Etosha Pan - the third largest lake in the world ?

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ABSTRACT

Until today, two alternatives have been discussed in order to reconstruct the Cainozoic evolution of Etosha Pan. In the tradition of the early investigations by Jaeger (1926/27), Wellington (1938), Shaw (1988), Shaw & Thomas (1989) and Stuart-Williams (1992) picked up the idea that Etosha Pan is a desiccated palaeolake. While concluding that the Cunene River never played any role in the evolution of the Etosha Pan, Rust (1984, 1985) describes the evolution in terms of the well-known concepts on the morphology of cuesta landforms and 'scarp retreat' is regarded as the decisive process. Thus the 'super pan' of Etosha resulted from pluvial endorheic erosion processes, and its actual position was determined by epeirogenetic (Etosha depression) and stratigraphic (Kalahari sediments) conditions.

Based on a geomorphological-sedimentological-pedological approach of environmental research and in accordance with the present knowledge of the Cainozoic landscape evolution of the southern African continent as a whole, Buch (1993) describes the erosional history of Etosha Pan as a consequent development from the long-term sedimentation history of the even more extended continental interior depocentre of the 'Etosha Basin'. A shallow saline-alkaline playa lake environment can only be attributed to the terminal phase of the Etosha Basin during the late Tertiary. Neither the reconstructed 'Lake Etosha' at 35 ka by Stuart-Williams (1992) nor the existence of a perennial lake at any time during the upper Pleistocene is proved by the findings presented by Buch (1993), Buch & Zöller (1992) and Buch *et al.* (1992).

Since the turn of Pliocene to early Pleistocene, Etosha Pan was excavated by continuously working denudation processes operating on the pan's floor in the seasonal rhythm of water inundation (rainy season) and extensive deflation processes (dry season). Thus, the geomorphodynamical evolution of Etosha Pan during the Quaternary gives evidence for persisting semi-arid climate conditions over a long period of the younger geological history. This conclusion is of value not only for the reconstruction of palaeoenvironmental change in southern Africa, but also for a reliable predictions of the potential landscape ecological impacts of future climatic change.

INTRODUCTION

As a contribution to the publication of Marsh & Seely (1992) on 'Oshanas - sustaining people, environment and development in central Owambo, Namibia', Stuart-Williams (1992) recently postulated an unconventional account of the Cainozoic evolution of Etosha Pan in northern Namibia (Fig. 1). The most remarkable results of these ideas are that Etosha could be regarded as the "third largest inland body of water in the world", if it would still exist today. And furthermore: "At its greatest extent, Lake Etosha was about 40 meters deep and covered an area in present-day Namibia and Angola of about 71 000 square kilometres" (Stuart-Williams 1992: 13). Lake Etosha should have persisted since +/- 35 000 years ago (Fig. 2). Larger inland lakes are known today only from the Caspian Sea (371 000 km^2) in central Asia and the Lake Superior of the Great Lakes (83 300 km^2) in northern America. Lake Victoria in eastern Africa covers an area of 68 800 km^2. These findings by Stuart-Williams contrast considerably with the results of investigations of Buch (1993) which are based on a geomorphological-sedimentological-pedological approach of environmental research during extensive field and laboratory investigations between 1989 and 1992. The present paper discusses the ideas of Stuart-Williams (1992) and earlier studies published by Jaeger (1926/27) and Rust (1984/85) in the light of the own investigations.

PREVIOUS RECONSTRUCTIONS ON THE EVOLUTION OF ETOSHA PAN

The Etosha Pan has inspired geomorphological research since the middle of the 19th century, when in 1851 the first Europeans, Charles John Andersson and Sir Francis Galton, reached the semi-arid landscape in today's northern part of Namibia (Andersson 1856). Owing to the enormous size (4 760 km^2; east-west extension 120 km, north-south extension 80 km), the flat floor and several reconstructed so-called 'terraces', the excavated erosion form of Etosha Pan was interpreted as a dried-up palaeolake by Jaeger (1926/27). The desiccation of former Lake Etosha was thought to be the result of the drainage capture of the upper Cunene River by a pre-existing lower 'Proto Cunene', which was already draining to the Atlantic Ocean; problably climatic change also played an important role. The different reconstructed levels in the immediate vicinity of Etosha Pan in 29 m, 20 m, 12 m, 6 m, 3 m and 1 m above the present pan's floor were interpreted as 'lacustrine terraces' as a result of the falling water level of the lake. Wellington (1938) in principle agreed with Jaeger's findings.

These ideas on the genesis of Etosha Pan described by Jaeger (1926/27) and Wellington (1938) are still repeated in the international literature (Shaw 1988, Shaw & Thomas 1989, Stuart-Williams 1992). Like the 'Makgadikgadi

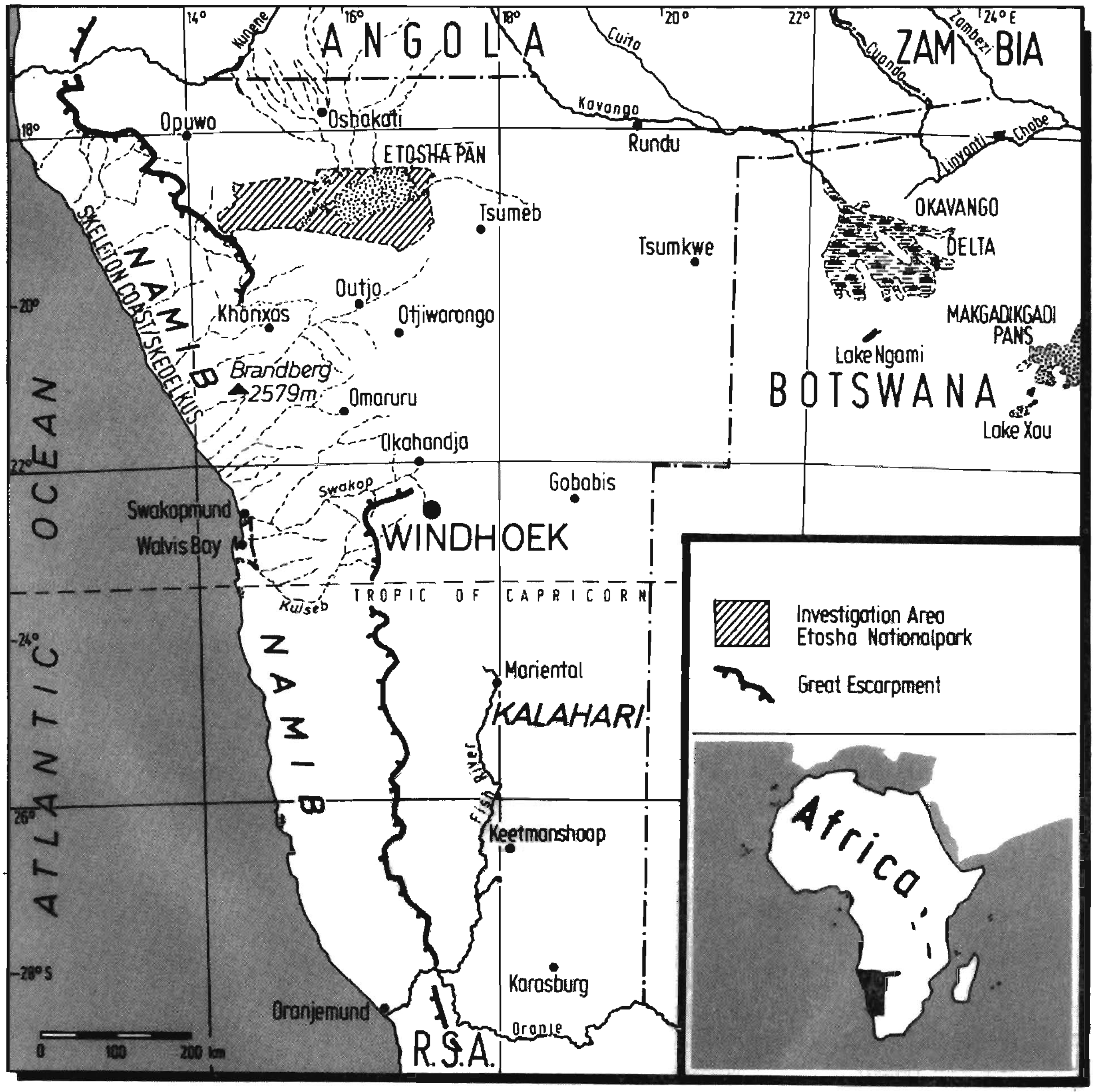

FIGURE 1: Location of the investigation area in northern Namibia.

Depression' in northern Botswana, Shaw (1988) assigns Etosha Pan to the 'palaeolakes' in southern Africa.

While concluding that the Cunene River never played any role in the development of the Etosha Pan, Rust (1984, 1985) introduced new prerequisites and geomorphodynamic processes in order to explain the genesis of Etosha Pan from the point of view of the morphogenesis of the whole Etosha catchment area. In the sense of Rust, the development of pans can be described in terms of the well-known concepts on the morphology of cuesta landforms, and 'scarp retreat' is regarded as the decisive process. Rust (1985) concludes that the Etosha Pan is a super pan, which resulted from endorheic pluvial erosion processes, and, that its actual position was determined by epeirogenetic (Etosha depression) and stratigraphic (Kalahari) conditions.

THE GEOMORPHOLOGICAL-SEDIMENTOLOGICAL-PEDOLOGICAL APPROACH TO THE PROBLEM (BUCH 1993)

Refering to the concepts of Jaeger (1926/27) and Rust (1984, 1985), the different interpretations are due to the inconsistent use of the term 'pan' (Alison 1899) in the international literature. According to Shaw and Thomas (1989) the term 'pan' (German 'Pfanne') is used synonymous to 'playa' (worldwide), 'playa lake', 'saline/salt lake' (Australia, North America, China), 'sebkha' (North Africa, Arabia), 'kavir' (Iran), 'salar' (Peru) and 'Salztonebene' (German language), although from a genetical point of view, completely different geomorphological and sedimentological features are encompassed in these terms.

