the editor is already working on this often quite long and tedious process in being considered by citation indices. Young academics and upcoming university professionals are especially encouraged and invited to consider this traditional journal—which has been on the “market of science journals” since 1966—as a media to communicate, and as an opportunity for meetings in minds to exchange global knowledge and ideas across scientific and cultural borders (cf. Heine, 2007 in PoA 28).

In the past (1970s to 1990s) quite regularly the scientific contributions of the Biennial SASQUA (South African Society for Quaternary Research) conferences were published within Palaeoecology of Africa. As a vision for future volumes the editor likes to propose that some follow-up editions of the series could have again a focus on SASQUA activities (“back to the roots”). The up coming SASQUA meeting is scheduled for September 2009 in Knysna, South Africa.

Fourteen papers are gathered together in this volume focusing on the most recent (Holocene) dynamics of the Central Sahara. They are mainly the outcome of the since 2005 DFG funded LIMNOSAHARA project (www.limnosahara.de) of the Universities of Würzburg, Giessen, FU Berlin (Germany) and Niamey (Niger). Many thanks go to all colleagues for submitting their papers to Palaeoecology of Africa.

Special thanks go to Roland Baumhauer for supporting the editing process. Formatting of the papers to the PoA layout was again reliably done by Erik Hock to whom I am most grateful. Ursula Olbrich revised numerous figures and assisted by carrying out cartographic work on the book. The Taylor & Francis team in Leiden (The Netherlands) with senior editor Janjaap Bloom supported in a professional manner the editorial work. Finally, I like to thank the Deutsche Forschungsgemeinschaft (DFG) for assisting in printing this volume.

Jürgen Runge
Bangui and Frankfurt
August 2008

In Memoriam

Johanna Alida Coetzee (1921–2007)

Klaus Heine

University of Regensburg, Institute of Geography, Regensburg, Germany

It is with deep regret that I have to report that Professor Joey Coetzee died in Somerset West on April 28, 2007. Quaternary and Palynological Research has suffered a great loss. We mourn a colleague of national and international distinction, a brilliant and honest scientist, who advanced the field of palynology in Southern and Eastern Africa. She has published palaeoenvironmentally relevant groundbreaking and pioneering investigations on African pollen of Cainozoic age.

Joey Coetzee was educated at Jeppe High School for Girls in Johannesburg and then University of Witwatersrand. She earned her master's degree in 1946 and subsequently worked at the Universities of Wits and Natal for a short time. In August 1946, she accepted a position as assistant in the Department of Botany at the University of the Orange Free State. Inspired by Eduard van Zinderen Bakker's pollen analytical investigations in East Africa, she embarked in testing the widely held hypothesis that pluvial phases correlate with glacial phases during the Last Glacial Maximum. Joey Coetzee devoted several years of intense work on these problems as a senior member of the research team of Eduard van Zinderen Bakker Sr. who headed the Department of Botany at the University of the Orange Free State and the Palynological Research Unit of the South African Council for Scientific and Industrial Research. For some time during 1953, Joey Coetzee worked in the Palynological Laboratory, Stockholm-Bromma, and also visited the colleagues in Bergen, Velp, Utrecht, and Cambridge. In the 1950s she worked on the pollen morphology of Southern African species and completed a collection and description of several thousand pollen grains and spores. It was the real base for any palynological study in Southern Africa. Furthermore, she analysed the air-borne pollen collected weekly for three years at seven different stations in South Africa and Namibia. The data of these pollen traps gave valuable information on the pollen spectra of the main vegetation types (e.g. Karoo) in their natural condition. In 1959 Joey Coetzee made a trip to East Africa, collected many pollen samples at the East African Herbarium at Nairobi and studied fossil pollen material from Uganda. In the following years she started her investigations of cores collected on Mount Kenya. All these and many other pioneering studies of Joey Coetzee marked the progress in the achievement of palynology and of understanding the past.

In 1964 Joey Coetzee had to leave her study to concentrate on her East African pollen analytical research. The core from Sacred Lake was finished and showed remarkable results (Coetzee, 1964). Joey Coetzee's findings led to the approval of the name *Mount Kenya Hypothermal* for the pollen zone which indicates a synchronous drop in temperature in many parts of Africa during the Upper Pleistocene. The general features of her diagram were a sound proof of the world-wide changes which occurred in the climate of the earth. Later, in her D.Sc.-Thesis (Coetzee, 1967) Joey Coetzee showed that the hypothesis 'glacial phases = pluvial phases in tropical Africa' was not true in Eastern and Southern Africa. This work, recently featured as a classic work in the journal *Progress in Physical Geography*, and probably the most cited palynological paper from the African continent, illustrates 'the very essence of Quaternary palaeoenvironmental reconstruction and, indeed of physical geography' (Meadows, 2007). Joey Coetzee rapidly acquired a reputation as an eminent researcher of palaeoenvironmental studies in Africa. She was among the first scientists to recognize the significance of changes in temperatures during the Last Glacial Maximum in tropical mountain areas of Africa.

