Overview of the geological and geomorphological evolution of the Etosha region, northern Namibia

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ABSTRACT

This paper gives an overview of the geological and geomorphological history of the Etosha region in northern Namibia. The long-term evolution of this landscape is characterized by a) the Precambrian to early Palaeozoic orogeny (Damara Orogeny, Owamboland Basin), b) a long period of geological consolidation and consequently c) a long period of tectonically more or less uneffected terrestrial erosion and denudation and the evolution of the Etosha Basin depocentre.

The geological-tectonical and geomorphological evolution determines the actual landscape-ecological differentiation in terms of the soil communities (including individual pedological properties and soil erosion processes) and the chemical groundwater quality. Together with the climatic differentiation in Namibia the abiotic factors control the complex system of biotic factors. This is most apparent in the strong relationship between soil and vegetation communities.

INTRODUCTION

The special status of the geological/tectonical and geomorphological evolution of Gondwana-Africa is well reflected in the Etosha region of northern Namibia (Fig. 1). The long-term evolution can be described by three features (Hüser 1979, 1989):

1. The predominately Precambrian (> 570 m.a.) to early Palaeozoic (570-290 m.a.) orogeny
2. the long period of geological consolitation and consequently
3. the long period of tectonically more or less uneffected terrestrial erosion and denudation.

New impulses for relief development through tectonical events in connection with the break-up of the Gondwana Continent are presumed to have taken place only as late as from the Cretaceous (141-65 m.a.)/Tertiary (65-1.8 m.a.) on (Buch 1993).

The geological/tectonical and geomorphological history of the Etosha region in principle is the history of the Damara Orogeny and the Owamboland Basin on the one hand and the long-term erosion and denudation of the Damara Orogeny, thus controlling the evolution of the Etosha Basin, on the other hand (Hedberg 1979; Momper 1982). The Etosha Basin which covers northern Namibia and southern Angola is the northwestern outlier of the even more extensive inland depocentre of the Kalahari Basin (Fig. 2).

THE GEOLOGICAL/TECTONICAL EVOLUTION OF THE OWAMBOLAND/ETOSHA BASIN PRIOR TO THE LATE CRETACEOUS/ EARLY CAINOZOIC (1000-65 M.A.)

The structural setting of the Owamboland Basin is closely related to the Precambrian/early Palaeozoic Damara Orogeny (Fig. 3). Intracontinental rifting between the Congo Craton in the north and the Kalahari Craton in the south from 1000 to 900 m.a. led to the deposition of coarse clastics of the Nosib Group, which forms the basis of the Damara Sequence (for details see Hedberg 1979; Miller 1983). The following period of seafloor-spreading between 730 and 650 m.a. is characterized by the formation of the carbonatic and dolomitic series of the Otavi Group in a marine shallow water environment of the so-called 'northern platform' shelf zone. Since the reversal of spreading to continental collision about 600 m.a., the geosynclinal cycle turned into an orogenic cycle in a more narrow sense. In connection with the main period of the morphological uplift during the Damara Orogeny (550-450 m.a.) and simultaneously stimulated erosion and denudation processes, the depositional environment in the northern foreland consequently changed from 'shallow-marine' (Otavi Group) to progressively 'terrestrial' during the deposition of the Mulden Group (northern molasse, 450-290 m.a.). Fine-clastic sediments of the Owambo Formation of the Mulden Group (siltstone, sandstone, schist, limestone and dolomite) already represent a late phase of the Damara Orogeny.

Major subsidence and the formation of large anticlines in the northern foreland of the Damara Orogeny led to the initial structural development of the closed inland basin structure of the Etosha Basin during the late Westphalian of upper Carboniferous (290 m.a.) (Momper 1982). The Etosha Basin represents a compound structural depression with three or four deep, closed sub-basins. According to geophysical examinations during oil and gas exploration, Momper (1982) showed that the western-most sub-basin with an area of more than 10,000 miles^2 is separated from two smaller central sub-basins by the northeast trending so-called 'Ondangwa Uplift'. Both smaller sub-basins developed as late as during the Mesozoic volcanic activity (Kaoko Formation). Buch (1993) recognized that the southernmost of the two smaller sub-basins is located in some depth beneath the present-