'Playas' and 'pans' generally show some common characteristics (Shaw & Thomas 1989); the most obvious of these is that both features occupy topographically low regions (on a regional or local scale) in a relatively flat,

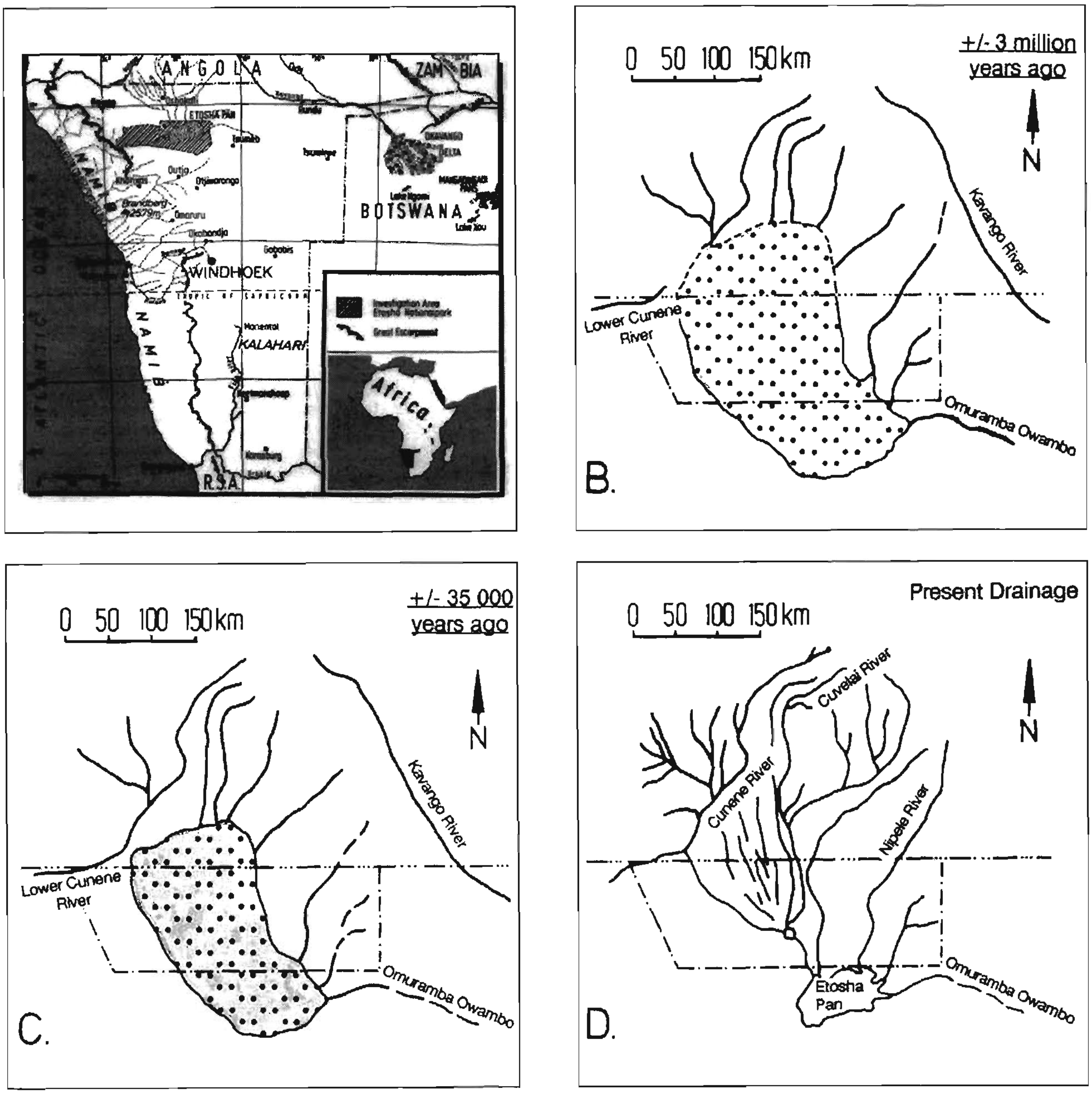

FIGURE 2: Evolution of 'Lake Etosha' in nowadays northern Namibia and southern Angola according to Stuart-Williams (1992).

A. Pre-7 million years ago internal drainage system with both the upper Cunene and the Okavango Rivers probably flowing into it. **B.** Approximately 3 million years ago. The saline Lake Etosha had a maximum depth of about 40 meters, reaching to the modern 1 120 meter contour line. The Kubango/ Okavango headwaters probably drained eastward. The lake area was an estimated 70 000 square kilometers, about the size of the present day Lake Victoria. **C.** About 35 000 years ago, the Cunene River captured its modern headwaters. Lake Etosha then drained to the sea via Etaka and Cunene Rivers, creating the well developed 17-20 meter relict shoreline. Water depth was approximately 23 meters. **D.** Present drainage. The upper portion of the Etaka can flow both northward and southward. The Omuramba Owambo, Nipele and Oshigambo Rivers are dormant. Current climatic conditions only generate small flows in the Ekuma River (Stuart-Williams 1992: 13).

arid to semi-arid landscape. In terms of surface hydrology they are essentially 'closed' systems, having no surface outflow. The flat playa/pan floor is - at least partially - covered by an ephemeral water body, and is almost free of vegetation or shows a halophytic vegetation cover. Potential evaporation dominates significantly over precipitation and other hydrological inputs. Besides these general characteristics, it is essential to differentiate between closed systems, where the sediment input on a long-term exceeds the sediment output and those where the relation is opposite. In this sence, Buch (1993) proposed that the term 'playa' ('salt lake', 'sebkha', etc.) should be used for aggradational features only and the term 'pan' ('Pfanne') should be restricted to erosion features. The differentiation of both is only possible on the basis of a detailed reconstruction of the Cainozoic evolution of the greater investigation area.

Concerning the Etosha region in northern Namibia in particular, the distinguishing between the depocentre of the 'Etosha Basin' and the excavated erosion form of the 'Etosha Pan' is most essential. As outlined by Buch & Trippner (1997) in more detail, the geological history of the 'Etosha Basin', which is the western outlier of the more extensive 'Kalahari Basin' in the centre of the southern African subcontinent, can be traced back as early as 290 million years ago (Stephanian, end of Carboniferous) (Hedberg 1979). Fluvial and fluvio-limnic

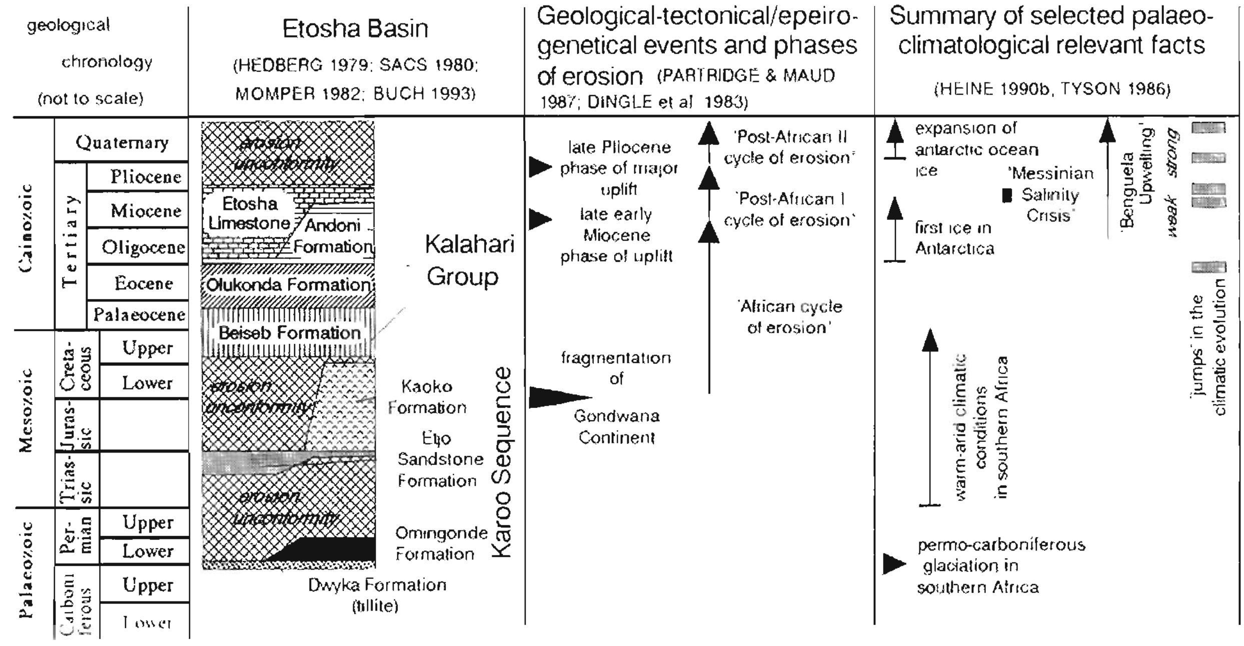

FIGURE 3: Overview of the Palaeozoic-Mesozoic-Cainozoic sedimentation and erosion history of the Etosha Basin and indications of supraregional important tectonical/epeirogenetical and palaeoclimatological events (Buch 1993 on the basis of Hedberg 1979, Heine 1990b, Momper 1982, Partridge & Maud 1987, Dingle *et al.* 1983, SACS 1980 and Tyson 1986).