It was 1973 when I first met Joey Coetzee. The location was the INQUA conference in Christchurch, New Zealand, in the shadow of the glacially shaped Southern Alps. Together with Eduard van Zinderen Bakker Sr. she presented a paper on *Global Temperature Changes and the African Quaternary Environment* (van Zinderen Bakker and Coetzee, 1973). After their talk I discussed with Joey the results: During the Quaternary, Africa has been subjected to a wide range of variations in humidity which for a long time have been considered to have been in-phase over the entire continent. The pattern of rainfall distribution and the evaporation rate, however, depend on global and local temperature conditions. The long-term variations in the earth's energy budget are therefore the primary cause of changes in the Quaternary environment. Correlations of radiometrically calibrated temperature curves are consequently of basic importance for the understanding of Quaternary chronology. Vegetation changes which occurred in the interior of Southern Africa during Late Glacial times show that detailed correlations existed between lower temperature and higher humidity versus higher temperature and lower humidity. This result indicates that climatic settings in this region differed fundamentally from that of tropical Africa (Coetzee, 1967) and that 'pluvial conditions' cannot be used for correlation purposes. In those days, my own chronological investigations of glacial deposits of the Mexican volcanoes showed that glacial climatic evidence is suitable for stratigraphic correlations neither (Heine, 1974) and thus my records from the New World tropics added to Joey Coetzee's observations. Since that time, Joey and I were friends and colleagues. I met Joey many times in Southern Africa during conferences of the Southern African Society for the Quaternary (SASQUA), in her home at Bloemfontein and, after her retirement from the university, at Somerset West. Several times we spent weeks together with colleagues from South Africa and Germany in the field, especially in the Kalahari and the Namib Desert (Figure 1). And we met in Europe, in the Austrian Alps, and in my home.

One of the most debated topics in Quaternary science which Joey and I discussed was methodological problems arising from the reconstruction of Late Quaternary palaeoenvironments by interpreting pollen data. The 'palynological records' of the Younger Dryas climatic oscillation, a millennium-long cooling event approx. 12.700–11.500 cal yr B.P. that interrupted the transition from the last glacial to present interglacial (Holocene) period, were subject to much debate in Southern Africa, Northern and Southern South America and New Zealand. Two conflicting hypotheses, both based on palynological sequences, have been proposed to document either this cooling event in the Southern Hemisphere (e.g. Heusser and Rabassa, 1987) or to question it (e.g. Singer *et al*., 1998). Joey's fundamental knowledge of the methodology of pollen research advanced my understanding of Quaternary vegetation changes and the palaeoclimatic implications, not only in Eastern and Southern Africa, but also in other regions of the earth. Despite the fact that Joey Coetzee anticipated finding evidence of the Younger Dryas in East Africa and described and correlated particularly marked temperature fluctuations in South Africa (Aliwal North site) during the Late Glacial with the European older Dryas, Allerød and Younger Dryas, she listened to and respected my diverse views about the existence of the Younger Dryas cooling in the Southern Hemisphere.

Another topic we argued about many times was the 'Pluvial Theory', established by Richard Forster Flint (1957) who suggested that the major periods of Northern Hemisphere ice advance were associated with phases of more humid climates in tropical Africa. Joey Coetzee's reconstruction of the LGM temperature depression of between 5,1 and 8,8 °C and more arid conditions relative to the present day in tropical Africa (Coetzee, 1967;

Figure 1. Rest during field work at Sossus Vlei, Namib Desert, Namibia. From left to right: Joey Coetzee, Louis Scott (in the back), Eduard van Zinderen Bakker Sr., Almut Heine. Photo: K. Heine, June 9, 1981.

van Zinderen Bakker and Coetzee, 1972) questions the 'Pluvial Theory' and corroborates my observations from tropical Mexico. What came through during our discussions was Joey's enthusiasm, and the exhilaration and intellectual stimulation of working on a collaborative interdisciplinary research field.

In the 1970s and 1980s, Joey Coetzee began research work to explore links between the Tertiary pollen records and the unique fynbos vegetation in the Cape region (Coetzee, 1978a, b, 1993; Coetzee and Rogers, 1982; Coetzee and Muller, 1984; Coetzee and Praglowski, 1984, 1988). She found that fynbos replaced palm-dominated subtropical to tropical woodlands that alternated with conifer forests during the Neogene and linked the process to global cooling and Antarctic glacial history (Scott, 2007).

Joey Coetzee edited *Palaeoecology of Africa and of the surrounding islands and Antarctica*, volume 10 to 17 (1978–1987) in collaboration with E.M. van Zinderen Bakker Sr. and volume 18 (1988). While volume 1 (1966) of *Palaeoecology of Africa* was devoted to reports which have been published during the years 1950–1963 under the title of 'Palynology in Africa' and deal with the initial research done on palynology in South Africa, Volume 2 (1967) showed that pollen analytical research could be linked with so many related disciplines that the entire field was better covered by the title 'Palaeoecology'. The volumes 1 and 2 show the achievements in African palynology, Joey Coetzee's very great importance and her contributions to the rapid development of palynological fundamentals during the years 1950–1965. Volume 3 (1967) was entirely devoted to the D.Sc.-Thesis by Joey Coetzee on pollen analysis in East and South Africa. It was this volume of *Palaeoecology of Africa* that made the series of the 'small yellow books' (Nicole

Petit-Maire, Durban Febr. 1, 1989) well-known among African palaeoenvironmentalists. In the 1970s and 1980s, *Palaeoecology of Africa* became a forum for research results of scientists from various countries studying the palynology, palaeontology, biogeography, glacial geology, volcanology, geomorphology, oceanography, limnology, (palaeo-) climatology, archaeology, anthropology as well as theories on ice ages. In the publication process, Joey Coetzee distinguished herself as a personality with high principles and an intense interest in scientific communication and interchange of ideas.