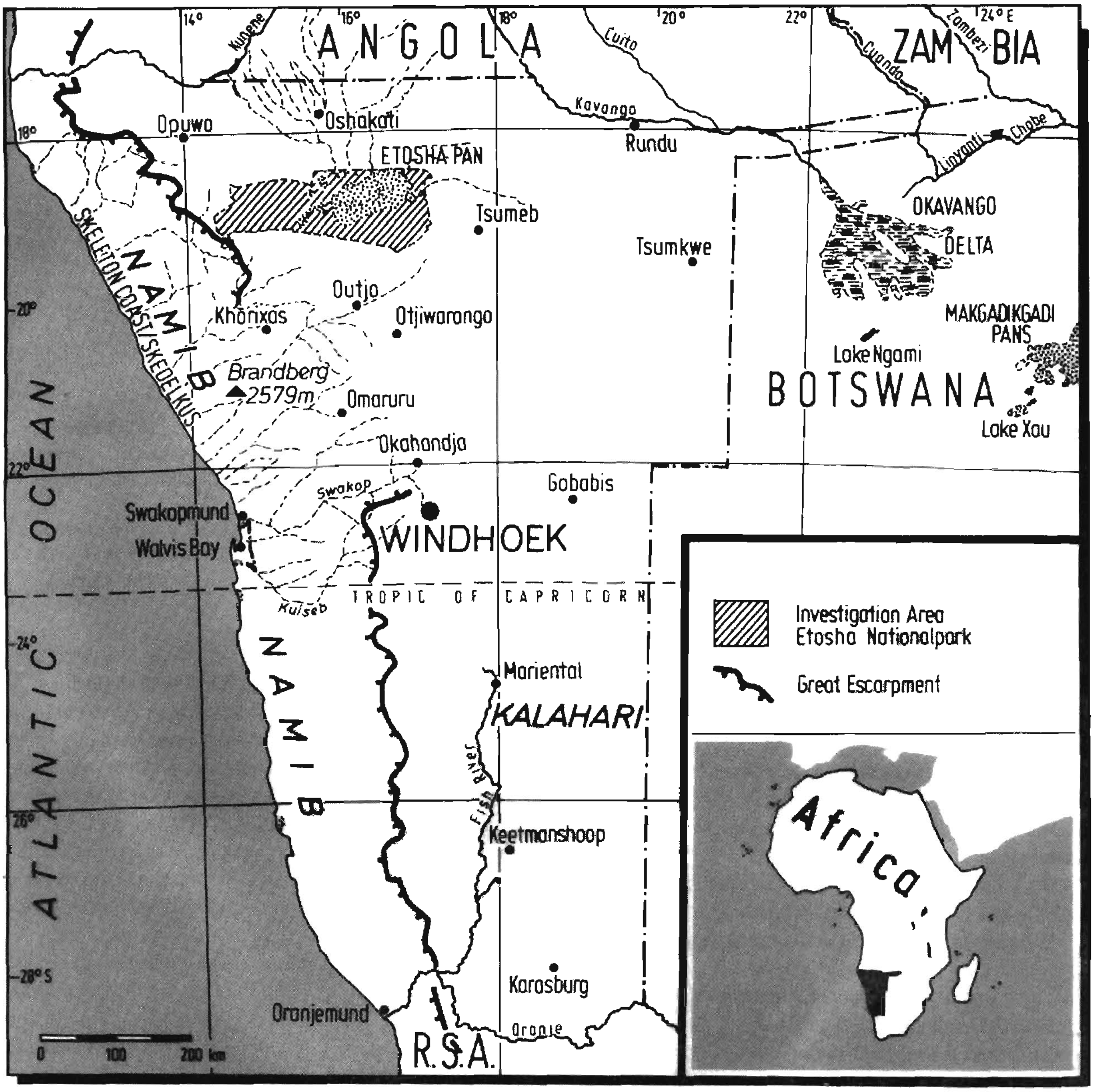

FIGURE 1: Location of the investigation area in northern Namibia.

day Etosha Pan. The centre of the large eastern sub-basin is identified at the Kavango River near the Namibian/ Angolan boundary (Hedberg 1979; Momper 1982).

Tectonically the region of the Etosha Basin had been comparatively stable since the Westphalian (290 m.a.). Moderate regional uplift, minor basin subsidence, and two events of gentle regional tilting are revealed by the sedimentary record within the basin (Momper 1982). The first event of regional tilting affected the pre-Kalahari sediments. The striking fault, which runs parallel to the southern margin of the present-day Etosha Pan, can be regarded as a result of this event of regional tectonical activity (Fig. 4). Several artesian springs (e.g. Agab, Klein Namutoni, Namutoni) along the southern margin of Etosha Pan can probably be related to this fault. The second event of regional tilting affected the entire sedimentary sequence of the Etosha Basin, including the sediments of the Kalahari Group (see below). There is evidence that on a regional scale the described tectonical events had a strong influence on the shape of the Etosha Basin depocentre and that they have determined the position of the centre of deposition since the late Upper Carboniferous (290 m.a.) (Buch 1993).

From the late Upper Carboniferous (Stephanian) till the end of the Lower Cretaceous, terrestrial sediments of the Karoo Sequence (290-100 m.a.) were deposited in the consolidated Etosha Basin (Fig. 3). The thickest record of Karoo sedimentation in the Etosha Basin is identified beneath the eastern part of the present-day's Etosha Pan with a thickness of 400 m (Hedberg 1979). The Karoo Sequence starts with the basal tillites of the Permo-Carboniferous Dwyka Formation, which may reach a thickness of 160 m in the study area (Hedberg 1979). Martin (1950) reconstructed the centre of Dwyka glaciation north of the Damara Orogeny in the morphological high positions north and east of the Etosha Basin. The ice lobes were moving in a westerly direction, to the Kaokoveld. Here, individual ice streams created steep U-shaped valleys. Tillites of the Dwyka glaciation are e.g. exposed at the Ruacana Falls of the Kunene River.