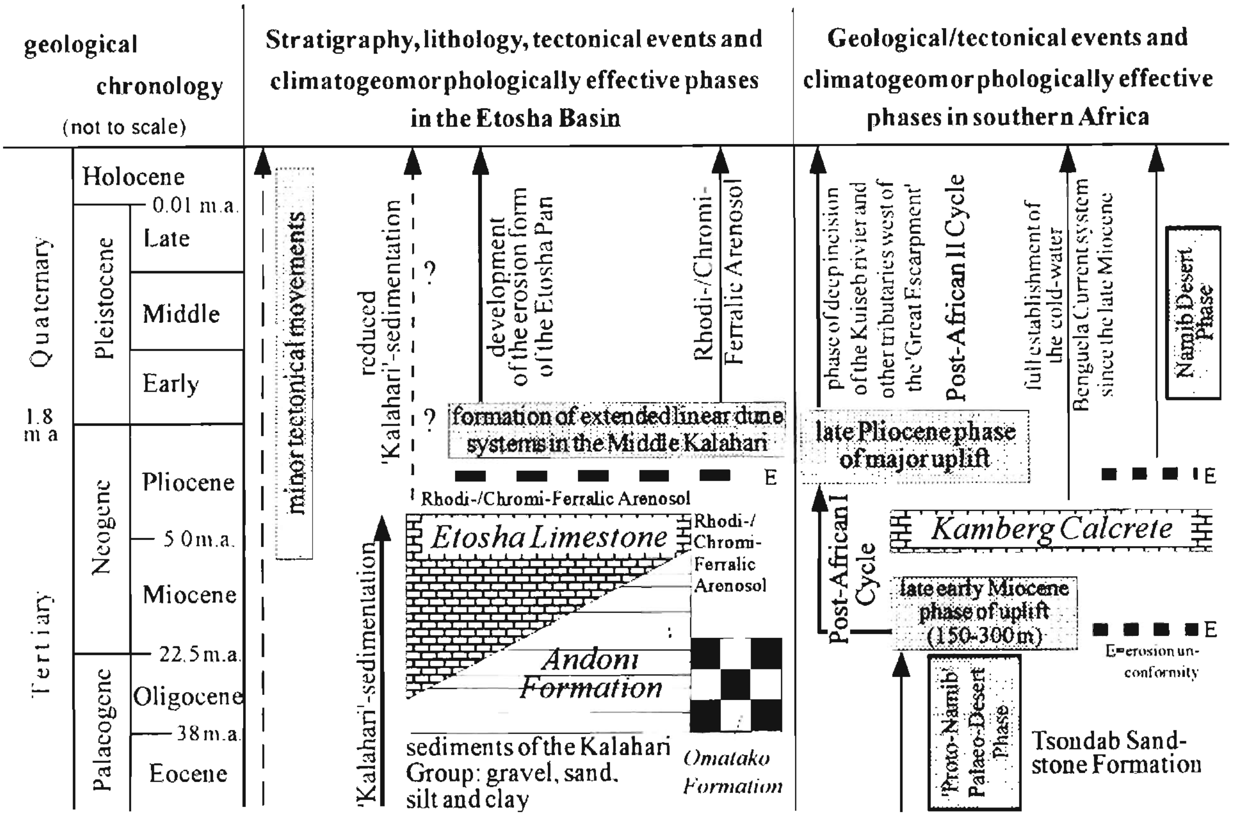

FIGURE 4: Reconstruction of the Cainozoic environmental change in Etosha compared to important geological/tectonical, geomorphological and palaeoclimatological events in greater southern Africa (Buch 1993 including investigation results by Besler 1991, Dingle *et al.* 1983, Hedberg 1979, SACS 1980, Hegenberger 1986/87, Momper 1982, Partridge & Maud 1987 and Ward 1987).

sediments of the 'Andoni Formation' (Kalahari Group, SACS 1980) and the calciferous evaporites of the so-called 'Etosha Limestone' (Buch 1993) terminated the long record of endorheic sedimentation at the end of Tertiary times (late Pliocene) (Buch 1993; Buch & Trippner 1997).

A geomorphological-sedimentological-pedological approach to reconstruct the Cainozoic environmental change in Etosha in more detail based on a stepwise integration of the below mentioned items (Buch 1993):

(1) detailed geomorphological inventory of the study area by 'classical' methods of terrestrial mapping and

'modern' remote sensing methods as well as laboratory analysis of standard profiles by means of sedimentological, pedological and mineralogical methods; interpretation of the results against the background of the present knowledge of the geological evolution of the greater study area (Hedberg 1979; SACS 1980; Momper 1982),

(2) reconstruction of 'topochronosequences' of the relief development on the basis of the spatial relation of single geomorphological forms and form associations, of form-sediment-relations and pedogenesis,

(3) acquisition of indications for the temporal dimension of the different stages of the geomorphological development from the pedogenetical point of view and in a supraregional context,

(4) differentiation of the relative-chronostratigraphical findings of the relief development by detailed pedostratigraphical evaluations of suitable sediments,

(5) calibration of standard-pedostratigraphies by using chemical and/or physical methods of age determination.

CAINOZOIC ENVIRONMENTAL CHANGE IN ETOSHA

For a better understanding of the Cainozoic environmental change in Etosha two features of Africa as part of the former 'Gondwana Continent' in terms of its geological-tectonical and geomorphological history need emphasis, i.e. (1) the African continent was characterized by a predominant Precambrian to early Palaeozoic setting of most of the orogeny, a long time-span of geological consolidation and a long record of continuous erosion (Hüser 1979); (2) as late as during Cretaceous and Tertiary times, tectonical movements produced new impulses of the relief development (Hüser 1989). The study area in northern Namibia is a good example of these features of the geological and tectonical history of the African continent. Terrestrial sedimentation of the continental interior 'Etosha Basin' during late Tertiary times only represents the terminal phase of a depositional history that began with the major subsidence of the basin structure after the Damara Orogeny primarily during Late Carboniferous (Westphalian), 290 m.a. BP (Momper 1982) (Fig. 3). Except for the tillites of the 'Dwyka Formation' deposited during the Permo-Carboniferous glaciation at the beginning of the 'Karoo Sequence', predominantly fluvial and fluvio-limnic sediments characterize the sediment record. Aeolian sediments of the 'Etjo Formation' ('Karoo Sequence') also invaded the region in the late Permian/early Mesozoic (Fig. 3).

The 'Kalahari Sedimentation' epoch started probably as early as late Cretaceous (Hedberg 1979; Momper 1982). According to the proposal by SACS (1980) the sediments of the 'Kalahari Group' are differentiated into the basal 'Beiseb Formation', the middle 'Olukonda Formation' and the top 'Andoni Formation'. Buch (1993) introduced the 'Etosha Limestone', which in parts developed simultaneously with the 'Andoni Formation' (Fig. 3 and Fig. 4). In general, the 'Etosha Limestone' completes the succession of the Kalahari sediments. In the Etosha region, the sediments of the' Kalahari Group' reach a thickness between only 50 m and up to 250 m (Fig. 5); here the 'Etosha Limestone' alone can be as thick as 30 m and more than 50 m (Buch 1993).

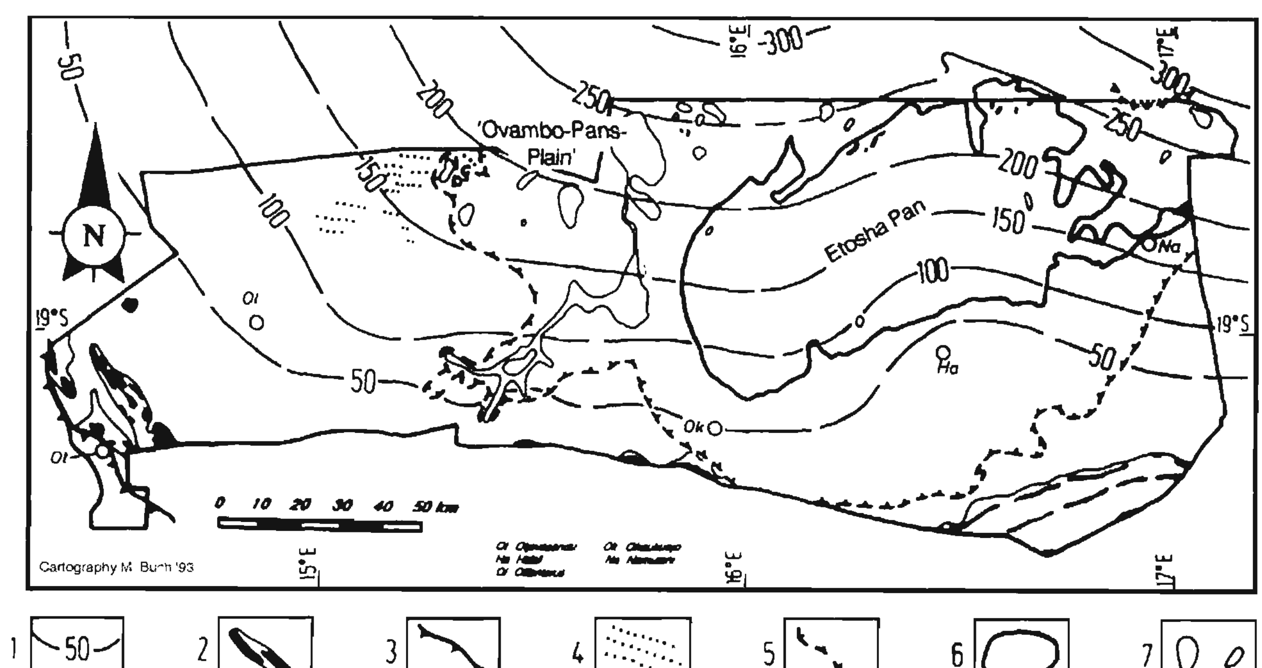

FIGURE 5: Important geological and geomorphological features for the reconstruction of the Cainozoic history of Etosha (after Buch 1993 and Hedberg 1979).