Joey Coetzee served on many committees in connection with Quaternary science and palynology. She was one who always gave credit to others rather than to herself. Through her far-ranging interests and achievements, she has left an enduring imprint on African palynological science. A world-class scientist, a woman of great integrity and an inveterate friend of animals, she was above all a nice fellow who just enjoyed nature in all its facets wherever she stayed.

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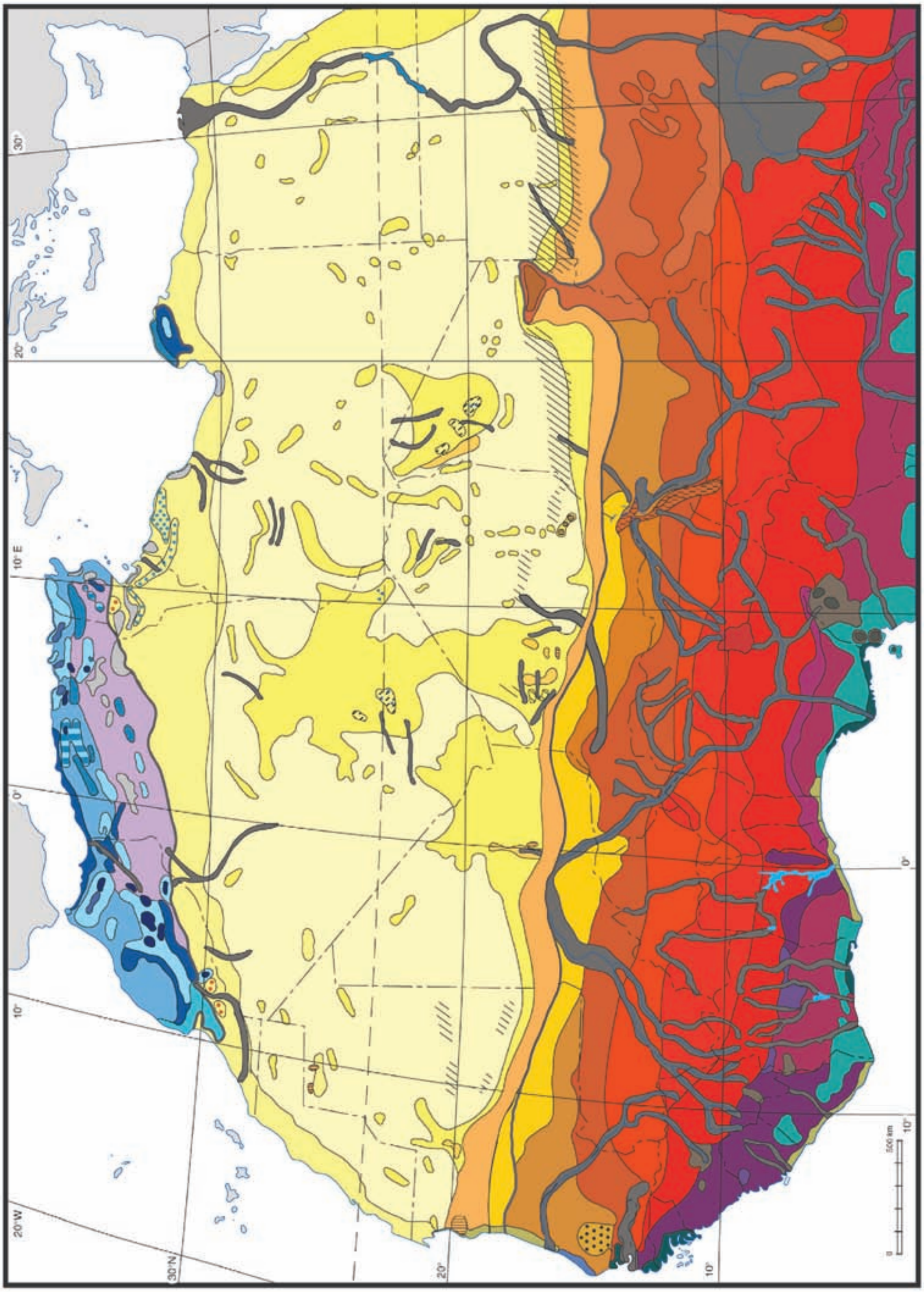

Schematic vegetation map of Northern and Western Africa (for text see chapter 4, pp. 63–89).

Schematic vegetation map of northern and western Africa

(draft: Schulz, cartography: Wepler)