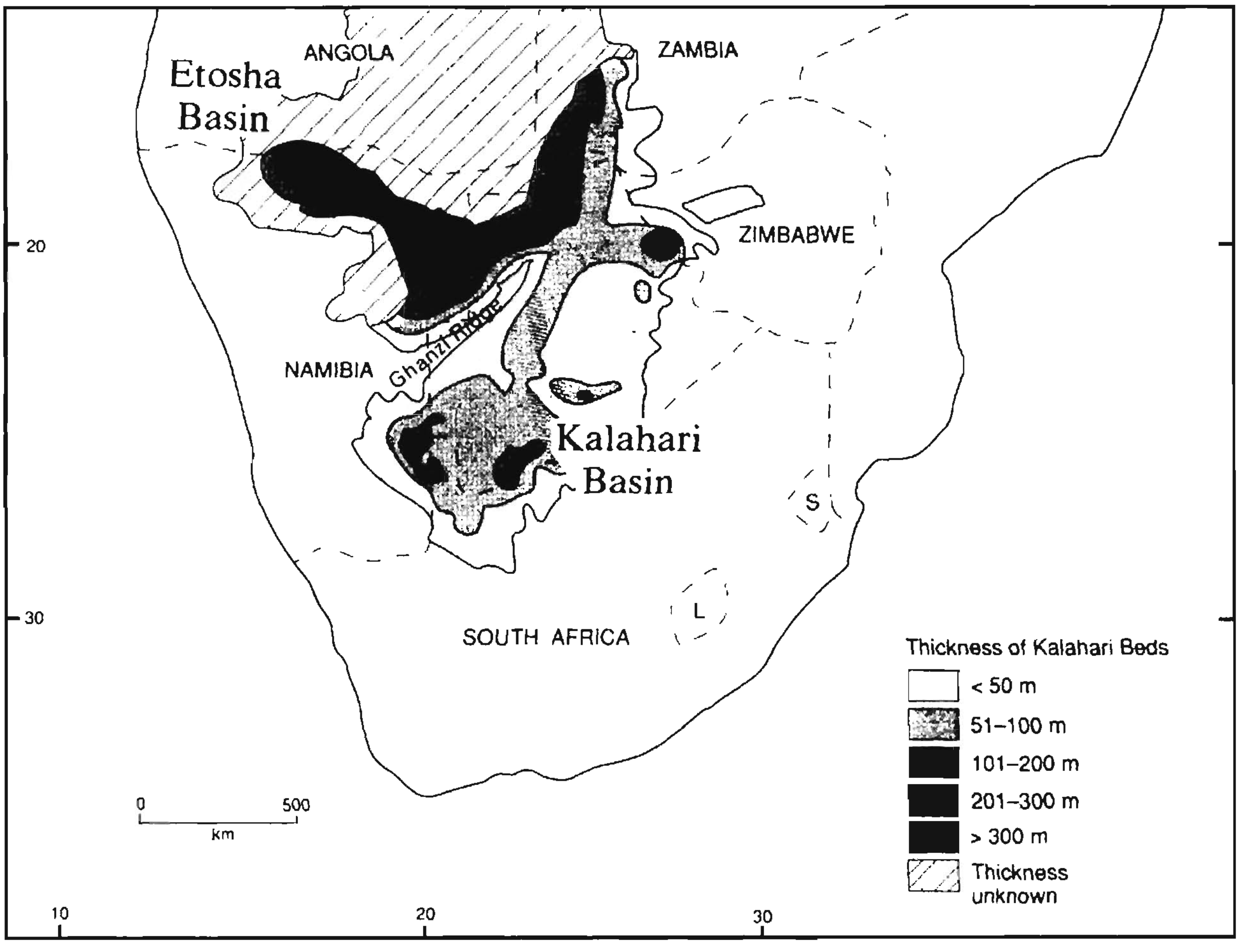

FIGURE 2: Distribution and thickness of the Kalahari Group sediments in southern Africa, constructed mainly from borehole data (after Thomas 1988).

The so-called 'Shale Members' of the Dwyka Formation in the sense of Hedberg (1979) or the 'Dwyka Shale Formation' as a part of the Ecca Group in the sense of Momper (1982) represent reworked and redeposited tillites, particularly west and northwest of the former glaciated area. Lithologically they mainly consist of conglomerates, dark-coloured (organic-rich) and partly dolomitic shales, siltstones, limestones and sandstones. The sedimentary environment in the Etosha Basin during the early Permian (280-250 m.a.) thus can be described as fluvial and fluvio-limnic.

Following a widespread period of erosion, the Etjo Sandstone Formation of both fluvial and aeolian origin was deposited under generally arid climates in the Etosha Basin over a time-span of about 50 m.a. between the early Permian (250 m.a.) and the end of the Triassic (200 m.a.). According to the few available borehole loggings, Hedberg (1979) reconstructs a facial change from a sandstone in the western and western-central areas of the basin to a sandstone and shales environment in the central and eastern parts.

Volcanics of the Kaoko Formation (200-120 m.a.) terminate the Karoo Sequence in the Etosha Basin. Although not recorded in any borehole up to now, aeromagnetic measurements help to identify at least two pronounced dyke swarms (Hedberg 1979; Momper 1982). One dyke swarm shows a north-south trending from the Angolan border at 16º15'E to the Etosha Pan, the other one a northeast-southwest trending in the Etosha Basin northeast of Tsumeb. There is evidence that the Kaoko volcanic episode between the turn of Triassic/Jurassic and the turn of Lower/Upper Cretaceous is related to the breaking-up of Gondwana and the beginning of the opening of the southern Atlantic Ocean (Momper 1982).

At the beginning of the sedimentary cycle of the Kalahari Group - possibly as early as late Cretaceous - the Etosha Basin already acted as an extensive depocentre in northern Namibia and southern Angola for a period of approximately 190 m.a.. Although the regional sedimentary history in detail is more complex than can be summarized here, the overall terrestrial depositional environment did not change very much. Fluvial and fluvio-limnic sediments predominate throughout the record, except the glacial tillites of the Dwyka Formation at the beginning of the Karoo Sequence. At least from the late Permian on also aeolian sediments have formed. It can be concluded that the Mesozoic depositional environment of the Etosha Basin did not differ very much from the Cainozoic and the present environment in Etosha.

DEPOSITIONAL ENVIRONMENT OF THE ETOSHA BASIN DURING THE CAINOZOIC (65-0 M.A.)