(1) isopaches of the sediments of 'Kalahari Group' (Hedberg 1979): (2) ridges of the 'Etoscha Bogen' ('Otavi Mountains') build up by quarzite and dolomite of the 'Damara Sequence'; (3) 'Great Escarpment' (in the morphological sense): (4) outliers of the system of linear dunes in northern Namibia with Rhodi-/Chromi- Ferralic Arenosols; (5) initial Pliocene/early Pleistocene form of the Etosha Pan; (6) present form of the Etosha Pan; (7) other pans.

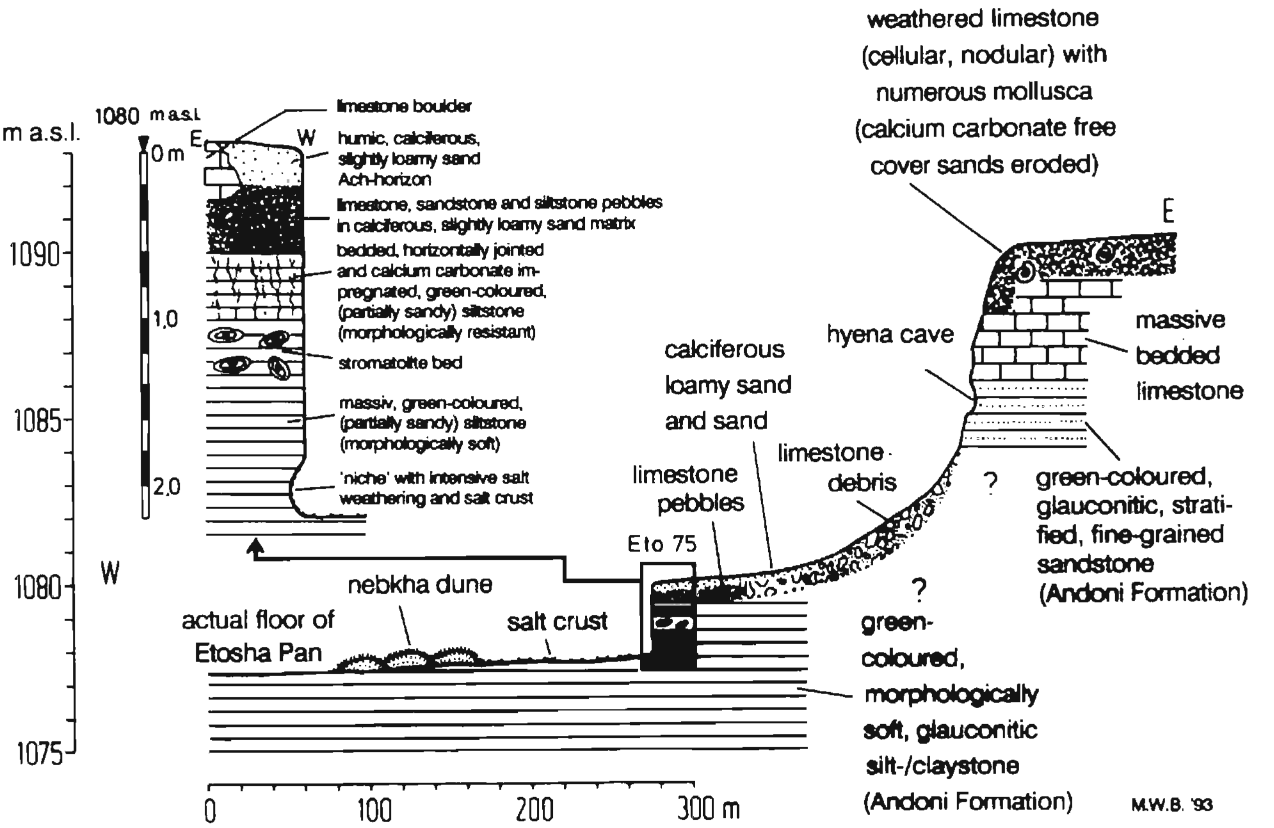

FIGURE 6: Cross-section of the type-locality of the upper Kalahari sedimentation at Poacher's Point Peninsula, northeastern Etosha Pan (Buch 1993).

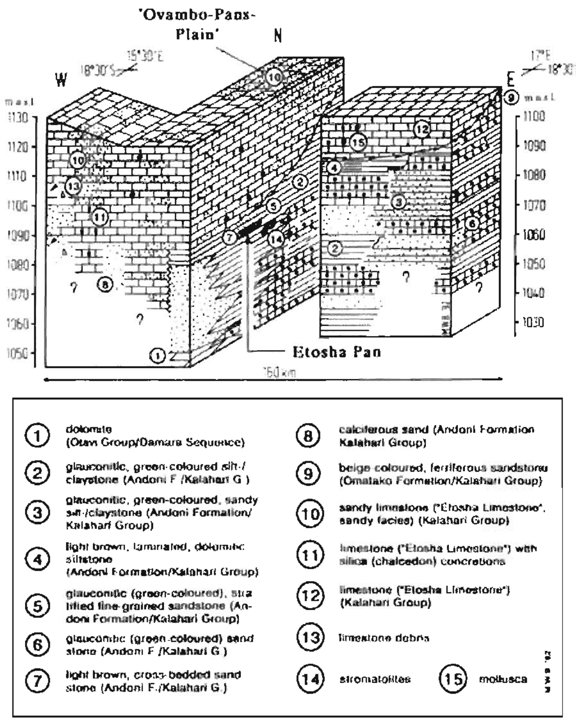

FIGURE 7: Schematic block diagram of the facial differentiation in the upper part of the Kalahari sedimentation of the southern Etosha Basin (Buch 1993, reconstructed on the basis of unpublished borehole data of the Department of Water Affairs, Windhoek).

The uppermost sequence of the Kalahari Sediments is well exposed only at two localities in the eastern part of Etosha Pan, at the western flank of 'Poacher's Point Peninsula' (Buch 1993) and at the southern end of 'Pelikan's Island' (Martin & Wilczewski 1972; Smith & Mason 1991). At the 'Poacher's Point' locality, the succession comprises 1.6 m of exposed green-coloured silt-/claystone at the base, with a bed of stromatolites in the upper part, grading into a stratified, light green-coloured, fine-grained sandstone, of which only 2 m are exposed (Fig. 6). The succession here is capped by 25 m of massive bedded to nodular-weathered 'Etosha Limestone'. Defined as the 'Poacher's Point Formation' by Smith & Mason (1991), the succession at 'Pelikan's Island' is similar, also bearing stromatolites/oncoids and furthermore some special features like ooids and silica concretions (see also Buch 1993).

From descriptions of borehole data, which were kindly provided by the Department of Water Affairs (Windhoek), Buch (1993) summarized the facies differentiation of the upper sequence of the 'Kalahari Group' in the southern part of the Etosha Basin (Fig. 7). The green-coloured silt-/claystone grades into a green-coloured sandstone facies, both horizontally and vertically. Most of the actual floor of the Etosha Pan is eroded into the silt-/claystone facies; the sandstone facies now being recognizable only in the northwestern and northeastern corner (Buch 1993; Buch & Rose in press). In the floodplain of the lower Ekuma River, outcrops of this green sandstone facies are fossiliferous. According to SACS (1980), both facies must be attributed to the 'Andoni Formation' of the 'Kalahari Group'. Concerning the 'Etosha Limestone', Buch (1993) differentiated between a typical and a sandy variation; the latter is the parent bedrock in the northern central landscape of the Etosha N.P. ('Owambo-Pans-Plain', Fig. 7), thus grading into calcareous sands and a silty sandstone in the adjacent southern Owamboland.

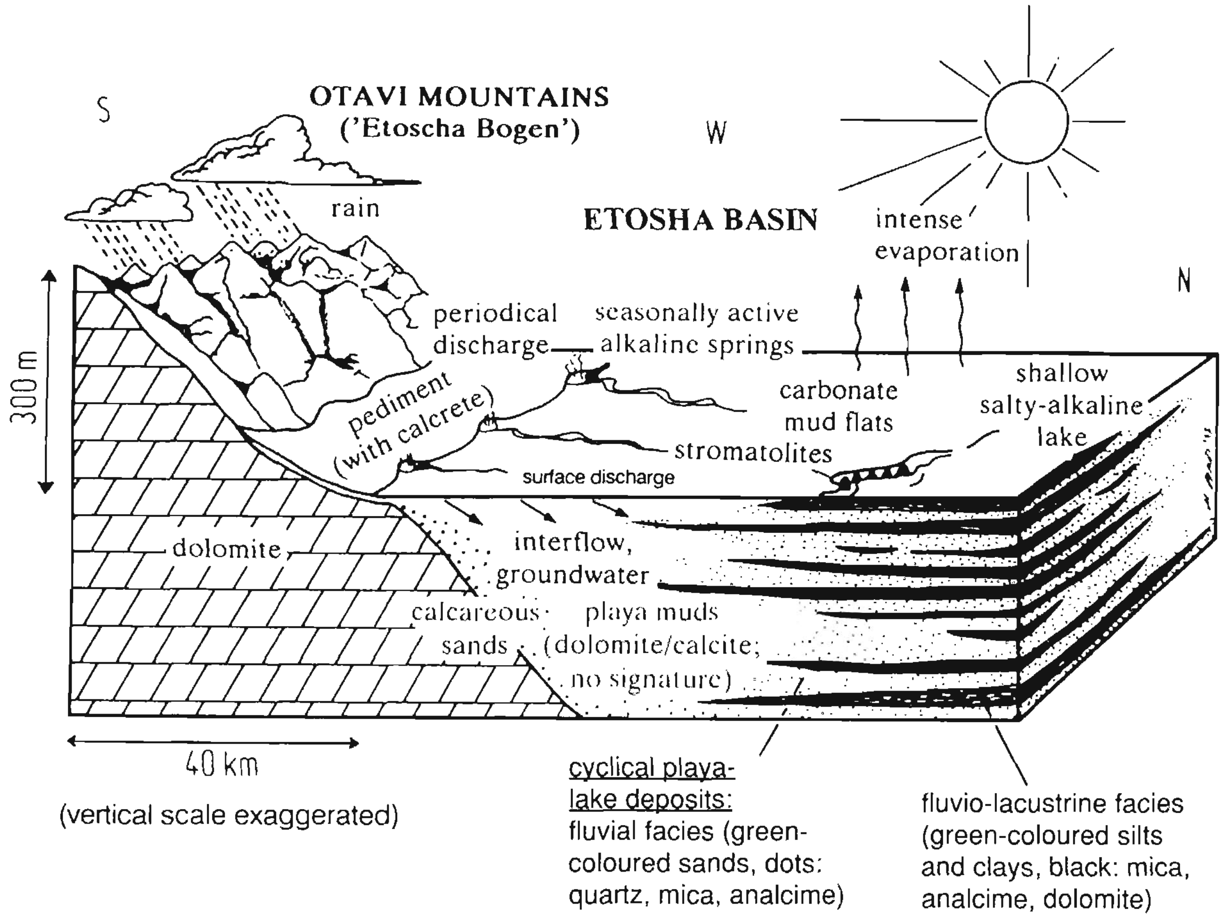

FIGURE 8: 'Playa-Lake-Complex-Model' for the late Tertiary southern part of the Etosha Basin (Buch 1993 adopted from Eugster & Hardie 1975).