A forest and woodlands

Mediterranean

coniferous forests and woodlands

1 *Pinus halepensis*

2 *Juniperus/Tetraclinis*

3 *Cedrus*

deciduous forests and woodlands

4 *Quercus faginea, Qu. afares*

sclerophyllous forests and woodlands

5 *Quercus suber, Qu. ilex, Qu. coccifera*

6 macchia/garrigue *(Olea, Pistacia. Erica)* and cultivated lands

7 *Argania* - woodlands

8 combination of scleroph. and decid. forests and woodlands

9 combination of scleroph. and conif. forests and woodlands

B steppe

10 *Stipa - Lypeum* - steppe

C semidesert

Sahara

11 *Gymnocarpus-Rhanterium-Ephedra Arthrophytum-Stipagrostis*-semidesert

12 *Artemisia-Ephedra*-semidesert in the High Mts. of the central Sahara

13 semidesert with med. shrub. *(Rosmarinus/Lavandula)*

14 semidesert with isolated *Acacia*-groups and plots

15 semidesert with isolated *Olea-Pistacia-Cupressus or Erica* -groups

D desert

16 contracted desert vegetation *(Acacia-Panicum/ Tamarix-Stipagrostis)*

17 enlarged wadi vegetation/pseudosavannas

18 ephemeral vegetation/achabs

19 extended ephemeral pastures/gizu

E savanna

20 *Acacia-Panicum*-savanna

21 *Maerua-Acacia*-savannas of isolated massives

22 *Acacia-Commiphora-Rhus* -savannas of the High Mts. of the Air

Sahel

23 *Acacia-Commiphora-Leptadenia*-savannas

24 *Acacia-Balanites-Leptadenia-Combretum*-savannas

25 *Acacia albida-Combretum*-savannas

26 *Acacia-Maerua-Balanites-Capparis*-savannas

27 *Acacia mellifera/A. senegal*-savannas

28 *Acacia-Piliostigma*-savannas

29 *Acacia*- thickets/ thornbush

30 Combretaceae-savannas *(C.glutinosum. micranthum. C.nigricans, Guiera senegalensis))*

31 *Acacia-Indigofera*-savanna

32 *Acacia-Boscia-Olea* woodland

33 *Juniperus-Ochna-Olea* woodland

F savannas and open forests

Sudan

34 *Parkia-Butyrospermum-Terminalia*- savannas

35 *Isoberlinia-Afzelia-Daniellia-Lophira*- savannas

36 Jos-plateau melange. *Isoberlinia-Carissa-Canarium- Ficus-Balanites*- savannas

37 Daniella-Lophira-Terminalia-savannas and forests

Guinea

38 *Albizzia-Triplochiton-Terminalia*- savannas and forests

39 *Celtis-Triplochiton-Terminalia*- savannas and forests

40 *Chlorophora-Antiaris*- forests-savanna mosaic

41 *Aubrevillea-Khaya-Lophira*- savannas

G rain forest

42 lowland rain forest *Lophira-Mapania* (west) *Lophira-Piptadeniastrum*- Caesalpiniaceae (east)

43 *Carapa-Pentadesma-Ficus/Parinari*- submontane forests

44 *Adenocarpus-Podocarpus Gnidia-Hypericum*- montane forests and heathers

45 *Ficus-Celtis-Cynometra*- coastal forests and swamps

H extrazonal units

46 *Avicennia-Rhizophora*- mangroves

47 coastal *Tamarix-Acacia*- shrub

48 Niayes (*Elaeis, Alchornea)*

49 riparian vegetation in different formations including sudd

50 sebkhas and chotts

51

Preface and Introduction

The environmental setting within the Central Sahara was subject to considerable changes during Late Quaternary, mainly driven by major global climate variations, although human impact increased constantly since Early Holocene.

Such global events can be reconstructed with the help of reliefs, sediments and palaeosoils and their specific morphological, chemical and mineralogical properties. The 14 papers gathered together in this volume are mainly the outcome of the interdisciplinary German research project LIMNOSAHARA (www.limnosahara.de) financed by the German Research Foundation (DFG). The investigations were carried out by a collaboration of multiple disciplines, reaching from physical geography, palaeopedology and palaeolimnology to palynology and prehistory. The project's focus is to ascertain new and established data on climate variations and associated palaeoenvironmental changes within the Central Sahara and to systematically collate and correlate them to results obtained from the Afro-Asian dry land belt and adjacent areas. The joint analysis of Late Quaternary landscape development and present environmental conditions in the Central Sahara will result in the modelling of Late Pleistocene and Holocene palaeoenvironments, emphasising various aspects. This will be achieved by transferring the highly localized information obtained from palaeolake sediments to the region by means of spatially high-resolution information about the morphodynamic processes currently shaping the landscape and the factors controlling them.

The first—introductory—chapter gives an overview of the geomorphological and palaeoecological research in south Central Sahara on the basis of a literature review. Subsequently different proxy-data sources are introduced and discussed to conclude on the former dynamics of the palaeoenvironment of the central part of Sahara.

The following chapter turns towards two aspects: on the one hand it summarizes and discusses more than 50 original publications on climate proxy- and on model-data from the Central Sahara; on the other hand, it compares the findings from the proxies with numerically modelled data by Kutzbach and Guetter's CCM0 estimations for African precipitation over time slices at 3, 6 and 9 ka. The presented combination of "empirical" *versus* "modelled" data is interesting as nowadays the discussion often is dominated by the model approach exclusively.

In chapter 3 extensive work on former lake/sebhka-sediments and fossil soils in the Seggedim region gave further evidence of Holocene palaeoenvironmental changes in an up to now not well explored region of NE Niger. In the paper a new 15 meter long core gained in 2005 is analysed and discussed by an interdisciplinary approach using geomorphological, sedimentological and geochemical investigations. A trend to more humid conditions at the beginning of the Holocene changing later on—while getting drier—into a sebkha environment with alternating salt and sand layers was evidenced by the findings. The fourth paper by Erhard Schulz and colleagues from Niger, Tunisia and France is dealing in the way of a review on different approaches of how to define and of how to characterize transitions, limits or boundaries of the Saharan desert. The authors mainly outline these by the vegetation and floristic content of the landscapes which are described in detail. The contribution illustrates the sensitivity of ecological margins due to former and future changes in climate.