According to Hedberg (1979) and Momper (1982) the terrestrial sediments of the Kalahari Group comprise the youngest deposits in the Etosha Basin since probably the

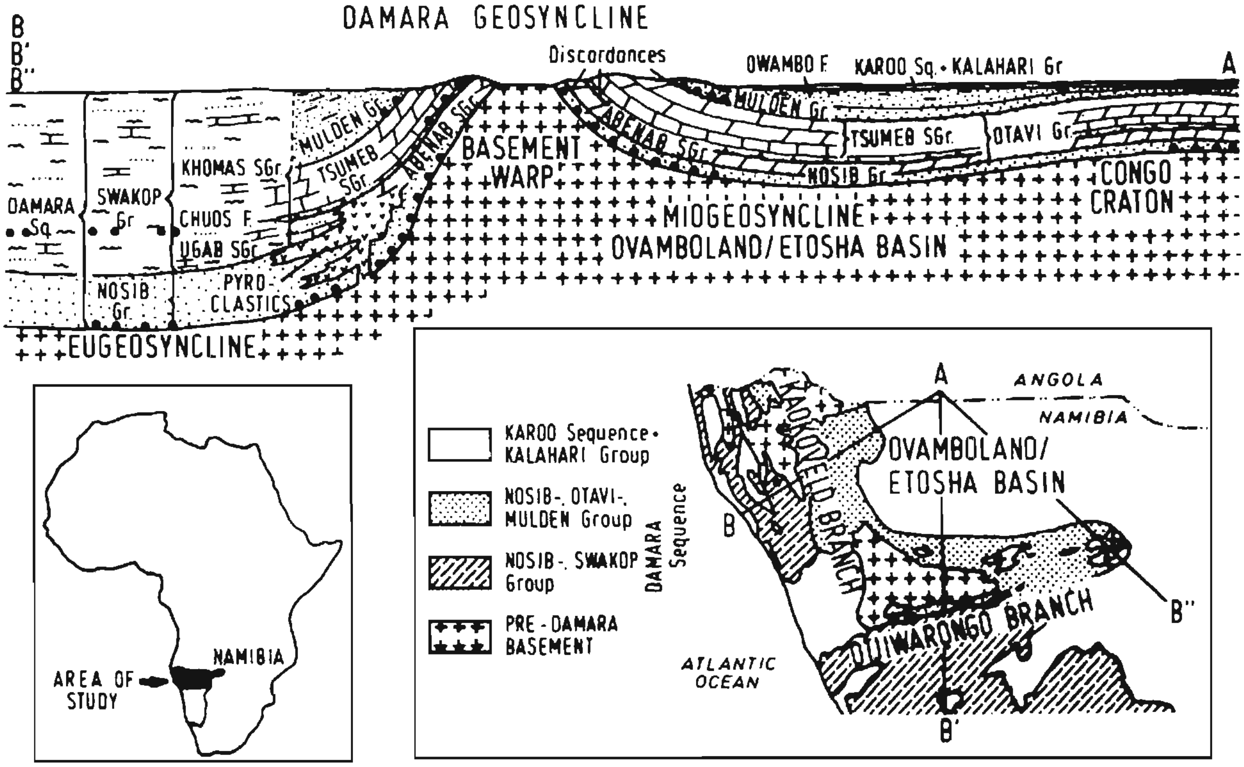

FIGURE 3: Simplified stratigraphic cross section from the Owamboland Basin (miogeosyncline) to the Damara eugeosyncline. Cross sections drawn from A to either B, or B', or B'' show generally similar stratigraphic relationships (after Hedberg 1979).

late Cretaceous. A clear differentation of the Kalahari sediments and the underlying late Karoo sediments locally is not possible due to post-Karoo erosion and missing biostratigraphical indicators (Hedberg 1979). According to borehole record, the Kalahari Group sediments consist of conglomerates, sand, sandstones, claystones and limestones.

The thickness of Kalahari sediments in the southern part of the Etosha Basin varies between only 50 m south of the present Etosha Pan and up to 250 m at its northern margin. A thickness of more than 500 m is reached only at the Namibian/Angolan border. Due to later erosion a thin cover of Kalahari sediments directly overlies the predominately dolomitic rocks of the Damara Sequence in the south and west of the Etosha National Park (Etosha N.P.). In general, the facial differentiation of finer-grained sediments (clays) in the centre of the Etosha Basin and coarser-grained sediments (sands) at the margins is the same, as it was described for the ancient depositional environments (see above). Thick calciferous series (locally more than 50 m thick) accompany the southern and western margin of the Etosha Basin, thus representing a transitional facies between the erosion and solution positions of the Otavi Mountains and the Kaokoveld ('Etoschabogen', Stahl 1940) with dolomites of the Damara Sequence (see above) and the centre of the Etosha Basin. For the calciferous facies of the Kalahari sediments, Buch (1993) introduced the term 'Etosha Limestone'.

SACS (1980) proposed a differentiation of the Kalahari Group of the Ovamboland into three formations: the basal 'Beiseb Formation' (30 m of reddish conglomeratic sandstone), the middle 'Olukonda Formation' (> 121 m of reddish-brown carbonatic sandstone) and the top 'Andoni Formation' (>134 m greyish-green to greenish-gray claystone and sandstone). Recently, Miller (1990) introduced the 'Nanzi Formation' describing a sequence of reddish semi-consolidated sandstone, shale or clay, and a basal clayey conglomerate, which was formerly interpreted as being part of the 'Beiseb Formation'. The 'Nanzi Formation' is believed to be of Cretaceous age.

Until now no final statements can be made on the exact dating of the individual formations of the Kalahari Group. The deposition of the Andoni Formation may have started as early as Oligocene (38-22.5 m.a.). In a shallow, saline-alkaline playa lake environment, the basal series of the Etosha Limestone along the southern and western margin of the Etosha Basin developed simultaneously with the green-coloured, sandy and silty/clayey facies of the 'Andoni Formation' (see also Buch 1997; Buch & Rose in press). The sandstone of the 'Omatako Formation' in Kavangoland (Hegenberger 1986/87) is correlated with the older sequence of the Andoni Formation, thus representing a predominately coarse lithofacies within the Etosha Basin of Tertiary time (Buch 1993). During the Miocene the lake-margin carbonate mud flat facies spread out. As described in more detail by Buch (1993, 1997) an age-range from Miocene (22.5-5.0 m.a.) to Pliocene (5-1.8 m.a.) can be regarded as most reliable for the major formation of the Etosha Limestone. In general the Etosha Limestone terminated the fluvial and fluviolimnic depositional history of the Etosha Basin.