Facies characteristics together with mineralogical/ geochemical and biological indications help to reconstruct the depositional environment of the late Tertiary Etosha Basin. Buch (1993) and Buch & Rose (in press) conclude that the depositional environment can be best described in terms of a drainage endpoint situation, which produced a shallow, salty-alkaline playa lake (Fig. 8). In correspondence to the 'Playa-Lake-Complex-Model' of Eugster & Hardie (1975), spatially differenciated precipitation of characteristic mineral-associations is typical. Along the southern and western rim of the Etosha Basin and in contact to the 'Otavi Mountains' mainly calcite and dolomite were precipitated, forming carbonate mud flats along the lake-margin. This sub-environment grades into cyclic playa-lake deposits (fine-grained sediments of the 'Andoni Formation': silt, clay and sand), where analcime is the predominant mineral, a 10 Å-mineral of the mica group occurs, and rarely sepiolite. Dolomite is still the dominant mineral locally. The lacustrine oncoids described by Smith & Mason (1991) further support the existence of a shallow, low-energy saline lacustrine environment. The occurrence of laminar and columnar stromatolites in particular, indicates storm-generated wave activity and periodical subaerial exposure. From oncoid morphology at least six distinct carbonate-precipitating lacustrine phases were reconstructed by Smith & Mason (1991). The spreading of the lake-margin carbonate mud flat facies characterizes the end of the fluvial and fluvio-limnic depositional history of the Etosha Basin.

Of consequence to the reconstructions are the questions, when and why the aggradation history of the Etosha Basin ended and when the erosion history of the Etosha Pan started. The question of dating was a matter of debate during recent years of investigations (see also Talma & Rust 1997). Martin & Wilczewski (1972) postulated that the limestone topping the profile at 'Pelikan's Island' may be of Pliocene age. In contrast ^{14}C-datings of limestone samples from the same locality by Rust (1984, 1985), suggest ages of 42 400 +/- 1950 a BP and 39 300 +/- 1470 a BP respectively, and thus stimulating speculations on an Upper Pleistocene development. Some indeterminate ^{14}C-data nevertheless pointed to an underestimation of the ages in Rust (1984, 1985). The recent geomorphological-sedimentological-pedological investigations by Buch (1993) showed conclusively that an age-range of Miocene (22.5 m.a. BP) to Pliocene (5-1.8 m.a. BP) can be regarded as the most reliable estimate of the era of the formation of the 'Etosha Limestone'. The basal series of the limestone which interfinger with the sediments of the 'Andoni Formation' may, however, date back to the Oligocene (38-22.5 m.a.).

In order to explain the causes for the major environmental change during the Cainzoic, the geological/tectonical and

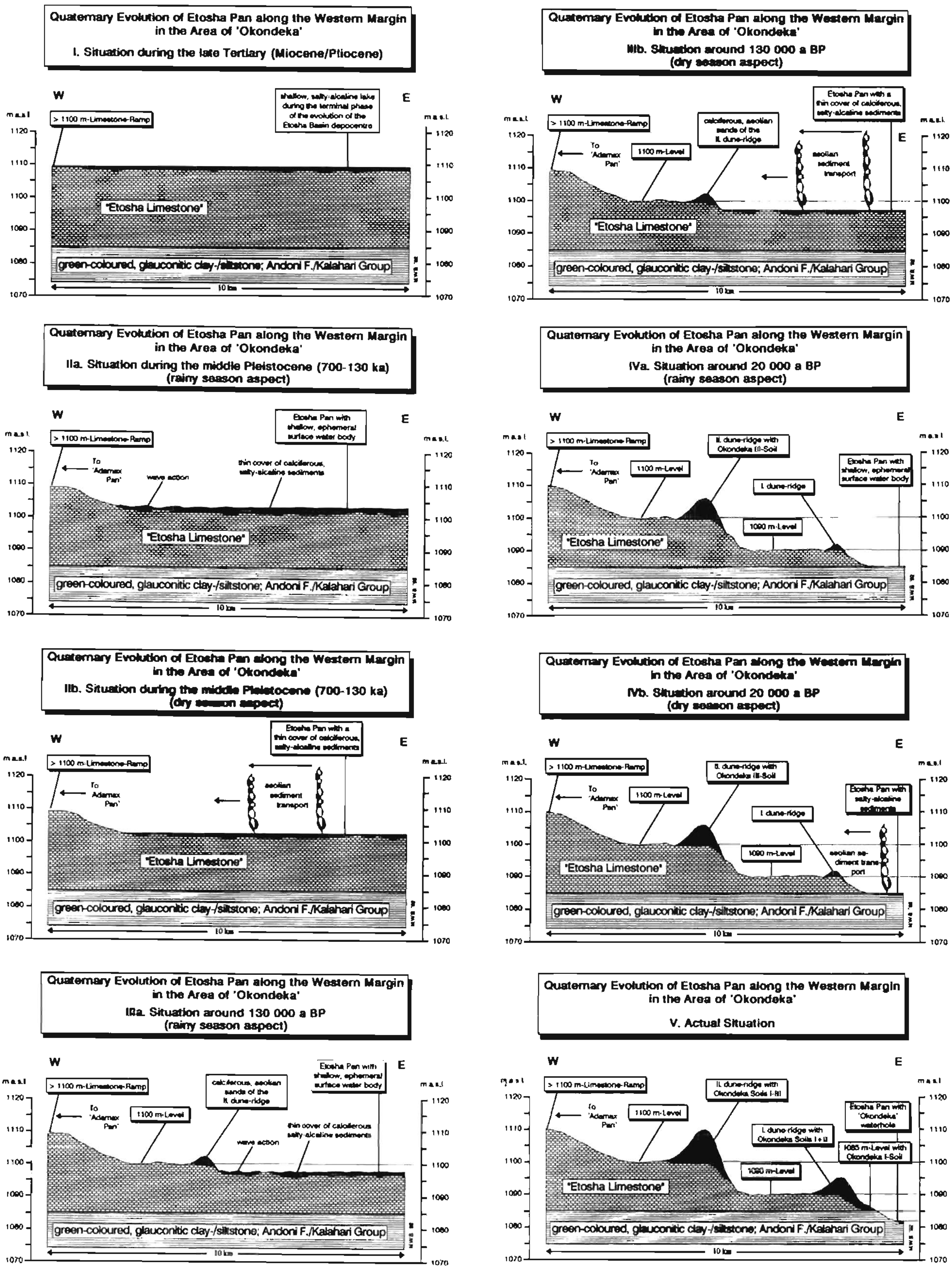

FIGURE 9: Succession of the late Tertiary and Quaternary evolution of Etosha Pan as examplefied along a transect west of Okondeka waterhole (Buch 1993).

palaeogeographical situation on a subcontinental scale should be considered. Along with the fragmentation of Gondwana since the turn of Jurassic to Cretaceous (Fig. 3), the development of the major drainage systems in southern Africa is characterized by a progressive drainage capture of endorheic systems by progressively more effective exorheic systems. Partridge & Maud (1987) and Thomas & Shaw (1988) give examples for this development (e.g. Orange River, Zambezi River). The major tectonical uplift and westward tilting of the subcontinent during late Pliocene in particular initiated a new cycle of relief development ('Post-African II Cycle' according to

Maud & Partridge 1989) that is responsible for the deep incision of the westward draining riviers like the Kuiseb (Ward 1987) (Fig. 4).

The drainage capture of the upper Cunene system by a pre-existing lower 'Proto Cunene' during late Pliocene cut off the sediment and water supply towards the southern part of the Etosha Basin, thus resulting in a complete desiccation of the former shallow playa lake (Fig. 9; I). The paleogeographical changes were accompanied by climatic changes during late Tertiary (late Miocene to Pliocene). For the western parts of the southern African subcontinent a major climatic impact in the sense of a pronounced 'aridification' is connected with the full establishment of the cold upwelling of the Benguela Current since at least 10 m.a. (Siesser 1978, Diester-Haass 1988) (Fig. 3 and Fig. 4). These climatic effects were not restricted to the Namib coast alone, where a change to hyper-arid conditions has occurred since the Pliocene, but resulted in semi-arid to semi-humid climatic conditions spreading to the interior of the subcontinent including Etosha (Coetzee 1980, Van Zinderen Bakker & Mercer 1986).