Location map of study sites

1 - Baumhauer, R. et al., Geomorphological Research in the South-Central Sahara in Review.
2 - Schütt, B. and Krause, J., A review of Holocene palaeoenvironmental research in the Central Sahara.
3 - Baumhauer, R. et al., Holocene palaeoenvironmental changes in Central Sahara.
4 - Schulz, E. et al., The desert in the Sahara. Transitions and boundaries.
5 - Felix-Henningsen, P. et al., Palaeo-climatic evidence of soil development on Sahelian ancient dunes.
6 - Herrmann, L. et al., Are there valuable pedological palaeo-environmental indicators in Northern Chad?
7 - Sponholz, B., New Discovery of Rock Fulgurites in the Central Sahara.
8 - Krause, J. and Schütt, B., Fluvial geomorphology of the Achelouma valley, NE Niger.
9 - Jousse, H. and Van Neer, W., Palaeoecology of the Giant Catfish (Arius gigas, Ariidae).
10 - Striedter, K.H. et al., Neolithic Domestication and Pastoralism in Central Sahara.
11 - Abichou, A., The microstratigraphy and micromorphology of a Holocene palaeolake in Southern Tunisia.
12 - Beckers, B. and Schütt, B., Different dimensions of recent vegetation dynamics of North and West Africa.
13 - Ousseïni, I. et al., The recent history of two Saharan mountains.
14 - Sani, I.M. and Ousseïni, I., The Sahelian and Saharan dune systems of Niger.

Figure 1. Location map of study sites.

The subsequent chapters five and six are concerned with (palaeo)pedological investigations. The paper of Peter Felix-Henningsen and members of his working group (Peter Kornatz, Einar Eberhardt) examines different soils developed on nowadays inactive dune systems in Mauretania, Niger and Chad as a proxy data source for palaeoclimatic interpretation. Besides conventional pedological analysis on the soil profiles also OSL dating was carried out. The overall results are mostly confirming the findings by other papers dealing with the course of Holocene environmental conditions in the Sahara. The second pedological paper gives an overview of a pedologically directed transect in Northern Chad in general search for suitable palaeoenvironmental indicators.

Based on extended earlier research on fulgurites that were formed by lightning strike to silicate rocks, the author introduces in chapter 7 two new observations on rock fulgurites from the Central Sahara. In contrast to dune sand fulgurites that indicate monsoonal thunderstorms up to 18°N in the Sahara during the Mid-Holocene, the observed rock fulgurites are not necessarily correlated to the palaeoenvironmental conditions as they could have been formed by lightning events in the course of ephemeric thunderstorm events.

On the basis of former geomorphological field work undertaken in the 1980 by the Würzburg working group, the so-called "Seeterrassental"—a catchment with only 31,5 km^2 in size—in the Mangueni Plateau of NE Niger has been revisited by Jan Krause and Britta Schütt (chapter 8) using modern differential GPS measurements and SRTM data to reconstruct Holocene flow velocity and discharge, also applying different hydraulic equations on three identified terrace levels.

The palaeoecological and ichthyological paper of Hélène Jousse and Wim Van Neer (chapter 9) studies the recent and former distribution of the Giant Catfish (*Arius gigas* Ariidae) in Westafrica, especially in the Niger basin. On the basis of the examination of a rare skeleton specimen from the British Museum anatomy of this species is studied and documented. The Holocene and the recent decline of this fish population is discussed from different perspectives considering former climate changes and also the influence of humans (subsistance fishing) in the region. In chapter 10 (Michel Tauveron and Karl Heinz Striedter) numerous findings of cattle bones and one almost complete cattle skeleton which had not been clearly identified as *Bos taurus* or *Bos primigenious* in the South-Eastern Algerian Sahara are suggesting palaeoenvironmental interpretations for the Holocene. Abdelhakim Abichou shows in his contribution (chapter 11) micromorphological investigations and cartographic surveys. In connection with some radiocarbon data the results allow the reconstruction of Holocene palaeoenvironmental conditions in the sebka Erg el Makhzen in Southern Tunisia.

Chapter 12 is not mainly palaeoenvironmentally adjusted. Brian Beckers and Britta Schütt examine by an actualistic approach vegetation dynamics by using NDVI data and GBCP rainfall estimates on a huge transect running from North to West Africa. It underlines the recent sensitivity of the Central Saharan landscape that might have been in a way similar to the palaeoenvironmental conditions. Aside of variations in rainfall also human induced effects on vegetation dynamics are considered.

Finally, the authors of chapter 13 (Issa Ousseïni, Aboubacar Adamou and Erhard Schulz) describe and discuss recent geoecological and environmental modifications in the Adrar des Iforas (Mali) and the Air (Niger) mountains that took and still take place against the backdrop of a civil war (the so-called "rebellion of Tuareg"). Therefore, this contribution is a combination of socio-economic and geopolitical with environmental and landscape issues. It is tried to show how environmental factors and dynamics of the environment can be linked to economic and political trends. Several very complex graphs/sketch maps represent time slices from 1910 to 2007 that are driving at a better understanding of this interdisciplinary approach. Another contribution (chapter 14) from the colleagues of the University of Niamey (Ibrahim Mamane Sani and Issa Ousseïni) makes an approach to understand the granulometric characteristics of the dune systems of Niger.