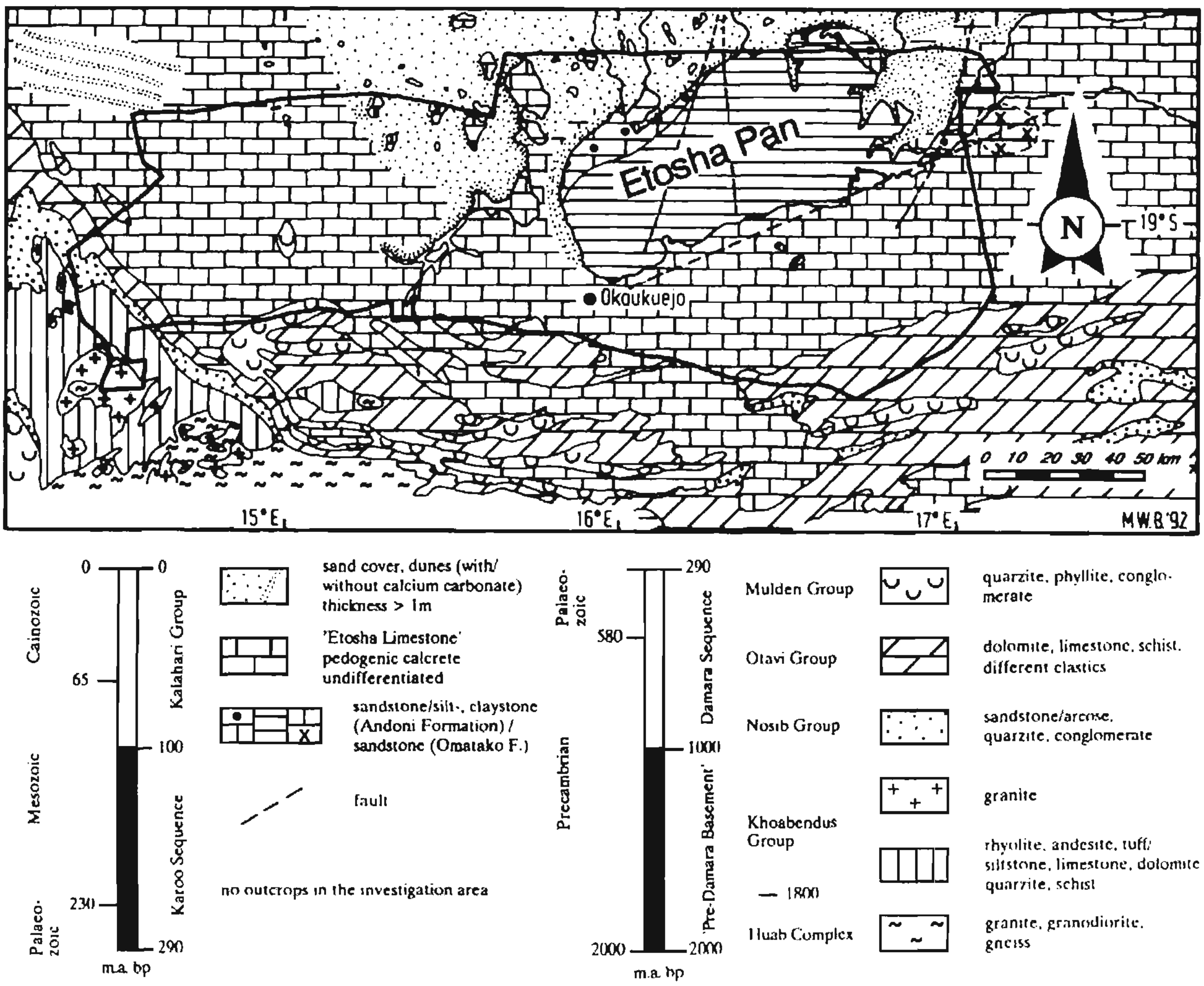

FIGURE 4: Reconnaissance survey on the geology of Etosha/northern Namibia (according to Geological Survey of SWA/Namibia 1980, supplemented; after Buch 1993).

REGIONAL SURFACE GEOLOGY AND CAINOZOIC GEOMORPHOLOGICAL EVOLUTION

The Figures 4 and 5 illustrate the regional geology and geomorphology of Etosha. According to the geological evolution described so far, two major geological units are identified for Etosha:

1. parent sedimentary rocks of the younger formations of the late Cretaceous/Tertiary Kalahari Group, in particular the widespread Etosha Limestone.
2. the 'Etoschabogen' (Stahl 1940) with dolomites, limestones, quarzites, sandstones, conglomerates, schists and phyllites of the Precambrian to early Palaeozoic Damara Sequence (Nosib Group, Otavi Group, and Mulden Group).

Another geological unit

3. the 'Pre-Damara Basement' ('Huab Complex' [metamorphosed and gneissic sedimentary, volcanic, and plutonic rocks] of the 'Kamanjab Inlier'), including the 'Khoabendus Group' (intermediate to acid eruptiva; clastic, carbonatic sedimentary rocks, metamorphites, volcanics) and younger intrusiva ('Kaross Granite' and 'Kamdescha Granite')

form the parent bedrock in the southwest of Etosha (Otjovasandu area and Kaross) (SACS 1980; Porada 1974). In this area, widespread erosion and denudation processes since the end of the Damara Orogeny and especially since the late Tertiary have stripped off the rocks of the Damara Sequence and exposed the oldest parent bedrock known in the study area with an age of > 1600 m.a. (see below; Fig. 3 and Fig. 4). No surface outcrops of Karoo age are known in Etosha.