As a result of the palaeogeographic/tectonic and climatic impulses, the geomorphodynamic system in northern Namibia changed completely during late Pliocene/Early Pleistocene. Aeolian activity was enhanced (Buch 1993), in accordance with Brunsden & Thornes (1979) and Brunsden (1980), who describe the transitional phase between cycles of relief evolution as the most sensitive. Loose sand, earlier deposited in the Etosha Basin or sandy weathering products of an earlier phase of soil formation (probably during the early Miocene [Heine 1994]) in the margin of the depocentre (e.g. Rhodi-/Chromi-Ferralic Arenosols and Rhodi-Eutric Cambisols on the sandstone-facies of the Omatako Formation in northeastern Namibia [Hegenberger 1986/87] or on the sandy facies of the 'Etosha Limestone' [Buch 1993]) provide the sediment source for the development of extended linear dune systems ('Alab'-dunes of Grove 1969) (Fig. 4). Evidence for the dating of the initial formation of these dune systems during late Tertiary and early Pleistocene is provided by geomorphological and pedological investigations (see also Heine 1990a). In northeastern Etosha N.P. and adjacent Kavango the linear dunes are superimposed by Rhodi-/Chromi-Ferralic Arenosols, which represent the most intensive in situ soil formation in the study area and comprise a pedogenesis during the entire periode of the Quaternary. Furthermore, during the Quarternary evolution of the Etosha Pan, the pan's floor was incised up to 30 m below the base-level of the dune systems (see below and Fig. 4). The linear dune systems in the northern regions of southern Africa therefore cannot be used in order to reconstruct the palaeoenvironment during the Last Glacial Maximum (LGM, 20-18 ka) (Deacon & Lancaster 1988; Lancaster 1988), although several phases of aeolian redeposition might have occurred during Quaternary time (Heine 1990a).

As soon as the sediment output by aeolian processes exceeded the sediment input by fluvial and fluvio-limnic processes, the sediment budget of the Etosha Basin became negative over the long term. Continuously operating denudation processes on the pan's floor in a seasonal rhythm of water inundation (rainy season) and extensive deflation processes (dry season) (Fig. 9; IIa/b) began to excavate the Etosha Pan.

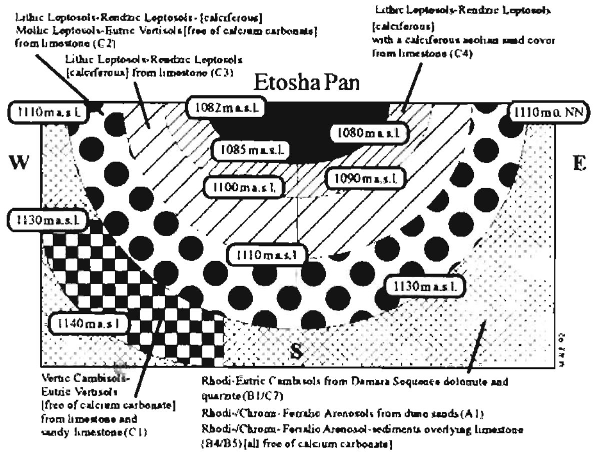

FIGURE 10: Schematic presentation of the zonal order of soil assoziations in the surrounding of Etosha Pan.

The extension of the Pliocene/early Pleistocene initial form of the Etosha Pan can be reconstructed by means of pedological findings. Rhodi-/Chromi-Ferralic Arenosols (inclusive Chromi-/Rhodi-Haplic Arenosol-sediments) from aeolian sands (mapping units A1, B4 and B5) and Rhodi-Eutric Cambisols from dolomite and quarzite of the 'Damara Sequence' (mapping units B1 and C7) (Buch 1993; Beugler-Bell & Buch 1997) occur in the surroundings of the initial pan form (Fig. 10). Both soil types represent the most intensive pedogenesis in the study area according to field descriptions and laboratory analyses (Buch 1993). In this sense, the Pliocene/early Pleistocene initial form of the Etosha Pan can be reconstructed by following the 1110 m a.s.l. contour line in the northern areas of the Etosha N.P. respectively the 1130 m a.s.l. contour line in the southern areas (Fig. 5). Thus, the initial Etosha Pan showed an asymmetrical form in terms of the elevation of the pan's floor, which was even more pronounced than the recent Etosha Pan (between 1077 and 1085 m a.s.l.). The lower relief positions are characterized by gradually younger soil formations from the 'Etosha Limestone', which are arranged in a zonal order around the present-day Etosha Pan (Fig. 10). The complete topochronosequence of soil associations comprises (from the actual pan's edge to the more distant positions): calciferous Lithic Leptosols-Rendzic Leptosols with an aeolian cover (mapping unit C4 till 1090/1100 m a.s.l.), calciferous Lithic Leptosols-Rendzic Leptsols (mapping unit C3 till 1110 m a.s.l.) and calciferous Lithic/Rendzic Leptsols and Mollic/Eutric Leptosols free of calcium carbonate (mapping unit C2, 1110-1130 m a.s.l.). An intermediate position is held by the completely decalcified Vertic Cambisols and Eutric Vertisols (mapping unit C1) of the 'Southern Owambo Plain' (1130-1140 m a.s.l.) in central Etosha N.P. (Buch 1993). These most intensive developed soil formations from limestone are found in a relief position, where in other areas also Rhodi-/Chromi-Eutric Cambisols and Rhodi-/Chromi-Ferralic Arenosols may occur (Fig. 10).

During the Quaternary the erosion form of Etosha Pan obviously developed under the same type of 'semi-arid' climate situation that is characteristic for the study area today. Since the late phase of Kalahari sedimentation, there exist neither geomorphological/pedological nor mineralogical/geochemical indications that prove the existence of a perennial lake within the boundaries of Etosha Pan (see also Buch 1993 in contrast to Heine 1990a). An aquatic environment during the rainy season and the first part of the dry season (February till May, during years with over-average flood events, so-called 'efundja'-years, also till August) and therefore a longer phase of moist conditions on the pan's floor promote the chemical weathering of the highly susceptible clastic sediments of the Kalahari Group including the 'Etosha Limestone'. After the total evaporation of water, the weathered overburden of the parent bedrock as well as the alluvial sediments at the pan margins at highly disposable for the processes of aeolian redeposition (Fig. 9; IIa/b). Thus it is most characteristic for the geomorphodynamics of pans that the sediment cover at the pan's floor is very thin. On the present floor of the Etosha Pan the sediment cover does not exceed a tickness of 150 cm, in large areas it is less than 100 cm and locally reaching a thickness of only 24 cm in the channel-like form south of the 'Oshigambo Peninsula' (see also Buch & Rose in press). Yet it must be realized that the predominante portion of the sediments is of par-autochthonous character, which means that it is already strongly influenced by the parent bedrock in terms of colour, calcium carbonate content, and mineralogy.

The importance of ephemeral standing surface water for the mechanism of surface degradation in the sense of pan geomorphodynamics is shown by the finding that the actual floor of Etosha Pan is most deeply incised in those areas (1077 to 1080 m a.s.l.), which are affected more frequently by seasonal water inundation. Today this is true for the eastern part of the pans' floor, including two channel-like features along the southern and northern edge of Etosha Pan (Fig. 11).

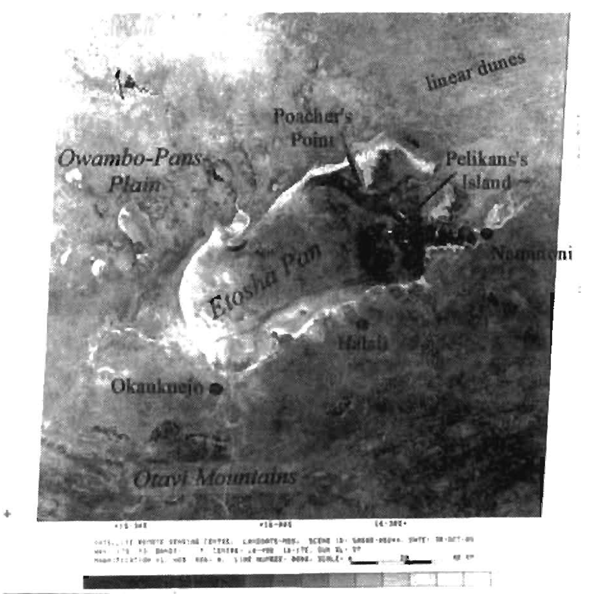

FIGURE 11: LANDSAT-MSS-image (channel 7, near infrared) of Etosha Pan, 30th October 1985.

The lowest and most frequently inundated positions of the actual pan's floor with outcropping sedimentary rocks of the Andoni Formation (Kalahari Group) are indicated by a dark grey value. Two channel-like feature accompany the northern and southern margin of Etosha Pan.

During the early to middle Pleistocene erosional processes of pan geomorphodynamics (as described above) were still operating on a surface that was developed in the 'Etosha Limestone' of end phase Kalahari time (Fig. 9; IIa/b). Carbonate dissolution of locally different intensities lead to a spatial differentiated karst morphological superimposition of the 'Etosha Limestone' (e.g. karst depressions, karst funnels, piping and subsurface karstic collapse; s.a. Wood & Osterkamp 1987). After the weathered residuals where blown out during the dry season, the stripped off karst depressions even more served as a local to regional catchment area. As a result of this positive feedback mechanism, the shallow incised depressions were enlarged laterally. Sediment removal by animals (Passarge 1904; Verhagen 1990), intensified weathering due to salt accumulation especially along the pan margins (Buch 1993) and scarp retreat in the sense of Rust (1984, 1985) might have contributed to the enlargement of the erosion forms (Buch 1993). In the long term, extended erosion surfaces developed.