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CHAPTER 1

Geomorphological and palaeoenvironmental research in the South-Central Sahara in review

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ABSTRACT: The main interest of the interdisciplinary "Limnosahara" research project of the German Research Foundation (DFG) composed of Physical Geographers, Palaeopedologists, Palaeobotanists and Archaeologists from the Universities of Würzburg, Berlin, Giessen, Frankfurt and Niamey, is to elucidate the Holocene palaeoenvironmental history of the Central Sahara. This introductory chapter gives an overview of the geomorphological and palaeoecological research in South-Central Sahara on the basis of a literature review. Subsequently different proxy-data sources are introduced and discussed to conclude on the former dynamics of the palaeoenvironment of the central part of Sahara.

1.1 THE SOUTH-CENTRAL SAHARA—GEOGRAPHICAL SETTING

The Southern Central Sahara, between 17° and 23°N and 11° and 15°E, belongs to the northern part of the hydrological Chad Basin. It is a typical part of the plateau and plains landscapes of the Central Sahara, framed in the West and East by the Saharan mountain regions of Aïr and Tibesti. To the North the study region extends to the southern fringe of the Murzuq Basin; to the South it reaches as far as the Sahara-Sahel boundary, marked by the northern limit of immobile ancient sand dunes.

The central and largest part of the study region is taken up by vast sand plains, the largest being the Ténéré, grading southwards into the sand seas Erg de Ténéré, Erg de Fachi-Bilma and the Grand Erg de Bilma, all characterized by closely spaced NE–SW oriented longitudinal dunes. The sand plains and ergs are interrupted by N–S-oriented scarplands, partly broken up into isolated massifs or plateau remnants, a common feature of their western forelands being elongated endorheïc depressions. They are like stepping stones between the most conspicuous landforms in the North of the region—the

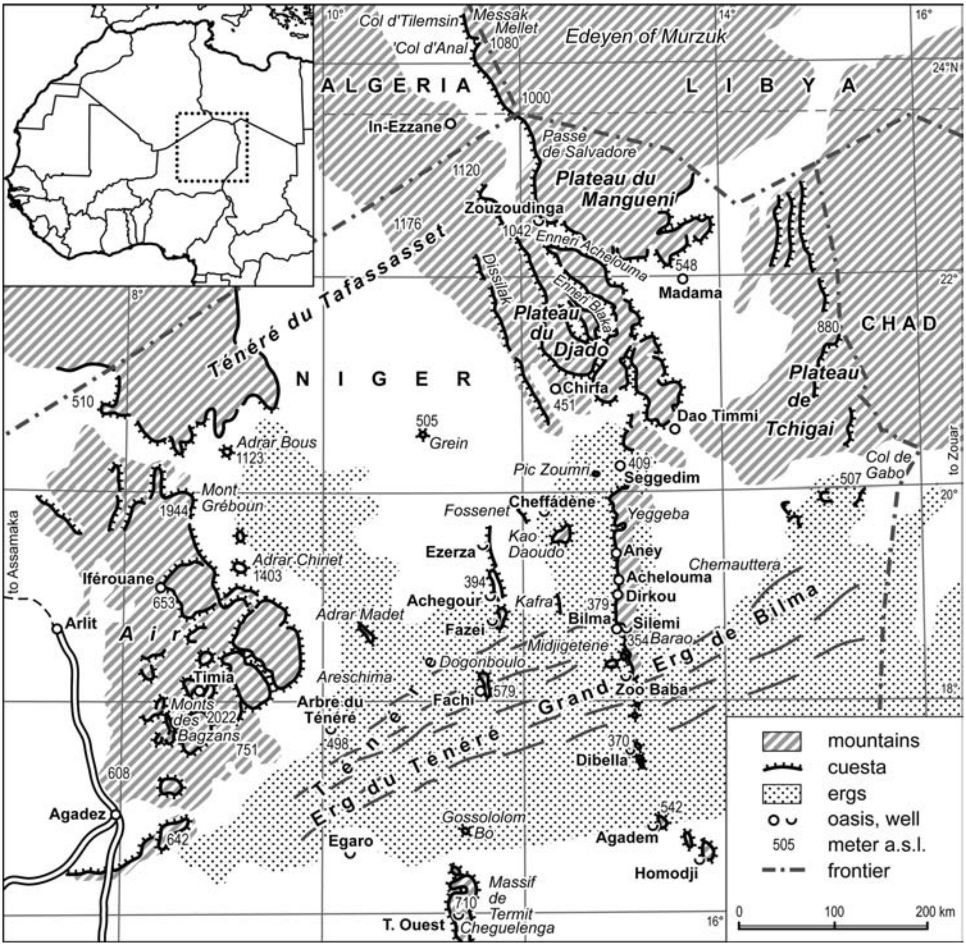

Figure 1. Location map of NE-Niger.

plateaus of Djado and Mangueni at the southern fringe of the Murzuq Basin—and the fossil dune region of Tin Toumma and In-Madama to the South, already belonging to the geomorphological Lake Chad Basin. The average elevation of the entire area is 400 to 500 m asl; the escarpments may rise above the forelands by heights ranging from a few tens of metres to several hundred metres (Figure 1).