The carbonate rocks of the Damara Sequence that form the Otavi Mountains and Kaokoveld (1200-1800 m a.s.l.) are subject to extensive karstification since their subaerial exposure. Typical karst features like solution rills, sink holes, caves with drip curtains and stalagmites as well as collapsed caves with an open lake (Otjikoto Lake, Guinas Lake) characterize the landscape. Due to local differences in the intensity of karstification, the Damara Sequence carbonate rocks produce an unconfined or leaky and discontinuous aquifer (Hoad 1992). Consequentely the actual depth of drilled boreholes is variable, ranging from 30 m to 200 m. Recharge strongly depends on the amount of rainfall. Hoad (1992) considered that recharge may vary from 0% to 4% of rainfall. Thus it is important to notice that during pronounced periods of drought (Engert this volume) there may be no recharge. The typical Ca^{2+}, Mg^{2+}/HCO_3 dominated system of the groundwater reflects the character of the geology (Rahm & Buch this volume). In terms of groundwater use, the Damara carbonate aquifers fulfil the requirements of the

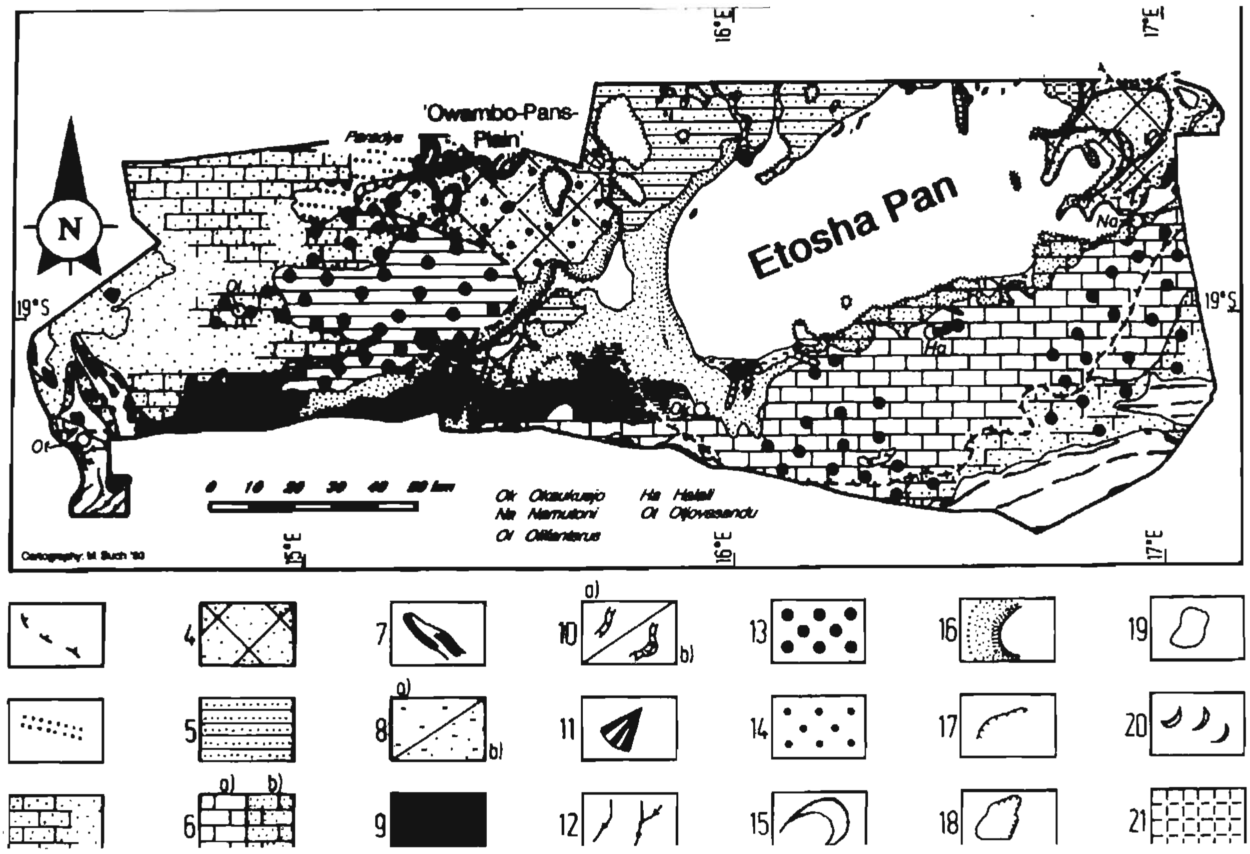

FIGURE 5: Reconnaissance survey on the geomorphology of Etosha, northern Namibia (after Buch 1993).