Extensive remnants of higher elevated positions of the former floor of Etosha Pan were defined as the „1100 m-Level" and the „1090 m-Level" by Buch (1993). The 1100 m-Level sets in northwest of Okaukuejo and accompanies the western margin of the actual Etosha Pan (Fig. 12). In the latitude of the 'Ekuma' delta, the 1100 m-Level

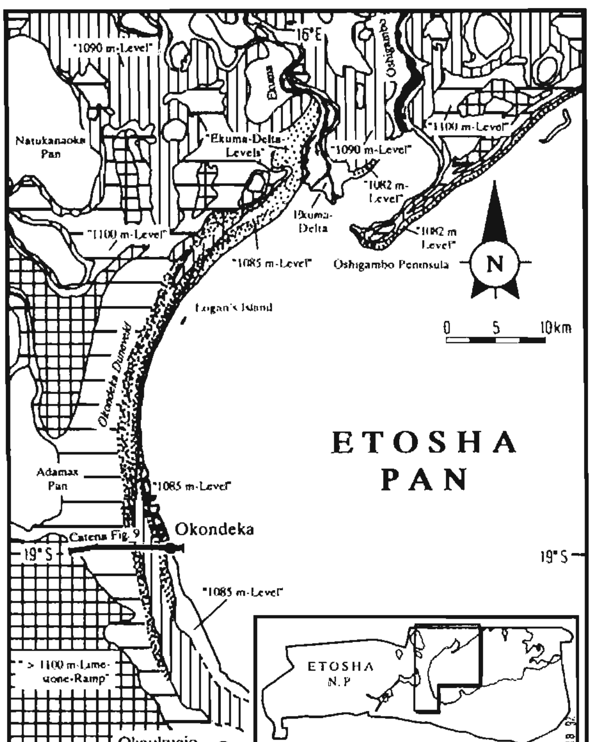

FIGURE 12: Geomorphological map of the western margin of Etosha Pan. The map is showing the higher located positions of the pan's floor at 1100 m, 1090 m and 1085 m a.s.l., which can be dated in relation to the chronostratigraphy of the lunette dunes (see also Figure 13).

widens and forms the so-called 'Owambo-Pans-Plain' (Buch 1993) with a north-south extension of 17 to 22 km. All the smaller pans gathered in the Owambo-Pans-Plain (Fig. 5) are connected by the 1100 m-Level. The 1090 m-Level adjoins to the north and can be mapped along the western margin of Etosha Pan as far as northwest of Okaukuejo, where it vanishes in the gradual rise of the 'limestone-ramp' south of the Etosha Pan (Fig. 12).

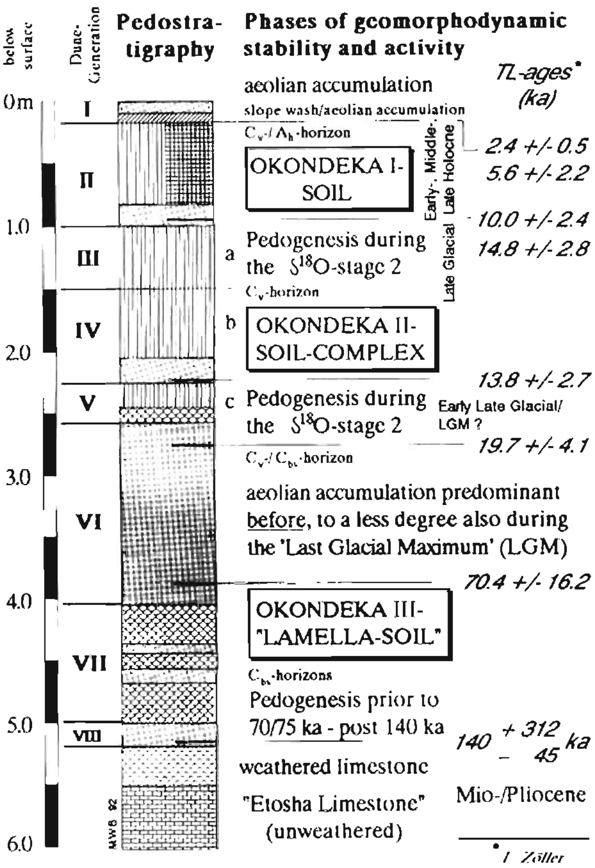

FIGURE 13: Summary of the TL-calibrated pedostratigraphy of the western lunettes of Etosha Pan, northern Namibia (Buch & Zöller 1992).

The standard profile is reconstructed according to the field description of 29 individual profiles along the western margin of Etosha Pan.

The terminal phase of the active formation of the 1100 m-Level and the 1090 m-Level is dated by means of the pedostratigraphical differentiation of the western marginal (lunette) dunes which overlie these levels. Further information is provided by eight thermoluminescence age determinations of the record of calcium carbonate-rich aeolian sediments at the type-localities near 'Okondeka' waterhole (Buch & Zöller 1992; Buch *et al.* 1992) (Fig. 13).

These findings give evidence that the aeolian accumulation at the windward edge of the 1100 m-Level began towards the end of the middle Pleistocene at about 140 ka, when the floor of the Etosha Pan was already incised below 1100 m a.s.l. (Fig. 9; IIIa/b). With this undercutting, vast areas of the Owambo-Pans-Plain were cut off from the hydrological system and thereby from the actual geomorphodynamics of the greater Etosha Pan. From then on, the shallow depressions in the central north of Etosha N.P. developed as independent pans, only fed by the local precipitation and runoff. As a consequence, the traditional geomorphodynamical sequence continued, but the effectiveness of the processes was retarded, so that erosion forms such as 'Paradys Pan' (1097 m a.s.l.) today are not incised as deeply as the Etosha Pan (1077-1085 m a.s.l.). On the other hand, the ephemeral runoff from southern Angola and Owamboland since the end of the middle Pleistocene concentrated to the area of the present Etosha Pan, i.e. during the Quaternary evolution the zone of maximum incision shifted from west to east. Furthermore, by comparing the initial Pliocene/early Pleistocene form of Etosha Pan with the recent Etosha Pan the surface of the actively formed pans' floor was reduced by 57% from about 11 150 km^2 to 4 760 km^2.

While the continous denudation and incision of the Etosha Pan continued from 140 ka till 20 ka, the accumulation of carbonate-rich aeolian sands at the leeward side of the pan already reached a thickness of roughly 4 m on top of the 1100 m-Level in the vicinity of 'Okondeka' (Buch & Zöller 1992) (Fig. 9; IVa/b). Between the end of $S^{18}O$-stage 6 (< 140 ka) and the end of $S^{18}O$-stage 5 (> 75/70 ka), the „Okondeka III-Soil" (initial cambic horizons of lamella-type) was formed synsedimentary with the aeolian sedimentation (Fig. 13).

At an age of somewhat more than 20 ka (Buch & Zöller 1992) and probably as early as 32 ka (Heine pers. comm.), another dune ridge started to accumulated on top of the former pans' floor at 1090 m a.s.l. (1090 m-Level) (Fig. 9; IVa/b). Around 20 ka the incision of the Etosha Pan reached the boundary surface between the hanging 'Etosha Limestone' and the lying greenish-coloured silt-/claystone of the Andoni Formation at 1085 m a.s.l.. As described in more detail by Buch *et al.* (1992), this change of the sediment source in the area of the Etosha Pan can be detected by mineralogical and chemical analyses of the clay fraction of the dune sediments. Whereas the aeolian sediments older than 20 ka are characterized by high contents of calcite and the presence of predominantly palygorskite (d = 10.5 Å) with minor contents of sepiolite (d = 12.2 Å) and probably mica (d = 10.0 Å), the aeolian sediments younger than 20 ka are characterized by low calcite contents with sepiolite and analcime with an Si/Al ratio of about 2.4 as major constituents, and small amounts of mica. The only known source for the first-mentioned mineral association is up to know a residuum of the 'Etosha Limestone', while the second mineral association is typical for the clastic sediments of the 'Andoni Formation'.

The actual situation at a transect west of 'Okondeka' is represented in Figure 9 (V). During the last 20 000 years, two soils of the type of initial cambic horizons („Okondeka II-Soil-Complex" and „Okondeka I-Soil") have developed within the record of aeolian sediments of the I. (inner) and the II. (outer) dune ridges along the western margin of Etosha Pan. Provided that the rate of aeolian sedimentation was high (as it is the case for the sequence of the I. dune ridge), the „Okondeka II-Soil-Complex" can be differenciated in three phases of soil formation (a-c), which occurred between the Last Glacial Maximum

(LGM: 20-18 ka)/beginning of the Late Glacial and the end of Late Glacial/beginning of the Holocene (Fig. 13). The pedogenesis of the „Okondeka I-Soil" comprises only the early half of the Holocene. TL-ages of 5.6 +/- 2.2 ka respectively 2.4 +/- 0.5 ka indicate a new activation of aeolian geomorphodynamic during the middle to late Holocene.

Since the formation of the 1090 m-Level, additional erosion levels with an extension of sometimes not more than a few hundred meters can be reconstructed along the western, northern and eastern margins of the Etosha Pan. The most differentiated sequence of former pan floors is mapped as the 'Ekuma-Delta-Levels' by Buch (1993), which comprise five erosion surfaces (1089, 1087, 1085/84, 1082/81 and 1080 m a.s.l.) below the 1090 m-Level and above the recent Ekuma-floodplain. Within the sediment record of the 1085 m-Level, the typical „Okondeka I-Soil" is developed, thus indicating that the phase of active pan floor geomorphodynamics ended already at the beginning of the Holocene (see Fig. 9; V). In the north-eastern corner of the Etosha Pan, 'Andonivlakte' represents two erosion levels at 1082 m and 1083 m a.s.l. (Buch 1993). Another erosion level at 1085 m a.s.l. is defined here as the 'Acacia-Level' as indicated by a typical *Acacia sp.* vegetation association.