The meteorological and climatological data situation of the region is extremely poor in terms of space and time. There are only few weather stations, and their data are often not available for political reasons. The plains of the Central Sahara are particularly sparsely equipped with only ten weather stations, almost all of which are located along its northern limit. For the South-Central Sahara, the only more or less complete record is that from the station at Bilma (18°41'N, 12°55'E, 335 m asl) from 1922 onwards. For the military post of Madama to the North (21°51'N, 13°45'E, 546 m asl), rainfall data are only available from 1939 to 1943. Because of the lack of proxy data, meteorological publications on the present climate and climatic history of the region are largely model-based and often rely too much on the transfer of data from deep-sea cores to be a suitable basis for further studies in a continental region such as this (e.g. Flohn and Nicholson, 1980; Kutzbach, 1980; Adams and Tetzlaff, 1984; Macayeal, 1993; Cubasch *et al.*, 1997; Montoya *et al.*, 1998; Stauffer *et al.*, 1998; Crowly, 1999; von Storch *et al.*, 2000). Ultimately, the factors governing the climate of the Central Sahara are its latitudinal position within the trade-wind belt and its extreme continentality. Although the region is affected by tropical monsoonal air from the Equatorial Atlantic and, in the North, by the Mediterranean circulation, neither influence modifies the extreme aridity of the region. At a low cloud cover throughout the year and summer maximum temperatures of above 40 °C, average annual precipitation is barely above 20 mm.

1.2 GEOLOGICAL SITUATION

The post-Palaeozoic development of Eastern Niger to the south rim of the Plateau du Djado was described by Faure (1966); together with the work by Pirard (1964) on the hydrogeology of Eastern Niger, this study is still the foundation of all geological work in the region. The Southern Central Sahara consists of a wide-ranging system of tectonic basins and broad uplifts. Mainly in the transition areas, gently inclined Palaeozoic, Mesozoic and Tertiary sediments, unconformably overlying an etchplain cutting across the Precambrian metamorphic and crystalline basement, have been eroded to form the typical plateau and scarpland terrains of the Central Sahara. The core of the South-Central Sahara belongs to the geological basin of Bilma; to the North, the plateaus at the southern Murzuq rim are part of the geological Murzuk Basin, while to the South, the Massif d'Agadem is part of the geological Chad Basin (cf. Faure, 1966).

The geological basin of Bilma occupies an area of 400 × 300 km in the centre of the Nigrian part of the hydrological Chad Basin. Its longer axis is delineated by the Bilma Escarpment. The western half of the basin, delimited by outcropping basement to the North, South and West, has been filled by up to 1.000 m of Cretaceous to Palaeocene continental and marine sediments, without any underlying Palaeozoic strata (Faure, 1966). Hardly any geological and geomorphological information has been published about the eastern parts of the Bilma Basin. To the West the Bilma Basin is separated from the Aïr Mountains by the grabens of Achegour and Adrar Madet, to the Southwest, by the Téfidet-Lake Chad graben system from the Termit Basin. To the North, there is just a gradual transition to the Murzuq Basin.

Within the system of Central-Saharan basins and uplifts the geological Murzuq Basin, approximately 1.000 × 600 km large, has a central position, geologically and morphologically being a depression with elevated rims. The gently inclined strata form an almost uninterrupted fringe of outward-facing escarpments around the basin (Grunert, 1983). Because of the basin structure, the ages of the sediments exposed at the surface decrease from the rim to the centre (Klitzsch, 1970, 1971). Along the southern fringe, the surficial rocks are mainly marine sediments of the Upper Carboniferous and the continental series of the Mesozoic, up to the Lower Carboniferous (Plauchut *et al.*, 1960). As mentioned, the southernmost parts of the Central Sahara belong to the geological Chad Basin.

1.3 GEOMORPHOLOGICAL AND QUATERNARY EXPLORATION

More recent geological studies of the South-Central Sahara have mainly been undertaken by the "Würzburg Africa Research Group" headed by Horst Hagedorn. From 1977 to 1991, ten expeditions to the region were carried out, with varying participants. From 1992 to 2000 all of the Nigrian part of the South-Central Sahara was inaccessible because of

Figure 2. Emi Fezzan, Butte of the northern Plateau de Tchigai.

civil-war-like conflicts. Except for a few selective studies on the prehistory of the region, carried out on the Djado Plateau from a base in Algeria (Striedter *et al.*, 1995; Striedter, 1997, 1999), a whole decade passed without field work in this part of the Sahara.

Only a small number of studies exist on the Late Quaternary evolution of the South-Central Sahara. Those by Faure (1966), Servant (1973), Servant-Vildary (1978) and Maley (1980) have their regional focus in the Chad Basin; the Saharan space is dealt with only marginally and very selectively. The north easternmost parts of Niger, in particular from east of the plateaus of Djado and Mangueni to the Chadian and Libyan borders, is still largely unknown from this perspective, except for some reports by French colonial officers (e.g. Capit. Freydenberg, 1907), and some geological reconnaissance work (Dalloni, 1948; Kilian, 1937; Kilian and Furon, 1934; Pirard, 1964).

1.3.1 Tertiary to Mid-Pleistocene landform history

According to the stratigraphy described by Faure (1966) and Klitzsch (1970, 1971), post-sedimentary landform development in the Central Sahara began after the deposition and diagenesis of the Messak/Nubian Sandstone of the rim of the Murzuq Basin and of the Bilma and Emi Bao formation of the Bilma Basin. The shaping of the present landscape should already have started in pre-Upper Cretaceous times. From the study of the major landforms of North-Eastern Fezzan and groundwater studies of the Central Sahara, Klitzsch (1974) and Klitzsch *et al.* (1976) place the Messak Sandstone in the Jurassic and also assume that an escarpment landscape had already developed in pre-Late Upper Cretaceous times.