1 boundary of the Pliocene/early Pleistocene initial form of the Etosha Pan; **2** linear dunes with Rhodi-/Chromi-Ferralic Arenosols; **3** thin cover of calcium carbonate-free sands (Rhodi-/Chromi-Ferralic Arenosol sediments) over limestone; **4** calcium carbonate-free cover sands (thickness > 1 m) with Xanthi-Ferralic Arenosols; **5** Plains with (Humi-) Cambic Arenosols-Eutric Cambisols from sandy limestone; **6 a)** parent limestone, **b)** parent limestone with a thin cover of calcium carbonate-rich, aeolian sediments; **7** ridges of dolomite and quarzite (Damara Sequence) with pediments; **8 a)** calciferous, fluvial sediments, **b)** calcium carbonate-free, fluvial sediments; **9** calcium carbonate-free fluvial/colluvial sediments over limestone; **10 a)** trough-shaped valley, **b)** trough-shaped valley with palaeochannels; **11** alluvial fan; **12** talweg in a V-shaped valley relief; **13** concentration of solution forms in limestone with Eutric Vertisols and Mollic Leptosols (ʃ indicates the occurance of these forms in a plain relief); **14** concentration of hollow moulds in sandy substratum with 'Para-Vertisols'; **15** sandy 'beach ridge' (calcium carbonate-free substratum), reworked by aeolian processes at the top; **16** calciferous lunette dune, grading into calciferous cover sands and calcium carbonate-free lunette dune; **17** scarp; **18** pan (erosion form) with/without scarp; **19** pan's floor; **20** erosion remnant of the '1082 m Level' and the '1080 m Level' with a barchan-like configuration; **21** hardpan of the Andonivlakte.

chemical 'A' and 'B' standards of the Department of Water Affairs (1991), which describe excellent to good drinking water quality for human consumption (Auer 1993, 1997; Gammer 1993; Hoad 1992).

Towards the north and east the mountainous region of the 'Etoschabogen' drops rapidly away to the plain landscapes of Etosha and Owambo (Fig. 5). All the landscapes east of the Great Escarpment (1200-1080 m a.s.l.) have in common that they belong to an endorheic drainage system and the Etosha Pan represents the lowermost topographic position. Either the Etosha Limestone, a green-coloured clay-/siltstone and sandstone of the Andoni Formation (locally also a sandstone of the Omatako Formation), or fluvial and aeolian sands overlying these sediments of the Kalahari Group form the substratum of the plains.

In general a pediment zone mediates between the dolomite mountains and the plains. In these landscape positions the most highly developed soils of the study area, medium deep developed Rhodi-Eutric Cambisols/Rhodi-Ferralic Arenosols from dolomite and quarzite, may be preserved (Buch 1993; Beugler-Bell & Buch 1997). Typically a pedogenetic calcrete of a thickness of a few centimeters to decimeters is developed at the base of the solum, in contact to the parent bedrock (Buch 1993). Towards the plains the pedogenetic calcrete of the pediment zone grades into the much thicker sedimentary facies of the Etosha Limestone. In some distance from the mountainous region, isolated inselbergs occur (e.g. Helio Koppies; Fig. 5), showing the same type of geomorphological and pedological configuration at a smaller scale. In the pediment zone of the central south of the Etosha N.P., a thin cover of calcium-carbonate-free colluvial sands (Eutric Fluvisols of mapping unit D2; Beugler-Bell & Buch this volume) is mapped on top of the pedogenetic calcrete/Etosha Limestone. These sediments are believed to originate predominatly from the weathered quarzites of the Mulden Group in the adjacent Otavi Mountains.

The Etosha Limestone of the plains shows typical features of karstification. Within closed solution forms, which range from a few meters to hundreds of meters in diameter, in situ soils of a Vertisol type are developed (Buch 1993; Beugler-Bell & Buch 1997). With increasing distance of the present position of the Etosha Pan, the soil communities derived from the Etosha Limestone show an increasing intensity of pedogenesis (for details see Beugler-Bell & Buch 1997; Buch 1997). In marginal positions of the Etosha Basin depocentre the Vertisols in the solution forms are associated with reddish or yellowish coloured sandy sediments from the mountainous regions. In the far west of the Etosha N.P. weathered outcrops of the Etosha Limestone occur side by side with a thin cover of reddish coloured aeolian sediments (see below; Rust 1985).

In accordance with the mineralogical and chemical properties of the sedimentary rocks of the Andoni Formation of the Etosha Basin (Buch & Rose in press), which reflect a saline-alkaline depositional environment, the chemical water quality in boreholes and natural springs of the plains differs significantly compared to the Damara carbonate aquifers (see above). This so-called 'Kalahari Aquifer' was examined in its eastern marginal part by Hoad (1992). Extended assessments by Auer (1993) and Gammer (1993), covering the total area of the Etosha N.P., reveal that the Kalahari aquifer is typified by a sodium chloride type groundwater ('C' and 'D' standard of the Department of Water Affairs 1991 and extended 'E' standard of Gammer 1993). Therefore the irrigation potential of the groundwater is very limited, especially in the light of an unfavourable drainage situation in the majority of soils of the Etosha and Owambo plains. Towards the recharge area in the mountainous regions in the south and west of the Etosha Basin there is a gradual increase of the alkaline-earth metals Ca^{2+} and Mg^{2+} (Rahm & Buch 1997). According to the evaluations up to now, the hydrochemistry of the Kalahari aquifer can be interpreted as a complex system of early precipitation of alkaline-earth metal compounds proximal, and ionic exchange and mixing distal to the recharge zone (Rahm & Buch 1997; Hoad 1992). Mixing is the result of groundwater having come into contact with saline-alkaline sediments of the Andoni Formation (Hoad 1992).

Geomorphological activity during the Pleistocene concentrated on two regions in Etosha: the Etosha Pan (as defined in the boundaries of the late Pliocene/early Pleistocene initial form and including the landscape of the 'Owambo-Pans-Plain') and the Great Escarpment (Otjovasandu area and Kaross) (Fig. 5). The major tectonical uplift and westward tilting of the subcontinent during late Pliocene initiated a new cycle of relief development ('Post-African II Cycle' according to Partridge & Maud 1987) that is responsible for the deep incision of the westward draining (exorheic) riviers like the Aap and Omingonde in western Etosha (Buch 1993). Progressive erosion led to an eastward shifting of the Great Escarpment in the morphological sense towards the inland plateau. Thus the actual soil erosion problems (man-induced accelerated erosion and denudation processes) in the westernmost regions of Etosha (Buch 1993; Beugler-Bell & Buch 1997) result to a certain degree from the high natural risk potential and the susceptibility to these processes.