Further information on the specific processes of pan geomorphodynamics during the middle and upper Pleistocene is provided by the comparison of the geomorphology along the western, northern, eastern and southern margin of the present-day Etosha Pan. The western margin of Etosha Pan is characterized by the continuous accumulation of aeolian sediments, which were blown out from the bare pan floor and transported by dominant north-easterly winds during at least the last 140 000 years. All the other pan margins are affected by an enhanced aeolian accumulation only since the middle to late Holocene (see above); the windward sides of the northern margin (levels between 1082 and 1080 m a.s.l.) are predominantely affected here. This is in good accordance with the findings in the area of the Owambo-Pan-Plain, where all the small pans show lunettes at its western margins. In contrast, the eastern margin of the Etosha Pan is characterized by numerous larger and smaller 'bay-like' features, the most prominant of which are mapped as the two 'Mushara-Levels' (1100 m and 1090 m a.s.l.), the 'upper Andoni-Level' (1083 m a.s.l.) and the 'lower Andoni-Level' (1082 m a.s.l.) by Buch (1993). Even on the floor of the actual pan, three extented 'bay-like' features can be reconstructed, which are known as the 'Andoni Bay', 'Stinkwater Bay' and 'Namutoni Bay'. This association of geomorphological forms as well as 'beach ridges' of sand and/or pebbles on a more local scale indicate that limnic-littoral geomorphodynamical processes persisted along the eastern side of Etosha Pan during at least the last 140 000 years. The formation of 'beach ridges' do not necessarily require a permanent lake. As proved by recent observations of the rangers in Etosha N.P., 'beach ridges' can be formed during the short period of aquatic conditions, when a 0,5 m high waterlevel may rise to a waterlevel mark of up to 1,0 m due to wave action caused by stormy winds from north-western and western directions. Aeolian accumulation of blown-out sands from the pan floor is restricted to the immediate vicinity of the eastern pan margin. Therefore, on the calcium carbonate-free sands of both 'Mushara-Levels', a soil of Xanthi-Ferralic Arenosol-type with a depth of up to 1 m developed during the same time-span of 140 ka respectively 20 ka, while the lunettes were build up by the accumulation of calcium carbonate-rich aeolian sands along the western margin of the Etosha Pan. The younger 'Acacia-Level' is characterized by a less intensive Cambic Arenosol (solum +/- 60 cm deep) (Buch 1993). Towards the south of the Etosha Pan, the inclining erosion surface of the so-called 'limestone-ramp' - not differentiated in any distinct level - leads from the actual pan margin in the north to the pediment zone of the 'Otavi Mountains' in the south.

DISCUSSION

As far as a lake situation in the northern part of nowadays northern Namibia and southern Angola is concerned, it is most important to differentiate between the term 'Etosha Basin' (the depocentre) and the 'Etosha Pan' (the erosion form). In this sense, a perennial lake (including phases of lake shrinkage) can be only attributed to the Etosha Basin during the Cainozoic. The Cunene system never played any role in the development of the Etosha Pan (Rust 1984, 1985), but it fed the Etosha Basin till the end of Tertiary. However, the former long-term depositional history played an important role for the following erosion cycle. As concluded by Rust (1984, 1985), the evolution of Etosha Pan is the result of endorheic erosion processes operating in an epeirogenetically (Etosha Basin) and stratigraphically (sediments of 'Kalahari Group') controlled landscape position.

The postulated lake situation reconstructed at +/- 3 my bp (Pliocene; Fig. 2) by Stuart-Williams (1992) could be only accepted if it were not somehow related to the present-day Etosha Pan. What we know as Etosha Pan today did not exist during that time. Therefore the postulated maximum depth of 40 m following the modern 1 120 m contour line for a saline Lake Etosha at 3 m.a. BP (Stuart-Williams 1992) must be discarded because of a complete lack of field evidence. What is interpreted as a well developed 17-20 m relict shoreline along the western margin of Etosha Pan (1097-1100 m a.s.l.) by Stuart-Williams (1992) (see also Thomas & Shaw 1991: 135) has proved to be a double ridge system of pan margin dunes or lunette dunes according to Hills (1940). The reconstructed lake situation at 35 ka therefore cannot be accepted (Fig. 2). In this context it must be kept in mind that the geomorphodynamical forming of the 1100 m-Level is considered to be older than upper Pleistocene (the last 130-125 000 years), according to the evidence provided by the TL-calibrated pedostratigraphy of the aeolian sediment record of the II. (outer) dune ridge (Fig. 9; V and Fig. 13).

If a permanent lake had existed within the boundary of the present Etosha Pan between 3 my and 35 ka BP (Stuart-

Williams 1992) a vast volume of limnic sediments would have to be expected in this area. On the contrary, the detailed descriptions of 16 hand-augered profiles backed up by sedimentological, mineralogical and chemical laboratory analyses so far give evidence that the parent bedrock of the 'Andoni Formation' (sand-, silt- and claystone facies) is virtually outcropping on the actual floor of Etosha Pan. This situation is typical for the pan genesis (see also Heine 1981). Only at 'Fisher's Pan' do sediments reach a thickness of more than 260 cm, thus indicating that this small outlayer of Etosha Pan acts as a sediment trap for the ephemeral drainage from the east (Buch 1993).

Information on environmental change in the vicinity of the Etosha Pan over the last 140 ka is provided by the pedostratigraphical differentiated record of the aeolian sediments at the western margin. The mineralogical and chemical findings support the idea of a progressive incision of the pan during the Quaternary. During the longest period of the last 2 m.a., erosion and denudation processes were operating in the 'Etosha Limestone'. The 'Andoni Formation' (clay-, silt- and sandstone) was exposed only since about 20 ka (Fig. 9 IV a/b). The aeolian sequence with the initial cambic horizons of the „Okondeka I-III" palaeosoils at the western margin of the Etosha Pan furthermore indicate only minor changes of phases of relative 'geomorphological stability and activity' in the sense of Rohdenburg (1970), that can be explained in terms of the historically known climatic fluctuations and rainfall anomalies. The palaeopedological findings in particular do not support the opinion - which formerly were derived mainly from the inpretation of ^{14}C-data of calcretes - that the intervall between 35 and 25 ka was the last major wet period in southern Africa (see Deacon & Lancaster 1988; Heine 1988 and Stuart-Williams 1992 in comparison to Heine 1991, 1993 and Buch 1993). The 'semi-arid' character of the climate persisted not only during the upper Pleistocene but during the entire Quaternary as indicated by the evolution of the pan in general (s.a. Rust 1984, 1985).

CONCLUSIONS

Etosha Pan is one of the most remarkable geomorphological landforms of the world. In order to reconstruct the evolution of Etosha Pan two alternatives have been discussed since the early investigations by Jaeger (1926/27), namely that 1. Etosha Pan is a desiccated palaeolake, or 2. Etosha Pan is an erosion form. The first explanation is undoubtedly more dramatic, but on the basis of a geomorphological-sedimentological-pedological interpretation of the origin of the pan, no proof was found that Etosha Pan is a desiccated palaeolake (Buch 1993). A shallow saline-alkaline playa lake environment can be only attributed to the terminal evolution of the Etosha Basin during the late Tertiary. The Etosha Basin is the even more extended centre of inland sediment deposition with a long geological history. Due to palaeogeographical/tectonical and palaeoclimatic changes that effected the whole southern African subcontinent during the Pliocene, the Etosha Pan in presently northern Namibia developed as an erosion form during the last 2 m.a.. From a geomorphological and palaeoenvironmental point of view this type of long-term evolution of a landscape is as fascinating and noteworthy as the desiccation of a palaeolake.

It is not the aim of the present paper to develop a 'general model' that can explain the genesis of all pan and pan-like forms in southern Africa. Further investigations should therefore focus on the question, which individual mechanisms could be recognized under specific environmental conditions. In the tradition of earlier observations by Passarge (1904) that very large numbers of congregating wild animals play an important role for the long-term pan genesis and persistent actually forming processes in southern Africa, the ecological model developed by Verhagen (1990) is one more facet, which helps to reconstruct the complex pan geomorphodynamics (see also Buch 1993). Smaller sized pans can virtually be explained by this ecological model alone. However, geomorphological forms in the dimension of the Etosha Pan are seen to be related to the present or a former hydrological system. Here, it is important to learn from the Quaternary geomorphological evolution of the Etosha region that a persistent long-term linkage to an extended catchment area obviously generate the largest erosion forms. The interruption of this surface drainage in the central-north Etosha N.P. initiated the gathering of the smaller and less incised pans of the 'Owambo-Pans-Plain' (see also Marshall 1988).

Judging from the published investigation results of the Makgadikgadi region in the middle Kalahari (e.g. Deacon & Lancaster 1988; Heine 1987), the Quaternary evolution there appears to be more complex than in Etosha, including phases of a perennial lake situation and pan geomorphodynamics. According to the present knowledge, the difference between the Makgadikgadi and the Etosha region is identified in the different drainage system history of the Okavango - the last endorheic catchment of a perennial river system in southern Africa - on the one hand and the Cunene River on the other hand. In conclusion, pan genesis is regarded as a specific type of geomorphodynamical process, which is typical for persistent semi-arid climate conditions over a long period of the geological history. In this sense, pans in the Etosha region are not at all relict landforms as stated for the pans of the southern Kalahari by Lancaster (1978), but still actively formed features under the present environmental conditions.

At a first glance the discussion whether Etosha Pan is a desiccated palaeolake or an erosion form might seem academical. However, the origin of the pan is of the utmost applied interest. Palaeoenvironmental reconstruction provide basic information for climate modelling. By testing the simulations against the geological record the data are used to validate individual 'General Circulation Models' (GCMs) (Street-Perrott 1991). It is expected that GCMs provide reliable predictions of future climatic change, especially with regards to estimations of the impact of the increasing atmospheric CO_2. This ultimate aim can be only achieved if the basic palaeoenvironmental information is as realistic as possible.

In order to test GCM models against the real world, fluctuations in the levels of tropical closed lake systems had initially been thought to provide the most widespread and best dated evidence in low latitudes (Kutzbach & Street-Perrott 1985). The early euphoria about the use of lakes to represent global climatic change has been replaced by a more cautious and critical attitude (Street-Perrott & Harrison 1985; Deacon & Lancaster 1988). Although Etosha Pan fulfills the requirements of a closed hydrological system it should be accepted that this does not necessarily imply the existence of a palaeolake.

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