In contrast, Faure (1966) for the Bilma Basin and Busche (1982) for the western and southern rim of the Murzuq Basin and the northern parts of the Bilma Basin assume an Upper Cretaceous age of the Bilma and Emi Bao formation and the Messak Sandstone. Up to the onset of the Cainozoic, the study region was part of a depositional surface rimmed by the exposed crystalline uplifts of Gargaf-Hoggar to the North and Northwest, and the Tibesti-Syrte uplift to the East and Northeast (Busche, 1982). To the South, during the Palaeocene and Eocene, the sea reached Western Niger, Mali and North-Western Nigeria (Greigert and Pougnet, 1967). The marine transgression from the South did not go beyond the present foreland of the Tibesti Mountains (Klitzsch, 1970). For the continental realm between the seas, Erhard (1956) and Elouard (1959) identified a time of lateritic deep weathering under a humid-tropical climate, based on their study of the *Continental Terminal*, the southern correlative sediment of extended etchplanation to the North. According to Faure (1966), tectonic uplift in Eastern Niger since the Upper Eocene and the Oligocene caused the large-scale removal of the lateritic weathering mantle there. For the southern and western rim of the Murzuq Basin, Busche (1982), in his comprehensive study on the development of the region, together with the Djado Plateau and northern “Kaouar” (summarized by Baumhauer, 1986; Baumhauer *et al*., 1989; Skworonek, 1988; Busche, 1998) proposed a downwearing by etchplanation of the Messak Sandstone by at least 100 m. To him, the humid to wet-and-dry tropical conditions favouring etchplanation—of the *African Surface* of King 1967, cf. also Gellert (1971)—persisted to the Miocene, as Eocene sediments have also been etchplanated and intensive chemical weathering can be traced to at least that time, with decreasing intensity even to the end of the Tertiary (Busche, 1982; 1998). In a persistingly humid environment intensive silicification, following the almost complete removal of the lateritic weathering mantle, affected the level landscape close to a high groundwater level. Busche (1982, 1998) regards such silicified surfaces as a special type of planation landscape preserved on the plateaus of the Central Sahara, and also as a time marker: the end of silcrete formation, i.e. its beginning dissection, coincided with a time of increasing crustal movements, expressed in the doming and onset of volcanism first in what was to become the Hoggar, and then also in the Tibesti Mountain regions. Following silcrete formation there began a time of intensive surficial and subsurface silicate karstification, it appears to have continued to the Early Pleistocene (cf., among others, Busche, 1982; Busche, 1998; Busche and Sponholz, 1992; Hagedorn and Sponholz, 1990; Sponholz, 1992).

The tectonic movements increasing since the Miocene uplifted most of the Cretaceous continental sediments and also, South of 17°N, the parts of Eastern Niger blanketed by the *Continental Terminal*, whereas the Chad Basin to the East began to subside. This led to a general gentle tilting of the strata to the East, together with continued downwearing by planation of parts of the rising terrains by an average of 100 m, the *grand creusement postérieur au Continental terminal*, followed, during the Early Pleistocene, by another phase of erosion during which also the Pliocene fluvial sediments (quartz gravel beds incorporating fragments of *Continental terminal*) were dissected in the North, and erosion to the South increased from 50 to 150 m (Faure, 1966). At the same time, in the region of subsidence west and northwest of present Lake Chad, up to 1.000 m of sediment were deposited of the *Groupe du Tchad* (Pirard, 1967), and, in the centre of the geological Chad Basin, about 100 m of the *Bahr el Gazal* series (Servant, 1983).

According to Busche (1982, 1998) uplift still under the conditions of tropical chemical weathering, and a continuation of silicate karstification. The combined processes, up to the end of the Tertiary, resulted in the formation of a landscape of erosion scarps rimming dissected plateaus and a lower level of intra-plateau basins and etchplains. Regional differences of uplift and thus of different efficiency of etchplanation caused scarps to become a few hundred metres high, like the Messak Mellet now forming the western geomorphological rim of the Murzuq Basin, only a few tens of metres, like the southernmost parts of the Dissilak escarpment forming the western rim of the Djado Plateau, or, intermediate, the Bilma Escarpment. The latter is further characterized by the fact that selective planation, following intensive sandstone karstification, could keep pace with the rate of uplift, so that much of the original surface was transformed into a pattern of plateaus and basins (Busche, 1982; Busche, 1998). The fluvial and aeolian transformation of the landforms took place under semi-humid to semi-arid climates of the Early Pleistocene: also the lowermost etchplain level became fluvially dissected, those parts of the Late Tertiary etchplain abutting against the escarpments and rims of intra-plateau basins became more steeply inclined pediments, escarpment and inselberg profiles became steepened, with the development of a free face, and the endorheïc scarpfoot depressions (see above) came into existence (Busche, 1982, 1998) towards the end of the Early Pleistocene or somewhat later, during an extremely pronounced arid phase (Busche and Stengel, 1993; Busche, 1998).

As described by Grunert (1983), in a detailed study focusing on the ancient landslides formed along the heterolithic parts of escarpment slopes of the western and southern rim of the Murzuq Basin, the slides followed a period of fluvial dissection and slope