As already concluded by Rust (1984, 1985), the evolution of Etosha Pan as a landform is the result of endorheic erosion processes operating in an epeirogenetic (Etosha Basin) and stratigraphically (sediments of Kalahari Group) controlled landscape position. For more details on the Quaternary evolution of the Etosha Pan, reference is made to Buch (1993, 1997), Buch & Zöller (1992), Buch & Rose (in press) and Buch *et al.* (1993).

Aeolian sediments cover the Etosha Limestone in vast regions of western and northern central Etosha and along the western margin of the present Etosha Pan. Extended systems of linear dunes ('Alab'-dunes of Grove 1969) in northern Namibia, southern Angola and northern Botswana were initially formed during the late Tertiary and early Pleistocene (Heine 1990; Buch 1993, 1997). Outliers of these dune systems, which are superimposed by an intensive in situ soil formation of the Rhodi-/Chromi-Ferralic Arenosol-type, are mapped in the northeastern corner as well as in the central north ('Paradys') of the Etosha N.P. (Fig. 5; Beugler-Bell & Buch 1997). Redeposited reddish to yellowish sands of the linear dunes form a thin sediment cover on top of the Etosha Limestone in northwestern Etosha (Rhodi-/Chromi-Ferralic Arenosol sediments of mapping unit B4 and B5).

Calcium carbonate-rich sands that have been blown out from the almost bare floor of the Etosha Pan, were accumulated along its western margin by the prevailing northeasterly winds and form so-called 'lunette' dunes (Fig. 5). The TL-calibrated pedostratigraphy of the lunettes gives evidence for environmental change in Etosha during the last 140 ka (Buch 1993; Buch & Zöller 1992; Buch *et al.* 1993; Buch 1997). This new methodological approach of palaeoenvironmental reconstruction overcomes the problems that have recently become evident from the ^{14}C-calibrated chronostratigraphies in southern Africa (Heine 1991, 1992; see also Talma & Rust 1997).

CONCLUSIONS

The geological-tectonical and geomorphological evolution determines the present-day landscape-ecological differentiation of Etosha (Buch 1993). In detail, there exists a strong correlation between geology and pedology in terms of individual chemical and physical properties of the soils and their distribution (Buch 1993; Beugler-Bell & Buch 1997). Together with the climatic differentiation in the study area, which in particular is characterized by a strong hygric gradient from east to west (Van der Merwe 1983; Engert 1997), the soil communities control the distribution of the vegetation communities (Buch 1993; Du Plessis 1992; Le Roux *et al.* 1988). Due to the human population pressure and, consequently, a growing demand on water resources in northern Namibia, the assessment of groundwater availability, groundwater recharge and groundwater quality has gained increasing attention during the last years (Hoad 1992; Auer 1993, 1997; Gammer 1993; Rahm & Buch 1997). Here again, the geological-tectonical and geomorphological background is essential to an understanding of the hydrological environment.

Under the present semi-arid climatic conditions, the interannual changes between wet and dry season not only control the biological rhythm, but also characterize the geomorphodynamic system in Etosha (Buch 1993). In general, aeolian processes dominate during the dry season and fluvial processes during the rainy season. Recent measurements of the aeolian redeposition at the western margin of the Etosha Pan (for the experimental design see Buch 1990) support the idea that a maximum of aeolian activity occurs at the end of the dry season and the beginning of the wet season, when the topsoil is extremely dry and the vegetation cover is thinned out (Beugler-Bell & Buch 1997). Weathering and soil formation processes certainly reach on effective maximum during the peak of the rainy season, but can operate as long as their is sufficient moisture available. Thus, the manifestation of a pedogenesis during the interannual change between a wet and a dry season is controlled by the balance between potentially possible soil formation and geomorphodynamics, both erosion/denudation and aeolian accumulation processes. The present mean annual rainfall between 300 mm and 500 mm in the study area is sufficient for a soil formation, which is typical for a semi-arid environment. Therefore, different intensities of pedogenesis identified in the study area today essentially reflect the soil-forming factor 'time'.

Compared to other investigations in southern Africa, Buch (1993) and Rust (1985) conclude from the reconstruction of the Cainozoic landscape evolution of Etosha that this type of a semi-arid geomorphodynamic system was persistent during the entire Quaternary (last 1.8 m.a.) and in particular during the last 140 ka (Buch & Zöller 1992; Buch *et al.* 1993). Nevertheless the geological-tectonical events during the late Tertiary are an important prerequisite for the later geomorphological evolution. This is well reflected in the geomorphological evolution of the Etosha Pan as an erosion form (Buch 1997).

The discussion on climatic changes during the next 30 to 50 years in southern Africa in general as well as in northern Namibia in particular is focussing on the identification of a possibly rhythmical change of wet and dry spells in the historical record. A more comprehensive knowledge of rainfall oscillations during the past might be helpful in predicting the future development. Intensive statistical analyses by Tyson (1990, 1991) and co-workers have revealed a remarkable persistent quasi 18-years oscillation with 9 years of over-average rainfall and 9 years of under-average rainfall for the summer rainfall region of the Republic of South Africa. However, in northern Namibia the rainfall oscillation pattern appears to be more complex with superimposed individual cycles of a duration between 2 and 20 years (Engert 1997). Nevertheless we are still far away from predicting possible rainfall changes in future, especially when the high spatial variability of the rainfall in northern Namibia is considered (Buch 1993).

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